TECHNICAL BACKGROUND ON LINEAR INDUCTION MOTORS IN TRANSPORTATION

June 1970

OFFICE OF HIGH SPEED GROUND TRANSPORTATION
FEDERAL RAILWAY ADMINISTRATION
U. S. DEPARTMENT OF TRANSPORTATION

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CONTENTS

FOREWORD

In March 1966 the office of High Speed Ground Transportation awarded a contract to study the linear induction motor and its feasibility for high speed ground transportation. In June 1967 the report resulting from this study was published.* It concluded that a linear motor was feasible for this application and recommended that a full scale motor be built and tested.

At the time of writing (June 1970) this full scale motor and a vehicle in which to test it has been completed and has been operated at low speeds on a short test track. Operation on the Department of Transportation's high speed test track near Pueblo Colorado is planned to begin in a few months.

In addition to this activity a second generation linear induction motor is now in the design phase. This 8000 horse power motor, together with an on-board power conditioning unit is intended to be used as an all electric propulsion system for a 300 mph tracked Air Cushion Research Vehicle which is also in the design phase.

All of this work has been sponsored by the Office of High Speed Ground Transportation.

Seven technical papers have been selected to form a technical background on Linear Induction Motors applied to ground transportation. Three of these papers come from Britain and four from the United States. The national origin of the papers is largely fortuitous and no comparisons are intended between the work that is going on in these two countries and in other countries such as France, Germany, Japan and Russia.

For those not familiar with the subject, it is recommended that the papers be read in the order presented.

The first paper forms a convenient introduction to the Linear Induction Motor. It is a survey type paper which lists different configurations of the linear induction motor that are possible and compares these configurations with each other and with other types of linear electrical machines.

The second paper gives some of the background of the U.S. linear motor test program and its status in early 1968.

The third paper is a more general treatment of linear induction motors in high speed ground transportation applications.

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*Study of Linear Induction Motor, Its Feasibility for High Speed Ground Transportation Report No. P.B. 174866 available for $3.00 from
The Clearinghouse
U.S. Dept of Commerce
5285 Port Royal Road
Springfield, Virginia 22151

The fourth paper deals with many factors involved when considering the application of linear motor propulsion to an existing railway system. It concludes that for the British Rail System, linear motor propulsion is not recommended at the present time.

The three remaining papers deal in more detail with the U.S. Linear Motor Rail Test Vehicle program.

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Torrance, California June 1970

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Linear-Motion Electrical Machines

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Abstract—A survey of linear-motion electrical machines is presented. Although various types of dc and ac linear machines are briefly mentioned, linear induction motors are the main concern of the paper and they are discussed in considerable detail. Based on topological considerations, a classification of these machines is presented and their development through the last 70 years is reviewed. A brief qualitative description of the newly developed hybrid machine is also included. Analysis and design problems, and some solutions, as unique to linear machines are discussed. Several possible applications of these machines are included.

Introduction

The great majority of electrical machines are designed to produce rotary motion, thereby exploiting the blessings of circularity which man has enjoyed since the discovery of the wheel. The forces of electromagnetism may, of course, also be employed to produce linear motion, as for example, in a linear induction machine in which the primary member consists of a row of coils carrying currents in phase progression. A simple method of introducing linear machines is that the primary member resembles a conventional rotary machine stator which has been cut by a radial plane and subsequently unrolled, as shown in Fig. 1. A number of different types of linear machines may be developed in this way although, as will be seen later, the linear machine family does not consist only of flat machines which result from such an unrolling process.

It is almost a general principle that when an engineer makes a device in a different size, or of a different shape, or with a new material, he changes the whole operating conditions and the new product may have such different characteristics as to change basically its field of application. In the case of linear electrical machines the effect of linearization is to introduce new phenomena which generally reduce their performance below that of corresponding conventional rotary machines. The history of linear machines tells the story first of the struggle against the factors which detract from performance and of increasing willingness to accept reduced performance for specific applications in which the linear machine offers advantages in other ways.

The changes in operating conditions imposed by changes in shape will first be discussed, using the induction machine to illustrate the processes.

Topological Considerations

Many characteristics of ac machines and of induction motors in particular, are explained in terms of the concept that the primary member sets up a rotating magnetic field in the airgap. That the splitting and unrolling process is likely to modify the characteristics is evident from the fact that any linearly traveling field must now have a start and a finish. Moreover, it is apparently unnecessary for the primary unit to be designed to have an even number, indeed even an *integral* number of poles.

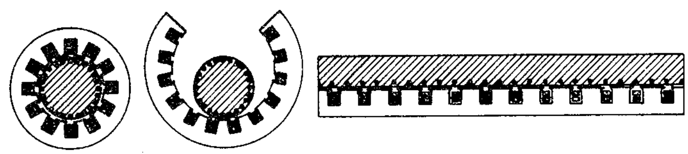

Fig. 1. Imaginary process of unrolling a conventional motor to obtain a linear induction motor.

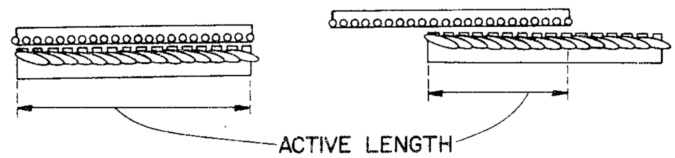

Fig. 2. Active length of primitive form of linear motor is reduced once motion takes place.

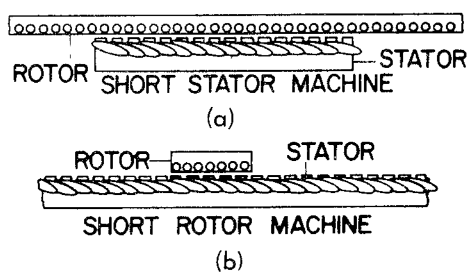

Fig. 3. Basic types of linear motor.

Perhaps even more fundamentally, a linear machine which consisted of an exact copy of the result of mentally "unrolling" a conventional squirrel-cage motor, as shown in Fig. 2, could only be used in a limited number of cases; for to allow the secondary member to move is to lose an ever-increasing amount of the motor as the "cage" emerges at one end, laying primary coils bare at the other. It is clear that where motion over a considerable distance is required with a limited amount of power, either the primary or the secondary member must be elongated.

Such elongation leads at once to two major classes of linear machine which may be designated "short primary" and "short secondary." An example of each is shown in Fig. 3. In general, the short primary is by far the cheaper to build and to run. The secondary member can be simplified in form, often to a simple sheet of conductor and the whole system is only fed with current over a small proportion of its length. In certain situations, however, a compromise arrangement may consist of a long sectionalized primary in which only the sections actually in use are energized.

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The "Sheet-Rotor Motor"

The arrangements so far described have assumed both members to consist of electrical conductors in slots in a laminated steel core, which is the usual arrangement in a rotary machine. With such a structure, however, there exists, in addition to the tangential electromagnetic thrust which the machine is designed to give, a purely magnetic pull between the oppositely magnetized surfaces. In a cylindrical machine only the out-of-balance pull resulting from any asymmetry which may exist is observable. The fact that even this amount may be sufficient to worry the designer of rotary motors indicates the size of the problem which is introduced by the linearizing process.

Accordingly, double-sided flat machines have been developed in which the secondary conductors are no longer housed in slots but operate in the airgap and the magnetic circuit is closed by a steel block only in the region which is energized. Generally, it is advantageous for this second block to be fitted with a secondary primary winding to assist in driving flux through the secondary conductor. The development of the double-sided motor is illustrated in Fig. 4. In the final stage the secondary member is simplified constructionally in that it consists of a solid sheet of conductor, but even this last change of form serves to modify the operating conditions.

Fig. 5(a) shows a typical current flow pattern in the case of the ladder-type secondary conductor (the linear equivalent of a cage rotor). Bar-to-bar currents may only flow via the end conductors, but in the case of a solid sheet, current flow patterns, as shown in Fig. 5(b), are obtained. The effect of longitudinal currents under the active zone is to reapportion the airgap flux so that a higher density exists along the central regions of the machine than along each side. An analysis of this effect has recently been published [6].

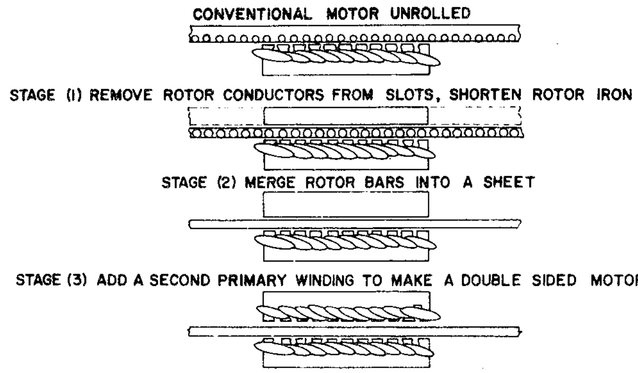

Fig. 4. Development of the "sheet-rotor" motor.

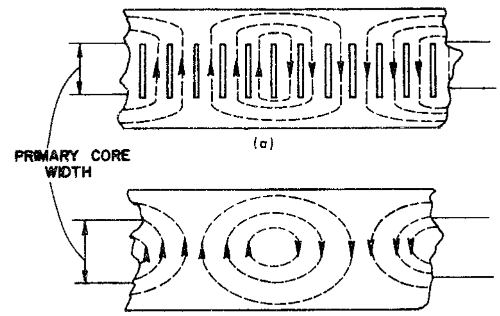

Fig. 5. Current distributions in (a) slitted secondary plate, (b) sheet rotor.

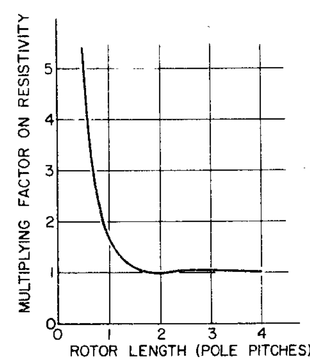

Fig. 6. Effective increase in rotor resistivity due to "short-rotor" effect.

Edge Effects

In addition to the effects of the lateral edges of the primary, further effects, not present in cylindrical machines, occur due to the front and back edges of whichever member is the shorter. In both classes of machine the action of these edges is first to produce standing waves in the magnetic core in addition to the usual traveling component. Second, when relative motion between primary and secondary members occurs, electrical transients are set up by the edges. These "entry" and "exist" edge effects have been analyzed in some detail in earlier publications [3], [12], [25], [35], [37], [59]–[62], [69], and only a summary of these results is included here.

In a short secondary machine, the effect of the transients is hardly noticeable when the length of the secondary is at least 2 pole pitches. For shorter secondaries the effects can generally be represented by an apparent increase in resistivity of the secondary conductor. Fig. 6 shows this increase varies with secondary length in a typical case. In short primary machines the effects are more complex, but the principal features are as follows.

1) The flux distribution along the length of the machine is nonuniform, the distribution varying with speed. In general, the effect is as if the relative motion sweeps the bulk of the flux to the back of the machine.
2) Extra losses, not calculable by conventional machine theory, are incurred in the secondary member in the case of a series-connected machine, and in the primary in the case of parallel connection.
3) The force is not calculable by conventional formulas, being, in general, somewhat lower than for conventional machines. Both this effect and the previous one are noticeably affected by the number of poles along the primary and by the speed: the lower the speed in relation to synchronism and the greater the number of poles, the less the effects.

4) As a consequence of 3), the machines will not run light, as motors, at the indicated synchronous speed. The difference is not marked, except for machines with fewer than 4 poles.

In a conventional machine with cylindrical symmetry the only difference between motors in which primary coils in each phase are connected in series and those in which they are connected in parallel is related to the operating voltage–current ratio, i.e., to the operational impedance of the machine. In linear machines the question of series or parallel connection is a vital one, affecting such questions as the effective use of the material of the electric and magnetic circuits, the efficiency, power factor, etc. This aspect has also been dealt with at length earlier [35], [37]. Generally, it is better to parallel connect a short secondary machine and to series connect a short primary motor. Parallel connection tends to fix the flux distribution at the expense of possible high local current densities or even short-circuit conditions. Series connection insures no local I^2R loss but allows nonuniform flux distributions. A complete duality between electric and magnetic circuits exists for the two types of connection.

Forces Perpendicular to the Driving Direction

Recently, applications have been found for single-sided linear motors in which the secondary may or may not contain ferromagnetic material. Examples are shown in Fig. 7. In this case there exists on the secondary conductor, in addition to the tangential thrust, a thrust away from the surface (the opposite of a magnetic pull). Indeed, the secondary conductor can be levitated in a stable condition in this manner [36]. The whole question of forces perpendicular to the pole surface is a complex one, involving the solution of a multilayer problem [17]. However, it is by no means obvious in the case of a double-sided machine, with only one primary winding in which the secondary conductor is fixed to the unwound ferromagnetic block [Fig. 7(a)], whether the normal force between the members is even attractive or one of repulsion. Also, a quite remarkable result is the fact that a sheet rotor between a pair of wound primary blocks which assist each other in driving flux through the sheet is unstable under the action of normal forces, being attracted to whichever block it happens to be nearer. In this the rotor appears to resemble a slab of ferromagnetic material, although only qualitatively for the electromagnetic side pull is relatively small.

So far, forces in the direction of field travel (which the designer seeks to produce) and forces normal to the pole faces have been considered. In a direction perpendicular to each of these two (i.e., a direction which could be described as "athwartships"), forces may also result from asymmetry of either magnetic or electric circuits. In the case of the sheet-rotor machine, for example, longitudinal currents under the active zone put the secondary sheet in lateral tension and any departure from a truly central position will result in lateral forces tending to increase eccentricity, i.e., to shoot the plate out sideways. This effect may perhaps be explained most readily in terms of the action of a linear-shaded pole motor on the lateral axis.

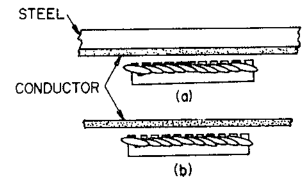

Fig. 7. Examples of single-sided motors.

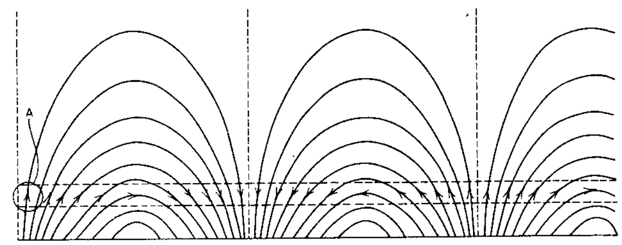

Fig. 8. Mechanism of "rack and pinion" motor.

Ferromagnetic material in the secondary member, on the other hand, tends to be pulled back into line when displaced laterally, and the question of whether a composite secondary (for example, the form shown in Fig. 2) is stable or unstable laterally is again a complex one, the net effect depending on speed, relative thickness of conductor, airgap, etc. One feature, however, appears to emerge from experimental results, although it has never been confirmed theoretically for the general case, viz., secondary members which are repelled normally from their primaries are laterally unstable. Members which are attracted are stable.

A particularly interesting feature of an open-sided machine [Fig. 7(b)] is that the field pattern above its surface contains, in addition to the expected traveling component of the field, a purely rotating component, a fact which can be demonstrated by cutting a small hole in a piece of card and placing it over Fig. 8 with the hole in the card initially over the circle A. Movement of the card across the page so that the hole traverses the space between the dotted lines reveals a continuous change of direction of magnetic field such as to produce a backward-rolling field which can be utilized to drive small cylindrical rotors in the manner of a "rack and pinion" [43]. Such an arrangement is perhaps the complete hybrid between linear and rotary machines.

Axial Flux Machines

One further form of machine remains to be described. Returning to Fig. 1, the linear motor was shown to be developed as the result of unrolling a conventional cylindrical stator. If the flat primary thus produced is rerolled about an axis parallel to the direction of field motion, as shown in Fig. 9, an entirely different form of cylindrical structure is produced in that the field now travels along the bore of the primary. The structure could be described as an electromagnetic "gun." One advantage of this type of structure is illustrated in Fig. 10. Conventional rotary machines and flat-linear machines carry primary windings which could be

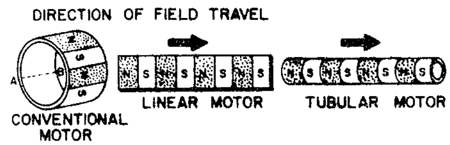

Fig. 9. Development of a tubular motor.

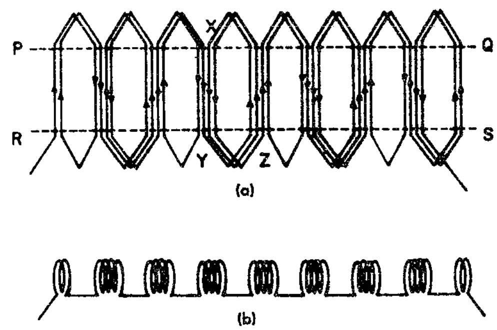

Fig. 10. End-turn advantages of tubular motor windings.

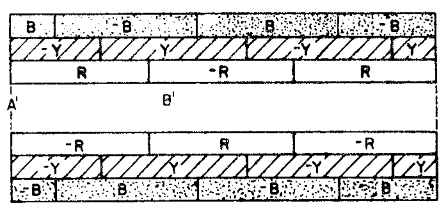

Fig. 11. Three-layer continuously wound tubular motor.

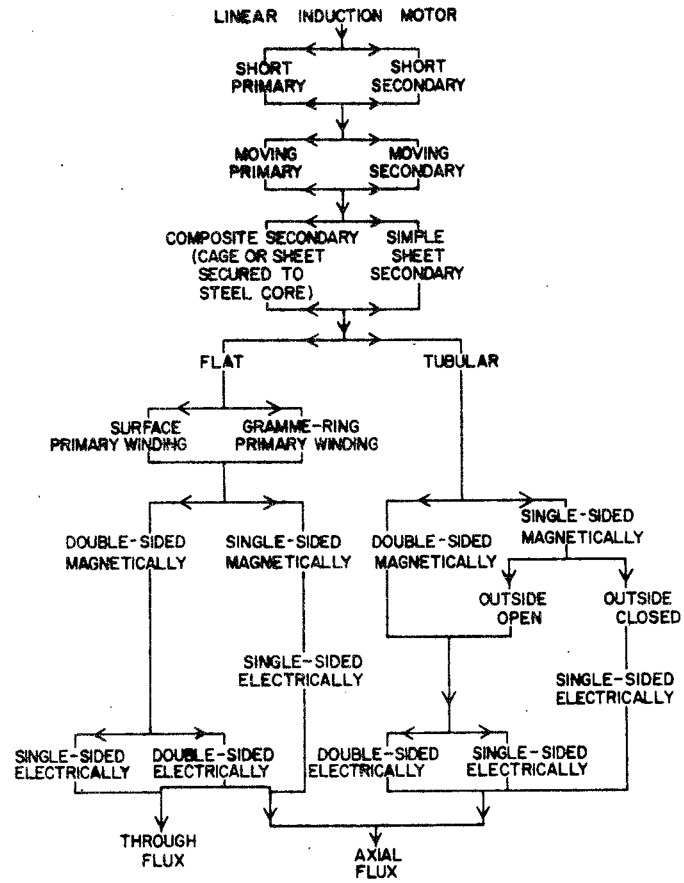

Fig. 12. Topological classification of linear induction motors.

said to be useful only where they pass through the slots, i.e., between the dotted lines in Fig. 10(a). End windings are necessary to route the currents from pole to pole, and apart from the fact that they provide cooling area, they could be said to be wasted. In a tubular motor the winding is rolled up so that PQ falls on RS and the winding may be seen to consist only of circular coils in a row, as shown in Fig. 10(b), or as continuous layers of wire (see Fig. 11), simplifying manufacture considerably.

Topological differences between the tubular motor and the flat machine do not end, however, with the electric circuit. Fig. 9 shows that all the flux emanating from, say, an N pole, must now pass *axially* through the secondary in order to reenter the S pole. It is, therefore, essential that the secondary member contain sufficient ferromagnetic material to contain the flux from a pole pitch (including 100 percent standing wave) so that the core of the secondary member is likely to impose a "bottleneck" on the magnetic circuit.

The tubular motor is a particular example of a whole class of linear motors which includes double-sided flat machines, as shown in Fig. 4, in which the two primary windings are connected so as to produce oppositely directed fluxes into the secondary which thereafter pass axially along the latter. Such machines have been described as axial flux motors [37]. End effects in axial flux motors are different from those in flat machines. While the surface winding of a flat machine demands that a current passing in one direction across the machine must ultimately return in the other, so that $\int J dx = 0$, an axial flux machine may impose any nonintegral pole number from the excitation system. Detailed calculations on axial flux edge effects have also been carried out [37], [48].

One representation of the classes into which linear induction machines can be divided is shown in Fig. 12. By following a route from top to bottom, a particular machine is defined completely. The top three sections indicate simply that every machine falls into one of two classes as regards which member moves, which is the shorter, and whether the secondary contains ferromagnetic material or not. Some of the terminology used is explained in Fig. 13. The definition of "double-sided magnetically," for example, is that the primary structure should contain ferromagnetic material on each side of the secondary. Thus, the simple development shown in Fig. 2 is classed as "single-sided magnetically," the fact that the secondary steel moves making it a composite secondary motor. For this same structure to be double-sided, it would need to carry an additional steel block, as shown in Fig. 13(d). The steel in the secondary serves to reduce effective airgap rather than to carry axial flux. An example of such a machine would be one in which the secondary member consisted of a sheet of aluminum impregnated with steel rivets.

Fig. 12 illustrates the very large number of different kinds of linear machine which result from the combination of various features. Each of the horizontal strata involves fundamentally different factors when theoretical and/or eco-

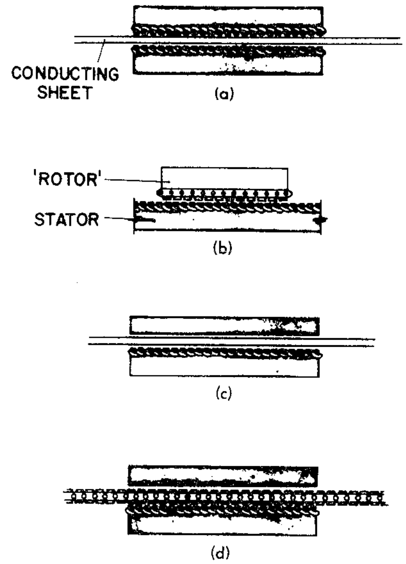

Fig. 13. Some examples illustrating the topological classification. (a) Double-sided electrically and magnetically sheet rotor. (b) Single-sided electrically and magnetically composite rotor. (c) Double-sided magnetically, single-sided electrically, sheet rotor. (d) Double-sided magnetically, single-sided electrically, composite rotor.

nomic assessment of a given system is attempted. Fig. 12, of course, may be used upside down in which case it illustrates that the through flux–axial flux dichotomy is as fundamental as that of short primary–short secondary.

Some combinations which are physically constructable have been deliberately omitted from this classification in view of their economic impracticability. For example, in a flat machine, single-sided magnetically, it is hardly likely to be profitable to fit a second primary winding in space on the opposite side of the secondary from the steel block housing the first winding. On the other hand, such a system is feasible with tubular machines, for the reluctance *outside* the outer primary winding can be relatively low even with air as magnetic circuit, as was shown previously [41].

Historical

The earliest specific reference to linear machines appears to be a patent of 1890 by the Mayor of Pittsburgh relating to induction machines [85]. This was followed by a patent in 1895 by the Weaver, Jacquard, and Electric Shuttle Company who, judging by their title, had high hopes for its use as a shuttle propelling device in weaving looms. Certainly, subsequent patent literature reveals that the most active development of linear induction motors between 1900 and 1940 was in connection with shuttle propulsion, although no one appeared to have commercial success with the device, largely no doubt, on account of the relatively high cost of the electrical system compared with the loom itself. Nevertheless, considerable ingenuity was shown by textile engineers who were sufficiently versatile to advance the ideas of double-sided motors, sheet-rotor motors and tubular motors.

In 1905 there were two separate proposals to use linear induction motors as a railway propulsion mechanism. The first of these [82] proposed short sections of primary embedded in the track which could be switched on as required. The second [84] proposed a primary unit carried on board the vehicle with a sheet-rotor reaction rail on the track. The latter idea was virtually the forerunner of several of the large-scale experiments which are being carried out in several countries at the present time. The fact that Zehden's idea had to wait over half a century before finding commercial exploitation is perhaps due primarily to the ability of other forms of propulsion to satisfy the limited demands of the day regarding speed, acceleration, and reliability.

In 1917 came the first tubular motor which was in fact a dc reluctance machine with switched primary coils [15]. Intended as a missile launcher, the evidence is that it was never developed beyond the model stage. In 1923 a flat induction motor was proposed as a drive for a continuous moving platform system to run below 42nd Street between Times Square and Grand Central Station. A test track was built, but the proposal never came to fruition.

With the development of nuclear power came the need to pump liquid metal, in particular, sodium–potassium mixtures of high conductivity. Both ac and dc types were produced: double-sided flat versions, and tubular motors [5]. The ac machines included not only induction types, but conduction machines (similar to the dc machines), and these could be said to represent the earliest (indeed, perhaps the only) linear ac commutator motors. Flat types were generally preferred to tubular machines since the latter involved breaking the pipeline in the event of a primary winding burn-out. One ingenious hybrid in this family consisted of a more or less conventional cylindrical stator, producing a rotating field, inside of which the liquid metal was routed in a helical channel from end to end of the stator; thus, it made use of the angle-field principle which was subsequently the basis of an experimental variable speed motor [80], [81].

The first large-scale transport application came in 1946 with the development of the Westinghouse aircraft launcher, the Electropult [86]. The primary coil system was mounted on a carriage and the secondary consisted of a winding in slots in a ferromagnetic structure. The motor was very similar to the primitive machine shown in Fig. 2 with extended secondary. Two full-scale tracks were built, one $\frac{5}{8}$ mile long, the other just over a mile. Fig. 14 shows the primary unit on the runway. Current collection was by means of brushes running in the slots alongside the secondary member. Fig. 15 shows an aircraft attached to the primary unit by a sling. The motor developed 10 000 hp and attained speeds over 225 mi/h. A 10 000-pound jet was accelerated to 117 mi/h in a 540-foot run in 4.2 seconds from rest. The system was finally abandoned on the grounds of high initial cost.

Another very interesting linear motor project which was also initiated through aircraft requirements was the dc linear motor developed at the Royal Aircraft Establishment, Farnborough, England, in 1954 [57]. This double-sided flat machine fired missiles weighing several pounds up to speeds of over 1000 mi/h. Space research initiated further experiments in 1961 in an attempt to exceed such

Fig. 14. The "Electropuit."

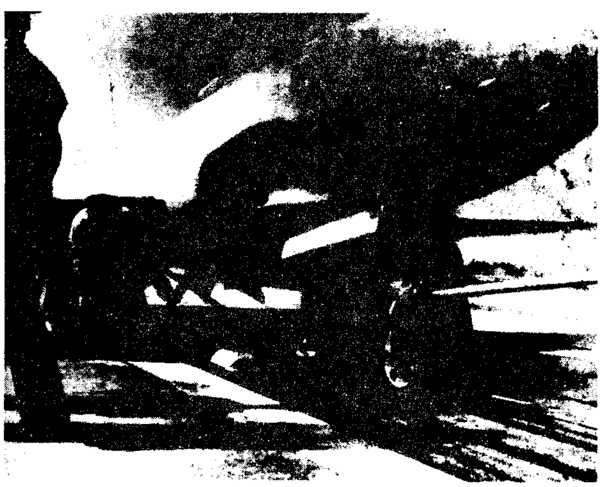

Fig. 15. Primary unit on its track.

speeds with a view to being able to simulate the impact of meteorites on space capsules at "hypervelocities" in the order of 30 000 to 160 000 mi/h [70]. The system which attempted to economize on power input while avoiding direct feed of 3-phase power to the moving part is shown diagrammatically in Fig. 16. The moving coil collects current from a rail by means of a sliding contact and returns it via the stationary coil to a second sliding contact so as to produce a leading and traveling energized section. This experiment failed, but the reason why it failed is particularly interesting because it is fundamental to such systems in that, for any given terminal velocity, there is a minimum mass of metal which can be made to reach that velocity without melting. This rule is closely allied to another which arises in the study of force production by induction systems [36] and may be thus stated: the ratio of the rate of change of temperature of a secondary conductor (assuming no loss of heat by any form of cooling) to its acceleration in unre-

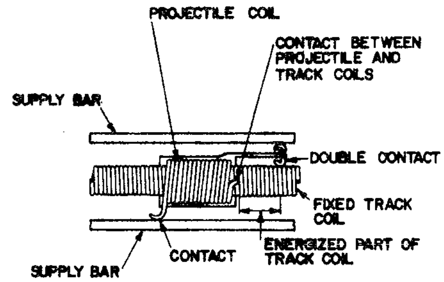

Fig. 16. The hypervelocity induction system.

sisted motion due to the forces of induction is inversely proportional to a power of a linear dimension. This law may be paraphrased in the following manner. "As you make an object smaller you must ultimately melt it before you move it."

The law was formulated in connection with electromagnetic levitation systems, whose devices could be said to constitute linear motors producing force vertically upwards. Much work has been done on such machines and, while their theory of operation extends and in some cases interleaves with that of more conventional linear motors in most fascinating ways, a detailed treatment of levitation systems is beyond the scope of this paper. References to published work other than [36] can be found in the excellent book by Geary [14].

One other aspect of linear motors concerns machines designed to produce oscillating motion without the use of external switching means. In 1956 it was shown that a polyphase induction system could be so designed [22]. This was extended in 1962 by West and Jayawant to include single-phase motors operating as ferroresonant devices [78]. Synchronous oscillating machines were developed in 1960 [30]. By comparison with induction machines, the linear version of the dc machine is in its infancy, although its usefulness as an actuator has now been forecast [16].

Applications

On the basis of topological considerations, a classification of linear induction machines is given in Fig. 12. Because the applications of linear-motion electrical machines range from instrumentation (such as electromagnetic flowmeters) to high-speed ground transportation, it is rather advantageous to divide linear machines into the following classes from applications standpoint:

1) force machines and transducers,
2) power machines,
3) energy machines.

In general terms, some of the applications of linear machines have been mentioned in connection with their historical development. Based on the above classification, force machines, which operate essentially at standstill or at low speeds, find applications as transducers, relays, solenoids, and actuators. The power machines, which often operate at high speeds and must have high efficiency, have

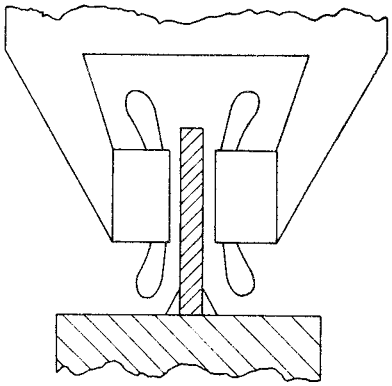

Fig. 17. A track layout.

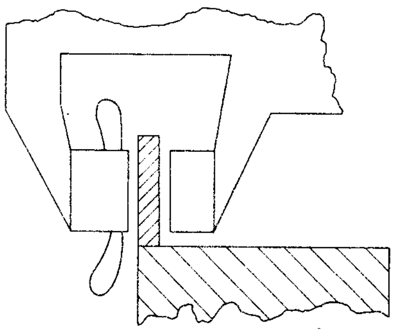

Fig. 18. An alternative track layout.

numerous applications. Some of these include electromagnetic pumps, belt conveyors, linear motors for high-speed ground transportation, magnetohydrodynamic generators, hydromagnetic converters, etc. The energy machines are often large machines and have been used as aircraft launchers (Figs. 14 and 15). Other applications of energy machines have been proposed as impact extruders and accelerators. Naturally, it is not practicable to include a detailed discussion of any of the above-mentioned topics here. In the following, only some of the unique possible applications of the linear machines are presented. For more details references cited in this section may be consulted.

Transportation

Among the various linear machines, the linear induction motor seems naturally suited for applications to transportation systems and offers certain advantages over other schemes [87]. As mentioned earlier, the idea of using a linear induction motor for transportation is an old one, and some of the recently proposed schemes seem to be based on a 1905 United States patent [84]. Between 1905 and the mid-sixties the only other development of the linear induction motor for propulsion was the Westinghouse "Electropult" (Figs. 14 and 15). However, in the fifties experiments with linear induction motors (at the University of Manchester, England) revitalized the interest in the field [22]–[26], and since then considerable progress has been made toward the applications of linear induction motors for propulsion and transportation.

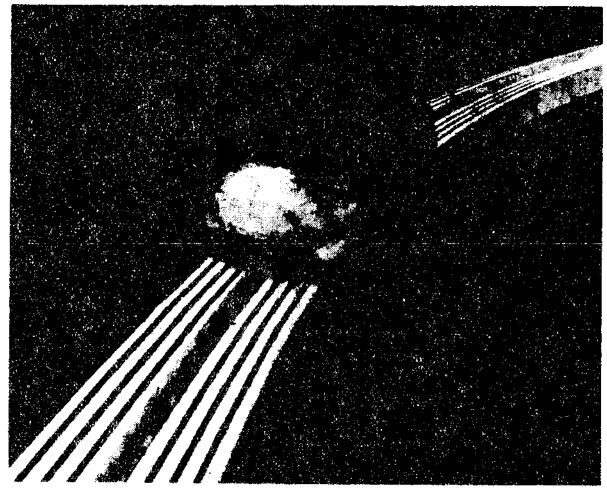

Fig. 19. A tracked hovercraft.

As pointed out earlier, the linear induction motor consists of a stator, or a primary, and a rotor, or a secondary. Various considerations indicate that for traction purposes it is desirable to mount the primary on the vehicle and let the track serve the purpose of the secondary. Track layout and economy have been considered in some detail in [42]. While [87] proposes the scheme shown in Fig. 17 for track layout, [42] suggests several alternatives, one of which is shown in Fig. 18, for electrically single-sided, but magnetically double-sided, motor. It is noted that the motor shown in Fig. 17 is double-sided electrically as well as magnetically.

Because the linear motor for transportation is essentially a power-producing machine, it must be a high-efficiency and, consequently, a high-power (or large) machine. (*Note:* Garrett Corporation is reported to have developed and built a 2500 hp linear induction motor for a 250 mi/h train [89].) The fact that the machine has to be large is a blessing, since it is possible to design large efficient machines which could operate with large airgaps and large pole pitches [34], [37], [41], [42]. While it is true that large airgap is a disadvantage to the linear motor [7], it is not the airgap that solely determines the efficiency of the motor. The relationship between the goodness factor (introduced to aid the design of electrical machines [34]) and the airgap, pole pitch, and the properties of the material is considered in the next section.

Regarding starting, speed control, and braking, methods applicable to the conventional rotary induction motor are suitable for the linear motor also. Some aspects of speed control and braking are available in [42] and [87]. In summary, the linear induction motor seems quite suitable for transportation purposes from an electrical viewpoint, although considerable mechanical problems have yet to be solved. A high-speed tracked hovercraft model is shown in Fig. 19.

Liquid-Metal Pumps

Low-density liquid metals, such as sodium and sodium–potassium alloy, are considered suitable coolants for nuclear reactors. For pumping such liquid metals, which have

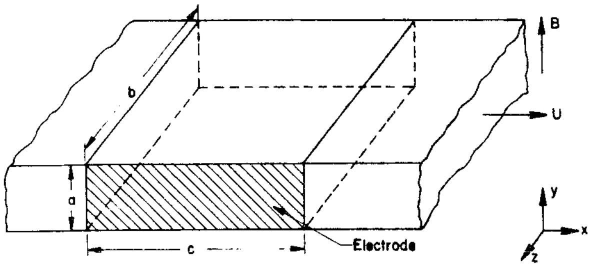

Fig. 20. A rectangular channel.

high electrical conductivities, electromagnetic pumps offer a possible application [5], [47], [77]. These pumps operate on the basis that a pressure is developed within the fluid carrying current in the presence of a magnetic field. The pressure p developed by an electromagnetic pump is obtained from the Lorentz force equation, and is given by

$$\nabla p = \boldsymbol{J} \times \boldsymbol{B} \tag{1}$$

where $\boldsymbol{J}$ is the current density at a point within the fluid and $\boldsymbol{B}$ is the flux density at that point.

Depending on how the current flow is imparted to the circulating fluid in the pump, a liquid-metal electromagnetic pump may be a conduction pump or an induction pump. Evidently, the dc pump could only be a conduction pump, whereas an ac pump may either be a conduction or an induction pump.

The dc electromagnetic pump, in principle, may be considered the simplest linear machine, and it operates on the same principle as the conventional dc motor. A simplified form of the dc pump is shown in Fig. 20, where the fluid flow, and the external magnetic field are mutually perpendicular. If I is the current through the fluid, the pump pressure p is given by

$$p = \frac{IB}{a}. \tag{2}$$

Noting that u is the velocity of the fluid, the flow q through the pump is

$$q = uab \tag{3}$$

and the pump output P_o is given by

$$P_o = pq = \frac{IB}{a}(uab) = Iuab = IV. \tag{4}$$

The ohmic loss in the fluid is

$$P_f = I^2R = \rho J^2 abc = \rho \frac{I^2 b}{ac} \tag{5}$$

where ρ = resistivity of the fluid.

In the above discussion, the effect of armature reaction has not been considered. Due to armature reaction the flux-density and current-density distributions both become distorted [Fig. 21(a)]. This leads to low pump pressure and low efficiency. A simple arrangement for compensating the armature reaction is shown in Fig. 21(b), from which it

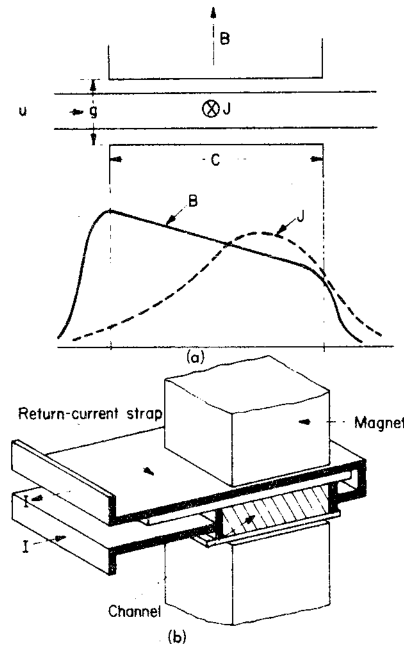

Fig. 21. (a) Armature in a dc pump. (b) Compensation of armature reaction.

can be seen that the main current flowing through the fluid is returned back through the magnet by means of a pole-face winding.

The mode of operation of the dc pump can be reversed to make it operate as a generator, and a pump–generator combination can be used to make a hydromagnetic converter [47], which has the terminal characteristics of an ideal transformer.

Among the ac electromagnetic pumps, the induction pump is preferred to a conduction pump. The linear induction pump is similar, in principle, to the linear induction motor. The presence of the fluid, however, makes the analysis of the pump somewhat complicated [5]. For the channel dimensions shown in Fig. 20, the pump output P_o is given by

$$P_o = P_p(1 - s)s \tag{6}$$

where s = slip, and

$$P_p = \frac{1}{2\rho}\mu^2 ab\lambda u_o^2 H_m^2 \tag{7}$$

is known as the induction-pump parameter. In (7), u_o = synchronous speed of the traveling field, λ = wavelength (or twice pole pitch), H_m = maximum value of (a sinusoidally distributed) field intensity, and μ and ρ are, respectively, the permeability and the resistivity of the fluid. The ohmic loss in the fluid can be expressed as

$$P_f = P_p s^2 \tag{8}$$

and the ideal efficiency of the pump is $(1 - s)$.

So far only rectangular cross-section channels have been considered. However, a tubular pump is also practicable (Fig. 22) which operates on the principle of an axial flux tubular motor. A comparison of operation of various forms of liquid-metal electromagnetic pumps is given in [5] and [47].

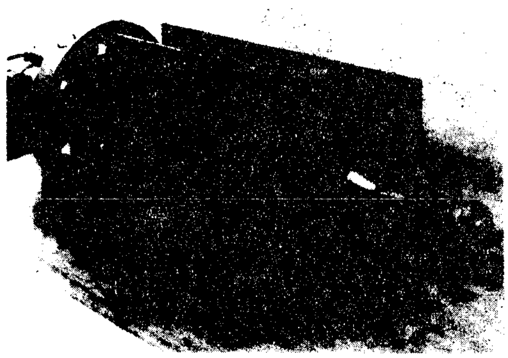

Fig. 22. A tubular induction pump.

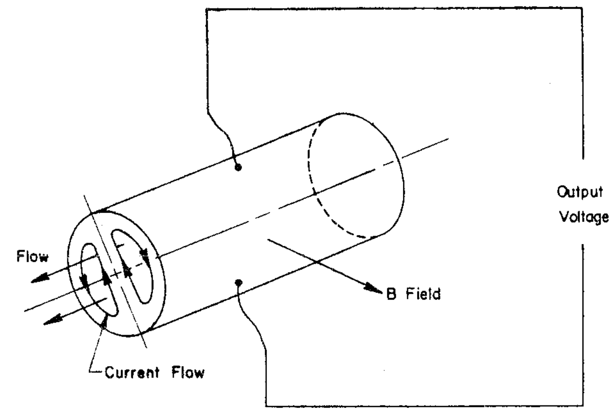

Fig. 23. An electromagnetic flowmeter.

As with the linear induction motor, there are problems associated with the induction pump, also. These are considered in the next section.

Electromagnetic Flowmeters

For transportation and liquid-metal pump applications, the linear machines operate as motors. As generators, the linear machine configuration has been proposed for use as magnetohydrodynamic ac and dc generators. These are not included here because extensive literature is available on this subject [3], [4], [10]–[12], [18], [56].

Electromagnetic flowmeters [59], [60] offer another example of generator mode of operation of linear-motion machines. These flowmeters are based on the principle that an EMF is induced in a conducting fluid moving in a magnetic field at right angles to the direction of the flow. Such a flowmeter may be called a transverse-field flowmeter (Fig. 23). Other forms of flowmeters include axial current and radial flowmeters. The main advantage of the electromagnetic flowmeter is that its output voltage is linearly proportional to the volumetric flow rate. There is, in practice, some departure from this ideal situation because of edge effects, velocity profile changes in the fluid, armature reaction, variation of the electrical properties of the electrolyte, etc.

A flowmeter may utilize a dc field or an ac field, and each has its own merit. With ac fields, polarization at electrodes and thermoelectric and electrochemical dc potentials can be avoided. The dc field flowmeter has the advantage that it avoids skin effect. The dc meter is simple and is less expensive, whereas the ac meter is suitable for electrolytic conductors, for small flow rates and for fluids with small conductivity.

The performance of the flowmeter is measured in terms of its sensitivity S defined as

$$S = \frac{V}{bBu} \tag{9}$$

where V = output voltage, u = mean velocity of the fluid, B = applied magnetic field, and b = separation between electrodes. Several expressions for sensitivity have been derived in [60]. The sensitivity for a transverse-field flowmeter with rectangular channel of nonconducting walls is unity, if the contact resistance of the fluid is zero. On the other hand, for highly conducting walls

$$S = \frac{a}{a + w\sigma_w \rho_f} \tag{10}$$

where w = thickness of the channel wall, a = semiwidth of the channel, σ_w = wall conductivity, and ρ_f = fluid resistivity.

Diverse Applications

Single-sided linear induction motors have been used in the steel industry for stirring molten metal [9], [21], [66]. The electromagnetic induction stirrer has several advantages, as pointed out in [66], but the stirrer inherently has a low efficiency because of relatively large airgap and small pole pitch.

Another interesting application of the linear induction motor has been proposed for impact extrusion [19], [31]. In this case, the machine is an energy producing machine, and although the overall energy efficiency of the original machine was low [19], it is expected that the energy efficiency could be improved.

Several applications of the linear induction motor have been suggested in the textile industry [22], [23], [27]. In particular, a back-to-back flat-linear induction motor acts as an electromechanical oscillator and has possible applications for shuttle propulsion and package winding.

Other applications of linear induction motors have been proposed for overhead cranes, automatic curtain rods, and door operators.

The application of linear motors for conveyors seems quite promising [25]. Some conveyor systems using linear motors are shown in Fig. 24 and Fig. 25.

Finally, applications of linear short-stroke actuators and thrust producers have also been proposed [16], [28], [48].

Some Analysis and Design Problems

The linear machine differs from the conventional rotary machine in two respects. First, in contrast with the rotary machine, the linear machine has a "beginning," or entry edge, and an "end," or exit edge. Second, as compared with the rotary machine, the linear machine has a larger

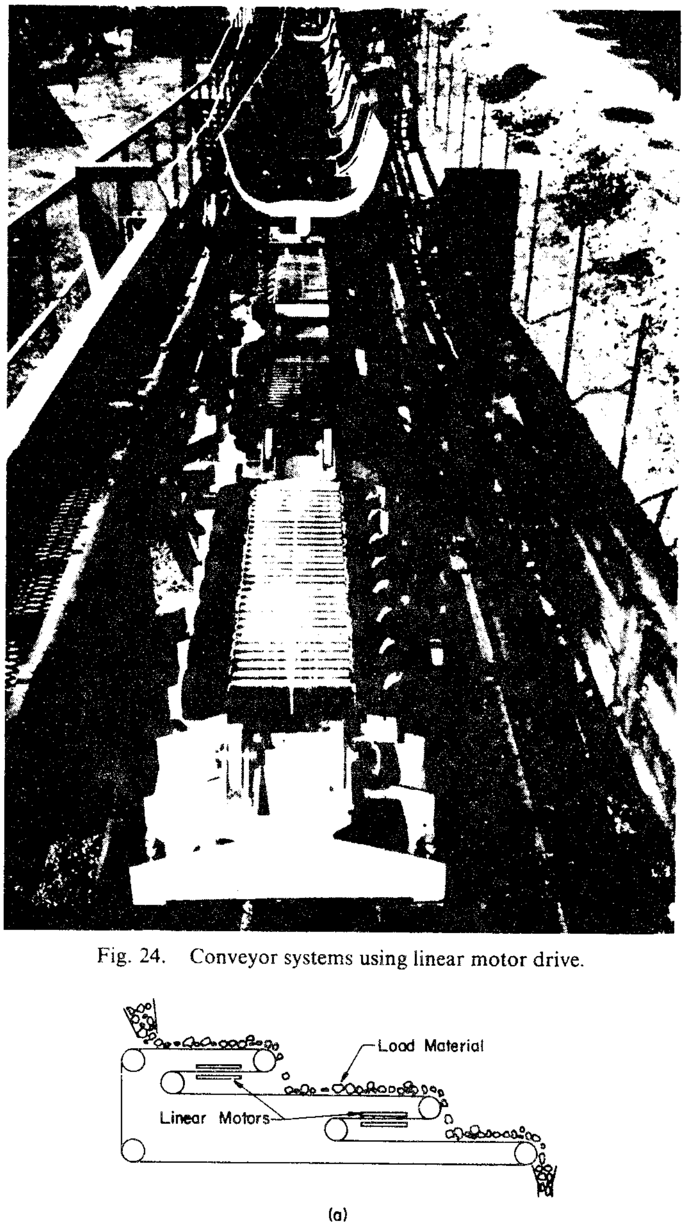

Fig. 24. Conveyor systems using linear motor drive.

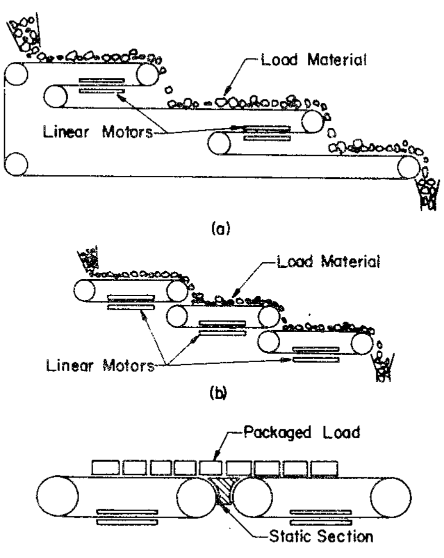

Fig. 25. A conveyor system.

gap. The usual consequences of edge effects [3]–[6], [12], [46], [64], [72]–[76], and large airgap [34], [37], [41], [42], are as follows: reduced power output in generator or motor operation; a pressure loss in electromagnetic pump [58]; nonlinear calibration of flowmeters [59], [60]; and low efficiency and small power/weight ratio in all cases. It is a challenging problem to design a linear machine to overcome the aforementioned undesirable features.

Considering the airgap problem first, the concept of the goodness factor, introduced earlier [34], is recalled. Since the force in a machine is the product of current I and flux ϕ, and the current is produced by a voltage V, and the flux by a current I_m, the product of the current/unit voltage I/V, and the flux/unit current ϕ/I_m, is a measure of the performance of the machine. The goodness factor G is thus defined by

$$G = k\frac{I}{V}\frac{\phi}{I_m} \tag{11}$$

where k = a proportionality constant. Noting that $I/V = 1/R$ (a conductance) and $\phi/I_m = L$ (an inductance), (11) becomes

$$G = k\frac{L}{R}. \tag{12}$$

For an ac machine, the velocity being proportional to the angular frequency ω, and the power being the product of force and velocity, G can finally be expressed as

$$G = \frac{\omega L}{R} \tag{13}$$

where the constant of proportionality has been chosen as unity. For a linear induction machine with sheet rotor, the goodness factor has been found to be [34]

$$G = \frac{2\mu_0 f p^2}{\pi g \rho} \tag{14}$$

where f = frequency, p = pole pitch, g = airgap, and ρ = surface resistivity of the rotor. Clearly, for machines with large airgap, the goodness factor can be increased by increasing the pole pitch.

Numerous interpretations of the goodness factor are now available in [45], [79], and [87]. It seems that the concept of the goodness factor is particularly useful in the design of linear machines. It is not that large airgap is desirable, but (14), at least, indicates that large airgaps could be tolerated and the goodness factor could be improved by adjusting one or more of the quantities p, f, and ρ. A method for optimizing the design of a slow-speed linear machine is given in [48], and could prove useful in other cases as well.

The next phenomenon that is unique to linear machines (and some special-purpose rotary machines) is the edge effect. The consequences of edge effects have been divided as transverse-edge effects [6], [55], [72]–[76], and entry- and exit-edge effects [3]–[5], [12], [37], [46], [52]–[56], [67]–[76], [87]. It is beyond the scope of this paper to present an account of the various methods. The references just cited give considerable details pertaining to the various methods. In general, however, the methods of analysis of edge effects can be considered to be based on 1) circuit theory and 2) field theory. In the circuit theory approach, a distinction is made between a series-connected and a parallel-connected machine [35] and a number of equivalent circuits have been derived for the "short-stator" as well as for the "short-rotor" machine [37]. These circuits, in turn, can be used for the analysis of the linear machine. In the field analysis, the basic equation is the equation for the magnetic vector potential A in the airgap of the machine. This equation takes the form [12], [46]

$$\nabla^2 A - \mu\sigma \frac{\partial A}{\partial t} - \mu\sigma u \frac{\partial A}{\partial x} = 0. \tag{15}$$

The solution to this equation, subject to appropriate boundary conditions, leads to the determination of the magnetic fields in the airgap of the machine. The fields, in turn, yield some of the performance characteristics of the machine. It may be pointed out that it is not practicable to solve (15) for the most general case. Only simplified and idealized models are amenable to this method of analysis.

For the study of edge effects in dc machines several methods are available [58]–[61], [66], [67], and modifications of magnetic circuits and winding distributions have been suggested to reduce the edge effects.

Conclusions

In the changing fashions of engineering several features have emerged which have been favorable toward the use of linear motors, notably, that *overall* economic evaluation of a project is more important than the efficiency of an individual component. Of the developments in linear induction motors themselves, by far the most important have been concerned with the magnetic circuit. Throughout nearly a hundred years of rotating machine development the shape of the magnetic circuit remained virtually unchanged so that the old doctrine of "a good machine has a small airgap" was bound to be upheld. The "goodness factor" method of analysis showed that the airgap length was to be related to other physical dimensions, some of which (like pole pitch) could be more potent in their effect on performance (appearing as a squared term) than airgap length so that new *shapes* of motor offered new degrees of flexibility in design.

Perhaps one of the surprises of linear motor development has been the extent of the diversity of shapes of machine which have been possible. Fig. 12 effectively lists over 100 types of machines which are structurally different from each other and it is almost certain that this classification is incomplete. Indeed, history may record that at this time whole families of linear motor remained to be discovered.

Linear motors have presented new challenges to theoreticians, for the essential discontinuities in the magnetic field patterns have rendered them incapable of analysis by means of the so-called "generalized machine theory." The latter is now seen to be limited to conventional rotating machines, which by the nature of their small airgap and their homogeneity in the axial direction (any slice in a radial plane is the same as any other slice) makes their analysis basically a one-dimensional problem.

The history of engineering has shown how rarely the theory of a new device has preceded its utilization. The job of the engineer is to exploit physical principles by any known means. Often these means have been analogs which, while being far from rigorous, have been extremely useful. The process of discovering new analogs for linear machines is one in which the authors continue to be engaged.

Acknowledgment

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I. R. C. A. — U. I. C.

" HIGH - SPEEDS " SYMPOSIUM

(VIENNA — 1968)

SECTION III : NON-CONVENTIONAL TECHNIQUES

[621 .333 : 656 .222 .1 (73)]

Linear induction motor research in the U.S.A.

Paper presented by :

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« Our nation knows a lot about the engineering and economic and efficiency aspects of transportation. Such knowledge has produced the greatest system of airlines, rail lines, pipe lines, highways and waterways in the world. But we do not have a very good understanding of the social effects of transportation. We have hardly begun to sound the depths of the human implications of our transport decisions. »

Alan S. BOYD
U.S. Secretary of Transportation

Introduction - The background.

The private automobile and the commercial aeroplane together account for a very large portion of the passenger transportation in the United States. Unfortunately, both these modes of transport are presently suffering from congestion. The two following quotations illustrate the point :

« A portent of the imminent automobile-sponsored catastrophes occurred in Boston on December 30th, 1963, when all downtown traffic ground to a jarring halt at 3 pm. This granddaddy of all traffic snarls required six hours to untangle. (1)

» It is 5 pm in New York. Twenty-five jetliners are waiting, with engines running, for their turn to go thundering down the runway at John F. Kennedy International Airport.

» They are also waiting at La Guardia, Newark and Philadelphia.

» And stacked layer on layer in holding patterns near the airports, dozens more flights are waiting to land. Waiting and waiting as they work their way to the bottom of the stack.

» More flights are on the way. Some have been ordered to reduce their speed to delay their arrival in New York until the daily traffic jam has cleared.

» New York-bound flights are lined up for takeoff in Washington. They remain on the ground because they use less fuel there than they would circling and waiting at the end of their trip. » (2)

Under normal circumstances and given time these congestion problems would undoubtedly be solved. However, the growth of megalopolitan areas predicted by our demographers over the next decade or two may not allow enough time, and the « social costs » of the solutions that emerge naturally may not be acceptable.

In 1962, Senator Claiborne Pell of Rhode Island brought this situation to the attention of the U.S. Government and the

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(1) Numbered references are listed at the end of the paper.

late President KENNEDY established a task force to look into the matter. This resulted in the initiation of the Northeast Corridor Project in the Department of Commerce under Dr. Robert NELSON. The Department of Commerce contracted with the Massachusetts Institute of Technology (MIT) to do a Project Transport Study which was executed under the guidance of Dean William SEIFERT.

The MIT study indicated that a linear induction motor was a likely candidate for the propulsion element of some of the new ground transportation systems that were considered necessary to solve the transport problems of the Northeast Corridor and other similar megalopolitan areas. The Office of High Speed Ground Transportation, which is directed by Dr. Robert NELSON and which is now part of the new U.S. Department of Transportation, has undertaken the study of new technology in order to accelerate the development of improved Ground Transport. The linear induction motor is included in these technology studies. My company was fortunate in being awarded a contract by this Office. This contract called first for a study of the feasibility of a linear induction motor as a propulsion element and later for the building of a full scale prototype for test. The work performed under this contract will form a large part of this paper.

The linear motor - A description.

Since the linear induction motor is a device that is not widely used at present, a brief description of some of the forms it can take and their advantages and disadvantages is in order.

A conventional rotating induction motor consists of two electromagnetic members, the stator and the rotor, which are separated by a small air gap. In the majority of cases, the stator is the wound primary member, its laminated steel core carries insulated windings which are connected to the polyphase A.C. power supply and which produce the synchronously rotating magnetic field in the air gap. The rotor of such a motor has a magnetic core which carries uninsulated windings short circuited upon themselves, often called a squirrel cage winding. Currents are induced in these short circuited windings which react with the rotating magnetic field in the air gap to produce the driving torque of the motor.

A linear induction motor can be considered to be derived from the rotating motor by a process of cutting and unrolling both the primary and secondary members and then of greatly increasing the length of one of the unrolled members. Figure 1 *a* illustrates this process for the case where the primary is the member whose length is increased and which is attached to the ground. Applying polyphase A.C. power to the primary windings of this linear motor will induce currents in the short circuited secondary and will produce a thrust between the two members. This thrust will tend to produce a linear motion of the motor secondary. In this and subsequent figures the air gap between moving and stationary members has been considerably increased in order to show details of construction.

This particular arrangement of a linear induction motor is classified as a single sided short secondary configuration. It can be used to indicate the advantages and disadvantages of linear motors in general as well as the advantages and disadvantages that are peculiar to the configuration. Considering first linear motors in general, the advantages are :

Thrust is produced without physical contact. So the motor is suitable for use with all types of guidance and suspension systems including air cushion.

Speed of the motor is unlimited, since there are no large centrifugal forces. So it is particularly suitable for high speed vehicles.

There are no wearing parts such as gears and bearings.

The motor does not produce noise, or vibration, nor does it pollute the air.

The moving parts are light weight (since only one member of the motor is moving). This leads to the possibility of high accelerations and the ability to negotiate steep grades.

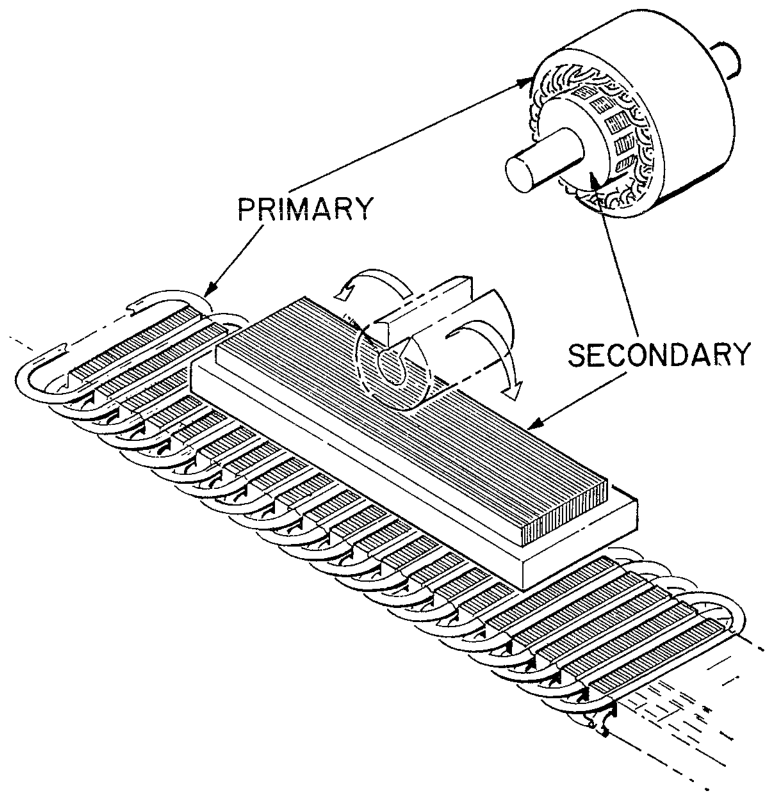

Fig. 1 *a*. — Single sided short secondary linear induction motor.

The disadvantages are :

A small air gap must be maintained between the moving and stationary members of the motor.

The length of the member attached to the ground makes it expensive.

The motor is sized by thrust, and in low speed applications there is no possibility of gearing down a small motor to produce large thrusts.

Considering next the single sided short secondary configuration, the major advantage is that no power need be supplied to the moving member. The major disadvantages are the expense of the long wound primary member, and the large attractive force (approx. 3 to 10 times the thrust) that exists between the moving and stationary members.

A rotating induction motor can be turned inside out by making the squirrel cage secondary the stator member and the wound primary the rotor. This arrangement requires that the A.C. power be fed to the primary by means of sliding contacts. In the same way an unrolled linear motor can be turned upside down by making the short circuited secondary the member that is increased in length and attached to the ground. The primary now becomes the short moving member, and must be supplied either by sliding power pickups or by a power source that moves with the primary. This single sided short primary configuration reduces the expenses of the long stationary member but requires either a power pickup or an on-board power supply. It, too, suffers from a large attractive force between the members. We shall see later that the largest linear motor ever built in the United States was of this configuration.

If one takes the configuration shown in figure 1 *a,* cuts the secondary member into two pieces just above its windings, introduces an additional air gap between these two

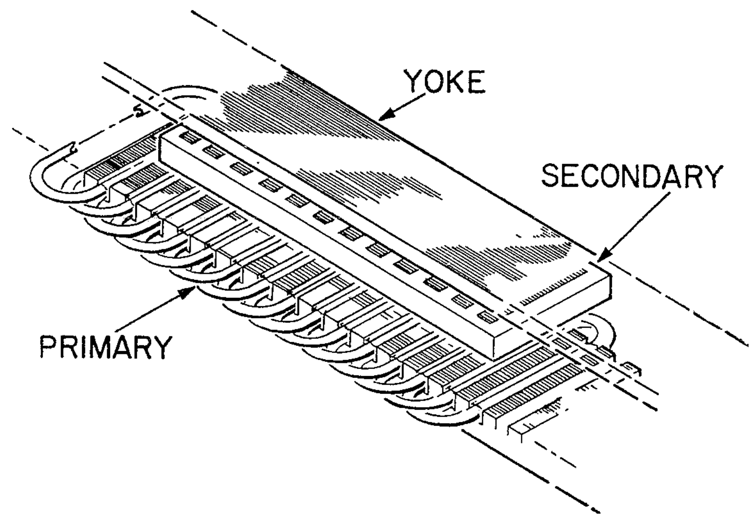

Fig. 1 *b*. — Single sided short secondary linear induction motor with stationary secondary yoke.

pieces, greatly elongates the secondary yoke piece and attaches it to the ground, a new configuration shown in figure 1*b* results. This configuration does not suffer from the large attractive force between moving and stationary members that exist with the two single sided configurations already described.

A more useful configuration can be derived from figure 1*b* by doubling the height of the short moving secondary member, adding slots and a second primary winding to the stationary elongated secondary yoke. This configuration, shown in figure 1*c*, is classified as double sided short secondary. It will produce twice the thrust of the corresponding single sided configuration, the moving member is lighter and there is no attractive force to be dealt with, it is therefore preferred over the single sided version for most applications. The moving secondary member of this configuration is a com-

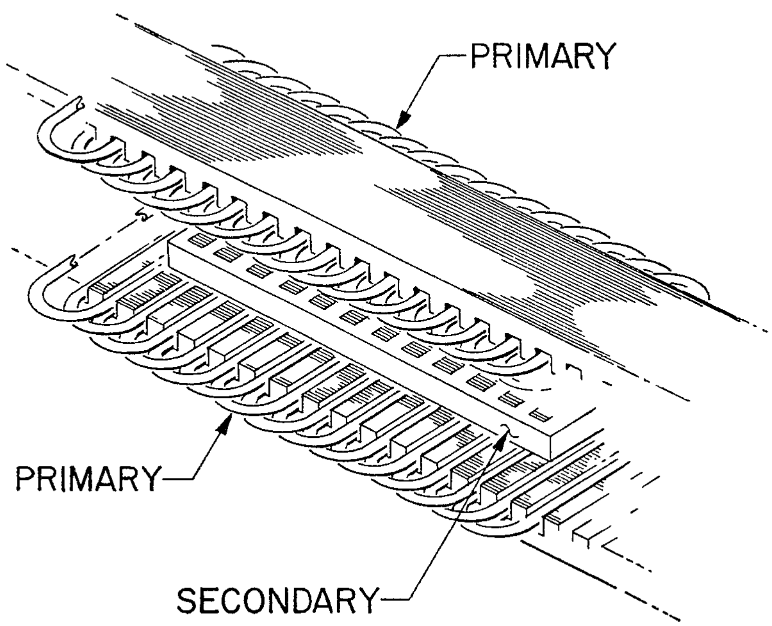

Fig. 1 *c*. — Double sided short secondary linear induction motor.

posite, consisting of high magnetic permeability teeth and a high conductivity squirrel cage winding. If one is willing to increase the magnetizing current flowing in the primary windings, then the composite secondary can be replaced by a homogeneous one consisting entirely of high conductivity winding, which would take the form of a sheet of copper or aluminum. This, of course, represents the ultimate in simplicity of the secondary moving member, but the long double sided stationary member is expensive, and this configuration can be justified economically only in applications where the traffic density is very high.

Linear induction motor performance.

The rotating form of the induction motor is the most popular of all the many types of electric motors. As a consequence, its technology is well developed and its performance is well understood (3). The behaviour of the linear form of the induction motor is basically just the same as that of the rotating form. There are two effects that are responsible for almost all the differences in performance between the linear and rotating forms of the motor. The first is related to the fact that mechanical considerations dictate an air gap for the linear motor that is substantially larger than the « natural » air gap that the designer would choose to use in a rotating motor of the same physical size. The second is due to the fact the linear motor has a beginning and an end in the direction of travel which gives rise to « end effects ». The rotating motor, of course, has no such beginning or end and so no end effects.

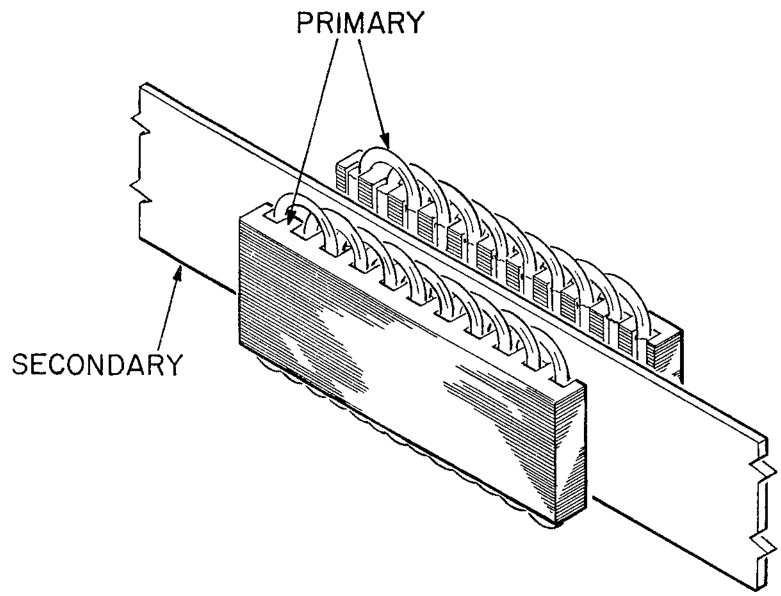

Fig. 1 *d*. — Double sided short primary linear induction motor.

The inverse of this double sided short secondary configuration is the double sided short primary configuration which is shown in figure 1*d*. The long stationary secondary member may be either composite or homogeneous (homogeneous is shown) and is referred to as the reaction rail since it transfers the thrust reaction to the ground. If one chooses to use homogeneous secondary material this represents the ultimate in simplicity and cost of the long stationary member. For this reason it is the preferred configuration for applications with lower traffic density.

The end effects result in some additional power losses and in a parasitic drag which is a function of slip (4) (5). However, the motor used in traction applications tends to be relatively long in the direction of travel so that the end effects become less important, and do not greatly affect the motor's performance. The large air gap lowers the power factor and increases the size of the motor for a given thrust, but does not affect the general form of the motor's characteristics. With the differences due to these two causes in mind, one can treat the performance of the linear motor in just the same manner as that of the rotating motor.

Two modes of operation of the linear motor will be considered, a constant frequency and a variable frequency mode. Figure 2 shows characteristics of a double sided short primary linear motor having a homogeneous reaction rail. These characteristics have been calculated using the classical equivalent circuit method, allowance has been made for end effects, and they depict operation at constant frequency and constant motor terminal voltage. The similarity to rotating induction motor performance is evident.

The thrust versus speed characteristic of this motor would be usable for a traction application, but the low efficiency and low power factor that exist at all speeds except those that are within a few percent of the maximum speed represent a major drawback. A vehicle propelled by such a motor would probably take about 5 minutes to reach cruising speed. Designing the linear motor to deal with the large losses occurring in the primary windings during this period is some penalty, but the main problem is in designing the power distribution system that will supply the large KVA at a low power factor and still maintain the voltage at the motor terminals. Another disadvantage is that there is no control over the cruising speed of the vehicle. There may also be a problem with local heating of the reaction rail at standstill and very low speeds of travel.

The performance of a short primary linear induction motor that is operated from a constant frequency power supply can be significantly improved by using a reaction rail of higher resistance at the lower motor speeds. At any motor speed less than the speed of maximum thrust there is one value of reaction rail resistance that will give a thrust equal to the maximum thrust. If this value of reaction rail resistance is used at all speeds then the KVA consumed by the linear motor is constant and equal to the KVA at the speed of maximum thrust. The dotted lines for thrust and KVA shown in figure 2 show operation with this « ideal » value of reaction rail resistance at all speeds

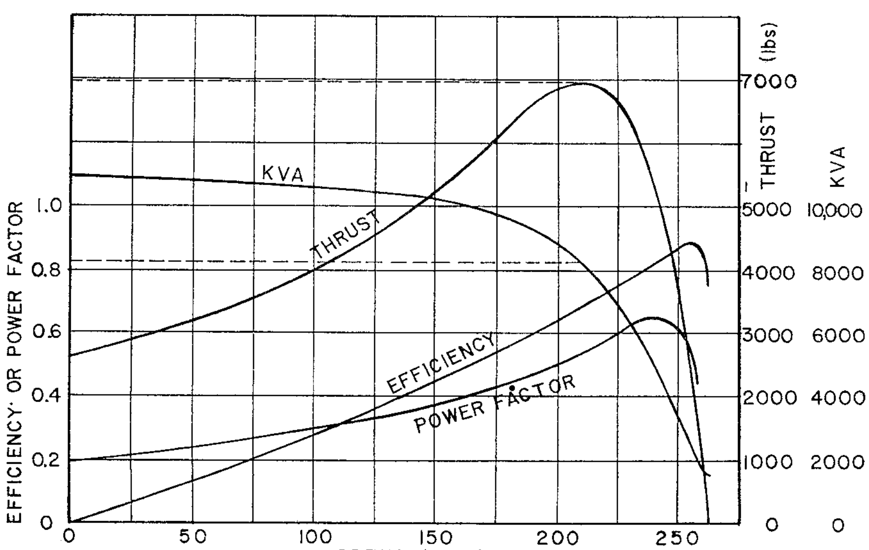

Fig. 2. — Linear induction motor performance: constant frequency and voltage.

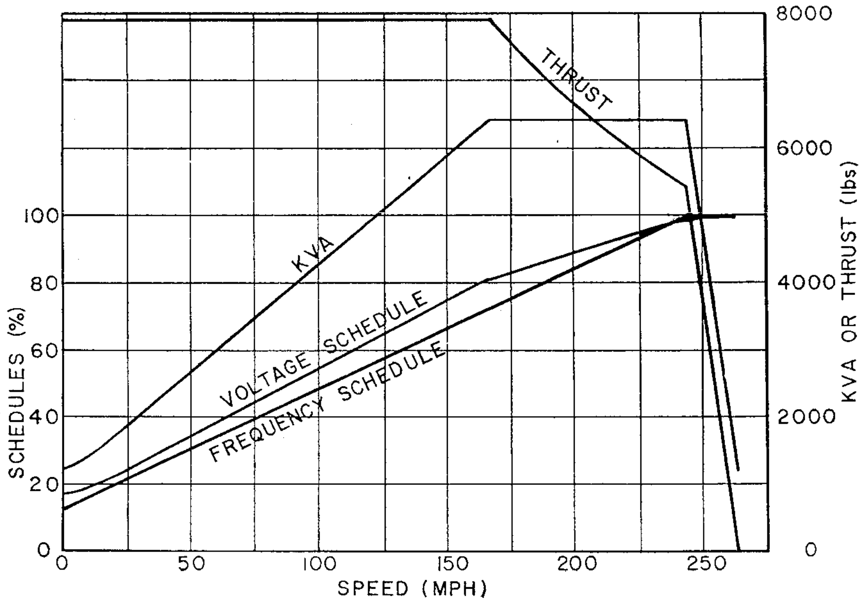

Fig. 3. — Linear induction motor performance: variable frequency and voltage.

below that of maximum thrust. It is possible to have a relationship between reaction rail resistance and distance from a given point that will fulfill the condition of « ideal » resistance for one particular relationship between linear motor speed and distance. Any departure from either of these relationships will result in lower thrust, so the dotted lines of figure 2 represent the upper limit of what might be achieved in practice.

If a power source capable of producing variable frequency and variable voltage is available then the performance of the linear induction motor is greatly improved over its performance on constant frequency. Figure 3 shows the thrust versus speed characteristic of the linear motor of figure 2 when operated with the frequency and voltage varied according to the schedules shown. At all speeds, except for a small range between about 190 and 240 mph, the thrust produced by variable frequency mode of operation is considerably better than that of the constant frequency. The maximum KVA required to produce this improved accelerating thrust is only 59 % of that required with the constant frequency mode of operation, and at standstill it is only 11 %. The power loss in the reaction rail at standstill is only 11 % of that at constant frequency and reaction rail heating at very low speed is not a problem. The extra losses in the motor primary during acceleration are only about half those occurring with the constant frequency mode and do not represent a design penalty.

It will be noted that the frequency schedule calls for constant frequency above about 240 mph. This produces a sharply falling thrust versus speed curve which holds the linear motor speed approximately constant at a speed close to 250 mph. If some other speed had been chosen for the point of constant frequency then the speed of the linear motor would be held approximately constant near this speed, thus providing a ready means of speed control of the linear motor. The losses that occur in the motor when it reaches equilibrium at constant speed are low enough that continuous operation is possible at any speed below 250 mph. Thus it appears that variable frequency operation is much the most desirable mode of operation. Essentially, the whole of the problem of the variable frequency approach lies in the power source needed to provide the necessary frequency and voltage and the controls for this power source.

Comparison with other methods of propulsion.

At speeds below about 200 mph the wheel is presently by far the best means of support, guidance and propulsion for ground vehicles which can use some form of prepared roadway. At speeds higher than this the wheel begins to encounter difficulty in providing the large propulsive force needed to overcome vehicle inertia and the increased vehicle drag. Non-load bearing wheels have been suggested but do not seem likely to provide a solution in all situations. One therefore looks to forms of propulsion which do not rely on contact with the roadway. Airplane propulsion systems such as propellor and jet engines which produce thrust by reaction with the air are candidates and so are the linear turbines and linear electric motors which react with the ground, but do not require direct contact with it. There is very little information available on the linear turbine at present. For this reason it is not included in these comparisons.

The propulsive efficiency of three types of airplane propulsion system (6) is compared with that of a linear motor in figure 4. These curves show that, because the airplane systems produce their thrust by reaction with fluid air, 15 % or more of the energy used for propulsion is wasted in moving the slip stream. The linear motor produces its thrust by reaction with the solid ground so the backward velocity of the « slip stream » is zero and the propulsive efficiency is virtually 100 % at all speeds. This difference in propulsive efficiency, which reflects in energy cost, is important but would not in itself be decisive.

The airplane systems of figure 4 all employ an open cycle gas-turbine heat engine as their prime mover. The linear motor could have an on-board prime mover, which would most probably be an open-cycle gas turbine. These turbines, in their present form, produce so much heating of the air that operation in a tunnel becomes a problem, they also have some « social cost » debits.

The propellor and the linear motor can be powered electrically. The electric motor is clean, has low noise and produces only a fraction of the tunnel heating. The propellor itself is quite noisy, requires a larger cross section of tunnel and produces overturning moments on the vehicle. The linear electric motor then seems to be the best choice, provided the expense of the reaction rail can be justified. If the high speed vehicle is to be operated in an evacuated tunnel then the linear motor seems to be the only choice.

History of the linear motor in the United States.

The earliest use of a linear motor in a railroad application in the United States that we are aware of dates back to 1851 when Charles Grafton Page (7) used oscillating linear electric motors to drive a railroad locomotive through the same system of cranks used with steam locomotives of the day. The locomotive was tested on the tracks of the Washington and Baltimore Railroad; we believe the tests were successful

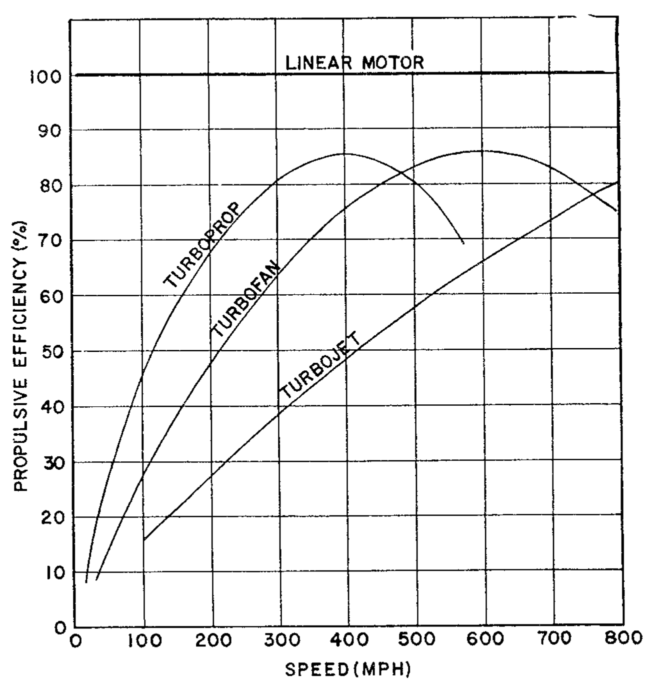

Fig. 4. — Propulsive efficiency of various propulsion systems.

TABLE 2

Fuel cost

Quantity	*Auto*	*HHSV*
Cost of fuel ¢ / gall. (*)	25	—
Cost of fuel ¢ / kW-hr	—	1.2
Miles per gallon	15	—
Energy consumption kw-hr / mile	—	11
Cost per mile ¢	1.67	13.2
Number of seats	6	84
Cost per seat mile ¢	.28	.16
Speed mph	65	250

(*) Exclude Federal and State Taxes (used in part for highway building and maintenance).

6-1/4 miles of track per vehicle. The cost of the homogeneous reaction rail is likely to be no less than \$ 4 per running foot(*) or \$ 130 000 per vehicle. The cost of the linear motor on the vehicle will be only a fraction of this, so there is considerable incentive to design the linear motor for minimum reaction rail cost.

With present day construction costs it seems reasonable to assume our hypothetical vehicle could be built in quantities of 50 to 100 for about \$ 200 000 each or about \$ 2 400 per seat. Table 1 compares the cost of this vehicle with that of a private automobile. This table shows that the first cost of the automobile on a per seat basis is much less than our vehicle, and when the longer life of the vehicle is considered the per seat per year cost is still 1-1/2 times that of the automobile, but when the larger number of operating hours per year of the vehicle is taken into consideration the vehicle cost is about half of the automobile. When the difference in average speed is considered the first cost per seat mile is almost 10 to 1 in favor of our vehicle.

(*) Estimated installed cost of the reaction rail alone.

In table 2 the fuel or energy costs of an automobile cruising at 65 mph on a super highway are compared with those of our hypothetical vehicle cruising at 250 mph on its air cushion guideway. The table shows that the automobile cost is about 1-1/2 times that of the vehicle despite the fact that it is moving a about 1/4 the speed.

The mechanical maintenance cost of the hypothetical vehicle will be extremely low since the only wearing parts are associated with the power pickups, the air cushion blowers and the car auxiliaries such as air conditioning. Any comparison with the automobile is meaningless because the difference is so great.

The other major cost item is that associated with the amortization and operating costs of the fixed assets — guideway, stations, etc. Any assessment of these costs involves the manner in which the accounting is going to be done and is beyond the scope of this paper.

Prototype linear motor for test.

The feasibility study report suggested that a full scale 2 500 HP prototype linear motor be built and tested at speeds up to 250 mph. The Office of High Speed Ground Transportation strongly supported this recommendation and the work of building this prototype is proceeding.

The linear motor is designed to produce a continuous thrust of 3 750 lbs at any speed up to 250 mph. This is 2 500 HP at 250 mph. The motor is of the double sided short primary configuration and uses a homogeneous reaction rail. The feasibility report recommended a composite reaction rail to give best performance, but the costs dictated the use of a homogeneous rail for the prototype. Figure 6 shows a drawing of the motor.

It is designed to use 1/4 inch thick aluminum reaction rail, with a clearance air gap of 5/8 inch each side, making a total distance from core to core of 1-1/2 inches. This rather large air gap was chosen for the design point of the motor so that it would give acceptable performance at clearance air gaps as large as 1.0 inch each side. The drawing of figure 6 shows how the clearance air gap can be adjusted by the use of spacers placed in the center of the U shaped motor support frames. It is planned to operate the motor at these large clearance gaps as a part of the testing program. It will also be operated with 1/4 inch clearance gaps, when of course it will have the capability of producing more than 2 500 HP.

Because of the large design point air gap the size and weight of the motor are large. The stack height is 10 inches and the length is 168 inches which is a total of 3 380 square inches for the two sides. The design thrust is 3 750 lbs or 1.1 lbs per square inch.

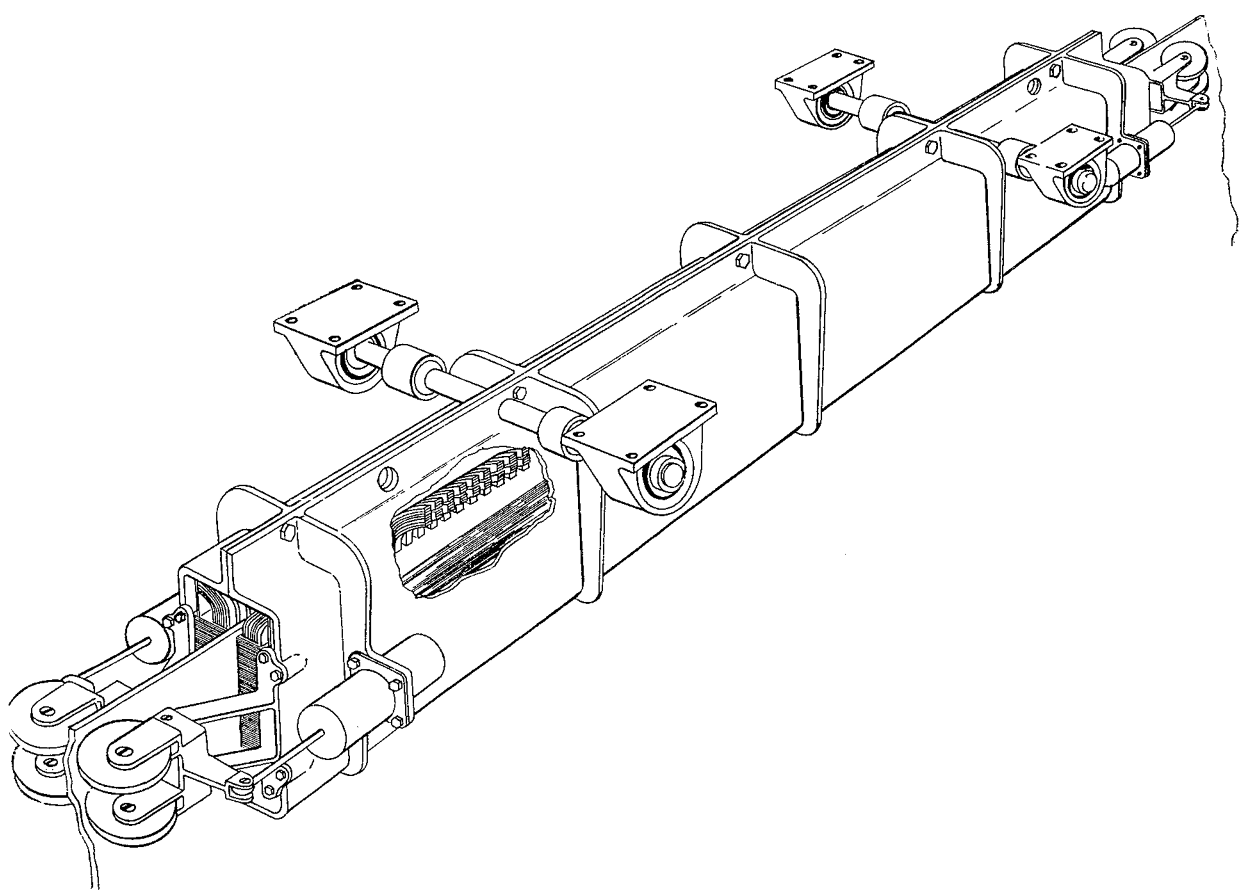

Fig. 6. — 2 500 HP prototype linear induction motor.

The pole pitch of the motor is 13.5 inches which, with a slip due to load of 10 Hz, gives a linear speed of 250 mph with an input frequency of 173 Hz.

The motor is wound with 12 poles and three phases using 5 slots per pole per phase. A conventional double layer lattice type winding is used having single turn coils with 2/3 pitch. All the pole groups of each phase on one side of the motor are connected in series (this is required by the end effect flux). But the phases of the two sides of the motor are connected in parallel in order to keep the voltage as low as possible and thereby minimize insulation thickness and improve cooling. The three phase windings are connected in delta for the same reason. The motor primary and a portion of the reaction rail are cooled by air which is blown through the motor by a separate fan.

The test vehicle.

A perspective view of the complete test vehicle is shown in figure 7. It will be seen at once that this is not an air cushion vehicle but one that uses conventional steel wheels on standard railroad track. This arrangement was chosen partly to avoid simultaneous development of a linear motor and an air cushion vehicle and partly to gain experience with high speed rail vehicles such as those that would be required in an evacuated tunnel. An air cushion vehicle with linear motor propulsion is planned later in the program when experience has been obtained in the operation of this linear motor.

The aluminum reaction rail is mounted vertically mid-way between the two running rails. Larger than normal wheels (38 inch diameter) are employed and the frames of the bogies are designed so that nothing projects below the axles in the central part of the bogie. This allows the reaction rail to project 16 inches above the top of the running rails. The double sided linear motor straddles the reaction rail and is attached to the vehicle between the two bogies.

For the initial test an on-board supply system is planned using a 3 000 HP gas turbine engine which drives a 2 000 kW alternator through a single stage reduction gearbox. The turbine - gearbox - alternator assembly is mounted in the vehicle above the linear motor. The gas turbine, which is built as an aircraft propulsion turbine, is of the two shaft or free turbine type which enables the power output shaft to supply driving torque at any speed from stall to maximum. By coupling the alternator to the output shaft through a fixed ratio gearbox variable frequency A.C. power can be produced by the alternator. The gearbox ratio and the number of poles on the alternator are chosen to give an output frequency of 173 Hz at maximum speed of the turbine output shaft. This corresponds to 250 mph speed of the vehicle. At any speed of the vehicle, the speed of rotation of the alternator and the power turbine are almost directly proportional to the vehicle speed. (They would be exactly proportional if the linear induction motor had zero slip.)

This variable frequency mode will be normal operational procedure for the vehicle. The alternator voltage regulator is arranged to provide a terminal voltage directly proportional to its speed, and the vehicle is controlled by manipulating the gas turbine throttle. However, it is possible to operate the linear motor in a contant frequency mode by controlling the turbine and alternator at a constant speed with an engine governor. With this arrangement the acceleration of the vehicle is controlled by the excitation of the alternator, and the vehicle will reach an equilibrium speed determined by the governor setting.

The electrical system is arranged to provide dynamic electric braking from the linear induction motor. A three phase braking resistor, which is forced cooled by ram air, is connected across the terminals of the linear motor and the gas turbine throttle is set at « idle ». Under these circumstances the alternator spins at a speed slightly below that corresponding to the vehicle speed and it provides the magnetizing current needed by the linear motor under the control of the voltage regulator. The real power pro-

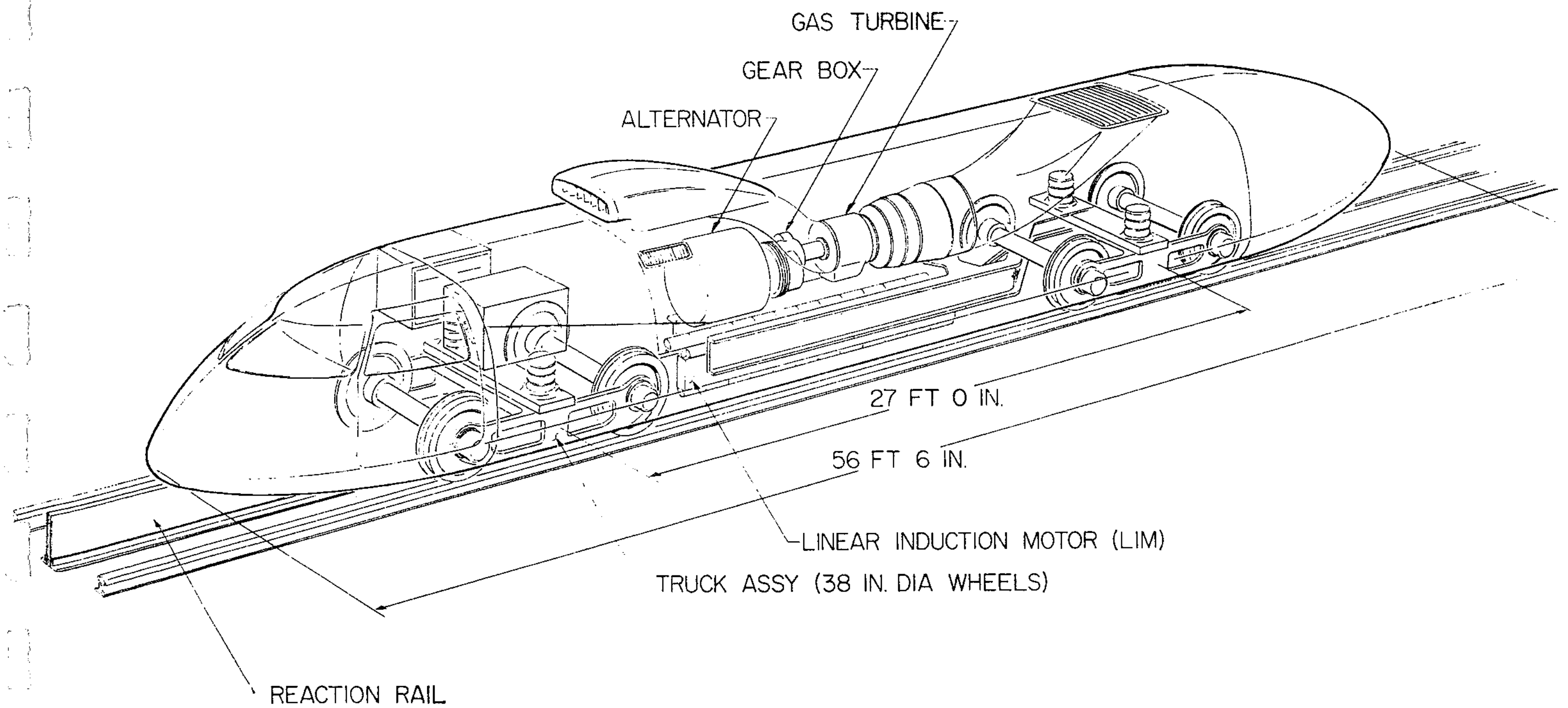

Fig. 7. — Test vehicle for linear induction motor testing.

duced by the linear motor acting as an induction generator is dissipated in the braking resistor. The magnitude of the braking resistor is varied to control the braking thrust. The dynamic brakes fade at some low vehicle speed and must be supplemented with friction brakes for the final stop and for parking.

There is a second gas turbine engine of about 200 HP on board the vehicle which is used to supply excitation power to the alternator, to supply cooling air to the alternator, the linear motor and the electronic equipment, to charge the battery and to start the main gas turbine.

The on-board electronic equipment includes the controls and regulators needed to operate the main power unit and the auxiliary power unit, instrumentation to measure innumerable variables, record some of them and telemeter others, and to receive commands from a ground based station for the purpose of complete remote control of the vehicle.

There is a small passenger compartment at the front of the vehicle with controls to permit operation from this position.

The linear motor is mounted to the vehicle in such a way that the weight of the motor is carried on the vehicle, the driving and braking thrusts are transmitted to the vehicle but the motor is free to move in the lateral direction with respect to the vehicle; it also has limited freedom to roll and to yaw with respect to the vehicle. This method of mounting to the vehicle is to allow testing of guidance systems for the linear motor which will keep it aligned with the reaction rail to close tolerances such as $\pm$ 3/16 inch. Two types of motor guidance are being considered; one employs rollers which bear on the reaction rail, the other is an air cushion suspension system which reacts on the sides of the reaction rail. A servo system which senses the reaction rail position and moves the motor into position may also be tested.

In addition to experiments using guidance of the motor to the reaction rail, it is planned to do experiments with the core to core distance of the linear motor increased by the use of spacers and the motor rigidly attached to the vehicle, in order to duplicate vehicle systems which do not employ separate motor guidance. To make these experiments more widely applicable it is planned to use different springs and dampers including a « solid connection » between the bogies and the linear motor, thereby varying the amount and type of movement of the linear motor with respect to the reaction rail.

This vehicle is built primarily for test purposes. It has a gas turbine prime mover on board because this is the most convenient power source to use at this stage of the program. Operational vehicles will almost certainly be powered electrically by some form of power pickup.

The schedule calls for delivery of this vehicle to the test site ready for testing in December 1968. It is planned to present more detailed drawings and pictures of the vehicle and its component parts at the meeting in Vienna. If time permits, some of the more interesting experiments that are planned will also be discussed.

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Application of linear induction motors to high-speed transport systems

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Abstract

The linear motor has been chosen as the method of propulsion for the full-scale prototypes of several high-speed transport systems currently being developed. The paper sets out the problems of the electrical design of such systems, showing its interdependence with the mechanical and thermal designs. Attention is then concentrated on the double-sided flat linear motor with conducting-sheet secondary, which is thought to offer the greatest advantages for long tracks. Considerations of power supply, thrust and speed control and methods of braking are included. It is shown that a steel plate cannot be used as secondary conductor on economic grounds. The particular requirements of vehicles which are suspended on air cushions are considered throughout the paper and a concluding section discusses the possibility of using electromagnetic current collection for such vehicles.

1 Introduction

The idea of using linear induction motors for propelling trains dates back at least to 1905. One proposal[1] was to use an opened-out primary winding on the track. It was realised that the cost of providing such apparatus continuously for hundreds of miles would be prohibitive, and it was proposed to use short sections of stator at intervals along the track, with provision to switch on the appropriate sections when required. Another proposal[2] of the same date showed a double-sided motor primary mounted on the vehicle. This arrangement is effectively the one now proposed for several large-scale experimental tracks, and Zehden's patent could therefore be said to have been over half a century ahead of its time. In many cases where an original concept precedes its exploitation by such a long period, the reason for the delay can often be ascribed to the need for a new material or device to realise the full potentialities of the idea, and such was the case of Charles Babbage, who, in 1838, conceived the high-speed computer, an idea which had to wait over half a century for the development of the thermionic valve. In the case of linear motors, however, no such new tool was needed, and that no large-scale transport system using this propulsion has ever been built may be attributed to the ability of other forms of propulsion to satisfy the limited demands of the day regarding speed, acceleration and reliability.

The first big development in linear traction motors was undoubtedly the Westinghouse aircraft launcher 'Electropult' built in 1945.[3] In this machine, the primary winding was carried on the vehicle, so that the whole of the energised portion of the machine could be used continuously, at the expense of supplying the moving member with power, necessitating brushes and continuous conductors for the whole length of the track. The carriage developed some 17000lbf of starting thrust and had a maximum speed of 225mile/h. It remains the largest linear motor which has ever been built. That this project was finally abandoned on the grounds of cost is not surprising, for while the moving-primary arrangement allowed full use to be made of the power input, the design failed to make the best use of materials, for the secondary member, embedded in the track, consisted of conductors in slots in a laminated-steel slab over a mile long. The motor was virtually the linear equivalent of a wound-rotor induction motor.

In the 1950s, the case for the 'sheet-rotor' type of motor was reopened at Manchester University, using a short primary winding to drive a 4ft-diameter aluminium disc, and, at the suggestion of one of the authors, demonstration test tracks were set up, first at the University, and later in collaboration with British Railways at the Gorton locomotive works. These machines were too slow to provide information relating to transient effects introduced by the edges of the primary winding. The Gorton machine was restricted to 100yd of track, the maximum speed attained was about 30mile/h (synchronous speed 34mile/h) and the goodness factor[5] was of the order of 4. Edge transient effects were therefore heavily damped.

The experiment, however, served to stimulate a revival of interest in the linear motor as a traction drive in several parts of the world. A test track was set up in Japan, where it is now proposed to equip a fully operational high-speed line with linear-motor drive. A recent report[4] prepared for the US Department of Transportation recommends the building of a 2500h.p. prototype linear motor capable of producing speeds of 250mile/h, and the French Aerotrain organisation has quoted 1970 as a possible date for the incorporation of linear-motor drive into their air-cushion vehicle. In this country, it is proposed to build a test track for full-scale tracked-hovercraft trials, and this also will incorporate a linear motor.

In view of such activity, it seemed appropriate at this time to set out the problems of designing linear motors and their associated control systems, and to indicate the present state of research into these problems. It will be appreciated that much of the experimental confirmation has had to be obtained by simulation, since no high-speed track exists, although results obtained on machines designed for purposes other

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than high-speed transport are now proving useful. Linear motors are finding application in many fields and these applications may be divided broadly into three classes:

(*a*) force machines
(*b*) energy machines
(*c*) power machines.

The fact is emerging that force machines, which consist essentially of machines operating at standstill or at low speeds, are most useful in small sizes, their principal advantage being that of convenience. Their design is relevant to that of a traction motor on starting. The accelerators in class (*b*) can be large machines, and offer the advantage of low cost (when designed as sheet-rotor motors). Their operation clearly overlaps that of high-speed transport, and it should be remembered that the Electropult was in this class. Machines of class (*c*) must have high efficiency, and therefore be of high speed and, of necessity, be large motors. It is true to say that no experimental machines of this kind have so far been built, perhaps because to set up an experiment in this class is like playing a game of poker in which it costs £100000 just to be dealt cards. This alone could account in part for the

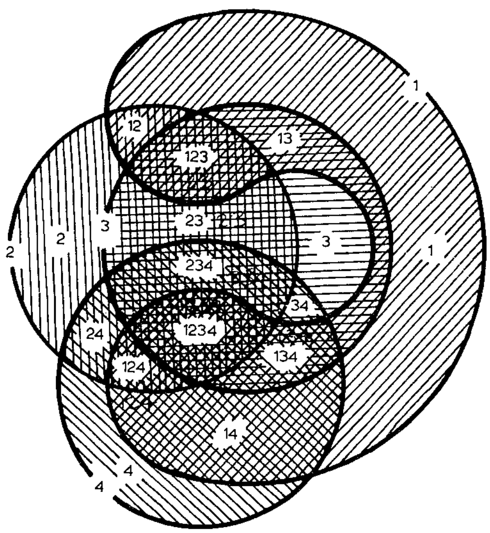


Fig. 1

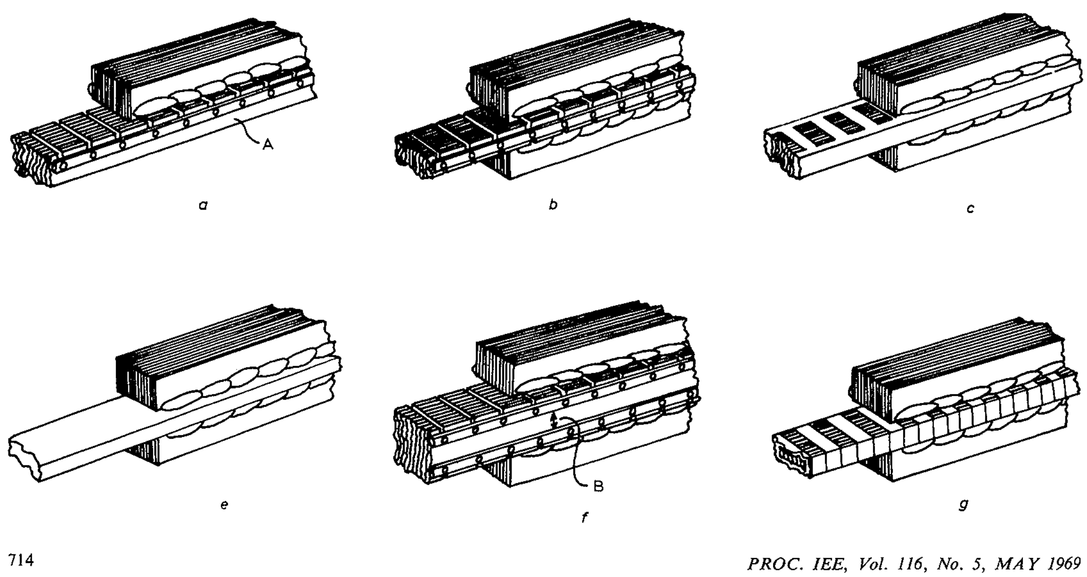
Diagram illustrating interplay between different circuits of a propulsion system

time interval between the original concept of linear-motor traction and the first full-scale trial. At the same time, however, it should be pointed out that there has been, over the past 30 years, a shifting of emphasis in engineering design from what is 'efficient' to what is 'reliable', and this also may have played a part in promoting the reappraisal of linear traction motors which is now taking place.

In a recent paper[5] discussing how the 'goodness' of a machine might be assessed, it was pointed out that every electrical machine could be considered to consist basically of the interlinking of an electric circuit and a magnetic circuit. Within the broader concept of a machine system designed for a specific application, it may be said that it is the interplay between four, rather than two 'circuits' which is involved, the four circuits being described generally as electric, magnetic, thermal and mechanical. Some aspects of design involve only two of the circuits. For example, the underlying philosophy behind the sheet-rotor construction could be said to involve only the electric and magnetic circuits, whereas subsequent choice of rotor-plate thickness involves all four. The whole subject could be said to be analogous to four intersecting loops, as shown in Fig. 1, such that there are regions which are contained in only one of the loops. Other areas are contained by two loops, others by three and there is a region which is a part of all four. Within a framework of this complexity, it is impossible to write a comprehensive account of all aspects in a paper of this length, nor has enough work been done to be authoritative about the majority of the regions. Indeed, it is one of the objects of the paper to illustrate how much more remains to be done before complete economic assessment of a system can be attempted. Attention is concentrated on the electrical aspects of linear-motor design in an attempt to make the paper complementary to the recent presentation at the IRCA/UIC 'high speeds' symposium in Vienna,[6] in which emphasis was placed on the mechanical design.

2 Topology of a linear-motor drive

Earlier papers[7–9] have dealt with the advantages and disadvantages of linear-motor drive compared with other forms of propulsion. In view of the development of large-scale prototype vehicles now taking place, it is known that large linear motors will be required to be designed, and that there are some applications for which the linear motor is accepted as the best alternative.[10] This paper is, therefore, not so much concerned with assessing the economic feasibility of linear-motor drive but attempts to present alternative approaches to the design of systems and indicate which alternative shapes of motor are most favourable in particular conditions of service.

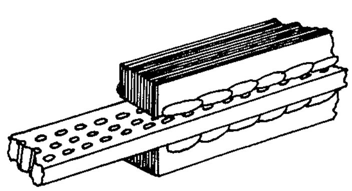


2.1 Primary/secondary location

A relatively simple example to illustrate this, and one which involves perhaps the most fundamental decision regarding the form of motor to choose, is whether the primary should be mounted on the vehicle or on the track. The advantages of a stationary primary are that no power supply is required on board the vehicle, that the secondary member carried can be simple and robust, and, like its rotary counterpart, requires neither electrical nor physical contact with the ground. In a sheet-rotor construction, the secondary member can also be very light. Attractive though these advantages are, they are generally more than offset by the cost of providing primary coils in slots along most of the track length. Nevertheless, such a system is being seriously considered in situations where the traffic density may be great enough to utilise a large part of a permanently energised track, and an assessment carried out at the Massachusetts Institute of Technology has estimated that the use of 7ft of primary per 100ft of track, with vehicles 100ft long, involves the use of 116000lb of steel and 39100lb of copper for each mile. It must be added that a primary-energised asynchronous system cannot readily be controlled from the primary side, for control of excitation affects all vehicles, and to attempt to regulate their speeds and/or spacing on the track by secondary control destroys the inherent simplicity of the secondary member. Historically, apart from the 1905 proposal of Reference 1, there is evidence that some experimental work was carried out on track-primary motors in 1923 in connection with a proposal for a continuously moving platform in New York between Times Square and Grand Central Station,[11] although this was essentially a slow-speed system. However, except in very special circumstances, it would appear that high-speed systems should be designed with the primary mounted on the vehicle.

2.2 Single- and double-sided motors

The most obvious form of linear motor is that obtained by imagining a conventional squirrel-cage motor to be split and unrolled, and this results in a machine in which both primary and secondary members consist of slotted, laminated steel, the secondary containing a conducting ladder as shown in Fig. 2*a*. This was the form proposed in Reference 1, and indeed the one used in the Electropult. One of the immediate results of a change of shape from cylinder to flat slab is that the opposite side of the secondary becomes available for the application of further m.m.f., virtually without increase in secondary material. In cylindrical structures such an approach would lead to overhung bearings and difficult mechanical design and manufacture, and has only been used in very small servomotors, but in linear motors the double-sided technique has a natural advantage. Immediately there are two alternatives:



d

Fig. 2

Alternative structures in linear motors

a Linear equivalent of a conventional squirrel-cage motor
b Double-sided cage machine
c Simplified form of *b*
d Sheet rotor containing ferromagnetic rivets
e Plain sheet-rotor machine
f Double-sided cage motor with axial flux
g Simplified form of *f*

(*a*) The two parts of the primary can assist each other in driving flux through the secondary (N pole on one block faces S pole on the other) and the secondary may be reduced to the form shown in Fig. 2*b*, in which no secondary core corresponding to the portion A in Fig. 2*a* is required. Constructionally, this type of rotor is difficult, but other forms of it may be readily envisaged if the semiclosed slot form is abandoned in favour of the open slot, when individual slabs of laminated steel may be let into a conducting slab, as shown in Fig. 2*c*. Since laminating the steel of an induction-motor rotor is often a technique more related to constructional convenience than to operational necessity, the steel inserts could be made solid and could simply consist of a multiplicity of rivets, as shown in Fig. 2*d*. Both these types of sheet rotor with steel inserts were considered in the US Department of Transportation study contract, which reached the conclusion that the system shown in Fig. 2*d* was the best of all for the high-speed project. The ultimate development of the N–S system is shown in Fig. 2*e*, where the secondary consists simply of a conducting sheet. The approach to this form via the alternative approach of removing the secondary cage of a conventional induction motor from its slots has been dealt with previously.[7]

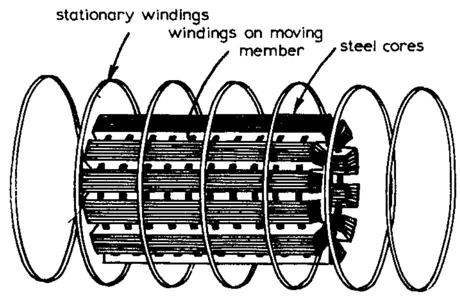


Fig. 3

Tubular motor with open magnetic circuit

(*b*) The two parts of the primary can be of similar instantaneous polarity and drive a flux axially along the secondary member. Such an arrangement requires a conducting structure on both sides of the secondary, as shown in Fig. 2*f*, and a secondary core whose dimension B is sufficient to accommodate, in the worst condition, the total flux per pole. Although these requirements appear to make the secondary member somewhat cumbersome, it must be remembered that the great advantage of the N–N system is that currents in both primary and secondary members can flow in simple circular coils, for this is the basic structure of the tubular motor.[12] This feature can be exploited in the design of one member, as shown in Fig. 2*g*, since no penalty in end-winding material is then incurred in that member by increase in pole pitch. A tubular system for both members could only be used, however, in a high-speed system in which the vehicle is not mechanically in contact with the ground, since the shorter member of a tubular motor cannot be suspended, except from the ultimate ends of the longer member. That good magnetic circuits may be obtained in tubular motors without the use of steel in the outer member[13] makes an interesting form of tubular motor, as shown in Fig. 3, possible for some of the more futuristic projects such as those mentioned by Chergwin,[10] in which vehicles are propelled in evacuated tunnels.

2.3 Track layout

Perhaps the greatest single factor which has inhibited the development of linear motors has been the tendency to apply the theory and economic considerations of conventional cylindrical-motor design directly to linear machines without modification. Generations of students of machine theory were brought up to believe that only machines with small air gaps could be 'good' machines, despite the entire success of large alternators with 7in airgaps.

In many forms of linear motor, and certainly in all those connected with high-speed transport applications, there are two basic considerations which, as far as choice of topology is concerned, must override all others:

(*a*) The track member is thousands of times the length of the vehicle member. This implies that, like the running rails of a conventional railway, at any one time the rail consists mainly of inactive material.

(*b*) The air gap between the members is many times the length of the air gap used in conventional induction-motor design.

2.3.1 Track-member economy

As an example of the potency of the first of these considerations, a double-sided motor of the type shown in Fig. 2*e*, with the primary mounted on the vehicle, may require a track plate $\frac{3}{4}$ in thick. Perhaps other design considerations have required it to be of aluminium alloy, which costs 3s. 0d./lb. The dimensions of the primary will, to some degree, dictate the width of the track plate, and the designer of the former will appreciate that an $\frac{1}{8}$ in reduction in the plate width will save £10000 in the cost of aluminium alloy alone on a 100mile track. In the light of such considerations, it would appear that the simple sheet-rotor construction of Fig. 2*e* is to be preferred to all others, especially since it has the added benefit of eliminating all magnetic pull between fixed and moving members. Even with this type of construction, the designer must use all his skill and ingenuity to reduce the track-plate section. For example, the primary units must be long and narrow, and it is fortunate that this also tends to minimise the transient-generated losses due to the front and back edges of the primary,[12] since a long motor would inevitably be designed to have a large number of poles. An interesting form of motor, not included in the several possibilities shown in Fig. 2, can be used to good effect in conjunction with certain types of track, of which three examples are shown in Fig. 4.

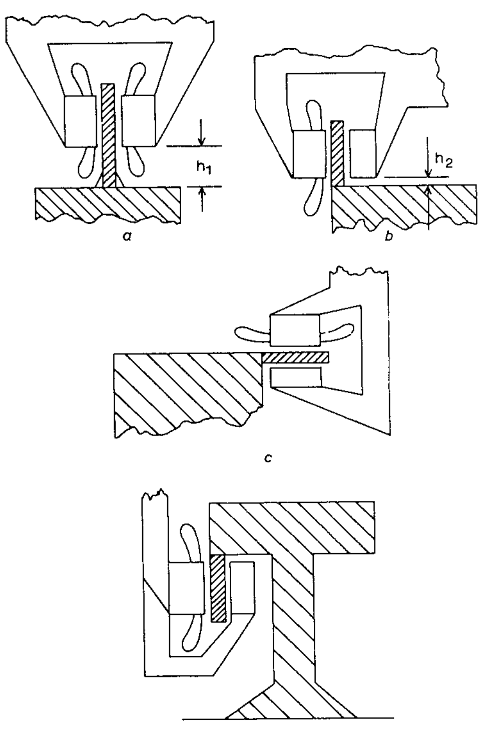


Fig. 4

Utilisation of motors which are magnetically double-sided but electrically single-sided

a Double-sided sheet-rotor motor
b Removal of one winding reduces ground clearance
c Horizontal arrangement with reduced clearance
d Rotor plate protected from obstacles and snow

One of the limiting factors in primary design is the space occupied by the end windings, for space must be allowed in the track to accommodate these, and yet the track plate must be as narrow as possible. Earlier papers[2, 6–8] have suggested various forms of sheet-rotor arrangement for both horizontal and vertical track plates and Fig. 4*a* is typical of these. The height h_1 is determined by the end winding and even though the plate itself may extend no further beyond the lower edge of the primary steel than is demanded electrically, the remaining support is expensive, and the total height determines such mechanical quantities as plate stiffness (which in turn depends on whether the primary member is guided from the plate), which is affected by plate thickness. Economies in plate thickness pay an even greater dividend than economies in width.

In the arrangements shown in Figs. 4*b*, *c* and *d*, the primary is double-sided magnetically, but single-sided electrically, and this enables the height h_2 to be no more than is required to absorb vehicle movement with safety. Moreover the plain laminated-steel block, which acts as the return part of the magnetic circuit, is much more robust than the wound side of the motor, and therefore more able to deal with temporary obstacles (stones etc.) which may be encountered in a system such as that of Fig. 4*b*. Fig. 4*c* shows a horizontal-plate system, while 4*d* is a possible arrangement for a suspended track, which has the advantage that the plate is protected from temporary obstacles and snow.

The penalty for adopting the single electrical feed is that such designs will include wider slots and narrower teeth than those of doubly fed systems, and this will result in a lower tractive force per unit area of pole surface, so that a singly fed primary will be longer and heavier than its doubly fed counterpart by a factor of between 1 and 2, depending on the copper/iron ratio employed.

The struggle to reduce plate section must ultimately encounter restrictions due to primary length, not the least of which is the requirement to negotiate curves. Although the curvature of high-speed tracks is never likely to be severe, there is no doubt that the lengths of primary which plate economy demands will influence the choice of mechanical clearance between pole face and plate, and thus the choice of overall air gap, and hence the entire electrical design. This is merely an example of the complexity of this aspect of the problem, illustrated by the area 1234 in Fig. 1. It is, of course, possible to articulate a very long motor, although it should be remembered that if a long motor is divided into sections magnetically, each portion will be subject to the edge-transient restriction that the full-load slip should be of the order of $n/(n + 3/2)$, where n is the number of poles in a section rather than in the motor as a whole, unless two conditions are fulfilled:

(*a*) The separation between the magnetic parts of two adjacent sections should be short enough to insure that the exit-edge flux from one block has not decayed appreciably before re-entry. (The time constant of decay for this region can be calculated using the formulas for open magnetic circuits developed in a recent paper[13]).

(*b*) The relative phases of the exciting windings in two adjacent sections should be such as to constitute a continuous wave, as shown in Fig. 5.

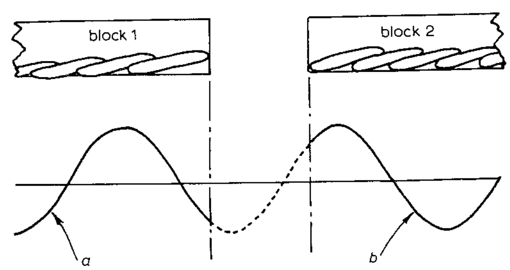


Fig. 5

Preferred relative phasing of articulated stators

a Instantaneous travelling wave in block 1
b Instantaneous travelling wave in block 2

3 Special features of sheet-rotor machines

The foregoing arguments point towards the sheet-rotor motor as likely to prove the most economical form of high-speed drive. Attention will now be focused on this type alone, and this reduces the complexity of the interlinks between the various circuits considerably. Specific aspects of design are now considered.

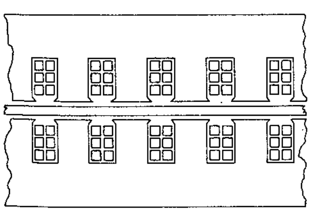
3.1 Designing for large airgaps

Although the mechanical guidance of the primary from the track plate is advantageous from the point of view of electrical design, and may ultimately emerge as vital to the whole economy of a high-speed system, it seems unlikely that the mechanical clearance between primary member and track plate can be reduced much below $\frac{1}{4}$in for speeds above 200mile/h. In any case, the pole faces will need to be protected against abrasion and weather, and will probably be faced with a nonmagnetic, low-conductivity sheet, such as stainless steel, whose thickness contributes to the effective air gap.

The adoption of sheet-rotor construction, however, has as one of its main objectives (perhaps second only in importance to reduction of track costs) the establishment of the mechanical clearance between primary and track as a noncritical dimension in the basic design considerations.

The paper dealing with the goodness of a machine[5] showed that it was not the absolute air-gap length, but its relationship to pole pitch, which ultimately fixed the quality of an induction machine. Despite this, doubts have since been expressed, in many places informally, and in at least one place formally,[9] that it is possible to design linear motors with high efficiencies and power factors when the air gap is of the order of 1–2in. It seems necessary, therefore, to emphasise again in the present paper that such quantities as efficiency and power factor can be determined absolutely by goodness factor.[5] At the same time, the designer's scope in choice of mechanical clearance resulting from sheet-rotor construction will emerge.

If an increase in plate thickness proportional to the increase in air gap is used to keep the secondary goodness factor constant, a similar increase in primary copper section can be used to maintain G_1 constant, so long as it is achieved by increasing both slot width and depth, so as not to increase the proportion of slot leakage. It can be shown, therefore, that the two designs illustrated in Fig. 6*a* and *b* will have the same efficiency and power factor as each other. They may not, of course, have the same power/weight ratio, for the power output for any given speed is proportional to the force developed, which is proportional to the product of air-gap flux density and electric-circuit loading. Assuming that the primary teeth are always worked at the highest level of flux density considered possible from other points of view (such as core loss), the air-gap density depends largely on the slot-width/slot-pitch ratio. Current loading is similarly dependent on this quantity, so that the designer reaches his optimum by consideration of another link in the system of Fig. 1, namely the thermal circuit of the machine, and this largely determines the tooth width/pitch ratio.



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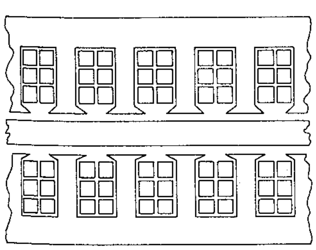


b

Fig. 6

Designs of linear motor having the same efficiency and power factor

It has been shown[14] that in linear-motor actuators designed for standstill operation, the ratio of air-gap flux density to stator-current loading is proportional to p/g, where p is the pole pitch and g the air gap. It was pointed out that well designed actuators using sheet-rotor construction, where g may be many times that of the conventional motor, should have very wide stator slots and very narrow teeth. This argument was based on designs for which $G = 1$, but it may easily be extended to machines running at slip σ. It should be emphasised, however, that the following argument is not a rigorous mathematical calculation, but that, like so many other aspects of electrical-machine design, it has some 'experience' built into it.

In actuator design, a useful criterion of effectiveness is the force which can be produced per unit of stator I^2R loss. To this end, it is convenient to evaluate the characteristics of such motors at constant current, in case they should be required to operate at speeds other than standstill. For a 3-phase sheet-rotor motor, in which core loss and secondary leakage can be neglected, the expression for the force produced by a total current I per phase at slip σ is given by

$$F = \frac{3I^2(R_2/\sigma)X_m^2}{\{(R_2/\sigma)^2 + X_m^2\}v_s}$$

where R_2 is the secondary resistance, and X_m the magnetising reactance per phase, v_s being the linear synchronous speed.

The force/slip curve is seen to have a maximum at $\sigma = R_2/X_m = 1/G$, and this represents the condition for maximum force per unit of stator I^2R loss. If, on the other hand, the designer wishes to optimise the ratio of output per unit of stator I^2R, the slip can be shown to be $\sigma = (1/G^2)\{\sqrt{(1 + G^2)} - 1\}$.

Similarly, whatever criterion is adopted by the designer, the slip will emerge as $\sigma = f(G)$.

If secondary leakage (expressed as $X_2/R_2 = G^1$) and core loss P_i are included, the slip would be more complex, being a function of G, G^1 and P_i.

In practice, examination of the characteristics of most commercial induction machines which are used efficiently (i.e. excluding those used with variable-slip control) reveals that the full-load slip rarely disobeys the relationship

$$\frac{3}{G} > \sigma > \frac{1}{G}\,.$$

The relationship between magnetising-current loading J_m and gap flux density B_g has been shown to be given by[12]

$$B_g = p\mu_0 J_m/\pi g$$

while J_m is related to the total stator-current loading and slip by the goodness factor so that

$$J_s = J_m\sqrt{(1 + \sigma^2G^2)}$$

where, at full load, σ lies (from experience) between $1/G$ and $3/G$.

Substituting these limiting values into the expression for J_s, and substituting into the formula for B_g, gives

$$\frac{B_g}{J_s} = \frac{\mu_0}{\pi k}\left(\frac{p}{g}\right)$$

where $\sqrt{2} < k < \sqrt{10}$, so that the designer may, in general, be seen to make the proportionality

$$\frac{B_g}{J_s} \propto \frac{p}{g}$$

flexible only to the extent of $\sqrt{5} : 1$.

Thus it will generally be found that well designed linear motors, even for high speeds, have a slot-width/slot-pitch ratio considerably greater than those of conventional induction motors, and this almost fundamental design feature should be taken into account in any comparison between rotary and linear machines. While a sheet-rotor linear motor with the same proportions of stator-slot dimensions might appear to have a much lower efficiency than a rotary machine, on account of its much larger air gap, this reduction might be very much smaller with a well designed linear primary.

It thus emerges that, electrically, the factor of fundamental importance is not so much the air gap, as the proportion of it which is filled with conductor, and that once 50% filling is passed, there is little point in striving to achieve smaller mechanical clearances. Thus, if it should emerge that such mechanical considerations as plate rigidity and longitudinal strength should require plates about $\frac{3}{4}$in thick, mechanical clearances of $\frac{3}{8}$in do not produce a serious handicap to the electrical designer. The electromagnetic-circuit combination is therefore suitably interlinked to the mechanical circuit, where air-gap clearance will have profound effects on initial track cost and maintenance.

3.2 Power supply and control

The three fundamental quantities to be chosen for power supply are voltage, frequency and number of phases. The last of these is relatively easily chosen, a 3-phase motor being preferable from almost all aspects. This does not imply, of course, that in systems where power is to be collected from the track, the latter transfer cannot be performed as a single-phase or d.c. operation. The choice of voltage is less complicated than that of frequency, the former affecting such quantities as power/weight ratio and efficiency only in matters of detailed design so far as the motor is concerned. For systems using track collection, it may be that the final choice of voltage will depend mainly on the system of current collection used, rather than on motor design. The choice of frequency, on the other hand, involves much more profound decisions regarding the entire system. Without embarking on a detailed discussion regarding the choice of pole pitch, Section 2.3.1 has shown that the primary member will be long and narrow, and it follows that vehicles designed for speeds of over 200mile/h could only make use of the existing power supplies at 50 or 60Hz (which would require pole pitches of more than 3ft), if at least some of the following can be tolerated:

(*a*) large primary core depth, and hence primary weight to be carried
(*b*) Gramme-ring windings, which would be difficult to construct and would introduce considerable leakage
(*c*) a large amount of track-plate overhang to accommodate return currents.

The designer of a system may well decide that the linear motor will require a special power supply of its own.

Once he has accepted this requirement, the system may be considered with a view to deciding whether the source of the special supply is to be located on the vehicle or on the ground, and whether the frequency supplied is to be fixed or variable. Without listing all permutations of possible arrangements, the leading contenders at present appear to be:

(*a*) *Generation on board:*
(i) mechanically controlled prime mover and alternator
(ii) fixed-speed prime mover and alternator with solid-state variable-frequency unit
(iii) fixed-speed prime mover and alternator

The first two only of these give a variable-frequency supply.

(*b*) *Track collection of power:*
(i) single-phase 50 or 60Hz or d.c. collection with solid-state phase and frequency convertor
(ii) 3-phase collection with solid-state convertor of simpler design
(iii) 3-phase collection of special, but fixed, frequency.

A study of the relative economic advantages of these various systems is beyond the scope of the present paper, but a few aspects which are common to several of the schemes may be dealt with at this point.

3.2.1 Operation from a fixed frequency

These methods have much in common with direct on-line starting of conventional squirrel-cage motors. One of the problems associated with the latter technique is that of ensuring that the rotor is not burnt out in the event of starting under load. The linear motor has a great advantage in respect of secondary heating for, at speed, fresh cool plate is continually entering at one end of the motor, while hot plate is emerging at the other, and this certainly enables higher than conventional ratings to be obtained in the running condition. At standstill, however, the part of the plate which is located immediately opposite the front of the vehicle member on starting will be called upon to contain all the heat generated by the passage of the entire motor primary when the latter is moving at its slowest. As it emerges, this region will have suffered the effects of standstill current for the longest possible period. While this current may be exceeded if braking by plugging is used, the vehicle is then, by definition, travelling much faster, so that the time of exposure to the larger current is very much shorter.

A simple evaluation of the maximum temperature rise in the plate may therefore be made by using the following assumptions. The regions of the plate which extend beyond the sides of the primary may be assumed to carry the same current density as the active parts of the plate do. It is therefore in order to make heat calculations per square unit of plate surface, and to assume no loss of heat by cooling during the few seconds likely to be involved. If the motor is designed to produce a specific force F newtons per square metre of plate area for a vehicle of mass M kilogrammes when the field speed for starting is v_s metres per second, the time t spent under the stator by the region in question is given by $\sqrt{(2l/f)}$, where l is the stator length and f its acceleration, which is assumed constant for the small speed range likely to be involved. If the total area of active motor is A square metres, $f = FA/M$. For a motor width W metres $l = A/W = fM/FW$.

The heat produced per square metre of plate in time t is given by

$$Fv_s t = v_s\sqrt{(2FM/W)} \qquad (1)$$

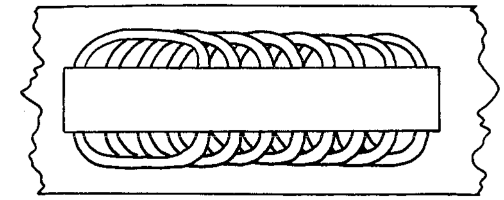
Thus the temperature rise T is given by this quantity divided by the plate thermal capacity.

It should be noted from eqn. 1 that the temperature rise is independent of the acceleration chosen. By substituting some typical values into the equation, it can be shown that the restraints on the design of the system due to plate temperature are not trivial, although by no means insurmountable. For example, a 30ton vehicle driven by a 200mile/h motor designed to give a starting thrust of 4lb/in^2 would produce, in an aluminium plate 1in thick and 18in wide, a maximum temperature rise of 104degC.

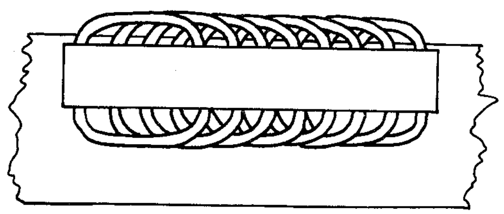
Operation from a fixed frequency involves a speed-control system based on voltage control, whereby the motor is allowed to slip under the action of the frictional drag and the acceptance of a basic rotor efficiency equal to the fraction of synchronous speed at which the vehicle runs. The shape of the speed/force curve of the motor can be arranged, to some degree, by design, although the techniques employed in the design of double-cage and deep-bar conventional motors are not available to the designer of a sheet-rotor machine, except in so far as thicker plates may be used to introduce more skin effect, but the plate thickness is more likely to be determined by mechanical considerations.

The components of the equivalent circuit which the designer may use most freely to shape the speed/force curve are the primary-leakage reactance and the secondary resistance. The latter component is particularly interesting in that an effective increase in plate resistivity can be obtained by restriction of plate-current flow, no matter how it is obtained. Several ingenious suggestions have already been made, which include[15] adjustment of the primary units from a central position over the plate to an eccentric position, as shown in Fig. 7. Such repositioning introduces lateral forces which could be utilised, for example, in a vertical-plate system, for supporting part of the vehicle's weight, or in a horizontal-plate system, for lateral stabilisation. Another suggested arrangement aims at changing the effective resistance by means of a series of graded slits cut in the edge of the track plate, as shown in

Fig. 8. Raising the primary blocks introduces restriction to current flow by the 'short-rotor effect'.[12] The possibility of a change in plate material at different positions along the track



a



b

Fig. 7

Use of reactor-plate edge in producing lateral force and/or change of resistivity

a With motor central, plate conductivity is a maximum
b Offset rotor produces vertical thrust and higher effective plate resistivity

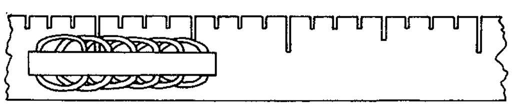


Fig. 8

'Graduated ruler' type of secondary plate for thrust control

also exists, provided it is accepted that the motor must not be called upon to start on a section intended to be traversed at high speed.

Perhaps the most important point to remember in considering an increase of plate resistivity is that, if the electrical design alone is being considered, it is fundamentally wrong to increase the secondary resistance by choosing a material of higher resistivity or by any change in the physical structure of the secondary (such as by drilling a multiplicity of holes in the plate) which does not lead to a reduction of total air gap. There is no doubt that on deciding that increased secondary resistance is required on grounds of force/speed-characteristic shaping, the electrical designer's natural instinct should be to reduce plate thickness, for this enables subsequent reduction of total effective air gap to be achieved with consequent increase in both primary and secondary goodness factors. Only when plate thickness becomes smaller than is tolerable from mechanical-strength considerations should other means of increasing resistivity be sought. For similar reasons it is basically wrong, electrically, to effect thrust control by mechanically moving the primary blocks away from the plate so as to increase the mechanical clearance, however convenient this may be from a control point of view.

A most profitable method of increasing plate resistivity involves only an extension of the method of thrust control using the plate edge,[15] so that the overall plate width is reduced until it overhangs the width of the primary member by a very small amount, if at all. Such a technique may allow reduction in plate thickness, for the reduction in width will give the plate greater lateral stiffness. For purposes of support, the extension of one edge of the plate is still necessary, but this might conceivably consist of some cheap, nonconducting material, such as concrete. The saving in cost between tracks whose cross sections are as shown in Fig. 9 could prove to be very large indeed. It has been shown[16] that for machines with high goodness factors (~20), the effective resistivity of the secondary plate is multiplied by only 2·1 when the plate extends half a pole pitch on each side of a stator whose width is also equal to half a pole pitch, but that reduction

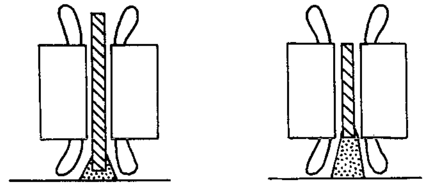


Fig. 9

Increase of resistivity by reduction of reactor plate width

of the overhang to a tenth of a pole pitch increases the multiplying factor to 3·8. Provided such increases in resistivity do not ruin the characteristics of the motor or demand such radical changes in choice of supply frequency etc. as to upset the economic feasibility, the designer is at liberty to make such track economies.

3.2.2 Operation on variable frequency

The main advantage of a supply controllable in frequency is that it enables the final elimination of moving parts to be made. Complete control of thrust, braking and speed can be effected throughout the journey without recourse to movable-primary units or a variable form of rail along the track. It is naturally assumed that control of frequency carries with it an appropriate control of voltage. The electrical designer may, in this case, use the lowest-resistivity rail available without embarrassment from leakage reactance, and his design of motor may run for long periods at low speeds with high efficiency. Whether these luxuries demand too high a capital cost is a question which only considerations of an individual project can decide, but there is no doubt that a most potent advantage of a variable-frequency system relates to the provision of regenerative braking and particularly to a form which allows electrical braking and, for hovering vehicles, the maintenance of suspension to take place in the event of a main-power failure. A discussion of some aspects of dynamic braking now follows.

3.2.3 Methods of braking

High-speed transport, especially by hovering vehicles, can be regarded as intermediate between ground and air travel and can, for several purposes, including braking, be regarded as low-level flying. At high speeds, the frictional resistance to motion is so great that mere removal of the whole or part of the driving thrust may be sufficient to produce the controlled rates of deceleration required in a normal run. It is only when higher braking forces than this are required that the freely suspended vehicle presents a problem. Of course, there is always the possibility of mechanically reconnecting the vehicle to the ground by means of some form of conventional friction brake, although the energy of a 30 ton vehicle moving at 250 mile/h is sufficient to raise the temperature of a ton of steel by 400 degC, and although half of this might be dissipated in the ground member, the quantity remaining is a serious deterrent to mechanical braking, except possibly as a final procedure for the reduction of the vehicle to rest from perhaps 50 mile/h, where other methods are less effective.

Where an electromagnetic-propulsion system such as a linear induction motor is used, it is possible to use the same apparatus as a brake; indeed, this is one of the principal advantages of this type of drive. Basically, there are two ways in which reverse thrust can be produced:

(*a*) by plugging, in which the direction of field travel is reversed

(*b*) by induction generation, in which the speed of the field is reduced below that of the vehicle.

The requisites of the first method are that the primary should remain connected to the supply, and this being so, continuous reverse thrust can be applied right down to standstill. The second method, the more interesting of the two, requires fundamentally no source of power, but rather an electrical sink into which the converted energy can flow, but it does require a reactive-power source, and can only operate down to a certain minimum speed.

Both methods, however, can provide high rates of retardation, whether or not the vehicle is airborne. The braking force being independent of adhesion for wheeled vehicles provides safety under all weather conditions. In contrast to friction braking, there is no risk of 'brake fade', but it must be remembered that the longitudinal thrust on the reaction rail is likely to be greater in emergency braking than in normal acceleration and that the braking condition will therefore provide the basis for the mechanical design.

Where the braking facility is required to be independent of the main power supply, only two methods are possible which make use of the existing motor. The first involves the provision of an emergency d.c. supply in the form of a storage battery, which can be used to energise the motor primary as a row of d.c.-fed magnets, which can be used to dissipate the vehicle energy by means of the eddy currents induced in the rail, at least down to a speed at which friction brakes can be applied. The speed/force characteristic which can be obtained from such a system is of typical R/X-dependent shape, resembling the characteristic of a conventional induction motor mirrored about the torque axis and displaced by the synchronous speed on the speed axis.

The second method is method *b* above, in which it is necessary to control the synchronous speed of the linear motor to ensure induction-generator action. Since this method involves conversion of the kinetic energy of the vehicle into electrical power, it is attractive in systems using air-cushion support where a part of the power generated can be used to drive the lift fans during the decelerating period. One particularly attractive form of regenerative brake is the invention of D. S. Bliss,[17] in which the problems of providing a power sink and of monitoring frequency are solved simultaneously by using a part of the motor primary as an induction generator, whilst the other part is used in the plugging condition to absorb the residue of the power. The system is shown schematically in Fig. 10. The auxiliary synchronous machine

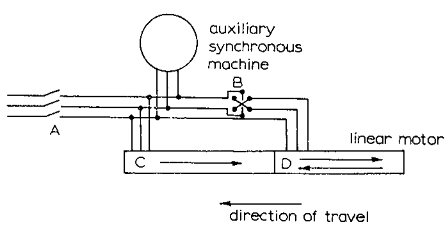


Fig. 10

Bliss's emergency-braking system

provides the reactive power for the induction generator in the emergency condition. In normal running, this machine runs as a synchronous motor which may take the form of the lift-fan motors themselves or, in a more sophisticated system, provide the power for the fans through a speed-controlling link, so that the fan speed may be maintained constant during an emergency stop. In the event of a main-power failure, such as represented by opening the switch A, the only control action necessary is to operate the reversing switch B. Since the synchronous rotary machine can no longer derive power from the mains, it must slow down, and in doing so reduces the excitation frequency to the linear motor. As soon as this frequency produces a field speed slower than that of the vehicle (a matter of a few percent of the prefault speed), the section C generates, supplying the fan motors with power, and the section D acts as a plugging motor. Thereafter the action continues throughout the deceleration until the synchronous machine can no longer supply enough magnetising current to maintain the induction-generator action, when the excitation of all machines collapses. This could be expected to occur at something less than 10% of full speed, but the precise point of collapse will largely depend on the linear-motor goodness factor.

With such a system, the whole of the kinetic energy of the vehicle is converted into heat in the secondary-reaction rail, except for the relatively small amounts lost in the primary windings and for the power used by the lift fans, which is largely dispelled into the air. The reaction rail is clearly a receptacle capable of containing such a large quantity of energy. Bliss's braking system is the a.c. counterpart of the 'suicide connection' used for braking d.c. machines.

3.3 Choice of pole pitch and supply frequency

Section 3.2 listed as *a*, *b* and *c* the restraints which prevent the designer from using a pole pitch large enough to allow mains frequency to be used for supply. The choice of pole pitch is one of the most difficult decisions facing the designer and it is certainly an example of a problem in the 1234 area of Fig. 1. In a paper of this length one can possibly do no better than indicate the opposite restraints to those in Section 3.2, listing the penalties for choosing a pole pitch which is too small. They are as follows:

(*a*) A small pole pitch results in a low goodness factor which implies a lowering of efficiency and power factor.

(*b*) If excessive primary leakage is to be avoided, the primary slot depth must be reduced as pole pitch is reduced, and even such reduction merely maintains X_1/R_1 constant at fixed frequency. Reduction in slot depth reduces the area available for primary copper, and hence reduces the specific output.

(*c*) As a consequence of *b*, the gap flux density is also reduced, since J_s is reduced for $\frac{B}{J} \propto \frac{p}{g}$ as shown in Section 3.1. Thus the specific output is further reduced.

(*d*) For a fixed synchronous speed, the supply frequency is inversely proportional to pole pitch. Higher frequencies result in higher leakage reactances and a lower power factor.

(*e*) Higher frequencies introduce the possibility of skin effect in the secondary plate, which, apart from its effect on power factor and the shape of the speed/force characteristic, is wasteful of track metal, for it implies that a portion of the plate is now included merely for mechanical strength.

(*f*) As a consequence of *a*, *d* and *e*, the required shape of the speed/force curve is likely to demand increased plate resistivity with consequent further reduction in G, efficiency etc.

Thus it emerges that, as pole pitch is reduced, a point is reached below which most of the important quantities such as specific output, efficiency, track cost etc., spiral to unacceptable values. It is probably true to say that the initial design studies which have already been carried out in various parts of the world have been primarily concerned with determining whether these two sets of constraints overlap or whether there exists an area, however small, within which the designer may work. The findings are unanimous that there is such an area, but it is interesting to observe that a good design makes concessions on almost all fronts.

For example, it is generally agreed that the specific force attainable lies between 2 and 5 lbf/in^2 of pole surface for a high-speed double-sided sheet-rotor machine. A well cooled mains-frequency motor could hope to attain 7 lbf/in^2. Secondary skin effect is by no means negligible, as will be shown in the next paragraph. It has emerged that the designers' range of pole pitches lies between 6 in and 15 in, with a preference for 9 in for speeds of the order of 250 mile/h. A second important feature which has been made clear from the various studies is that increases in maximum speed, above 100 mile/h, should be achieved largely by an increase of frequency rather than by an increase of pole pitch. This finding has been conveniently expressed in an American report[4] which says that the frequency should be 'one cycle per second per mile per hour', which is another way of saying that the pole pitch should be fixed at 8·8 in. While detailed design of individual systems will decide that this is subject to adjustment, it represents a good starting point in design in what would seem otherwise to be an endless sea of interdependence.

3.3.1 Skin effect

West and Hesmondhalgh[18] have investigated the current distribution in thick-cylinder drag-cup induction machines. Their results are directly applicable to the sheet-rotor machine, and the minor modifications necessary to account for the double-sided feature of a linear motor have recently been published.[12] The results may be summarised by saying that the effective secondary-plate resistivity is raised in the ratio of half the plate thickness to the skin depth δ, where δ is given by the usual expression $\sqrt{(2\rho_c/\omega\mu_0)}$, where ρ_c is the volume resistivity of the plate material and ω is the angular-slip frequency. This result assumes the whole of the air gap to be filled with conductor. A more accurate result, which takes into account the mechanical clearance on each side of the plate, can be obtained by extending the method of analysis to the multilayer problem as indicated by Greig and Freeman in a recent paper.[19] The extent to which skin effect must be considered in design can be judged from the fact that, at standstill, δ for aluminium alloy ($\rho_c = 4 \times 10^{-8}\,\Omega$m), for a supply frequency of 250 Hz, is approximately $\frac{1}{4}$ in, so that reaction plates over $\frac{1}{2}$ in thick must be subject to detailed calculations. Raising the resistivity by a factor of 4, however, would allow 1 in plates to be treated as conducting throughout for the purposes of calculating secondary resistance, even though it may be necessary to use the multilayer analysis to evaluate secondary-leakage reactance.

3.4 Choice of plate section and material

The basic mechanical requirement of the reaction rail is that it shall resist the longitudinal thrust arising from the emergency-braking condition. Electrically, if lateral magnetic pull and severe skin effects are to be avoided, the rail must be a nonmagnetic conductor. Assuming effective anchorage against vertical buckling, the criterion for the smallest mass of material is that E/D^2 should be maximum, where E is Young's modulus and D is the density.[20] Low cost, however, rather than low mass is the objective, but writing £ for the cost per unit mass, the figure of merit becomes $E/(£D)^2$. Aluminium alloys would appear to have a considerable advantage over the other conductors unless the required resistivity is very high, but even then the technique suggested in Section 3.2.1 may still permit the use of aluminium.

Flexural rigidity being a requirement, a section provided with lateral stiffening would appear to have advantages. It will be recalled that the thickness of the reaction plate over the areas swept by the primary pole faces contributes to the effective 'air gap' and should therefore be minimised. Longitudinal conducting paths outside this area are required but can be of any shape. Both mechanical and electrical considerations therefore point to something like a joint or channel section. Clearance considerations imply that support should be provided at one flange only, which should be shaped for easy fixing, and the other flange might be modified to a bulbous section. This construction, of course, excludes the possibility of exploiting the edge technique of Section 3.2.1.

Transmission of the propulsive or braking forces to the ground might be achieved through single anchorages for each section of reaction rail, lateral motion being permitted at other points of support or lateral restraint. Compressive and tensile forces would be imposed by frictional resistance to longitudinal motion at each support point as a consequence of thermal expansion and contraction. Expansion joints would be necessary at the ends of each section and space for connections would be available at the flanges. Gaps in the web would provide electrical transients but, as demonstrated in the early experimental work at Gorton, these are detectable but not objectionable. The provision of expansion joints may be desirable, not only to accommodate thermal changes due to weather conditions, but also because of heating due to the circulating currents occasioned by the passage of the primary.

An alternative arrangement would be to follow the practice employed for the installation of long welded rails,[21] in which the restraints to movement which occurs over relatively short lengths at each end of the section are sufficient to balance the forces exerted by the central section, which becomes therefore subjected to compressive or tensile stress as a result of inhibition of thermal expansion or contraction. It is likely that, in such a system, the buckling stress arising from heating will determine the requirements for flexural rigidity and lateral restraint rather than the traction and braking forces.

End-winding considerations point to an electrical preference for concentrating power into a single reaction rail rather than dividing the thrust between two or more. Difficulties of providing the necessary clearance, consideration of twisting forces and other vehicle-design factors, all of which are mechanical, suggest the use of twin rails. Such an arrangement may have other advantages if the reaction rails are used for lateral guidance or support of the vehicle (as they might be by using edge effects) or if they are also used as supply lines for the collection of electric power. If the electrical design dictates that the plate overhang is considerable, it seems highly probable that the single-plate system must be used, simply on the grounds of track cost, but it is interesting to note once again that the use of a narrow plate to produce an effective increase in plate resistivity may bring the twin-rail system within the limits of economic viability.

Whether or not the reaction rail is disposed in a vertical or horizontal plane must be determined by the method of support and connection to the main vehicle. Vertical curvatures are likely to be less pronounced than those in the horizontal plane, and the problem of design of any points and crossings which may be necessary may be simplified with the horizontal arrangement. On the other hand, a vertical rail should be easier to support, and, if the primary is directly supported from the main vehicle so as to participate in the vertical movements of its suspension, these can be accommodated without affecting the air gap.

The linear-motor stators are less massive than the vehicles themselves, and, because of their simple robust construction, they can be subjected to higher rates of acceleration than the passenger accommodation. It is permissible for them to be guided by the reaction rail independently, even if the main vehicle is also guided by this member. This permits the use of smaller air gaps than would be required to accommodate the lateral movement of the vehicle itself. Where the vehicle is guided separately from the reaction rail, it is not necessary to prescribe correct alignment between that rail and the guidance elements.

Guidance of the separately mounted linear-motor primary relative to the reaction rail is not critical, provided contact at speed is avoided. A stabilising, rather than a positive, action is required on a straight track with the vertical arrangement, although, with the horizontal arrangement, the weight of the primary can be applied to the reaction rail.

In both arrangements, some provision for withstanding centrifugal force on curves is necessary, on horizontal curves for the vertical plate and on vertical curves for the horizontal plate.

Wheels can, of course, be used to guide the primary along the reaction rail. This was the arrangement used in the Gorton experiment, and the one proposed in the American 250 mile/h prototype.[10] These wheels may be preloaded against the reaction rail so as to give rise to sufficient friction force at the periphery to accelerate and decelerate them in consonance with the action of the motor. The wheels and their bearings will, however, possess some rotational inertia, and, unless preloading is considerable, insufficient torque will be available for their acceleration, and slip will occur between wheel surface and reaction rail. Such slip was noted during the Gorton experiment.

Moreover, since the motor has no moving, and therefore wearing, parts, it would be disappointing to have to provide working parts simply to guide the motor. Air guidance is an attractive alternative, particularly if it is recalled that all that is required is to stabilise the secondary relative to the air gap rather than to centre it precisely.

Simple pressurisation of the pole faces would be attractive were it not for the necessity for an increased air gap to allow for the curvature over the full length of the secondary. Short independent stabilising pads at each end of the secondary coils might therefore be preferable and, with a beam or channel-section reaction rail, might provide both vertical and horizontal guidance. The gap of the guidance pads need only be sufficient to allow for variation of thickness of the reaction rail, which would be within the tolerance normal with rolled-aluminium section. Thus consideration can be given to aerostatic bearings working on viscous restraint rather than the hovercraft or similar bearings, which depend on a limiting volume of air passing on the conversion of pressure energy into momentum. Some augmentation of stabilising force by Reynolds wedge action may be possible at high speeds with suitably shaped pads.

Location of the guidance pads at the extremities of the secondary structure as in Fig. 11*a* provides maximum stability

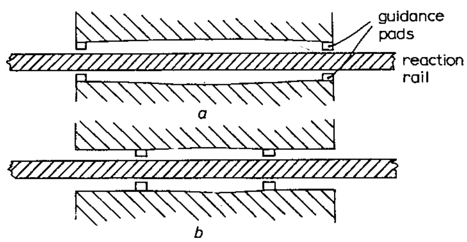


Fig. 11
Lateral guidance-pad positions

as regards rotation about a vertical axis. However, it is disadvantageous in that it requires the air gap to be sufficiently large to accommodate the full versine of the curve, doubled, of course, because both right-handed and left-handed curves must be allowed for.

Improvement can be achieved by arranging for the primary member to extend beyond the guidance point, as indicated in Fig. 11*b*. Some slight advantage might follow from further extension of poles so shaped as to reduce flux density at entry with a corresponding mitigation of end effects.

3.4.1 Restriction of current flow in narrow secondary plates

The possibilities of the use of the reaction-plate edges either as means for providing forces in a direction perpendicular to that of the motion of the vehicle (which can be used for ~~lateral~~ guidance or weight support), or as a means for increasing artificially the plate resistivity, depend on accurate evaluation of the extent of the effect. This has been done for the latter case in a separate paper,[16] and theoretical work is proceeding which will extend the analysis to cover the asymmetrically located plate. Experimental tests have shown that for certain pole pitches and goodness factors, lateral forces of the same order as those obtainable as driving thrust may be obtained.

3.4.2 Use of steel for reactor plates

It has frequently been suggested that, since steel is a reasonably good electrical conductor, use might be made of its ferromagnetic properties to improve the magnetic circuit. Magnetic pull, it can be argued, is not an insurmountable difficulty, particularly with large polepitch machines.

A complete theoretical investigation of the operation of a double-sided motor with a steel reactor plate would be extremely difficult on account of skin effect and saturation of the steel. The following simplified approach is included to demonstrate that steel cannot be a profitable material, for all the assumptions made are biased in favour of its use. The final result indicates that the characteristics obtainable with these assumptions are inferior to those with nonferrous conductor.

Fig. 12 shows two sets of possible flux paths through a double-sided machine (shown at synchronous speed for simplicity), the stators being arranged (as would be standard practice for a nonferrous plate) with the N poles facing S. West and Hesmondhalgh[18] have shown that, for practical pole pitches, over 90% of the flux passes straight through a nonferrous plate, even though it be an inch thick or more. With ferrous plates, however, the tangential flux path is likely to accommodate most of the flux, and it therefore matters little whether the two halves of the machine are connected N–S or N–N.

Assuming no saturation, so that μ may be given a value of, say, 800, with $\rho_c = 2 \times 10^{-7}\,\Omega$m for steel, at only 50Hz the skin depth is 1·12mm (0·044in). This suggests that, at

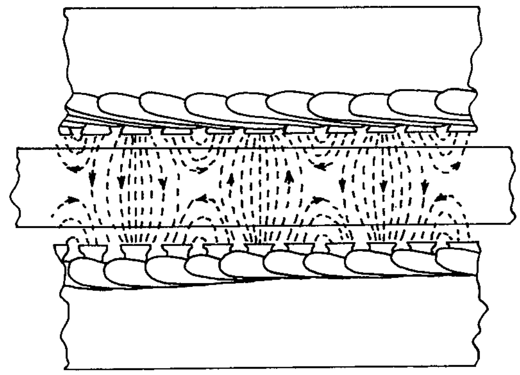


Fig. 12
Flux paths through a reactor plate for synchronous speed condition

standstill, virtually the whole of the flux passes axially along the reactor plate. Even at 5% slip, the skin depth is only 5mm (0·197in), so that, for double-sided motors, only plates less than 0·4in thick could show appreciable penetration from side to side when running at full speed.

The above results, however, are seriously affected by saturation of the steel. Fig. 13 shows the relationship between

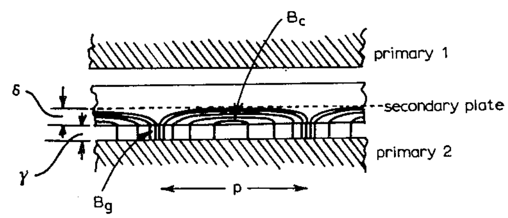


Fig. 13
Relationship between form of flux density in different axes and dimensions of system

the form of the air-gap flux density B_g, the plate axial density B_c and the dimensions of the system. The flux per pole entering the plate is $2p\hat{B}_g/\pi$, where p is the pole pitch, and, assuming the usual standing-wave effects due to the termination of the windings[22] (which double the core flux by comparison with that of a rotary machine), the whole of this must pass axially through a skin depth δ.

$$\text{Hence } 2p\hat{B}_g/\pi = \hat{B}_c\delta \qquad (2)$$

If the steel is assumed to saturate at $B = 2$T (i.e. it is assumed that its B/H characteristic is a vertical line at $H = 0$ up to $B = 2$, followed by the horizontal line $B = 2$), an alternative calculation for skin depth can be obtained by rewriting eqn. 2 with $B_c = 2$. The gap density is related to the magnetising-current loading J_m by the equation

$$\hat{B}_g = p\mu_0/\pi(\gamma + \delta)\hat{J}_m \qquad (3)$$

while J_m is that fraction of the total stator-current loading J_s, given by the equation containing the goodness of the machine, G.

$$\hat{J}_m = \hat{J}_s/\sqrt{(1 + G^2)} \qquad (4)$$

Leakage considerations will limit primary-slot depths. To a first approximation, slot-leakage reactance is proportional to slot-depth/slot-width, so that, as pole pitch is increased, slot depth may be increased in proportion, with the result that, for a given current density, current loading will increase in proportion to slot depth, and therefore to pole pitch, and we may write

$$\hat{J}_s = kp \qquad (5)$$

The goodness factor expressed in terms of the fraction of the gap filled with conductor g/t is given by

$$G = \frac{2p^2\mu_0 f}{\pi\rho_c \frac{g}{t}\left(\frac{p+W}{W}\right)} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (6)$$

the stator width being W and the term $(p + W)/W$ being a first approximation to Russell and Norsworthy's factor[23] for end-winding resistance.

In the context of Fig. 13

$$\frac{g}{t} = \frac{\gamma + \delta}{\delta} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (7)$$

The problem may now be restated as follows:

For a given value of k,

(a) At what p does δ equal half a plate thickness?
(b) What are the benefits to be derived from the use of longer pole pitches?
(c) Considering the ρ_c of steel, how does the best arrangement compare with machines run on aluminium plates?

Substituting eqn. 7 into eqn. 6

$$(\gamma + \delta)G/\delta = f_1(p)$$

and, from eqns. 2 and 5

$$\delta(\gamma + \delta)\sqrt{(1 + G^2)} = f_2(p)$$

where f_1 and f_2 are functions only of p and of constants relating to a given system, such as width of motor, frequency etc.

These two simultaneous equations enable δ and G to be determined, and hence an equivalent circuit to be derived for a given pole-pitch machine, which can be compared to an aluminium-sheet machine. The work is laborious, but easily handled by a computer program for various speeds, using σG in place of G.

Section 8.1 shows a worked example to illustrate the effect of increasing the pole pitch of a machine.

The general conclusions to be drawn are that G rises too slowly with p to produce machines which are comparable with aluminium-sheet-reactor machines of the same dimensions and speed. The plain fact is that so long as the skin depth is significantly small, the rotor conductor is effectively too thin to give a low enough R_2 in the equivalent circuit. When saturation has allowed penetration right through the plate (in the 12in example, a plate 1·4in thick would be largely penetrated), the effective μ is so small that the total gap reluctance is virtually the same as that with an aluminium plate, while the resistivity of the steel is perhaps 6 times that of aluminium.

4 Future developments

Forecasting future needs in high-speed transport is particularly hazardous, since it is so intimately linked with economics. Views on the relative importance of the various economic aspects change under almost the same influences as those which dictate fashions in clothing, so that it is fair to say that there are fashions in engineering. One must therefore be prepared to see adjustments made to accepted practice in almost all aspects of the system. The fact, for example, that $0{\cdot}1g$ is regarded as the maximum acceleration allowable for reasonable passenger comfort could easily be rejected if one considers the possibility of travelling from London to Brighton in 12min. For so short a period, many passengers would be prepared to be strapped into their seats as are aircraft passengers on takeoff and landing, and to tolerate $0{\cdot}5g$ for half a minute at each end of the journey.

Worries regarding the negotiation of curves by straight-sided linear motors could melt away overnight by a decision to limit curvatures to radii of 2500m or more, as was the case with the new Tokaido line. This would mean that the additional air gap necessary for a linear motor 5m long to negotiate the curve is only 0·5m. Nevertheless, the lateral acceleration imposed in rounding such a modest curve at 275mile/h is $0{\cdot}65g$ ($6{\cdot}25\,m/s^2$). Travel at such speeds requires entirely new standards of assessment.

Where existing alignments must be used, the good accelerating and braking performance of linear motors assists in observation of speed restrictions accompanying the negotiation of unavoidably sharp curves.

4.1 Brushless current collection

Not least of the problems will be that of collecting the power required for the vehicles. A recent paper[13] has suggested an inductive system requiring no physical contact between vehicle and transmission line, in which the trackside member can be reduced to its simplest form: a single wire which does not require a particularly small clearance between itself and the vehicle. There is no doubt that such a system would be enormously expensive. Neither is it considered feasible, unless the primary wires can be switched on section by section, as required by the vehicle, for continuous track transmission

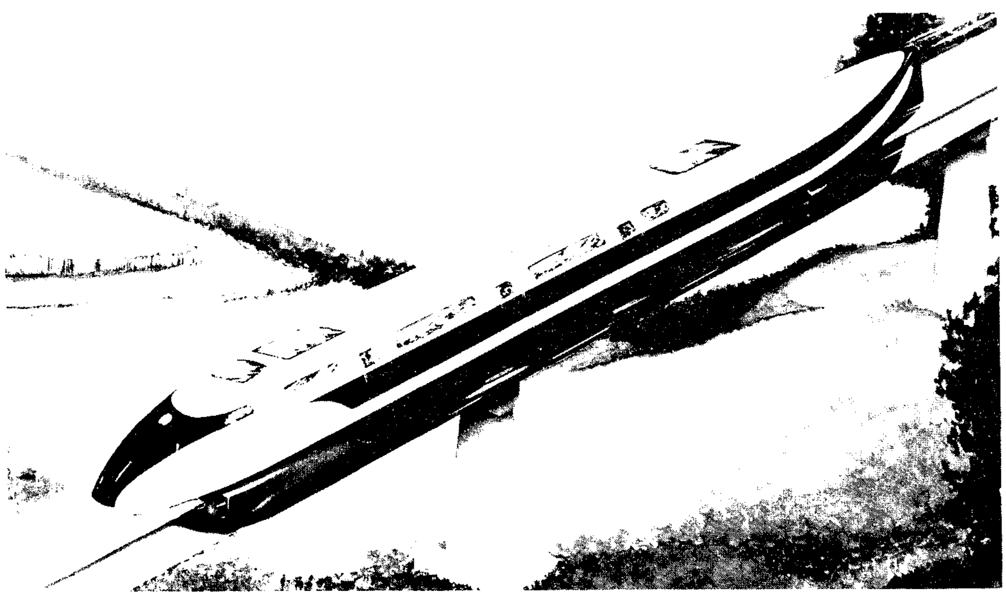


Fig. 14
Artist's impression of linear-motor-propelled high-speed vehicle

at the frequency and voltage required could never be justified economically. In some ways, it could be said that such a proposal is a return to the system of 1905, of switched sections of primary winding mounted on the ground. This, however, is not entirely the case, for the shape of the electromagnetic system proposed by the 'moving transformer' concept is altogether more favourable in terms of track cost, and places it in that economic no-man's land between what is known and proved and what can clearly be ruled out on grounds of cost. Investigations on the moving transformer are therefore continuing.

5 Conclusions

The main conclusion which emerges from the foregoing study is that the problems of mechanical design of a high-speed system are far greater than those which face the designer of a linear induction motor which is to provide the driving thrust. Even the mechanical considerations of the linear-motor design are more complex than the purely electrical aspects of the design. A great deal of work has been done on entry and exit losses of linear motors, and these can now be calculated with a high degree of accuracy. A recent American report has suggested that this can be regarded as a 1-dimensional problem, and that if skin effect in the secondary plate be taken into consideration, the problem could be said to be 2-dimensional. Within this contex, the work of H. Bolton[16] adds a consideration of the third dimension: the plate-edge effects. Indeed, this third dimension can be exploited to a considerable extent by the designer to minimise the cost of the reaction rail, a technique which has so far received formal treatment in no other publication.

The majority of the prototype vehicles currently being designed make use of sheet-rotor machines and this type of linear motor will probably go unchallenged in this field of application for some considerable time. Future developments in the field of high-power solid-state devices will be a dominant factor in choosing between different systems for particular applications. To this extent, the linear motor could be said to have been waiting for the new material to arrive but there is no doubt that the concepts of 1905 are about to be realised in practice. Fig. 14 shows an artist's impression of a high-speed tracked vehicle such as might utilise linear-motor propulsion.

6 Acknowledgments

The authors are extremely grateful to many of their colleagues for the interchanges of ideas which had led to much of the material in this paper. In particular they wish to thank D. S. Bliss of Tracked Hovercraft Ltd. and H. Bolton of Imperial College. The early work at Gorton was financed by the British Transport Commission, while present research is supported by the UK National Research Development Corporation and the Science Research Council.

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8 Appendix

k may be estimated as follows:

If $p = 6$in, it is reasonable to have slots 2in deep which occupy about 2/3 of a slot pitch. With a utilisation factor of 30% in a slot (assuming a mush winding) the copper depth per side is 0·4in. It should be noted that in using eqns. 2–5, $\hat{J}_s$, $\hat{J}_m$ etc. relate to a single side of the stator, since it is assumed that all the flux is contained in a skin depth. The winding factor is assumed to be unity.

At a current density of 3000 A/in^2 (r.m.s.), $J_s = 1200\,\text{A/in}^2$ and therefore $\hat{J}_s = 1200\sqrt{2}/0{\cdot}0254\,\text{A/m}$

whence

$$k = 1200\sqrt{2}/0{\cdot}0254 \times 6 \times 0{\cdot}0254 = 43{\cdot}7 \times 10^4\,\text{A/m}^2$$

For this example, the following values are assumed:

$$W = 4\,\text{in}$$
$$\gamma = 1/8^2$$
$$f = 50\,\text{Hz}$$
$$\rho_c = 20 \times 10^{-8}\,\Omega\text{m}$$

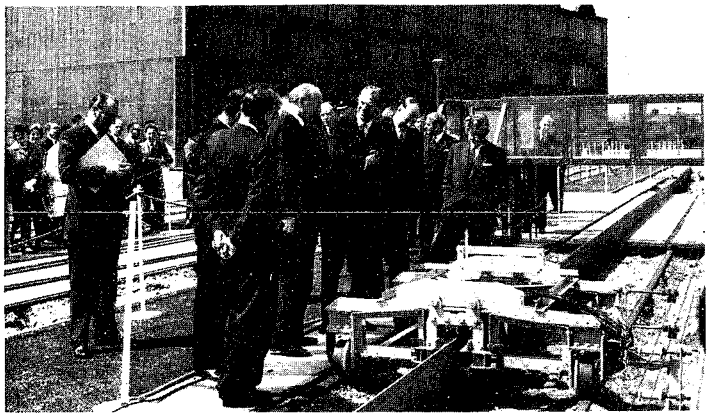
Solving for δ and G for a pole pitch of 6in.

$$\delta = 9{\cdot}2\,\text{mm}\,(0{\cdot}362\,\text{in})$$
$$G = 1{\cdot}38$$

also $B_g = 1900\,\text{G}$

whereas a pole pitch of 12in gives corresponding values

$$\delta = 18{\cdot}1\,\text{mm}\,(0{\cdot}713\,\text{in})$$
$$G = 3{\cdot}95$$
$$B_g = 1870\,\text{G}$$



The Duke of Edinburgh inspecting a linear motor test track at Derby Engineering Research Laboratories

APPLICATION OF THE LINEAR MOTOR TO TRANSPORT

A rational assessment of existing experimental data bearing on the problems of propelling railway vehicles

By D. S. ARMSTRONG, B.Sc.(Eng.), M.I.E.E., *Research Department, British Railways*

THE PAST DECADE has seen considerable interest expressed in the linear motor as a means of propulsion for railways or other forms of guided surface transport, and detailed theoretical analyses of performances have been published.[1, 2] The linear machine has also been studied extensively as a device for pumping liquid metals. [3, 4]

Propulsion in a linear motor is the result of a reaction between electric currents induced in a conducting plate and a travelling magnetic field which induces the current flow. The field is produced by a distributed polyphase winding in a laminated iron block (referred to as the stator). Stators are usually provided on both sides of the reaction plate, which may be horizontal or, preferably, vertical (Fig. 1).

In 1960 British Railways suggested that a linear motor with a vertical reaction plate fixed to the track and a two-stator winding on the train could be used for railway traction, and Professor Laithwaite, then working on linear motors at Manchester University, undertook the study of this application. A number of small motors were constructed and thoroughly tested at the University.

Following these initial tests, British Railways developed facilities for motors to be tested at speeds up to 30 mile/h. Fig. 2 summarises the results obtained with a small two-stator linear motor running on a vertical aluminium reaction plate.

In this case the continuous rated current was approximately 80 A, and the stators were 36 in long with a face width of 4 in.

It was subsequently discovered that the vertical plate two-stator motor had been proposed for railway traction at an earlier date and Fig. 3 is a sketch made by Zehden in 1905.[5]

Among the attractions of using the linear motor for railway traction are:—

1. the absence of sliding electrical contacts, rotating electromagnetic parts and gears;
2. freedom from the limitations imposed by adhesion;
3. reduction of the weight of the motor carried on the vehicle because the rotor element is fixed to the track (but, unlike rotating motors, linear motors cannot be geared-up and tend to be heavier than their rotating equivalent on vehicles which operate at low speed);
4. reduced cost of the electromagnetic part of the motor because of its simple construction;
5. improvement in thermal performance because the reaction plate losses are left behind as the motor proceeds;
6. freedom from restrictions imposed by the peripheral surface speed of rotating motors.

Use of a linear motor has corresponding disadvantages, and among them are:—

1. loading gauge restrictions
2. cost of reaction plate
3. lower efficiency and power factor
4. need for a lateral guidance system
5. difficulties on curved track and at points and crossings.
6. three-phase supply with variable voltage and frequency

Loading gauge restrictions

The space available outside the existing British Railways vehicle loading gauge is inadequate for a satisfactory linear motor. On the centre line of the track there is insufficient space between rail level and the lowest parts of present vehicles for a reaction plate and motor

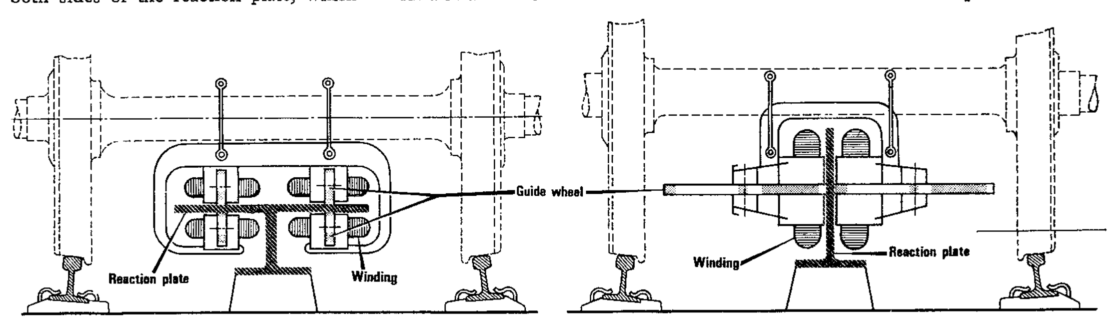


Fig. 1. Horizontal and vertical reaction plates within the space beneath a normal railway axle

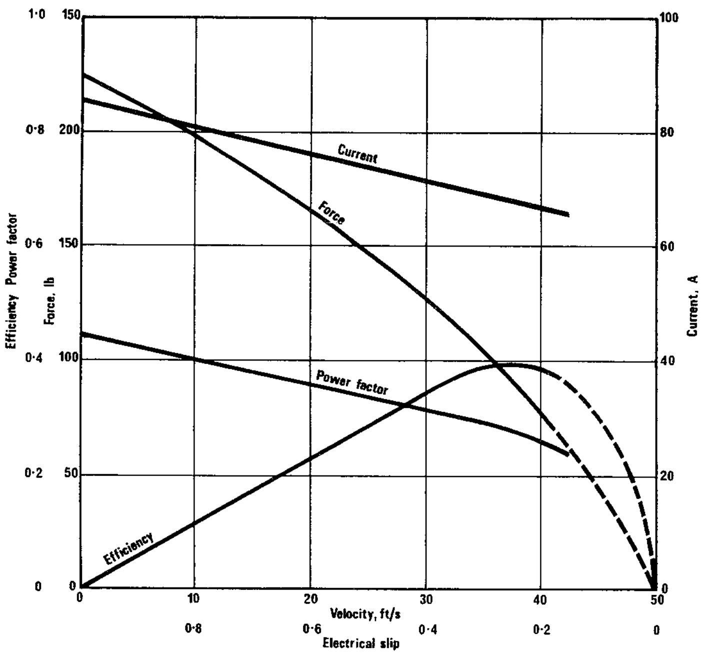


Fig. 2. Test results obtained with a small two-stator linear motor running on a vertical aluminium reaction plate

stators which would be capable of producing traction forces of the required magnitude. Outside the rails there may appear to be space to install reaction plates and motors, but when allowance has been made for guide wheels, running clearances and stator winding overhang, there remains a very small space for the active motor. Reaction plates outside the rails would also obstruct power tamping equipment.

It is therefore unlikely that linear motor propulsion can be used with existing railway vehicles, and it can only be considered for existing routes reserved for special vehicles, or for completely new routes.

Air gap

The effective air-gap is inevitably large when compared with conventional induction motors. It comprises the thickness of the reaction plate, a running clearance on each side of the plate, and some form of stator-face protection. If the motor has to traverse curves the running clearance can be very large indeed, for example, a motor 12 ft long travelling round a $\frac{1}{4}$-mile radius curve requires a clearance of about $\frac{3}{4}$ in on each side of the reaction plate. The total effective air gap can be as much as $2\frac{1}{2}$ in.

The linear motor has an open-ended magnetic structure. Power loss exists at the entry end of the motor because eddy currents are produced in the plate tending to resist the establishment of air-gap flux. At the exit end, most of the energy stored in the travelling flux is dissipated in further eddy loss in the plate. These losses, which are not present in rotating motors, vary with the relative speed of plate and flux, tending to increase rapidly in relation to the total power as the motor approaches synchronous speed. These losses will affect the optimum slip speed at which the motor should operate as they are reduced at certain slip values.

In any motor the average force produced at the air gap is limited by current loading and flux density. The continuous rating of a high-power d.c. series traction motor corresponds to an average output at the rotor surface of up to 5 lbf/in^2 at a surface speed of up to 8,000 ft/min, as is achieved in the A.E.I.282 motor used in the London Midland Region AL6 locomotives. Rotating induction motors are capable of developing similar forces because, although the mean flux density is only $1/\sqrt{2}$ times the peak flux density, there are no interpoles, no armature reaction effects and the squirrel-cage rotor can operate at higher current loadings than the d.c. rotor. A traction squirrel-cage motor may be able to develop 6 lbf/in^2 at 9,000 ft/min. For starting, these motors can be overloaded for short periods to produce 15 to 20 lbf/in^2.

Although two stators are used in the linear motor, the specific force is of similar magnitude. Calculations and tests on small 50 c/s motors suggest that the maximum force which can be expected from a 100 c/s force-cooled motor is of the order of 4 lbf/in^2 under continuous operating conditions. Forced cooling is considered necessary because the motor may be moving at too slow a speed to induce an adequate air flow over the motor from a ducted air intake.

Reaction plate

The surface of the existing running rails is inadequate, in both total available area and conductivity, for the production of useful traction forces, and a special conducting plate must be provided. The only material which appears to be suitable for this reaction plate is an aluminium alloy.

Copper cannot be used because of its high capital cost and the risk of theft.

A steel plate would be strong mechanically, but because of its high magnetic permeability skin effect is very marked and alternating fluxes tend to be confined to a thin surface layer, passing axially along the plate. When saturation has

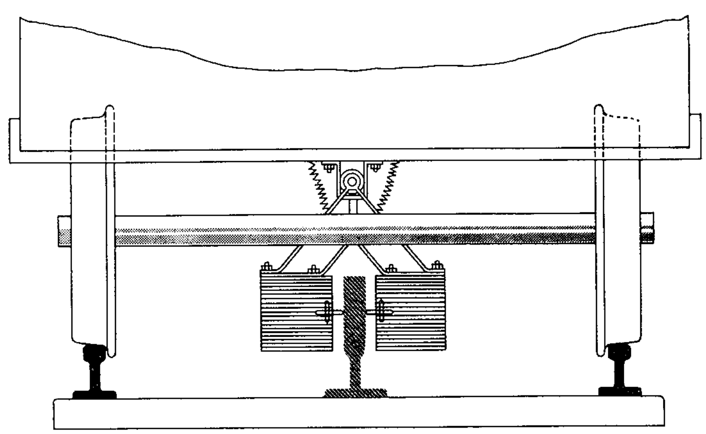


Fig. 3. Linear motor arrangement proposed by Zehden in 1905

allowed penetration right through the plate, the effective value of plate permeability may be so small that the total gap reluctance is virtually the same as that with an aluminium plate, while the resistivity of the steel is perhaps seven times that of aluminium.

Steel reactor plate

It is probable that a steel reactor plate can never be as effective as an aluminium plate. Fig. 4 shows the test performance of the motor used for Fig. 2 when running on a steel plate; the efficiency and power factor are significantly reduced.

A minor problem of steel plate motors is the presence of a resultant transverse force if the plate is closer to one stator than the other. This force can readily be carried by the guide rollers, but could tend to cause uneven wear of the rollers.

The use of an aluminium alloy raises considerations of thermal expansion and fatigue. If the plate is to be fixed to the sleepers of a conventional track it will tend to follow the vertical movement of the sleepers, and deflections of the order of 0·25 in are possible, producing stresses in the reaction plate tending to cause fatigue failure. Some more elaborate means of support might well be required.

The thermal expansion coefficient of aluminium is twice that of steel, but the modulus of elasticity is approximately 30 per cent. Thermal effects therefore produce stresses of lower magnitude than those found in steel rails and values of 2 to 5 ton/in^2 are to be expected. These stresses can safely be used with a butt welded plate. A further problem may be a tendency for a straight section to deflect into a wave pattern when temperature increases, and it is possible that sliding joints would have to be provided or plate thickness increased at the free edge.

From mechanical considerations, including the need to retain straightness during installation, an aluminium plate would have to be approximately 1 in thick. An inverted tee-section extrusion would be used with at least 14 in vertical height and perhaps 6 in width at the foot. The cost of material alone per single track-mile is approximately £20,000; a similar steel plate would cost about £9,500 per track-mile.

Guidance

The linear motor requires independent guidance, and a feasible method would use wheels running on the sides of the plate as shown in Fig. 1. Grease-lubricated roller bearings could be used, a low speed of revolution being desirable. A 2-ft diameter guide wheel would turn at 1,400 rev/min at 100 mile/h, giving an acceptable interval between lubrications. Speeds of this low order would be difficult to obtain with a horizontal reaction plate.

Other disadvantages of the horizontal plate are the need to make adjustments to allow for wear of the running wheels, and the problem of positioning a motor in the correct plane after crossing a gap in the reaction plate.

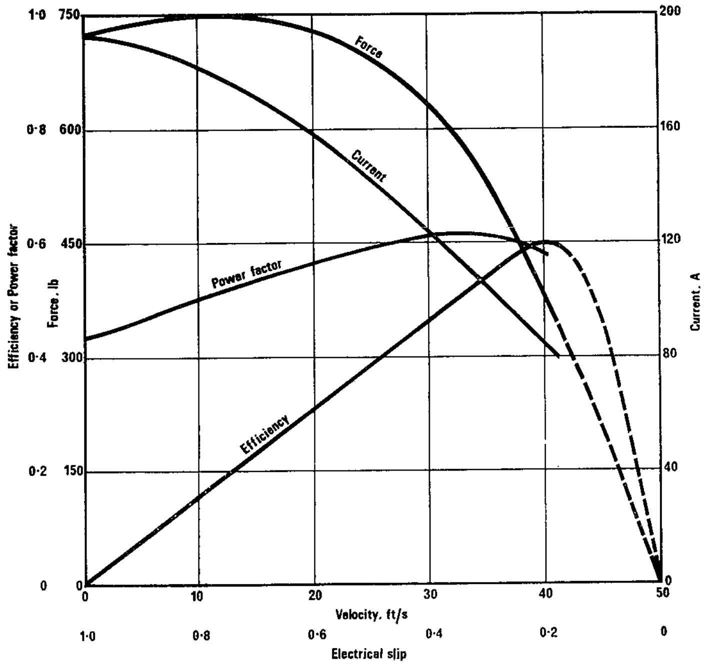


Fig. 4. Test performance of the motor used for Fig. 2 when running on a steel plate; the efficiency and power factor are significantly reduced

The plate cannot exert guidance forces on the motor beyond its limits of mechanical strength. For example, on a 15,000-ft radius curve at 150 mile/h the radial acceleration is 0·1 g and the guide wheels would have to exert forces of the order of 0·1 to 0·2 tons, well within the capacity of the vertical plate. Much larger forces would exist at irregularities in the plate, and maintenance of plate alignment to a high standard is essential.

At junctions on high speed lines it is necessary to provide a continuous plate for the two directions while allowing space for the considerable width of motor and guide wheels. A movable 200ft section could be required with consequent high capital and maintenance costs.

Braking

Various methods of providing electromagnetic braking are possible. Reversal of the phase sequence of the power applied to the linear motor will provide a brake force of up to the maximum propelling force, and control is available by variation of voltage and frequency. An alternative scheme could reduce the motor field speed to below the vehicle speed, and the motor would then act as an induction generator, feeding power back to the supply.

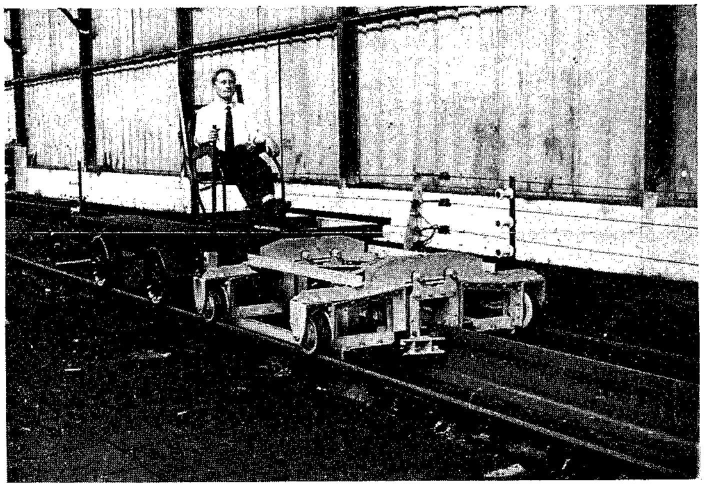
If the main power supply fails a self-contained system is possible with a separate prime-mover and alternator.[6] This acts as the excitation source for one linear motor operating as an induction generator, the generated power being used for reverse sequence braking in other motors. It may be possible to induce self-excitation with parallel connected capacitors, and an independent brake action is available in emergency if the stator windings are fed with direct current from a battery.

Starting performance

Although the linear motor is free from adhesion limitations, it can demand a high power input at standstill because the power loss in the reaction plate per unit force is proportional to the synchronous velocity of the magnetic field.

For example, if the top synchronous speed of the field is 150 mile/h, an attempt to start on reduced voltage without reducing the field speed would result in a power demand of approximately 350 lbf. A zero speed tractive effort of 55,000 lbf would then require a power input of 19·2 MW or 25,800 hp. At a supply frequency of 5 c/s with typical traction pole-pitches, a power demand of approximately 20 W/lbf should be attainable, but even this needs a zero speed power demand of 1·1 MW (1,470 hp) for 55,000 lbf.

If the motor develops 10 lbf/in^2 during starting the power input to the reaction plate would be approximately 200 W/in^2, and if a 1 in aluminium alloy



Man-carrying trolley undergoing tests at Swindon

plate is used, the plate temperature will rise at approximately 4·5°C/s. A motor 50 ft long, accelerating at 1 mile/h-s, will take 8·3 sec. to move the first 50 ft, and the plate temperature will rise by approximately 37deg.C. The 50 ft length of reaction plate will attempt to increase in length by approximately 0·5 in, and this must be accommodated either at expansion joints or by an increase in compressive stress.

Normal starting should present no problems. If a very frequent service were operated, or if a train failed to start, thermal cut-outs could ensure the safety of the plate.

Efficiency and power factor

A standard three-phase squirrel cage motor of traction rating is likely to have an efficiency of the order of 0·92 to 0·95 and a power factor of about 0·92. A d.c. traction motor has an efficiency of about 0·92.

A linear motor will tend to have a lower efficiency than a standard motor. This is because of the following four factors:—

1. additional power losses at the ends of the stators (which may be minimised at certain values of electrical slip). These losses are such that the optimum operating slip is between 0·03 and 0·1, limiting the theoretical secondary efficiency to 0·97 to 0·9 respectively.
2. additional stator copper loss due to current required for magnetising the larger air gap (this factor diminishes in effect as pole pitch is increased)
3. flat plate is used for the reaction plate and the secondary resistance will be higher due to the absence of large end-rings; the plate currents are therefore flowing in paths of higher resistance than in a squirrel-cage motor.
4. a reversible motor is required but the stator winding would normally be symmetrical. An optimum winding with a constant pole pitch should have different coils at entry and exit due to the change in phase of the current component associated with the change of flux envelope magnitude. It is not possible to provide a cheap switchable optimum winding, and the symmetrical winding will sacrifice something of the order of 1 or 2 per cent overall efficiency.

These considerations have led to the use of an efficiency of 0·88 for the economic assessment. The overall power factor of a linear motor with an aluminium alloy plate is likely to lie in the range 0·65 to 0·75.

Assuming that power factor correction costs are neglected, there would be an increase in electrical energy and maximum demand costs. It is suggested that the linear motor uses 4 per cent more energy than conventional rotating motors.

Energy consumption

A train weighing 550 tons, operating at an average speed of 75 mile/h over gradients typical for Britain, has an energy consumption of approximately 27 kWh per train mile. A 4 per cent increase at this speed represents an additional consumption of 81 kWh per hour which, at 0·63d per kWh, results in an increased cost of 4s 3d per hour. If 100,000 miles are run per annum at an average of 75 mile/h, the increase in energy consumption costs £285 per annum. This can be capitalised by multiplying the annual cost by 10, corresponding to a sinking fund investment which would pay £285 per annum for the life of the locomotive.

A steel plate motor would have an efficiency of approximately 70 per cent and annual energy costs would be greater by 33 per cent, representing £2,300 per annum.

An annual charge of £10 per kW of maximum demand is also payable, and a 4,000 hp unit will cost £1,200 more per annum, capitalised at £12,000. The steel plate unit would cost approximately £9,600 more per annum.

Power supply and control

As three-phase power cannot easily be collected at high speed, the linear motor locomotive would operate with a single phase industrial frequency supply with rectification and inversion to three phase on the locomotive. The motor requires a variable voltage variable frequency supply for smooth efficient operation over the whole speed range. Inverters are at present somewhat expensive, but as semiconductor costs fall and as quantity production lines are established for industrial drives, they are likely to become a great deal more competitive for traction duties.

The frequency range which the power supply must provide is not as wide as is required for a squirrel-cage motor because the full-load torque of the linear motor occurs with electrical slip frequencies in the range 3 to 10 per cent of maximum frequency, whereas the rotating motor operates from 1·0 to 2 per cent.

For a maximum frequency of 100 c/s, a minimum frequency of 3 to 10 c/s is required for the linear motor, a somewhat easier task than producing 1·0 to 2·0 c/s. It may be possible to operate over the whole frequency range without the need for a star-delta switching of the motor winding.

Adhesion

The ability to accelerate and brake at high rates is important for urban routes (of relatively slow average speed but with frequent stops) but becomes less significant on longer journeys. The performance of modern equipment with all axles motored is approaching the limit which passengers can tolerate without discomfort.

An example of such a system is the Oslo underground where vehicles with a 90 kW motor on each axle accelerate at 2·2 mile/h-s on gradients of up to 1 in 20. Wheelslip can be a problem, but the application of relatively simple detection and correction apparatus can give substantial improvement.

On urban railways it is seldom an economic proposition to demand acceleration rates much above 2 mile/h-s, even though there could be a reduction in the number of trains required for a given service.[7]

Due to a combination of effects including dynamic variations of vertical load on the wheel/rail interface and the increase in guidance forces, the effective traction coefficient of adhesion falls with increasing speed. At speeds substantially above 200 mile/h the tractive effort required may be so high and the adhesion coefficient so low that the vehicles may be unable to exert sufficient reliable tractive effort through an adhesion contact drive. The linear motor offers a means of propulsion for these high speeds.

Outline design

A linear motor might be designed to have an output similar to that of an AL6 25 kV electric locomotive as operating on the London Midland Region of British Railways. At 100 mile/h a tractive effort of 10,000 lbf is required with a continuous rating of approximately 20,000 lbf.

If the stator face width is chosen to be 8 in, the motor length would be approximately 42 ft, occupying the major part of the vehicle length. Depending on the curvature of the route the motor would be divided into a number of independently guided sections, perhaps 4 units each 11-ft long. With a supply frequency of 100 c/s the pole pitch would be 10 in and the slot pitch 1·67 in (using two slots per pole per phase).

Slot current

The slot current would be approximately 3,200 A, and if a current density of 3,000 A/in^2 is allowed the copper area per slot is 1·07 in^2. A space factor of 0·4 may be possible, giving a slot area of 2·68 in^2. A suitable tooth width is 0·6 in, the slot then being 1·07 in and the slot depth 2·5 in. The stator core depth should be at least 3 in, as much from considerations of mechanical strength as of flux density. The weight of the active electromagnetic parts of the motor is approximately 5 tons, which is similar to the weight of the active parts of the equivalent squirrel cage motors.

The motor design establishes the dimensions of the reaction plate. To provide an end-ring of acceptable conductivity the plate should extend one quarter of a pole pitch on each side of the stator core. On one side of the motor the full overhang of the stator winding, plus running clearance, must be accommodated. For the design given, the reaction plate should extend approximately $(2·5+8+6+3)=19·5$ in above the level of the rail.

The 6 in required for the winding overhang with only a 10 in pole pitch, emphasises one of the practical problems of using large pole pitches with two-layer or concentric windings. A gramme-ring winding encircling the stator would allow larger pole pitches to be used, but there are practical problems in supporting the free winding at the back of the stators and in carrying the stator laminations on supports passing through the interwinding spaces. A plate height of only 14 in has been considered in calculating costs on the assumption that, following construction of a full size motor, it may be found that the design was unduly conservative in rating.

The linear motor should have a superior power to weight ratio when compared with rotating motors when the linear vehicle speed exceeds the peripheral speed of conventional rotors. This will occur at about 125 mile/h. At this speed a linear motor supplied with 100 c/s three phase power would have a winding pole pitch of approximately 12 in.

If higher speeds are required the frequency or pole pitch can be increased. At higher frequencies the stator leakage reactance becomes large, and the electromagnetic properties of available motor materials are such that performance is adversely affected. It is therefore preferable to increase the pole pitch, subject to space being available for winding overhangs.

Locomotive cost

Linear motors are cheaper than equivalent rotary motors and a financial advantage of £5,000 may exist, but power conversion and regulation equipment will be no cheaper and may well be more expensive.

Although the variable-frequency variable-voltage power equipment will always be more expensive than a tap-change transformer plus rectifiers (or thyristor-tap changer) it is assumed, to give the linear motor the benefit of any doubt, that the power regulation equipment will not add to the locomotive cost.

It is unlikely that a significant reduction in total weight would be possible if a linear motor were used, but a lighter locomotive would require less energy to move it and an equivalent capital saving of £400 per ton may apply on some services. As a token of the possible weight reduction which might be made on a linear motor locomotive a capital sum of £2,000 is allowed.

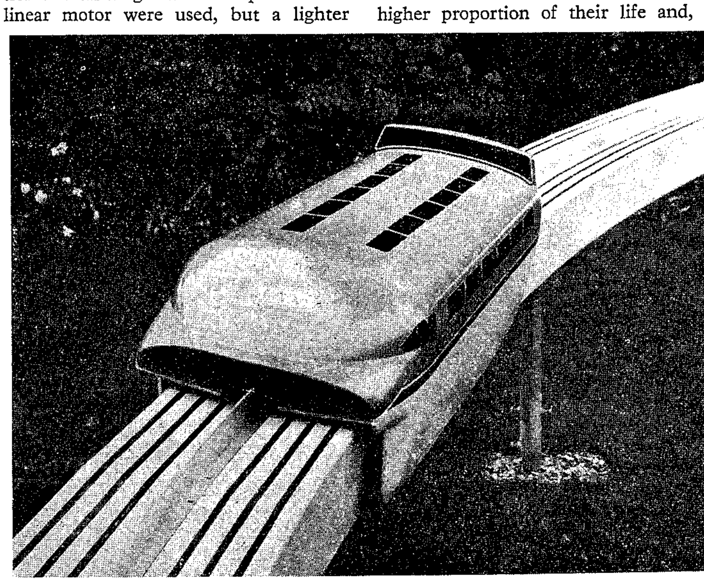
At speeds above 125 mile/h the weight of the active parts of the linear motor should be less than the active weight of rotating motors of the same power, and the vehicle would be lighter on that account, but increasing speed may involve an increase in the problems associated with motor guidance, vehicle riding quality, reaction plate year and mechanical loading of the plate on curves. These may offset the economic advantages of weight reduction.

Maintenance costs

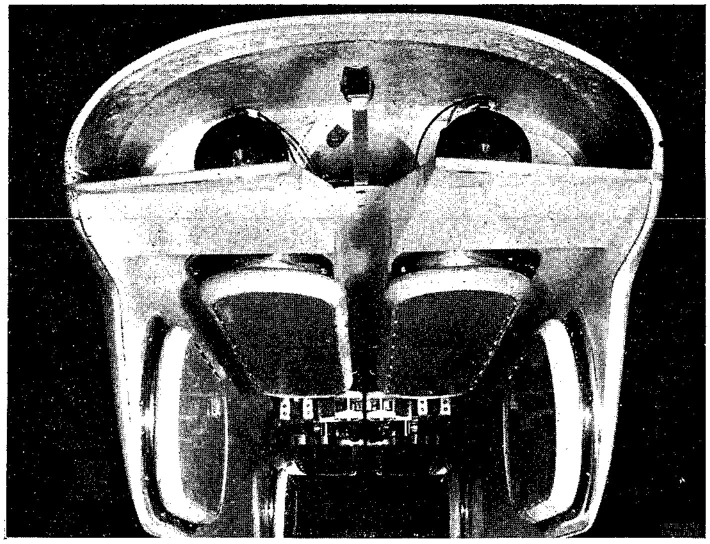
The elimination of d.c. commutators and gears will reduce maintenance costs, but the saving per locomotive would be at most £600 per annum. A capital saving of £6,000 has therefore been allowed. In practice the linear motor system would require a considerable maintenance expenditure on the guidance components and on the reaction plate. This could well exceed the amount now spent on traction motors.

The use of the linear motor for braking will reduce the cost of brake shoe replacement, but similar performance can be obtained by rheostatic braking of d.c. motors or reverse sequence supply to squirrel cage motors. Nevertheless a saving of £2,000 capital equivalent has been credited to the linear motor.

In so far as the electromagnetic parts of the linear motor are static it should be a more reliable motor. The locomotives should then be available for use for a higher proportion of their life and, in



Application of the linear motor to a Hovertrain



Underside of a model Hovertrain proposed by Hovercraft Development Limited. The linear motor and three-phase current collectors are in the centre of the vehicle

principle, fewer locomotives need be purchased.

The availability of electric units is approximately 80 per cent but only a small proportion of the faults can be attributed to the motor. For estimation purposes the optimistic assumption is made that an increase in availability from 80 to 85 per cent would be achieved. The number of locomotives could then theoretically be reduced by 6 per cent and a saving of 6 per cent per original locomotive is obtained. At a cost of £85,000 this represents a saving of £5,100.

Although the linear motor can only be used on a new or reserved track, it is possible to compare linear motor and adhesion drive systems on an economic basis and the approximate economic consequences of replacing 4,000 hp locomotives having d.c. motors by linear motored locomotives of the same power are in Table I.

Economics

The costs have been converted to equivalent locomotive cost and show the difference between the average "cost" of a linear motor locomotive (sharing the cost of the reaction plate between the locomotives) and the cost of each conventional locomotive. All other costs (track, signalling, overhead and so on) are assumed unchanged. It has been assumed that the number of single track miles per locomotive is six, a figure which attempts to make some allowance for the use of multiple-unit passenger stock.

It appears from the table that two conventional 4,000 hp 100 mile/h locomotives could have been bought in place of one linear motor locomotive.

If higher speeds and higher powers are considered the reaction plate will tend to remain unchanged in cost, electrical costs will rise with power rating and cost savings will rise with conventional locomotive cost. This will reduce the difference in cost but may not produce a conclusive change in relative costs below those speeds at which adhesion drive becomes ineffective due to its own intrinsic limitations.

The revenue earned by the linear motor locomotives may not be significantly higher in the speed range 100 to 200 mile/h as the duties on which freedom from adhesion limits will allow a heavier load to be moved are only a small proportion of the total. Where high speed systems are concerned, power rating, which is unchanged, is of greater importance.

Capital sum

An alternative method of costing the reaction plate is to consider a capital sum for the total route. If, for example, the Crewe to Glasgow route of British Railways were fitted with the reaction plate, the cost would be approximately £15 million. This is significantly greater than the cost of the conventional new locomotives which would be purchased if this route were electrified, and is of the same order as amount required (approximately £25 million) for complete electrification.

Table I. Comparison of costs with standard electric locomotives

	Reaction plate material	
	Aluminium alloy	Steel
Reaction plate costs ..	+ £135,600	+ £57,000
Electrical energy ..	+ £850	+ £21,000
Electrical maximum demand	+ £12,000	+ £96,000
Locomotive cost ..	− £5,000	− £5,000
Maintenance cost ..	− £8,000	− £8 000
Improved availability ..	− £5,100	− £5,100
Net cost difference ..	+ £130,350	+ £154,900

Hovertrains

If the guided air-cushion vehicle is accepted as an economic form of transport, then the linear motor should be considered as a means of propulsion, being a silent non-contact drive. The motor could act on a conducting plate mounted on top of the lateral guidance feature or plate mounted in a vertical position on the horizontal load bearing structure.

If the air-cushions have an adequate stiffness it may not be necessary to have separate motor guidance but it is not expected that an air-cushion system would locate the vehicle to within the 0·25 in tolerance which might be allowed for the motor air-gap.

The weight of the hovertrain should be kept to a minimum and a sliding contact collection of power would be preferable to carrying a prime-mover and generator. If a 400 c/s three-phase supply of a suitable voltage (perhaps 3kV) could be delivered to the hovertrain it would be possible to use a direct cycloconversion to give a variable-frequency variable-voltage supply without the need to carry a power transformer.

Other applications

Among other applications considered for the linear motor are banking locomotive units, passenger coach door motors and points motors. These are similar to one another in that they are slow speed/high force applications. In these cases the linear motor suffers from the fact that it cannot be geared to operate at a satisfactorily high surface speed. Winding pole pitches tend to be small, and the ratio of magnetising reactance to secondary resistance is too small to ensure a high power factor and full efficiency.

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LINEAR INDUCTION MOTOR FOR HIGH-SPEED TRACKED VEHICLES

K. M. Chirgwin, C. H. Lee, and P. J. Larsen*

Abstract

This paper describes a 2,500-hp linear induction motor (LIM) for a high-speed tracked vehicle designed and built by The Garrett Corporation for the U. S. Department of Transportation. The paper includes a discussion of the linear motor as an energy conversion device, a comparison of LIM power density with that of other modes of propulsion, and an explanation of where the LIM fits in the larger context of propulsion systems for land vehicles. An electrical design analysis is presented which includes the impact of the large airgap, end effects, and other departures from the conventional rotary induction motor. The problems of airgap control, speed control, and power supply are briefly analyzed. The full scale motor and the Department of Transportation high-speed test vehicle are described and illustrated.

Background

Few people deny that we have a transportation problem. There is a debate, however, as to whether it is a problem, a crisis, or a catastrophy. The means of transportation presently available are unable to cope with the demand. Congestion and delays are the result.

The private automobile and the commercial airplane together account for a very large portion of the passenger traffic in the United States. In Europe and Japan, however, railroad passenger trains with cruising speeds of approximately 125 mph are competing successfully for journeys up to several hundred miles. Recently in the United States for the Department of Transportation (DOT), Office of High Speed Ground Transportation (OHSGT) and the Penn Central Railroad started operating high-speed Metroliner electric passenger trains between Washington and New York. These Metroliner trains are capable of a top speed of 160 mph, but normally cruise over the good portions of the track at 125 mph.

The Metroliners represent a near term solution. The longer term will probably require ground vehicles having speeds not lower than 250 mph and perhaps as high as 500 mph. It was decided to explore the feasibility of linear induction motors as the means of propulsion at these speeds.

Both the Metroliners and the Japanese New Tokaido trains have a 1-hour rating of about 15 hp/ton of gross weight(1). If one assumes all this horsepower is used to overcome airdrag, it should be scaled up by the cube of the speed to give 57 hp/ton for a 250-mph vehicle. Since a test vehicle will probably be tested on a track of limited length where higher than normal accelerations and decelerations will be required, the target was raised to 100 hp/ton. Figure 1, taken from reference 2, shows how the power density of these vehicles compares with that of other ground vehicles and animals.

This figure shows that the steam train, the Metroliner, and the LIM test vehicle are all located toward the right side of the shaded area representing road and railway vehicles. The steam train and the Metroliner both fall below the Gabrielli-Von Karman line which means their resistance to motion is low. The steel wheel on steel rail gives very low rolling resistance, and for their speed these are well streamlined vehicles. The LIM test vehicle does not show up quite as well as the others in this respect being above the Gabrielli-Von Karman line. This is partly because extra power is provided for high accelerations and partly because a single vehicle has higher drag than a similar car in a long train.

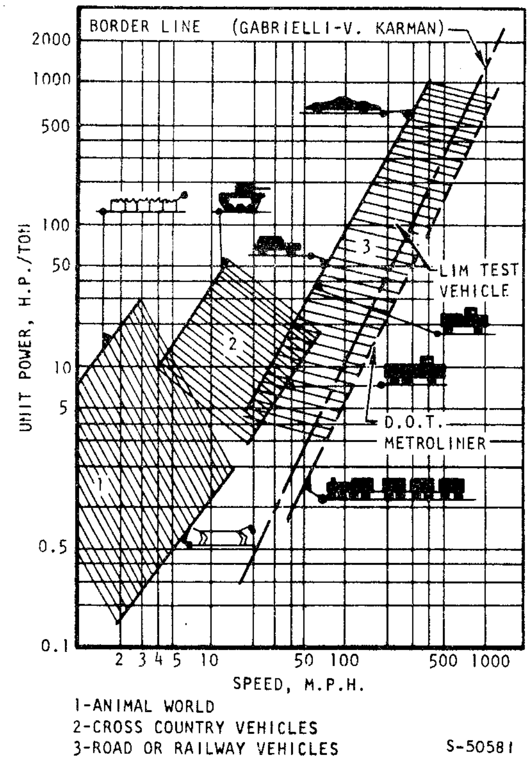

Figure 1. Energy Density of Ground Vehicle

Because this diagram is based on horsepower output it does not show the efficiency of the various vehicles and animals as energy converting devices. The steam locomotive, because it is a heat engine, having the Carnot efficiency as the best possible, is rather poor in this respect. The Metroliner being electrically powered has an efficiency from the point of power pickup of approximately 90 percent. Efficiency of the LIM is not as good as this because of the large airgap and end effects of the LIM, but it is a very satisfactory 85 percent at full speed.

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In March 1966, The Garrett Corporation embarked on a study of the linear induction motor and its feasibility for High Speed Ground Transportation(3). In June 1967, the design and building of a 250-mph 2500-hp LIM test vehicle was undertaken under a contract from the Office of High Speed Ground Transportation. This test vehicle (shown in Figure 2) will undergo low-speed testing on a 1/4-mile test track in Los Angeles in the Fall of 1969. At the end of 1969, it will be delivered to OSHGT ready for testing on a high-speed test track. This paper describes some of the activities that have occurred during this period.

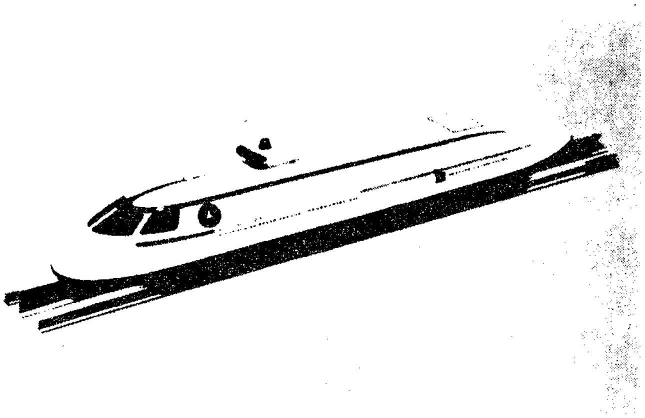

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Figure 2. The LIM Vehicle

A Description of the Linear Induction Motor

Since the LIM is not widely used at present, a brief description of some of the forms it can take and their advantages and disadvantages is in order.

A LIM can be considered to be derived from the rotating motor by cutting and unrolling both the primary and secondary members and then greatly increasing the length of one of the unrolled members. Figure 3 illustrates this process for the case where the primary is the member that is increased in length and attached to the ground. Applying polyphase ac power to the primary windings of this linear motor will induce currents in the short circuited secondary and will produce a thrust between the two members. This thrust will tend to produce a linear motion of the motor secondary. In this and subsequent figures, the airgap between moving and stationary members has been considerably increased to show details of construction.

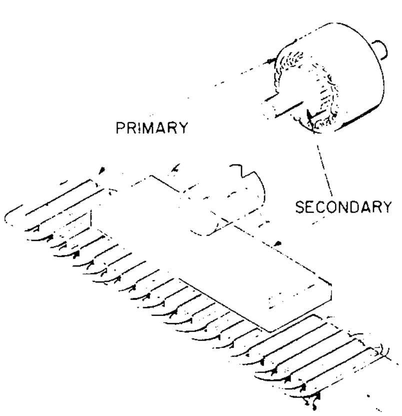

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Figure 3. Single Sided Short Secondary Linear Induction Motor

This particular LIM arrangement is classified as a single-sided short-secondary configuration. It can be used to indicate the advantages and disadvantages of linear motors in general as well as the advantages and disadvantages that are peculiar to the configuration.

The advantages of linear motors in general are:

- Thrust is produced without physical contact so the motor is suitable for use with all types of guidance and suspension systems including air cushion.
- Speed of the motor is unlimited since there are no large centrifugal forces. Therefore, the motor is particularly suitable for high-speed vehicles.
- There are no wearing parts such as gears and bearings.
- The motor does not produce noise or vibration; nor does it pollute the air.
- The moving parts are lightweight (since only one member of the motor is moving). This leads to the possibility of high accelerations and the ability to negotiate steep grades.

The disadvantages are:

- A small airgap must be maintained between the moving and stationary members of the motor.
- The length of the member attached to the ground makes it expensive.
- The motor is sized by thrust, and in low-speed applications there is no possibility of gearing down a small motor to produce large thrusts.

The major advantage of the single-sided short-secondary configuration is that no power need be supplied to the moving member. The major disadvantages are the expense of the long wound primary member, the large attractive force (approximately 3 to 10 times the thrust) that exists between the moving and stationary members, and the very large KVAR consumption of the long primary with an air return path for the flux. This latter disadvantage can be much reduced by dividing the primary winding into sections and by providing a switchgear to energize only that section opposite the secondary member. This configuration can only be justified economically when the traffic density is very high.

There is a variation of this arrangement, classified as a single-sided short-primary short-secondary machine, where the primary member is built in short sections with spaces between the sections. This arrangement is less expensive than the one having the continuous primary member, but still can only be justified economically by high traffic density.

A rotating induction motor can be turned inside out by making the squirrel cage secondary the stator member and the wound primary the rotor. This arrangement requires that the ac power be fed to the primary by means of sliding contacts. In the same way an unrolled linear motor can be turned upside down by making the short circuited secondary the member that is increased in length and attached to the ground. The primary now becomes the short moving member. This single-sided short-primary configuration reduces the expenses of the long stationary member but requires either a power pickup or an on-board power supply. It, too, suffers from a large attractive force between the members.

The large attractive force existing between the members of this configuration can be eliminated by adding a second short-primary member on the other side of the long secondary member. The attractive force now exists between the two primary members and the secondary "floats" between them. This is classified as a double-sided short-primary configuration and is shown in Figure 4.

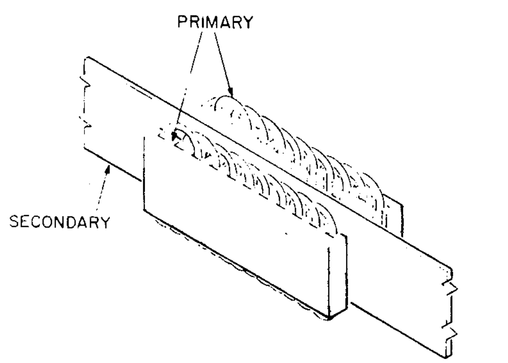

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Figure 4. Double Sided Short Primary Linear Induction Motor

The secondary member shown in Figure 3 is a composite comprising a squirrel cage made of a material having high electrical conductivity, and teeth and yoke made of a material having high magnetic permeability. In the secondary shown in Figure 4 all the magnetic material is eliminated, leaving only a homogeneous member of high electrical conductivity. This has the effect of reducing the cost of the secondary at the expense of increased effective airgap. This configuration with the homogeneous secondary is the one chosen for the LIM propulsion system. It leads to the lowest cost of the member that is as long as the railroad. The thrust developed by the LIM primaries produces an equal and opposite reaction force in the secondary member attached to the ground. Therefore, this secondary member is also referred to as the reaction rail.

Electrical Design of Linear Induction Motor

Theoretical Analysis

It was shown above that the LIM can have short primary or short secondary configurations. For high-speed ground transportation application, the short primary configuration appears to be more important. In a short primary machine, the primary winding should be series connected to avoid large currents in the leading end coils. The theoretical analysis in this paper, therefore, is concerned only with the short primary machine with series connected winding.

In making this analysis it is assumed that the current flowing in the primary winding can be represented by a moving sinusoidally distributed current sheet. The effects of primary slots and of current harmonics are ignored. The reluctance of the airgap is assumed to be uniform over the entire core. That is, tufting of the flux at the teeth is ignored. The end effect at the entering end of the motor is accounted for by setting the flux there always equal to zero as a boundary condition. This gives rise to two flux waves in the airgap of the motor: a normal traveling wave and an end effect traveling wave.

The analysis given here is abbreviated. A fuller treatment will be found in reference 3.

Refer to Figure 5 for the coordinate axis. X_1 axis is stationary with respect to the primary which is moving with a velocity u_2. The X_2 axis is stationary with respect to the secondary, such that

$$x_1 = x_2 + u_2 t \tag{1}$$

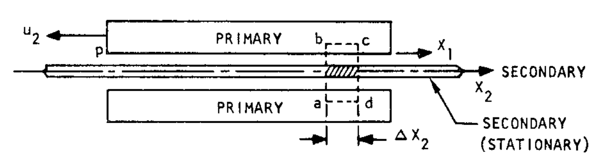

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Figure 5. Series-Connected Motor

As in a rotary induction motor, the primary current of the LIM can be resolved into two components: a magnetizing component and a load component. The load component of the three-phase primary current can be represented by a sinusoidal traveling current sheet

$$j_1' = J_1 \sin\left(\frac{\pi}{\tau_p} u_1 t - \frac{\pi}{\tau_p} x_1\right) \tag{2}$$

The secondary current sheet is exactly equal to the load component of the primary current but is in an opposite direction. Secondary current sheet, when referred to the X_2-axis, can be obtained by substituting Equation (1) into Equation (2).

$$j_{22} = J_1' \sin\left[\frac{\pi}{\tau_p}(u_1 - u_2)t - \frac{\pi}{\tau_p} x_2\right] \tag{3}$$

Consider an elementary area ΔX_2 wide and 1-inch high in the direction perpendicular to the paper in Figure 5. The induced voltage in a loop enclosing that area should be equal to the impedance drop around the same loop:

$$\frac{\partial b_2}{\partial t} \times 10^{-8} = -\rho_2 \frac{\partial j_{22}}{\partial x_2} - L_{22} \frac{\partial^2 j_{22}}{\partial x_2 \partial t} \qquad (4)$$

The primaries move to the left with a velocity u_2. Neglecting the fringing flux at the edge, the magnetic flux density perpendicular to the secondary to the left of point P (leading edge of the linear motor) is zero at all times. Since magnetic flux density cannot change suddenly in the presence of the short circuiting secondary, the flux density in the airgap between the primaries must build up gradually from zero at location P to a finite value. Substituting Equation (3) into Equation (4), and using b = 0 at P at all times as a boundary condition, the solution of Equation (4) is:

$$b = \frac{J_1' z_2}{\sigma u_1} \cdot 10^8 \left\{ \sin\left(\frac{\pi}{\tau_p} u_1 t - \frac{\pi}{\tau_p} x_1 + \phi\right) - \sin\left(\frac{\pi}{\tau_p} u_1 t - \frac{\pi}{\tau_p} \frac{u_1}{u_2} x_1 + \phi\right)\right\} \qquad (5)$$

Equation (5) indicates that the magnetic field in the LIM airgap consists of two traveling waves. The first traveling wave corresponds to the regular rotating field in a rotary machine. The second traveling wave has a shorter wavelength $\left(\lambda_2 = 2 \frac{u_2}{u_1} \tau_p\right)$ than that of the first and travels with the motor speed u_2 (not the synchronous speed u_1). For simplicity, the first traveling wave is called the normal traveling wave and the second traveling wave is referred to as the end effect traveling wave.

The normal traveling wave is magnetized by the magnetizing current in the primary winding. The end effect traveling wave is magnetized by a secondary current created by the end effect. The end effect traveling wave is stationary with respect to the secondary member but has a relative motion with respect to the primary winding. Both traveling waves induce voltages in the primary winding at line frequency. The normal traveling wave reacts with the secondary current to produce a forward thrust while the end effect traveling wave reacts with the secondary current, producing a retarding thrust. The net output force of the motor is the difference of the two thrusts.

The shape of the resultant flux wave in the airgap at various instants of time can be obtained by adding the two traveling waves. An example of how the shape of the flux wave varies with time is shown in Figure 6 for a slip σ = 0.5.

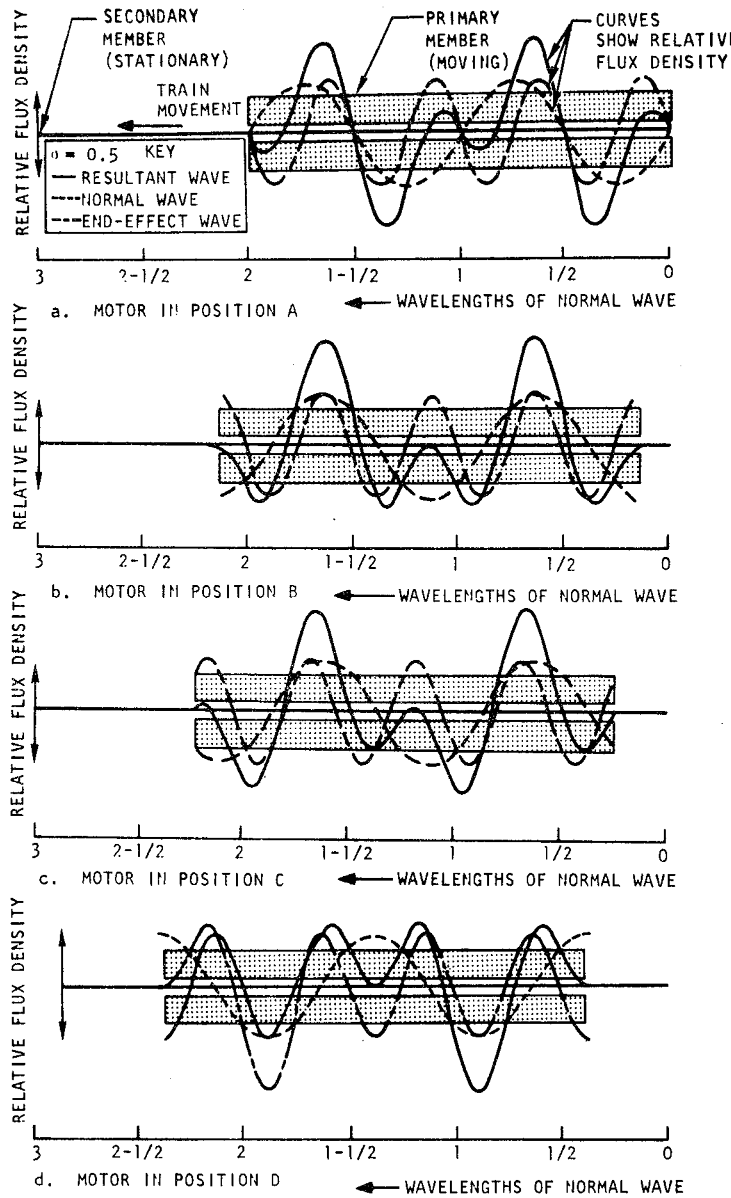

Figure 6. Traveling Flux Waves

In an actual machine, the end effect traveling wave will decay because of the energy dissipation involved. The flux distribution in an actual machine is then given by:

$$b = \frac{J_1' z_2}{\sigma u_1} \cdot 10^8 \left\{ \sin\left(\frac{\pi}{\tau_p} u_1 t - \frac{\pi}{\tau_p} x_1 + \phi\right) - \epsilon^{-\frac{x_1}{T_2 u_2}} \sin\left(\frac{\pi}{\tau_p} u_1 t - \frac{\pi}{\tau_p} \frac{u_1}{u_2} x_1 + \phi\right)\right\} \qquad (6)$$

The instantaneous force produced by the motor is given by:

$$F(t) = 8.85 \times 10^{-8} \int_0^{P\tau_p} b j_2 \, dx_1$$

$$= \frac{4.43 z_2 \ell_1 J_1^2}{\sigma u_1} \left\{ P\tau_p \cos\phi - \frac{\epsilon^{-\frac{P\tau_p}{T_2 u_2}} \sin\left(\frac{P\pi\sigma}{1-\sigma} - \theta_f\right) + \sin\theta_f}{\sqrt{D}} \right\} \tag{7}$$

lb/in. of stack

where

$$D = \frac{1}{T_2^2 u_2^2} + \left(\frac{\pi}{\tau_p} \cdot \frac{\sigma}{1-\sigma}\right)^2$$

$$\theta_f = \phi + \tan^{-1} \frac{1}{\sigma\omega T_2}$$

Equivalent Circuit

To facilitate understanding and visualization in design, the LIM is represented by an equivalent circuit as shown in Figure 7. This equivalent circuit is similar to that of a rotary induction machine, except that X_{2e} is not the secondary reactance and R_{2e} is not equal to r_2/σ. Both X_{2e} are R_{2e} are complicated functions of slip σ.

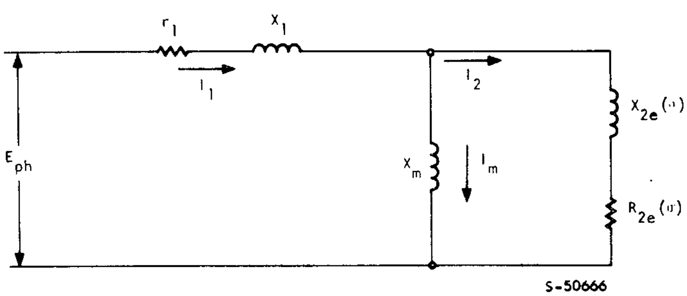

Figure 7. Equivalent Circuit of a Linear Induction Motor

The secondary constants are given by

$$R_{2e} = m\left(\frac{CK_w}{P\tau_p}\right)^2 \ell_1 \left\{ \frac{1-\sigma}{\sigma} z_2 \,(\text{F.F.}) + P\tau_p \rho_2 \left[1 + 2\Delta \frac{z_{2e}^2}{X_m^2} + \frac{\frac{\Delta Z_{2e}}{Xm}}{1 + \exp\left(-\frac{P\tau_p}{u_2 T_2}\right)} \right] \right\} \tag{8}$$

ohms per phase per side

$$X_{2e} = \sqrt{\left[F_1(\sigma)\ell_1 \frac{mCKw}{P\tau_p}\right]^2 - R_{2e}^2} \tag{9}$$

ohms per phase per side

where

$$\text{F.F.} = P\tau_p \cos\phi - \frac{1}{\sqrt{D}}\left[\exp\left(\frac{P\tau_p}{T_2 u_2}\right)\sin\left(\frac{P\pi\sigma}{1-\sigma} - \theta_f\right) + \sin\theta_f\right]$$

$$\Delta = \frac{T_2 u_2}{2P\tau_p}\left[1 - \exp\left(-\frac{2P\tau_p}{T_2 u_2}\right)\right]$$

$$F_1(\sigma) = \frac{z_2 C}{\sigma} \sqrt{(K_w - K_1 \cos\delta_1 + K_2 \cos\delta_2)^2 + (K_2 \sin\delta_2 - K_1 \sin\delta_1)^2}$$

The derivations of all the above expressions are given in reference 3. A glossary of symbols is given at the end of this paper.

At the trailing edge of the short primary, another kind of end effect exists. Any particular element in the secondary, just before leaving the primary, links a certain flux in the airgap. After that element leaves the primary, the flux within that element decays gradually. The magnetic energy of these fluxes is dissipated as I^2R losses. The total exit loss is given by

$$W_{exit} = \frac{0.785 \times 10^7 J_1^2 z_2^2 \ell_1 C_1 C_2 K_{sf} g u_2}{\sigma^2 u_1^2} \left[1 + \exp\left(-\frac{2P\tau_p}{T_2 u_2}\right) - 2\exp\left(-\frac{P\tau_p}{T_2 u_2}\right)\cos\frac{\pi P}{1-\sigma}\right] + 0.2\delta L_{22} \ell_1 J_1^2 u_2 \tag{10}$$

watts per side of primary

Departure from Conventional Rotary Machine

One feature of the LIM is its large magnetic gap. In a rotary machine, the separation between the primary and secondary members is determined by contact bearings. The surfaces of the primary and secondary are accurately bored or ground. The mechanical separation of the stator and rotor can be very small. In a linear motor, however, it is difficult to maintain a close clearance between the primary and secondary when the vehicle travels at a high speed.

The reaction rail is normally nonmagnetic to avoid the problem of unbalanced magnetic pull. This also contributes to the large magnetic gap. In the LIM test vehicle, the LIM is designed for a magnetic gap of 0.75 to 2.25 in. between the two primaries.

The direct result of the large magnetic gap is a low power factor. This low power factor, in turn, causes low efficiency and low thrust per ampere of line current. Other effects of large magnetic gap include large tooth tip leakage reactance, less influence from space harmonics, larger full load slip, and larger trailing edge exit losses.

Another feature of the LIM is the end effect, which tends to reduce the output and increase the LIM losses. The end effect in a short primary machine can be summarized as follows:

(1) Due to the leading edge, a second traveling wave with a decaying amplitude is created. This wave travels at $(1-\sigma)$ synchronous speed and produces a negative thrust. In a properly designed linear motor this traveling wave decays rapidly and does not create a serious problem.

(2) At the trailing edge, magnetic energy escapes continuously and is dissipated as an eddy-current loss in the secondary member. This loss varies with motor design. In general, it is in the order of 2 to 3 percent of the rated output.

(3) The end effect traveling wave causes a nonuniform flux distribution in the airgap. This in turn causes asymmetry in the three phases. When a balanced three-phase voltage is applied to the motor, an unbalanced three-phase current will result. This unbalance, however, is not serious and can be ignored.

(4) Because of the end effect traveling wave, the pull-out force of the LIM changes with the secondary resistance. Within a certain range an increase of secondary resistance will increase the pullout force.

(5) Because of the open ends, some limitation is placed on the winding connections. In general, series connection is preferred for the short primary configuration. Series or parallel connection is preferred for the short secondary configuration depending upon whether the secondary is magnetic or nonmagnetic.

(6) Another end effect is a double-line-frequency force fluctuation. This will produce a double-line frequency vibration of the motor assembly. This force pulsation is of small magnitude.

(7) In a linear machine with uniform winding, the peak flux in the back iron is twice as much as that in the corresponding rotary machine. If the primary winding is arranged such that the first and last poles have single-layer windings and all the intermediate poles have double-layer windings, the peak flux in the back iron of a linear motor will be the same as that in a corresponding rotary machine. Therefore, because of the open ends, a linear motor will have either thicker back iron or be longer in length than a comparable rotary motor. For a detailed explanation, see reference 3.

(8) The end regions in a linear motor secondary correspond to the end rings of a squirrel cage induction motor. The effect of the size of end regions to the linear motor performance can also be called end effect. If the secondary is not sufficiently wider than the primary stack length, part of the secondary inside the primary core area will be forced to serve as end rings for the secondary current. This will cause the linear motor to have reduced output.

The most important factor in reducing the leading edge end effects in the LIM is to prevent the secondary resistance from being too low. High secondary resistance helps to damp out the end effect traveling wave. As a result, LIM's have higher running slips than ordinary squirrel cage induction motors.

<u>Electrical Design Considerations</u>

One of the important parameters in sizing the LIM is the airgap length. Since the airgap of a linear machine is large, the airgap flux density should be relatively low. A peak gap density in the order of 25,000 lines/sq in. is considered appropriate for linear motors.

Because of the large airgap, the magnetizing ampere conductors per inch requirement is large. To obtain a reasonable ratio of useful current to magnetizing current, the ampere conductors per inch of motor length should be considerably higher in a linear motor than in a rotary machine. To limit the heat loss per unit area, the current density of the primary conductor is kept low. This can be achieved by using wider and deeper slots.

Three kinds of material can be used for the secondary member of the LIM induction motor: ferrous, nonferrous, and composite material.

The advantage of ferrous material is that its high permeability reduces the magnetizing current requirement.

One of the most important disadvantages to the magnetic secondary is the problem of magnetic pull. In a double primary machine, if the airgaps on each side of the secondary are not equal, magnetic flux densities in the two airgaps will be different. Since the lateral magnetic force between the primary and the magnetic secondary is several times larger than the useful tractive force developed by the motor, a difference in airgap lengths can result in a large unbalanced magnetic pull on the secondary.

Another disadvantage to the magnetic secondary is the high leakage reactance presented to the secondary current. The secondary leakage reactance will have saturation and skin effects, especially during motor starting under constant frequency operation. Primary end leakage reactance will also increase because of the proximity of the primary end winding to the end regions of the magnetic secondary.

To eliminate the problems of unbalanced magnetic pull and high leakage reactance, nonmagnetic material may be used for the secondary. This has an immediate disadvantage of the low magnetic permeability across the primaries resulting in increased magnetizing current. Since the thickness of the secondary is usually a small portion of the total magnetic gap, the increase is magnetizing current is not excessive.

A secondary member can be made of composite material by embedding steel bars in an aluminum plate. This is a compromise between the magnetic and nonmagnetic secondaries. The slight improvement in performance, however, does not justify the high expenses.

A nonferrous material, such as aluminum, is considered as the most practical choice for the linear motor secondary member.

Since the end winding configuration of the LIM may be different from that of a rotary motor, formulas of end leakage reactance, derived for rotary machines, may require modification before applying them to linear machines.

Because of the large airgap, the linear motor should have a reasonably large pole pitch to enable the use of a reasonable electric loading. However, a motor with large pole pitch has several disadvantages. First, the back iron of the primary must be increased because the flux per pole is increased with increased pole pitch. This results in a heavier machine. Second, in the primary winding, the ratio of the end turn length to the slot portion of the winding is high. Long end turns are obviously undesirable. Third, the secondary reaction rail must be higher because a greater pole pitch requires wider end regions due to the increased secondary current. Finally, for a given motor length, large pole pitch results in a small number of poles. However, the leading-edge end effect increases when the number of poles decreases. A good linear motor design must take into consideration all these factors.

A simple mathematical manipulation reveals that the linear motor of minimum size should have an airgap flux density such that the magnetizing component and the load component of the primary current are approximately equal. For better efficiency, however, the load component should be larger than the magnetizing component of the primary current.

The number of slots per pole in the primary member affects the winding reactance, harmonic content, and space factor in the slot. The considerations for choosing the number of slots in rotary machines are also applicable to linear motors.

Application Problems

Power Supply

The LIM for high-speed ground transportation demands an input frequency higher than 60 Hz so that the pole pitch would not become excessive. Based on reference 3, the operating frequency should be about 1 Hz for every 1 mph of vehicle speed. Three power supply alternatives are considered appropriate for LIM systems.

Constant Frequency Three-Phase Wayside Power (Figure 8). Constant frequency is applied to the LIM from starting to braking. Frequency conversion substations are provided along the right-of-way to convert 60-Hz utility power to the required operating frequency for the LIM. Spacing of these units depends on the traffic density and the voltage level but would typically be at 10-mile intervals. Low power factor current has to be supplied by the wayside power since the typical LIM power factor is about 0.6.

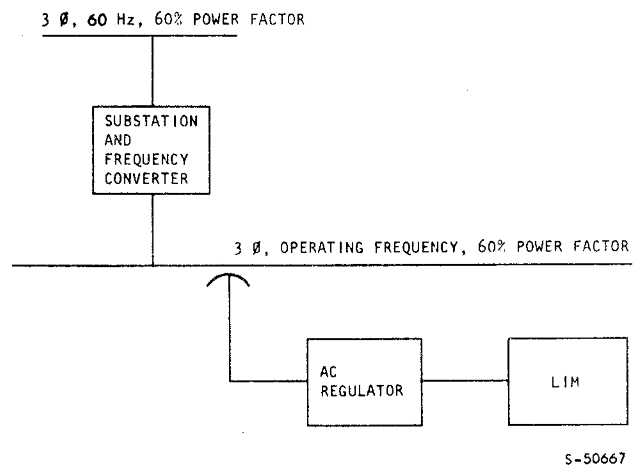

Figure 8. Constant Frequency Three-Phase Wayside Power

The large inrush current caused by starting the LIM can be limited by reducing the cross-section of the reaction rail at the passenger stations. The vehicle can be started between stations by reduced voltage from an onboard ac regulator. However, this method can provide only limited accelerating thrust, and should be used only in emergencies.

Voltage control by means of the ac regulator can also be used to eliminate jerk when crossing from one reaction rail resistance characteristic to another. When leaving or arriving at a passenger station, the voltage can be reduced at the transition and then reapplied smoothly so that no disturbance is felt by the passengers. This requires complicated control equipment.

The high slip in a constant-frequency LIM or a rotary induction motor produces unnecessary losses, except when operating at full speed. This means the energy consumed by a vehicle powered by a LIM operated on constant frequency is higher than a vehicle powered by a variable frequency motor.

Variable Frequency Three-Phase Wayside Power (Figure 9). Flexible and effective speed control of the LIM powered vehicle requires a variable frequency supply. Ground based power conversion equipment can provide such variable frequency.

In this power supply scheme, several track blocks with block interlocks, are provided between the two passenger stations. Two versions are possible: (a) on each block of track, the wayside frequency is variable and is controlled as a function of the vehicle speed (Figure 9a), (b) each block is supplied by constant wayside frequency with progressively higher frequencies from block to block until the maximum frequency is reached and with progressively greater lengths from block to block (Figure 9b).

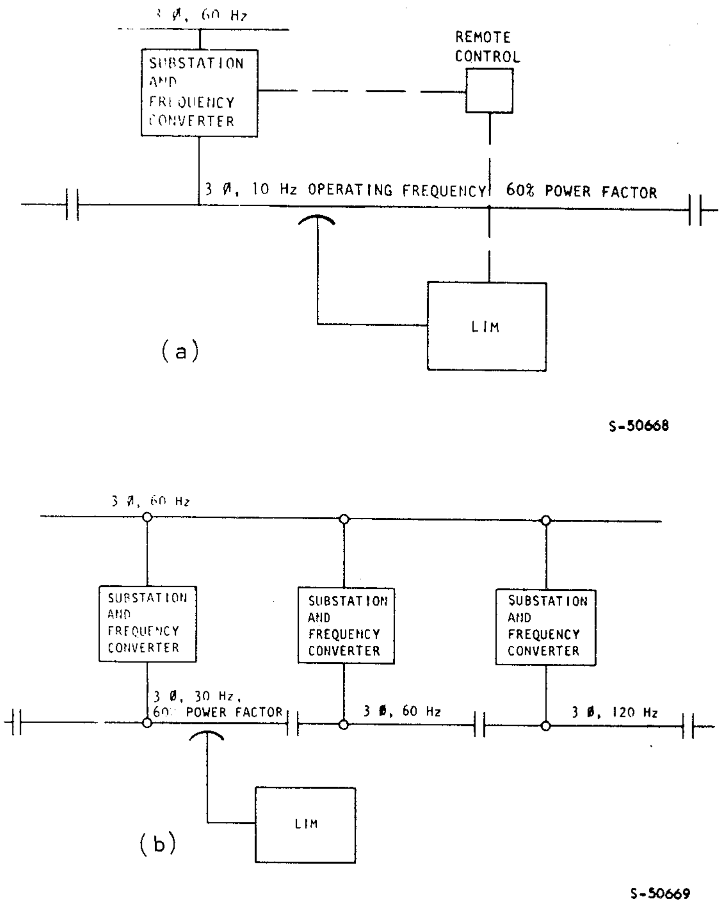

Figure 9. Variable Frequency Three-Phase Wayside Power

These variable frequency systems offer a greater flexibility for controlling train operation and better energy consumption than the constant frequency scheme. However, there are problems that exist in the special, noncommercial frequency power equipment and in the switchgear. Also, there is the penalty of carrying large reactive power in the power supply and distribution.

Commercial Frequency Single-Phase Wayside Power with Onboard Power Conversion (Figure 10). The three-phase variable voltage, variable frequency power for the LIM is supplied from an onboard dc-to-ac inverter. Variable voltage dc input to the inverter is provided through a smoothing choke from a phase delay rectifier circuit. The system is fed from constant voltage 60-Hz wayside power.

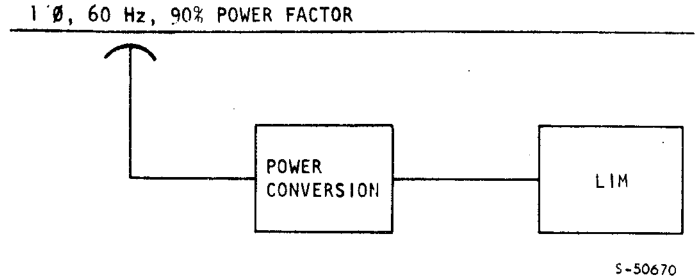

Figure 10. Commercial Frequency Single Phase Wayside Power with Onboard Power Conversion

In this system, since the wayside power is commercial frequency, nonstandard ground based frequency conversion equipment is not needed. Single-phase power makes power pickup problems significantly simpler. The wayside power demand is at the high power factor. Unscheduled starting at any position along the track is no problem. The onboard equipment in this system is, however, heavier than that of the two previous systems.

Speed Control

Many methods of controlling the speed of squirrel-cage induction motors are also applicable to LIM's. The speed control methods can also be used for starting the linear motor. A short discussion of the speed control methods is given below.

Frequency and Voltage Changing. A variable frequency supply with constant volts per cycle is the source of power for the LIM. The variable frequency supply onboard can be a cycloconverter, a dc-link frequency converter, or a variable speed turboalternator.

A cycloconverter is the lightest weight frequency converter. It is limited, however, by its needs for a high-frequency power supply. Also, the relatively high reactance of the high-frequency power transmission line would impair the cycloconverter operation, and would require very closely spaced substations. These limitations may exclude the cycloconverter as a variable frequency supply for the LIM drive.

The dc-link frequency converter provides a smooth and efficient control of the motor speed. This is perhaps the most practical method of obtaining variable frequency power for the high-speed vehicle.

The variable frequency turbo-alternator system uses a variable-speed free-spool gas turbine driving a synchronous ac generator. The weight of such a system is about the same as that of a dc-link frequency converter. However, some disadvantages make this system unfavorable: noise and exhaust problems, low turbine efficiency at reduced speed operation, and the necessity of a separate exciter drive.

Constant Frequency with Variable Secondary Resistance. In this system the reaction-rail resistance variable is used to control the running slip of the motor or to increase the accelerating thrust during motor starting. Voltage control should be used to eliminate jerk when the motor crosses from one secondary characteristic to another.

This is the most lightweight system for continuous speed control, although the energy consumption at low-speed operation is high because of the high secondary I^2R loss.

Constant Frequency with Pole Changing. This system provides step speed changes. To avoid jerk, voltage control is also necessary. The conventional two-step pole changing probably cannot provide sufficient torque to start a vehicle nor can it provide smooth acceleration.

Several new pole-changing schemes have been suggested such as phase mixing and pole amplitude modulation(4,5). The suitability of these methods for controlling LIM speed has not been evaluated.

Linear Induction Motor Test Program

A small model LIM had been built as part of the feasibility study for the purpose of confirming some of the theoretical predictions. This model was too small to give meaningful information about the problems of a full-scale motor. In fact, the only way to get this information would be to build the full-scale motor and test it at operating speeds. Because of the linear motion needed for either the primary or the secondary, it is difficult to perform this testing in a laboratory. A decision was therefore made to do this testing with a test vehicle capable of operating at full speed.

After it was decided to build a test vehicle the following choices had to be made:

Wheels vs Air Cushion. The vehicle that ultimately emerges may well be supported and guided by air cushions (Tracked Air Cushion Vehicle - TACV). To avoid the problems of simultaneous developments it was decided to limit the program to testing only the LIM. Accordingly, a vehicle having flanged steel sheels riding on a standard-gage railroad track was chosen as the one most likely to be capable of running at 250 mph without undue development problems.

On-Board vs Wayside Power Supply. The final operational vehicle will require a wayside electric power supply and current pickup. At present, however, current collection at 250 mph is yet unproven. To avoid having the test program dependent upon the successful development of a high-speed pickup it was decided to use an onboard prime mover as the source of power. To keep the weight of the test vehicle down to an acceptable value, a gas turbine was selected as the prime mover.

To operate the LIM at variable frequency, a gas turbine of the free-spool type is required. A General Electric T64-10 free-spool shaft turbine, with a rating of about 3000 hp at full speed was furnished as GFE. With allowance for efficiencies this would lead to a LIM with a full-speed rating of about 2500 hp.

Since the LIM test vehicle weighs 22 tons, the target of 100 hp/ton (Figure 1) can be achieved.

Design Considerations

The LIM test vehicle requirements are for 2500-hp continuous rating at 250 mph, that is, a continuous thrust of 3750 lb. The following design factors affect the size of the motor.

Airgap. The size of the airgap that is needed is dependent on several factors such as (1) the accuracy with which the reaction rail can be erected and maintained, (2) the performance of the LIM guidance system, (3) the radius of curves that must be negotiated, and (4) the weight and length of the LIM. It is apparent that determiation of the airgap is a complex problem involving many iterations. In the test program a range of airgaps was selected; therefore, the LIM was designed and built with an adjustable airgap which can be varied from 0.75 to 2.25 in. primary-to-primary separation. The design point is 1.5 in.

Specific Thrust. In accordance with guideline set by the feasibility study, the specific thrust should be between 1.2- and 2.4-lb thrust/in./side of motor active area(3). Since the LIM is operating with a large airgap for the test vehicle program, the lower end of the range of specific thrust should be used. This gives about 1500 in. of motor active area for each primary and defines the product of the stack height by the length of the motor as 1500 in.(2). The cost, size, and weight of the LIM are not greatly affected by the way this product is divided, therefore the longest possible LIM should be used. (The height and cost of the reaction rail are independent of the motor length, but vary directly with the LIM stack height.) Because of the need to negotiate curves(6) and requirements for motor frame rigidity, it was judged that a 150-in. motor is as long as is feasible. This provides a stack height of 10 in. and length of 150 in.

Selection of Frequency. Another guideline resulting from reference 3 is that the frequency should be about 1 Hz for every 1 mph of operating speed. This indicates a frequency at maximum speed of about 250 cycles. Since the output of the turbine gear reducer has a top speed of 5200 rpm, a six-pole generator running at this speed gives 260 Hz. A LIM for this frequency has 16 poles with 9-in. pole pitch, 10-in. stack height, 150-in. length, and a primary-to-primary separation of 1.5 in. This design was quite satisfactory at the design point, however, the thrust at a maximum separation of 2.25 in. was unacceptable.

By reducing the input frequency to 173.3 Hz (four-pole generator at 5200 rpm), a LIM with 10 poles, 13.6-in. pole pitch, a 10-in. stack height, and 1.5 in. separation was obtained. This LIM is heavier than the one designed for 260 Hz because both the end winding copper and the depth of the yoke are increased approximately 50 percent. Because of the better airgap-to-pole pitch ratio, however, the motor's performance at 2.25-in. separation is greatly improved. Also, the number of poles is large enough that the entering and leaving end effects are not too important.

Core and Windings. It was pointed out earlier that the windings of the ten poles must all be series connected. To achieve the best cooling of the windings the insulation thickness should be kept as small as possible which means that the lowest voltage possible should be used. To satisfy these two requirements the primary consists of a three-phase wye-connected winding made up of series-connected single-turn coils. This results in a rating of 1040-v line-to-line at a current of 1000 amps for each primary. The two primaries are connecte in parallel which gives a motor rating of 1040-v line-to-line at 2000 amps.

Detail B of Figure 11 shows the arrangement of the LIM core and windings. The core consists of strip laminations 4-1/4-in. wide by 12-ft 6-in. long notched on the inner edge. The laminations are stacked and cyclowelded to form a solid stack 10-in. high. Mechanical strength is imparted to the stack by providing a steel member of U-shaped cross-section which is attached to the stack with core clamping bolts, the U-member and the stack are spaced apart so that the whole assembly forms a box configuration.

The windings are conventional two-coil side per slot diamond shaped coils, with the end turns arranged in the usual manner on the top of the core, with the plane of the end turns vertical. At the bottom of the core, however, the coils are all bent at right angles as soon as they emerge from the slots so that the plane of the end turns is horizontal. This is done to bring the motor as close as possible to the ground, thereby minimizing the total height of the reaction rail. The group interconnections and lead attachments are made on the bottom end windings. The bottom end windings were chosen in preference to the top end windings because provision of extra room around the top would require a larger motor mainframe, whereas the bottom end windings are outside this frame.

<u>Cooling</u>. The cooling system used for the LIM is shown in Figure 11. For each motor primary there is a cooling system with a fan and air distribution duct to supply air to the motor at six points along its length. The air from the ducts enters a chamber formed by a fiberglass cover that surrounds the top end windings. After extracting heat from these end-windings the air passes downwards through cooling holes in the LIM core. The air from the core cooling holes enters a fiberglass chamber surrounding the bottom end windings. After cooling these windings it is exhausted to the atmosphere through holes on the end of the fiberglass chamber. In addition to this forced air cooling system, ambient air will be entrained by the reaction rail in the space between the rail and the motor active surface where it will cool this surface, and be exhausted to the atmosphere at the trailing end of the LIM.

Thermal analysis has shown that with this arrangement the LIM will have a continuous thrust capability of 3750 lb (2500 hp at 250 mph), and a short time thrust capability of 7500 lb (5000 hp at 250 mph).

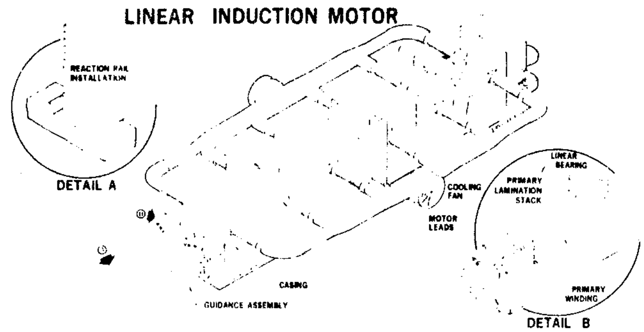

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Figure 11. LIM

<u>Guidance</u>. The purpose of the guidance system is to prevent physical contact between the LIM primaries and the reaction rail. Equipment used to attach the LIM to the vehicle, and to guide it along the reaction rail is shown in Figures 11 and 12.

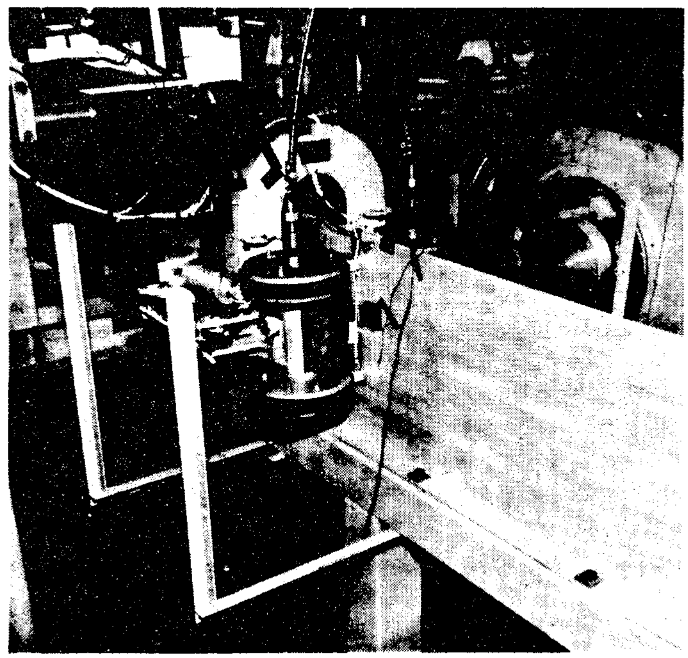

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Figure 12. LIM Test Setup

There are two points toward the ends of the LIM mainframe where attachment is made. At each of these points there is a swing pin with its axis in the direction of travel of the motor which allows it freedom to roll, and there is a linear bearing with its axis across the vehicle which provides the motor freedom to move laterally with respect to the vehicle. There are also two pairs of guidance wheels at each end of the LIM to maintain the correct LIM position with respect to the reaction rail no matter how the vehicle may be moving with respect to this rail.

The 10-in. diameter wheels have solid elastomer tires, a pair of which are mounted on an axle with vertical axis and on antifriction bearings in a carrier. The carrier is hinged about a vertical axis to the LIM mainframe. A pair of encased compression springs pinned to the carrier and the LIM mainframe applies forces which pinch the reaction rail between pairs of guidewheels on opposite sides of the rail.

By the use of different compression springs the pinch force can be varied and an adjustable hydraulic damper provided in parallel with each pair of springs, allowing the dynamics of the guidance system to be varied within limits.

Reaction Rail. The reaction rail is as long as the railroad, therefore it is important to minimize its cost, including installation, maintaining, and alignment.

For low cost, an aluminum alloy (6061 T_6) was selected as the material to be used. With this material the thickness required for electrical reasons is in about 1/4-in. However, since lateral guidance of the LIM is provided by the reaction rail it must be capable of supporting the reaction forces imposed by the LIM guidance system. A 1/4-in. thick sheet of aluminum is not capable of doing this. Therefore, a hollow rail construction was adopted as shown in Figure 11. This type of construction provides the necessary lateral rigidity while minimizing the amount of metal per unit of length. It is suitable for quantity production by extrusion.

The rail comes in 36-ft lengths. These lengths are joined by a proprietary welding process. The rail is erected on the track in such a way that it will be under tension when the temperature is between 0° and 135°F. Properties of the material are selected so that on the coldest day the rail will not be strained beyond its yield point 35 ksi. The relaxation of the pretension with aging of the material is very small.

Alignment tolerance limits have been established and an experimental 1/4-mile installation will be made to ensure that there are no problems in welding and installation.

Propulsion System

A companion paper describes the electric propulsion system of the LIM test vehicle, operation of the vehicle in accelerating cruising, and braking modes. An analog computer representation of the vehicle and propulsion system dynamics is also described, and experimental results obtained to date are presented.

Instrumentation and Telemetry

For safety reasons, the vehicle will be operated by remote control at high speeds. A two-way radio link will be used for remote control, monitoring, and PCM telemetering of the test data.

Conclusion

A study completed in June 1967 concluded that a LIM was feasible as a means of propulsion for ground vehicles at speeds of 250 mph and higher. A full size LIM having a rating of 2500 hp at a speed of 250 mph has been built and tested in the laboratory. A vehicle for testing this LIM as a high-speed test track is nearing completion. Low-speed vehicle tests will be performed in Los Angeles in the Fall of 1969.

The LIM suffers from a large airgap and end effects but nevertheless has an efficiency and a power factor that are satisfactory for the application though lower than those of comparable rotary motors. Solutions to problems related to speed control, power supplies, and motor guidance are available.

Acknowledgments

The authors wish to acknowledge the help of many persons both inside the Department of Transportation, The Garrett Corporation, and outside those organizations who have contributed to the work reported here. We believe that recognition is due to Professor E. R. Laithwaite; without his unflagging devotion to the cause of linear motors extending over a period of many years, the program might never have been undertaken.

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Glossary of Symbols

b — Flux density in airgap, referred to the X_1-axis, lines/sq in.

b_2 — Flux density in airgap, referred to the X_2-axis, lines/sq in.

C — Number of series conductors per phase per side

C_1 — Primary Carter's coefficient

C_2 — Secondary Carter's coefficient

F — Output force of motor per side of primary, lb

f — Frequency, Hz

g — Single magnetic airgap (includes the mechanical clearance and the nonmagnetic secondary), in.

J_1 — Amplitude of the equivalent primary current sheet, amp/in.

J_1' — Amplitude of the portion of the equivalent primary current sheet that is equal to the load component of the secondary current sheet, amp/in.

j_1' — Instantaneous value of the traveling wave J_1', amp/in.

j_{22} — Instantaneous value of the load component of the secondary current sheet, refer to X_2-axis, amp/in.

Ko — $\dfrac{\dfrac{6(1-\sigma)^3}{P\pi^2\sigma}}{\sqrt{1+\left(\dfrac{\tau_p}{\pi T_2\sigma u_1}\right)^2}} \sin\dfrac{\alpha\pi}{2(1-\sigma)} \sin\dfrac{\pi}{6(1-\sigma)}$

K_1 — $Ko \exp\left(-\dfrac{0.5\,\tau_p}{T_2\,u_2}\right)$

K_2 — $Ko \exp\left[-\dfrac{(P-0.5)\,\tau_p}{T_2 u_2}\right]$

K_{sf} — Saturation factor

K_W — Primary winding factor

K_w' — Winding factor for the end effect traveling wave

L_{22} — Secondary leakage inductance, in terms of the secondary, henry/in. of motor length/in. stack

ℓ_1 — Primary stack length, in.

m — Number of phases

N — Series turns per phase

P — Number of poles

R_{2e} — Equivalent secondary resistance per phase, referred to the primary, ohm

r_1 — Primary resistance per phase, ohm

r_2 — Secondary resistance per phase, referred to the primary, ohm

T_2 — Secondary time constant, sec

X_1 — Primary leakage reactance per phase, ohm

X_2 — Secondary leakage reactance per phase, referred to the primary, ohm

X_{2e} — Equivalent secondary reactance per phase, referred to the primary, ohm

u_1 — Synchronous speed, in./sec

u_2 — Motor speed, in./sec

z_2 — Secondary impedance in terms of the secondary, ohm/in. motor length/in. stack

α — Winding pitch, per unit

γ — $\tan^{-1}\dfrac{\tau_p}{\pi\sigma u_1 T_2}$

δ_1 — $\theta_2 - \theta_1$

δ_2 — $\theta_3 - \theta_1$

θ_1 — $\dfrac{\alpha\pi}{2} - \phi$

θ_2 — $\dfrac{\pi}{2} \cdot \dfrac{\alpha+2\sigma-1}{1-\sigma} - \gamma - \phi$

θ_3 — $\dfrac{\pi}{2}\ \dfrac{\alpha+2P\sigma-1}{1-\sigma} - \gamma - \phi$

λ_2 — Wavelength of end effect traveling wave, in.

ρ_2 — Secondary resistance, in terms of the secondary, ohm/in. motor length per in. stack

σ — Slip, per unit

τ_p — Pole pitch of the motor, in.

ϕ — Phase angle

ω — Frequency, rad/sec

ELECTRIC PROPULSION SYSTEM FOR LINEAR INDUCTION MOTOR TEST VEHICLE

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Abstract

The electric propulsion system of a high-speed tracked vehicle for linear induction motor testing is described. Electrical and mechanical features of the linear induction motor, together with methods used to cool, guide, and suspend it in the vehicle, are presented. An analog computer representation of the vehicle and propulsion system dynamics is discussed, and the predictions are compared with test results. Operation of the LIM test vehicle in accelerating, cruising, and braking modes is also described. Results of experiments conducted on a full cross section one-fifth length model are presented; pictures of the vehicle, linear induction motor, and turboalternator are included.

Introduction

A test vehicle will be available soon to test a 2500-hp linear induction motor (LIM) propulsion system at speeds up to 250 mph. This will be the first demonstration of a high-power high-speed LIM and is a vital step in achieving ground transportation systems suitable for the late 1970's and 1980's. These systems will have speed capabilities about twice the 125 mph of the fastest passenger trains in the world today.

The LIM test vehicle program was started in June 1967 at Garrett/AiResearch under contract to the Office of High Speed Ground Transportation (OHSGT).(1) At the present time, all major components have been manufactured and assembly of the test vehicle and an instrumentation trailer are well advanced. Low-speed testing will take place on a 1/4-mile test track in Los Angeles about the end of 1969, after which it will be delivered to the Government for testing at speeds up to 250 mph on a Government facility now being planned.

The reason why the LIM is necessary for high-speed vehicles is simple. Existing trains have rotary motors that drive through the wheels. At speeds much above 200 mph, the air drag on the train is so large that the wheels cannot develop sufficient traction to overcome the drag and they start to slip. The LIM overcomes this problem; it "pulls" itself along a reaction rail by electromagnetic force at any speed required. The LIM can also be used for other candidate high-speed vehicles such as the 300-mph tracked air cushion research vehicle (TACRV) under study by OHSGT. The TACRV has no wheels and must be propelled by jet engines and/or by the LIM. LIM propulsion is somewhat heavier than jet engines but has the increasingly important advantage of not producing noise or air pollution. Thus, the LIM is a prime candidate for the propulsion of high-speed vehicles.

Figure 1 shows an artist's concept of the test vehicle. The electric propulsion equipment and other components located in the test vehicle are shown in Figure 2; the actual body as of April 1969 is shown in Figure 3. The vehicle is 54-ft 15-in. long, 9-ft 9-in. wide, and 7-ft high over th skin. Its weight will be approximately 42,000 lb. An on-board control console and accommodation for a driver and engineer are provided at the front of the vehicle; no passenger space is provided since the vehicle is purely for research and development.

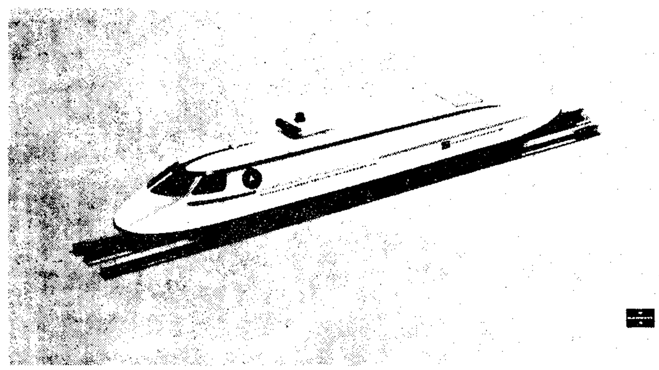

Figure 1. LIM Test Vehicle

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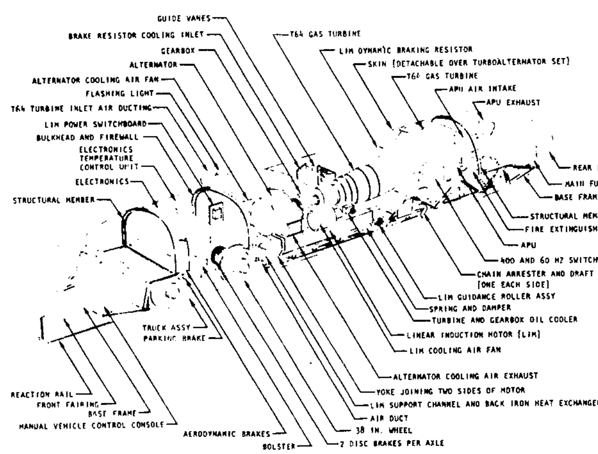

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Figure 2. Component Arrangement

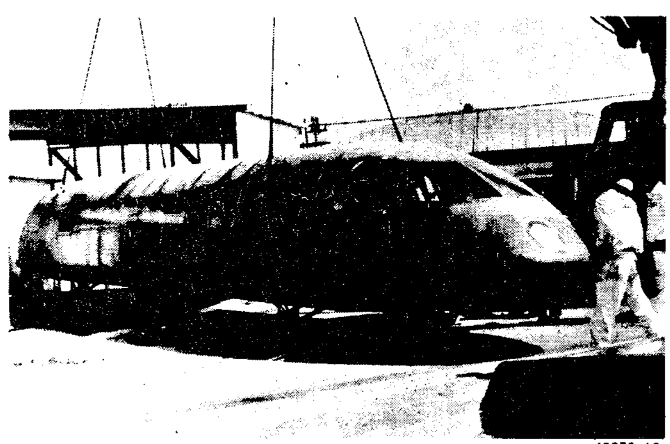

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Figure 3. Test Vehicle as of April 1969

(1) OHSGT, Department of Transportation, Contract 7-35399

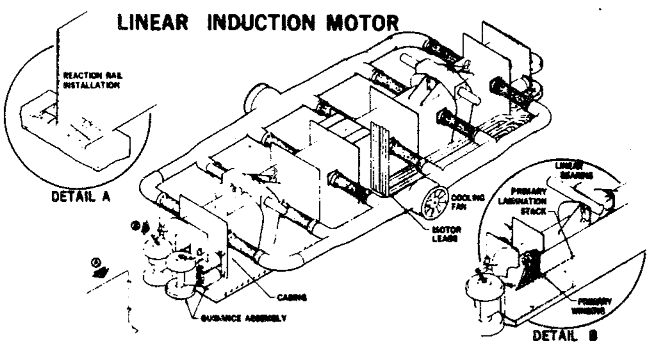
The test vehicle incorporates several interesting features in addition to the LIM. The trucks, an advanced design suitable for high speeds may yield useful data for uprating existing railroad equipment. At low speeds, the test vehicle will be operated from the on-board console while at high speeds it will be remotely controlled. The remote control console is located in a trailer which also contains digital data recording equipment and a computer to accept telemetered data from the vehicle at rates as high as 80,000 data words per second (1).

In its basic configuration, the test vehicle has an on-board turboalternator set to power the LIM. This configuration was selected because a wayside electric power pickup system will not be available when testing is started. When a wayside pickup system is built, the turboalternator set and the auxiliary power unit can be replaced by an electric power conversion unit yielding an all-electric LIM test vehicle.

A description of the essential design features and development of the linear induction motor and the electric propulsion system of the LIM test vehicle follow.

LIM Design and Performance

A double-sided primary LIM with an aluminum alloy reaction rail is used to propel the test vehicle (Figures 4 and 5).



S-50231

Figure 4. Linear Induction Motor

The decision making process in the design of the motor involved selection of air gap, electromagnetic sizing, lamination design, and winding design. Once these decisions had been made, the performance of the motor was calculated from linear motor theory which allows for performance degradation due to end effects (2). The power requirements for the alternator were established and the cooling air requirements determined.

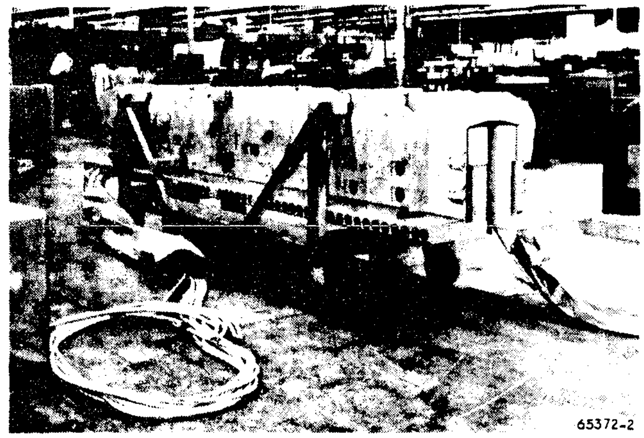


Figure 5. Assembled LIM Primaries

Selection of Air Gap

The air gap of a rotary induction motor is as small as can be practical from mechanical considerations. The pole pitch-to-air gap ratio, however, is one of the goodness criteria which affect the performance of the machine. Increasing the air gap reduces the power factor, efficiency, and output, but this can be compensated for by increasing the pole pitch.

For the linear induction motor, selection of the air gap was based on the dynamic analysis of the LIM and the vehicle, the type of construction of the reaction rail and of the guideway. Studies showed that a "mechanical clearance" in the order of 5/8 in. is required between each primary and the reaction rail (3). Since a nonmagnetic reaction rail is used, the electromagnetic air gap per primary is the sum of the mechanical clearance per side and half the width of the reaction rail.

The LIM is designed for a capability of changing the primary-to-primary gap from 3/4 in. to 2-5/8 in., so as to render it suitable for various "mechanical clearances" between primary and reaction rail and for various reaction rail thicknesses.

A primary-to-primary separation of 1-1/2 in. was used for the baseline design. Variation of output thrust as a function of the primary-to-primary gap is shown in Figure 6.

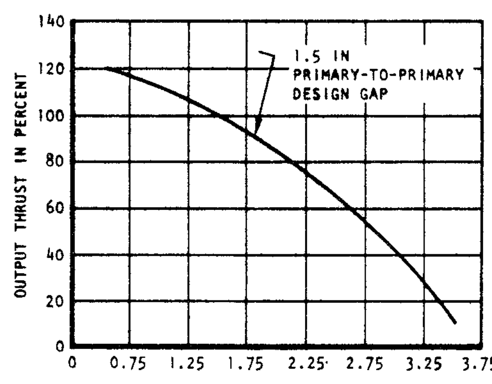


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Figure 6. Output Thrust Vs Airgap

Sizing

The study of linear induction motors from electromagnetic and thermal aspects indicated that the continuous thrust capability of a large air cooled LIM is in the order of 1.25 to 1.5 lb/sq in. of face area of both lamination (2).

Vehicle specifications called for a power output of 2500-hp at 250 mi/hr, corresponding to a thrust of 3750 lb. Based on this, two primaries, each with an area of 1500 sq in., can provide the desired thrust. The stack height of 10 in., determined by the truck geometry and the economics of the reaction rail, gave the required primary length of the LIM as 150 in.

Next the lamination design was considered. The velocity of the LIM is given by the traveling wave equation modified to account for the secondary slip.

$$v = 2 \lambda f (1-s) \tag{1}$$

where λ = pole pitch
f = frequency
s = slip
v = vehicle velocity

A frequency of 173.3 Hz at 250 mi/hr was determined by the maximum speed of the gas turbine at the gearbox output of 5200 rpm and by the choice of a 4-pole alternator. Thus, eq (1) yields a pole pitch λ = 14 in. for a typical s = 7%. With a 10-pole primary winding, the effective primary length is 140 in. Additional 10 in. were required to accommodate 2/3 of an additional pitch necessitated by the short pitch (2/3-pitch) winding. A single turn coil is used for the primary winding and there are five coils in series per pole per phase.

The "back iron" required was determined by the pole pitch and this in turn determined the width of the lamination.

An advantage of the 10-pole primary is that the large number of poles would minimize the end effects. Figure 7 shows the reduction in thrust output due to the end effects (2). The curve "thrust from equivalent circuit" is calculated from conventional induction motor theory.

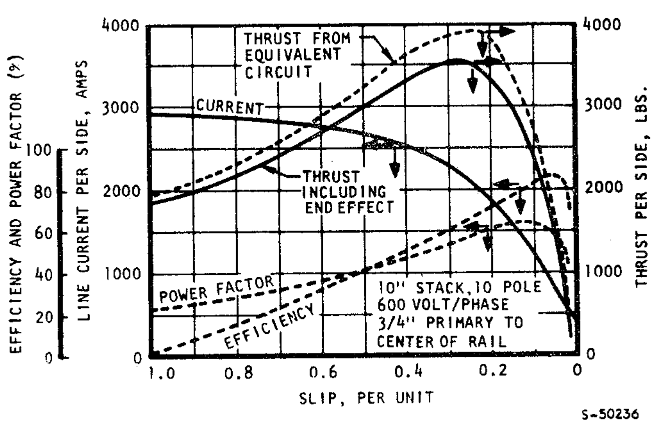

Figure 7. LIM Performance Data

During acceleration, the LIM has the potential to provide much more than its rated thrust for up to 5 minutes. The turboalternator set, however, cannot supply the additional electrical power that would be required, so, until a wayside power supply is available, the LIM can supply only its continuous thrust of 3750 lb.

Based on performance calculations, the efficiency, power factor and, hence current and power requirements of the LIM were established at 250 mph vehicle speed continuous rating as follows:

Thrust	= 3750 lb
Power output	= 2500 hp
Volts per phase	= 600 V_{LN} at 250 mph
Current	= 2000 amps
Frequency	= 173.3 Hz at 250 mph
Efficiency	= 85 percent
Power factor	= 61 percent
Primary-to-primary	= 1.5 in.

Model Approach

The design was verified by construction of a double-sided primary model which was one pole pair of the actual design. The lamination geometry, pole pitch, size of copper, and construction of the coil, were identical to the full scale LIM, the only difference being that the model primaries were two poles, or one pole pair, instead of the ten poles of the full scale motor.

Two types of tests were conducted: static and dynamic. The same one pole-pair double primary was used for both tests; the constraints and construction of the secondary were different.

Static Tests

The reaction rail was maintained in a vertical position by fitted rollers sliding in a pair of adjustable tracks. One end of the secondary was constrained by two strain gages. The sum of the two strain gage indications gave the thrust acting on the reaction rail.

Static thrust measurements were made by varying voltage, frequency, air gap, thickness of reaction rail, material of reaction rail, and width of the reaction rail end zone. As a result of these tests, the suitability of using 6061 aluminum alloy with T6 heat treatment was confirmed. Also, the geometry, such as the thickness, height, and configuration of the selected rail, was settled.

Figure 8 shows the locked thrust as a function of frequency and the effect of varying the thickness of the secondary. The primary-to-primary separation was 1-1/2 in.; the same physical separation was maintained for both 1/4-in. thick and 1-in. thick secondaries. There is a substantial reduction in locked thrust with a 1-in. secondary. The factor is approximately four at the low frequency end. At the high frequency end, the skin effect becomes important and has the effect of increasing the resistance of the 1-in. secondary. The factor is approximately two at the high frequency end.

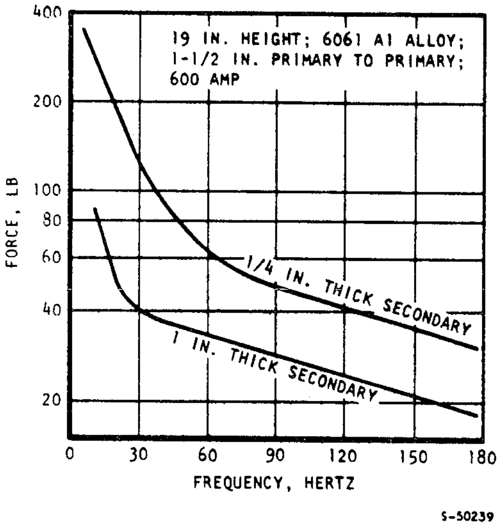

Figure 8. LIM One Pole-Pair Static Model Locked Secondary Test Data

Figure 9 shows the locked thrust as a function of air gap with a 1/4-in. thick by 19-in. wide 6061 aluminum alloy secondary. The input frequency is 13 Hz (rated slip frequency). Two curves are shown for locked rotor current of 600 and 400 amps. From these curves, it is seen that at a constant input current with increasing air gap, the locked thrust is reduced.

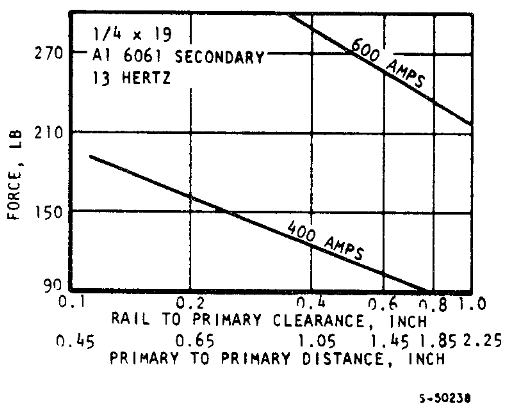

Figure 9. LIM One Pole-Pair Static Model Locked Secondary Test Data

Dynamic Tests

A nine foot diameter aluminum alloy disc was mounted between the two primaries of the one pole-pair LIM model to function as the secondary. Figure 10 shows a photograph of the disc and the double primaries. The disc was connected by a chain to the shaft of a gearbox. The gearbox provided a speed reduction and was connected to a dynamometer from which the output torque could be measured. The overall speed reduction from the dyno to the disc was 6.33:1. The system is illustrated schematically in Figure 11. Detailed dimensions of the model primary and disc are shown.

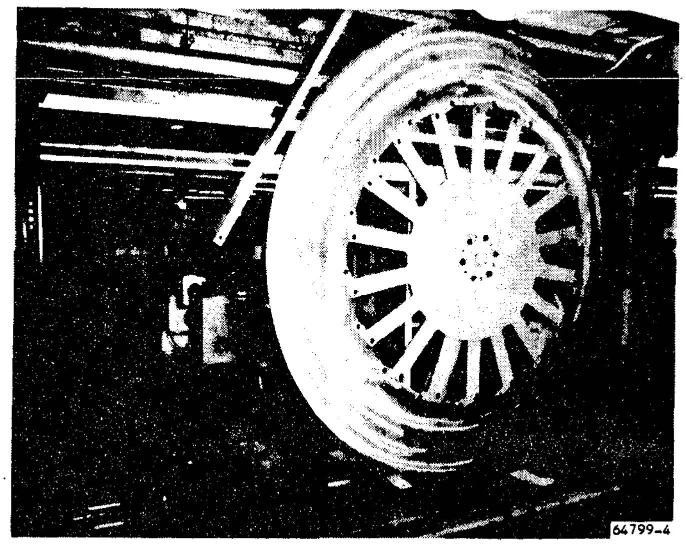

Figure 10. LIM One Pole-Pair Dynamic Model Test Setup

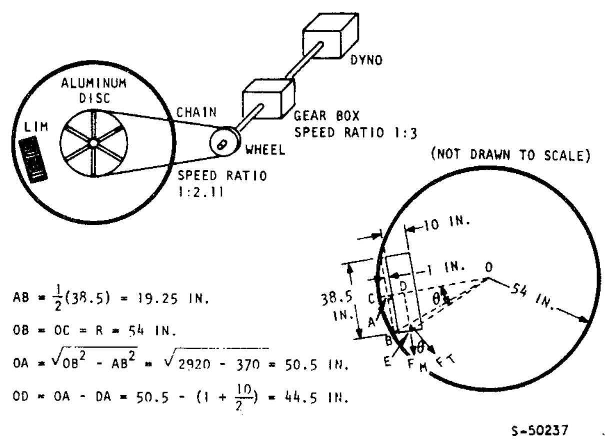

Figure 11. LIM One Pole-Pair Dynamic Model Dimensions

The dynamic tests were conducted at fixed frequency only. Commercial 60 cycle power was used and torque measurements were made at various voltages, air gaps, and slips. The torque was converted to thrust during the test data analysis. Figure 12 shows the performance curves at 60 Hz with a primary-to-primary separation of 1-1/2 in. and an applied line-to-line voltage of 55 v.

Verification of calculated performance by both static and dynamic tests provided the confidence to proceed with the full scale design.

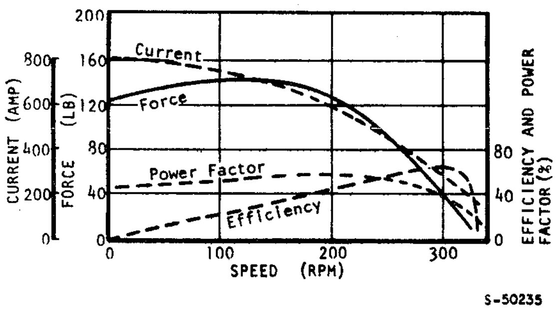

Figure 12. One Pole-Pair Dynamic Model Test Data

Propulsion System Design and Simulation

The LIM requires a power supply and power control system to provide the desired thrust or braking force at various operating speeds of the LIM test vehicle. Major components of the LIM propulsion system are the LIM, turboalternator set, auxiliary power unit (APU), brake system, and associated control, instrumentation, and switchgear units. All components of the propulsion system, with the exception of the APU, are installed on a power skid to facilitate installation and removal from the vehicle.

System Design Considerations

Early studies (2) indicated that the power source for the LIM should provide alternating current with a frequency of about one cycle per mph of speed along the test track. The voltage level of the power supply should not exceed 2000 v so that insulation thickness on the motor will not be excessive and so that the voltage will be compatible with commercially available switchgear. These requirements suggest that the power supply should be a variable-frequency, variable-voltage alternator with a constant volts per cycle output which will provide a constant thrust from the motor.

In the absence of a wayside power supply and suitable high-speed current collection system, the test vehicle has an on-board power supply. A GE T64-10 free-spool turbine engine was supplied by the Government to drive the alternator through a reducing gearbox. This engine has a torque capability from zero to some constant maximum value throughout the speed range of the power turbine shaft. This allows the motor thrust to be varied from zero to some maximum value over the entire speed range of the system.

System Performance

Maximum performance of the test vehicle is limited by the on-board power source. Other components of the propulsion system, the alternator, and the LIM, are designed to match the capabilities of the T64 turbine.

Turbine. The T64 was tested at a power rating of 3200 hp at sea level on a standard day. Early test plans, however, called for testing at altitudes up to 6000 ft. At this elevation, the normal rating of the T64 turbine varies widely with the ambient temperature. An ambient temperature range of -15°F to +80°F is considered, according to MIL STD 210A. The maximum normal rating of the T64 turbine is attained at about 0°F ambient temperature, 250-mph vehicle speed and 100-percent ram air recovery. This power output is 2780 hp at 13,600-rpm turbine nominal speed, and is limited by the gearbox stress limit of 1350 lb-ft output torque.

Linear Induction Motor. The maximum output of the LIM, as limited by the T64 turbine/gearbox rating, is about 2500 hp; at an overall gearbox, alternator, and LIM efficiency of 73 percent. This corresponds to a 3750-lb thrust at 250-mph vehicle speed. This is the rated thrust of the LIM for the test vehicle, when operating at 1.5in. primary-to-primary gap.

Alternator. Design performance of the alternator is defined by the output capability of the T64 turbine and by the reactive power requirement (i.e., the power factor) of the LIM.

The alternator is a wound-rotor machine with separate excitation provided to the rotating field through sliprings. Figure 13 shows the construction of the alternator stator.

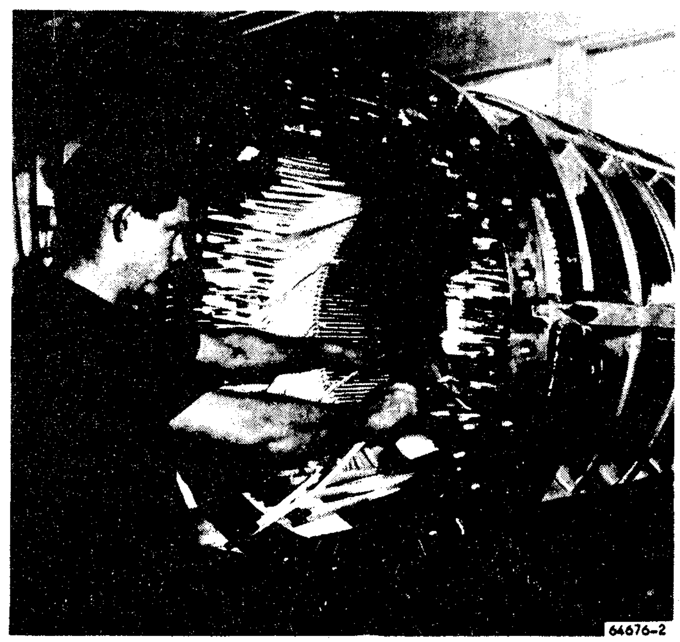

Figure 13. Alternator Stator Assembly

A summary of the alternator rating and design parameters is presented below:

Rating: 3000 KVA, 1.0 to 0.6 lagging power factor, 600/1040 v, 3-phase, 1667 amps, 4 poles, 5200 rpm, 173.3 Hz.

Weight: 4200 lb
Size: 37.5-in. dia x 47.5-in. long
Efficiency: 91 percent @ 3000 KVA, 0.6 pf

Reactances: $X_L = 0.0947$ p.u.

$X_d = 2.27$ p.u.

$X'_d = 0.236$ p.u.

$X''_d = 0.1167$ p.u.

Time Constants: $T'_{do} = 0.694$ sec (220°C)

$T'_d = 0.0721$ sec (220°C)

Propulsion System Control

Figure 14 shows the basic control system diagram. The power system control involves the primary functions described below.

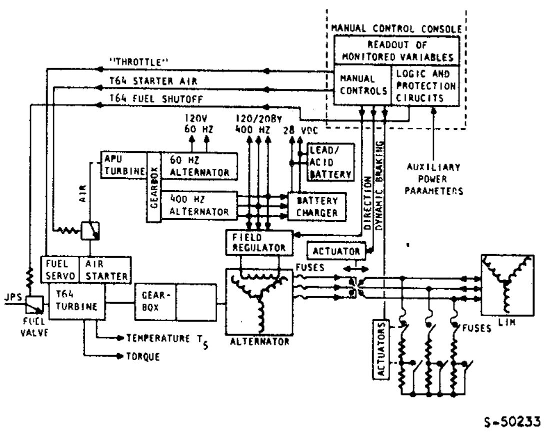

Figure 14. LIM Test Vehicle Control System

Starting. The auxiliary power unit is starting electrically. Bleed air is available from the APU at a rate of approximately 120 lb/min and 96 in. Hg abs pressure for powering the pneumatic T64 turbine starter motor. The T64 turbine starter motor is gear connected through a reduction gear assembly to a power takeoff provided for the starting system. Spin-up of the gas generator portion of the T64 turbine is accomplished by the air starter with the fuel control set at ground idle and energized igniter system.

Speed Control. Acceleration of the vehicle and vehicle speed control is accomplished by varying the throttle setting of the T64 turbine and by controlling the alternator field excitation. The T64 engine is controlled by the position of the two control shafts located on the fuel control assembly. These shafts, the α shaft (power control shaft) and the β shaft (condition shaft), control the fuel flow to the engine. The position of these shafts is set by a single servomechanism with the proper linkage to actuate both shafts. Thus, the engine can be controlled with a single control signal. The T64 turbine torque-speed characteristics as a function of the throttle control are shown in Figure 15.

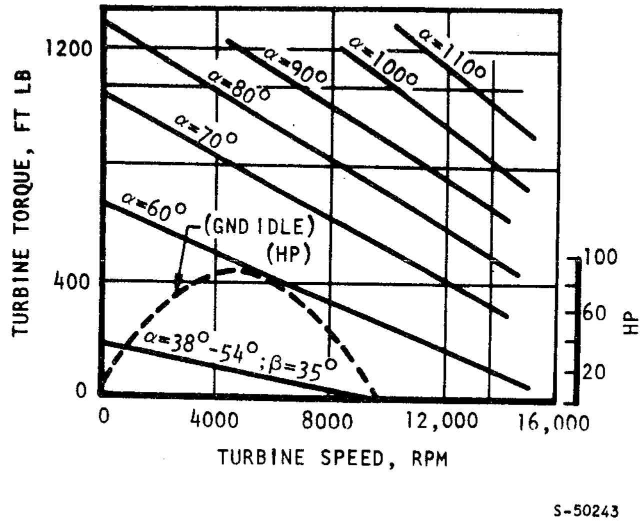

Figure 15. T64 Turbine Torque - Speed Characteristics

The other control variable available to the vehicle operator is alternator field flux. (By simple analogy, the T64 throttle may be thought of as the gas peddle and the alternator flux as the clutch.) A block diagram of the alternator field control is shown in Figure 16. The control loop contains an inner flux loop and an outer droop compensated flux loop with a maximum alternator current override. The inner flux loop is necessary to maintain loop response when the alternator current override is active. Droop compensation, proportional to the total alternator current, can also be set by the vehicle operator. This control circuit allows the operator to choose a desired flux level and then determine the amount of droop compensation needed to give essentially constant volts per cycle operation.

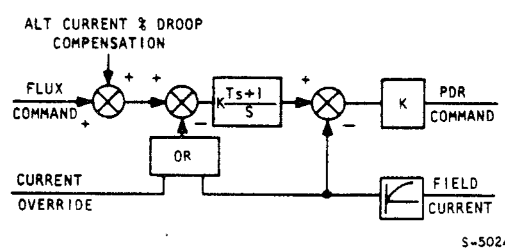

Figure 16. Alternator Field Control

Direction Selection. Selection of the forward and reverse traction modes is accomplished by reversing any two of the three LIM leads. Reversing is accomplished while the vehicle is at standstill. Before the reversing switch is actuated, the alternator field must be deenergized.

Dynamic Braking Control. In a free spool turbine engine, the power turbine and the compressor are operated from two different shafts. Consequently, the turbine cannot be used as a means of braking the vehicle. Therefore, it is necessary to provide an electrical resistance (braking grid) to absorb the power from the motor during braking.

Under braking command, the T64 turbine is throttled back to idle, and the braking resistors are connected across the LIM terminals. The field regulator maintains constant flux in the LIM; therefore, the maximum braking force is essentially proportional to the vehicle speed for a fixed braking resistor. While the resistor bank absorbs the generated electric power during braking, the alternator continues to provide reactive power.

LIM Propulsion System Analog Simulation

Introduction. As part of the analog computer simulation of the propulsion system, the following conditions were investigated: (1) high-speed acceleration, cruising, and braking operation of the LIM test vehicle, (2) low-speed operation, (3) effect of friction on reaction rail temperature rise at starting, and (4) simulation of the locked reaction rail test.

Results of the simulation were in good agreement with calculated performance data and with the limited test data (LIM model test) available to date.

During the simulation the maximum torque applied to the turbine shaft was limited to 1090 ft-lb based on information received from the manufacturer at that time. Subsequently this torque limit was revised, the new value is 1350 ft-lb. Since the turbine torque is proportional to the maximum thrust developed by the LIM, the revised torque limit allows a 25 percent higher thrust than that obtained during the simulation. Therefore, it should be noted that the 3050-lb LIM thrust recorded during the simulation corresponds to 3800-lb thrust with the higher turbine torque limit.

Analog Computer Simulation. To understand more completely the dynamic characteristics of the LIM propulsion system, an analog computer simulation of the system was generated. The simulation required approximately 150 amplifiers with appropriate amounts of nonlinear equipment and digital logic.

A schematic of the detailed analog simulation program of the LIM propulsion system is shown in Figure 17. A brief description of the analog representation of the principal blocks is given below.

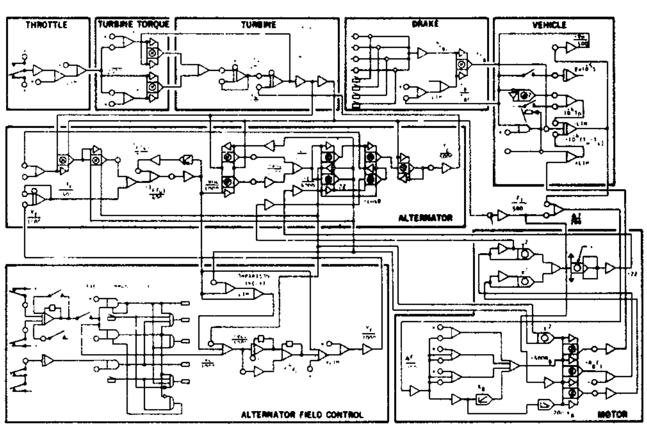

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Figure 17. Analog Computer Simulation

Turbine Throttle. The turbine torque command (T_{Tc}) to the turbine was generated as a function of throttle setting (α) and turbine speed (n_T) as shown below.

$$T_{Tc} = K_1 \alpha - K_2 n_T \tag{2}$$

This relationship is a good approximation of the turbine torque-speed characteristics shown in Figure 15. The constants (K_1) and K_2) were considered to be a linear approximation of the throttle setting (α), with different approximations being used for turbine operation on standard days vs hot days, and sea level vs 6000 ft elevation. The throttle setting itself was limited to a minimum value corresponding to turbine idle. No maximum throttle setting was generated, but during the simulation runs the throttle position was manipulated to prevent excessively high turbine speeds and torques.

In the simulation the power control or α shaft and the condition or β shaft of the turbine fuel control were represented by a single throttle setting (α). For the remainder of the description α refers to the combined throttle control setting. An $\alpha = 38^0$ value corresponds to the "minimum ground idle" condition. For values greater than 50^0 the simulated α throttle settings equals the actual power control shaft angle.

Turbine and Gearbox. The simulated turbine was considered to be an inertial mass (I) activated by the net of turbine command torque (T_{Tc}), and the loading torque of the alternator (T_G) referred to the turbine side of the gearbox. The speed reducer between the turbine and the alternator has a 2.613:1 ratio. The inertial mass (I) includes the rotating parts of the turbine, gearbox and alternator, all referred to a common speed.

The command torque was fed to the turbine through a first order lag representing the transport delay of the fuel control, while the loading torque was applied directly. Thus, the turbine speed (n_T) was defined as:

$$n_T \text{ (rpm)} = \frac{60}{2\pi I} \int (T_{Tc} - T_G) \, dt \tag{3}$$

Alternator. The simulated alternator was represented as having a direct mechanical link to the turbine (through the gearbox), and an electrical link to the LIM. As a result, the terminal voltage and current are common to both the LIM and alternator. Also, the alternator frequency (f_1) is directly related to the turbine speed (n_T)

$$f_1 = K_1 n_T \tag{4}$$

The internal electrical configuration of the alternator representation is quite complex. Briefly, however, the alternator voltage (V) is generated as a function of the alternator speed (n_G), field current (I_F), power factor ($\cos \theta$), and load current (I). Also accommodated in the simulation are field time constant (T_{do}), magnetic saturation, demagnetizing effect of armature reaction, and Potier reactance voltage drop.

Lastly, the alternator loading torque on the turbine was simulated as the power output of the alternator divided by the alternator speed. This was generated as a function of alternator voltage, current, speed and load power factor as follows:

$$T_G = \frac{K_G \, VI \cos\theta}{n_G} \tag{5}$$

Alternator Field Control System. The field current is generated from the field voltage through a first order lag representing the direct axis open-circuit transient time constant. The field voltage (V_F), which represents the dc output of the phase delay rectifier (PDR) of the field regulator circuit, is generated from two sources; one a direct feedback voltage signal from the alternator and the other a function of a command voltage (V_C), the feedback voltage (V_{fb}) and the alternator current. Included in this latter circuit is an OR gate to simulate a diode circuit allowing the passage of the larger of the two signals. This simulates the current limiting feature of the control system. The general control equation defining I_F is:

$$I_F = \frac{K_{c1}}{sT_{do}+1} \left(-V_{fb} + \frac{(T_2\ s+1)}{s}\right) \times \left(V_C + K_{c2}I - (K_{c3}I \text{ OR } K_{c4}V_{fb})\right) \tag{6}$$

The control voltage (V_C) is arbitrary and can be configured as a step, ramp or as otherwise desired. It corresponds to the FIELD CONTROL knob on the LIM vehicle control console.

Linear Induction Motor. Simulation of the LIM was considered to consist primarily of an impedance (Z) which was generated from the alternator frequency and the slip frequency (4). The slip frequency (Δf) of the LIM is defined as:

$$\Delta f = f_l - f_m \tag{7}$$

where f_m is directly related to the vehicle speed (V_m).

The two components of the impedance, (R_B) and (X_B), were generated as nonlinear functions of Δf. Thus,

$$R_B = \text{func.}\ (\Delta f) \tag{8}$$

$$X_B = \text{func.}\ (\Delta f) \tag{9}$$

$$Z = \left((f_l X_B)^2 + (R_l + f_l R_B)^2\right)^{1/2} \tag{10}$$

Where R_l represents the LIM primary as well as the alternator armature resistance. With an applied voltage, the magnitude of the motor current is defined as:

$$I = V/Z \tag{11}$$

and the thrust (T_m) developed by the LIM becomes:

$$T_m = K_m I^2 R_B \tag{12}$$

The K_m factor includes a thrust reduction due to end-effects.

Vehicle. The simulated LIM test vehicle was represented by the inertial mass (J) of the vehicle driven by the net thrust generated from the summation of the thrust developed by the LIM, aerodynamic drag (T_D) and mechanical brake force (T_B). The drag was considered to be a square function of vehicle speed.

The thrust was applied to the vehicle in conjunction with stiction (T_S) so that a moderate thrust was required to break away the vehicle from a stopped position. Thus,

$$V_m = \frac{K_m}{J} \int (T_m - T_S - T_D)dt \tag{13}$$

Vehicle Brake System. The available brake force is a nonlinear function of vehicle velocity. With a commanded brake force (T_{Bc}) generated from 0 to 100 percent of maximum in increments of 10 percent, the applied brake force to the vehicle was:

$$T_B = \left(\frac{T_B}{T_{Bc}}\right) \times T_{Bc} \tag{14}$$

High-Speed Operation. Performance of the LIM test vehicle during high-speed operation was simulated for sea level and 6000-ft elevation. Figure 18 shows the corresponding distance - speed curves. The approximately 25 percent difference in air density accounts for the higher aerodynamic drag and the correspondingly slower performance at sea level. (The turbine has a slight excess of power over what can be transmitted through the gear box, so decrease in available power with altitude has less effect than decrease in drag with altitude)

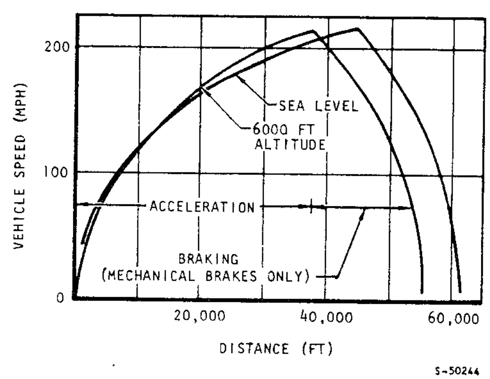

Figure 18. Speed Distance Curves

Dynamic behavior of the LIM propulsion system can be explained with reference to Figure 19a. The run can be divided into four regions:

1. Turbine Idle - During this interval the engine is operated at a minimum ground idle throttle setting ($\alpha = 38^0$). The turbine then operates along its idle torque-speed characteristics (Figure 15). No alternator field is applied; the turbine accelerates to approximately 9000 rpm in about 30 seconds. In addition to the inertial load (rotating masses of turbine, gearbox, and alternator) the turbine has to overcome the usual windage and friction losses. The latter two were neglected during the simulation.

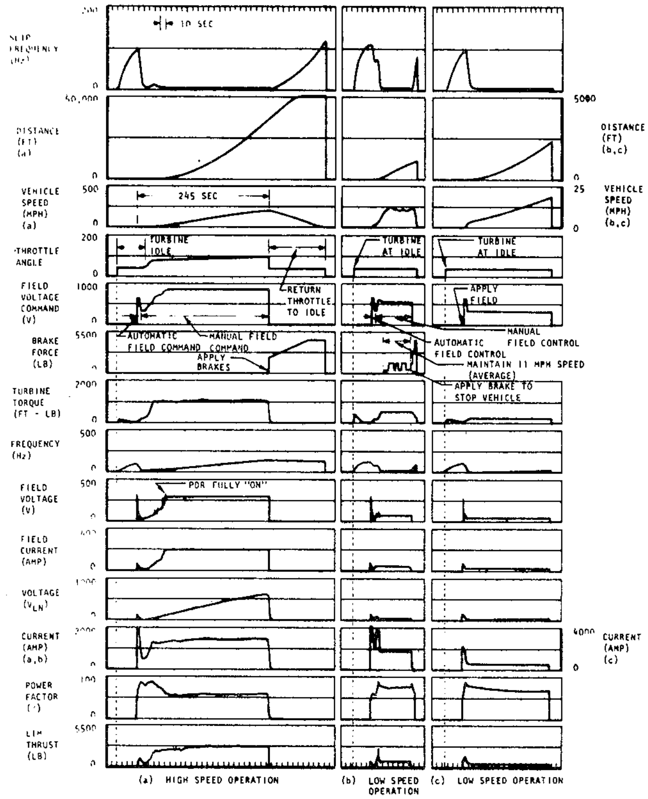

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Figure 19. Analog Computer Simulation

Since the vehicle is not moving the frequency and slip frequency values are equal.

2. Automatic Field Command - After the initial startup of the engine an automatic field voltage command is applied while leaving the turbine throttle still at idle. As field current develops the alternator generates electric power into the LIM primary. This electric power loads down the alternator and turbine output, with a subsequent slowdown by the turbine gas generator spools.

The fast ramping of the large field command signal assures first that an initially large thrust develops, and second that the alternator is sufficiently loaded to slow down the turbine speed. The former is needed to start to move the vehicle to prevent heating the reaction rail. (The effect of friction will be discussed further below). The latter results in a low slip-frequency, a condition needed for efficient operation.

3. Manual Field Command - At an appropriate time the field voltage command is switched from automatic to manual mode.

To achieve maximum performance the engine power and the alternator field excitation have to be applied rapidly. The maximum rate at which the throttle and field can be applied is limited by two conditions. If the throttle angle is increased faster than the turbine speed can respond, the turbine torque will exceed its 1090 ft-lb (later revised to 1350 ft-lb) limit. If the field excitation is increased faster than turbine power develops, the free-spool turbine will stall.

The field voltage, representing the dc output of the field regulator, reaches its limit at 300 vdc. This corresponds to the phase delay rectifier being fully on. With the field at its maximum value, output voltage of the alternator steadily increases with speed, thus providing essentially constant volts per cycle. During this period the throttle angle has to be steadily increased, at approximately the rate of the vehicle speed increase.

4. Braking - Before applying mechanical brakes, the turbine throttle is returned to idle, and the field command is returned to zero. The sequence of cutting back the turbine power before the field is reduced is important to prevent overspeeding of the turbine(a safety interlock ensures this).

The maximum brake force developed by the mechanical disc brakes is 4300 lb, based on a 60 in.^{2} piston area per wheel and an average 30 percent coefficient of friction. The maximum brake cylinder pressure is 30 psi. The brake force is a function of the vehicle speed. At 250 mph the maximum brake cylinder pressure is only 10 psi; at 80 mph it is 30 psi.

For better control the brake force can be applied in seven discrete steps between zero and maximum value.

Low-Speed Operation. The power output of the turbine at the "minimum ground idle" throttle setting is sufficient to accelerate the vehicle up to approximately 90 mph. For example, at the standard, sea level, static condition the turbine can develop 90 hp at approximately 5000 rpm with the throttle at idle. The dotted curve in Figure 15 represents the minimum idle power output of the turbine. The fact that the turbine cannot operate below this minimum idle setting explains the deliberately inefficient way of operating at slow speeds. A typical simulation of the lowspeed operation is shown in Figure 19b.

Similarly to that in the high-speed operation, the run in Figure 19b is divided into four sections. The first two, turbine idle and automatic field command, have functions identical to those described before. During the third interval, manual field control, the turbine throttle is left at idle, since the power output of the turbine already exceeds the load requirements corresponding to a low speed, in this case for example 11 mph. To maintain this speed, braking is applied as shown. The situation is not unlike a passenger car with automatic transmission, the "creep-torque" is sufficient to move the car unless the brakes are applied.

To be able to operate at low slip frequencies it is essential to load the alternator fast, which in turn rapidly slows down the turbine speed. Since the vehicle moves slowly, the reaction rail temperature rise is highly sensitive to the slip frequency. Selection of the automatic field command ramp-up and especially the time interval through which this field command signal is applied is important. For example, the approximately 1 to 2-sec application of a large field command in Figure 19b was not sufficient to slow down the turbine. By increasing this interval to 3 to 4 sec (Figure 19c), the turbine was slowed down in approximately 5 to 8 sec.

Reaction Rail Temperature Rise at Starting. The significance of reaction rail temperature rise was briefly discussed in connection with the high-speed and low-speed operations. It was concluded that for best results an initially large field input should be applied.

One factor influencing the starting performance is the friction and stiction existing between wheel and rail. Related friction-type effects, such as journal friction, imperfect grading, etc., were combined in this category. Figure 20 shows the estimated reaction rail temperature rise at the maximum temperature rise point. This is the location which is located under the leading edge of the LIM before the vehicle begins to move. It is heated during the interval the vehicle moves one motor length, approximately 12.5 ft. The temperature rise calculation is based on the assumption that all the heat generated in the reaction rail during this period is absorbed by the aluminum rail mass. The resulting temperature rise value is quite conservative.

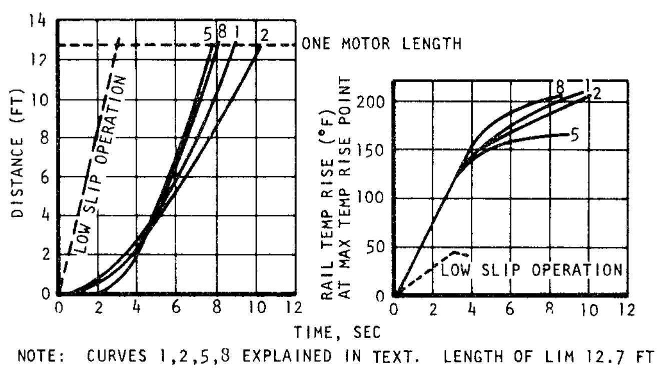

Figure 20. Reaction Rail Temperature Rise

Figure 20 shows four cases which were simulated with different friction and stiction values. These were:

Curve No.	Stiction (lb)	Friction (lb)	Time Field was Applied (sec)
1	330	120	2
2	330	240	2
5	660	120	5
8	660	120	3

Results of the simulation indicate that:

- Irrespective of friction values and the time interval that field is applied, the time required to move the vehicle 12.5 ft is approximately 8 to 10 sec. The temperature rise of the reaction rail is approximately 160° to 200°F.
- By applying the field for 5 sec rather than 3 sec, the temperature rise of the rail is reduced by 40°F.
- Temperature rise in excess of approximately 200°F requires special cooling of the rail
- The high temperature rise values are the result of the finite time (5 to 8 sec) required to slow down the turbine to a value which provides a small slip frequency. If a power supply with a fully controllable small slip frequency is provided, then a temperature rise of less than 50°F could be achieved, as indicated by the dotted curve of Figure 20.

Simulation of Locked Reation Rail Test. Results of the simulation were in good agreement with test data (Figure 21). The x marks were derived from the simulation, for a constant 600-amp primary current. The relationship between the parallel connected 10-pole full size LIM which was simulated on the computer and the series connected one pole pair model tested in the lab was also taken into account.

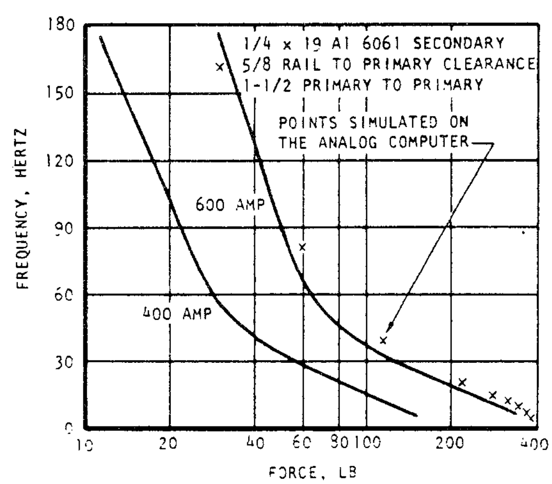

Figure 21. Locked Reaction Rail Test Data

Conclusions. The LIM propulsion system described in this paper appears to have the capability for 250-mph operation of the test vehicle. The analog simulation of the system shows analytically that:

- The system has the necessary thrust and efficiency
- The propulsion system is dynamically stable.
- Control of the system at high speeds is simple; control at low speeds requires constant minor adjustments to maintain steady speed.

The static and dynamic tests on the LIM model show experimentally that:

- The theoretical model used to design the LIM is satisfactory
- Performance of the LIM model revealed no serious problems in LIM operations.

These results suggest that, at least in these major areas, the system is a fully feasible and workable method of propulsion.

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CONTROL AND INSTRUMENTATION FOR A HIGH-SPEED RAIL VEHICLE PROPELLED BY A LINEAR INDUCTION MOTOR

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ABSTRACT

A 250 mph rail vehicle propelled by a linear induction motor is being built for the Office of High Speed Ground Transportation.* Due to safety considerations the vehicle will be unmanned at high speeds with radio links for remote control and telemetry. This paper deals with the selection and design of the required control and instrumentation systems, based upon aerospace telemetry techniques.

High data rate PCM telemetry (maximum rate 86,000 data words per second) is used to monitor vehicle operation as well as to transmit all test data back to the ground station for recording. An on-line computer is employed to format the serial data stream in real time to compatible 9-track digital tapes with inter-records gaps. Real-time monitoring of the vehicle parameters is performed by means of digital-to-analog converters and visual display devices.

An important consideration was selection of transducers for time-variable data, which are calibrated for gain and phase versus frequency. These time-correlated channels have equivalent sampling rates and uniform filter frequency response. Each sensor-amplifier-filter combination is adjusted for a similar damping factor and phase lag characteristic.

INTRODUCTION

The Office of High Speed Ground Transportation (OHSGT) has numerous active study, research and development programs pertaining to all aspects of Higher speed travel on the ground.[1] One of these is the 250 mph rail vehicle propelled by a linear induction motor (LIM) under construction by Garrett/AiResearch and scheduled to be delivered late in 1969.[2] Another is the tracked air cushion research vehicle (TACRV) now under study and expected to go into the hardware phase next year.

The Department of Transportation expects to build a new OHSGT Research Test Facility at a site still to be chosen at this date. Present plans call for an oval track with an end radius of over 2 miles ($< 1^{\circ}$ curve), and a total perimeter in excess of 20 miles. Two tracks are planned -- the outside to be a steel rail track and the inside a configuration for the tracked air-cushion vehicle. A ground station complex consisting of shops, maintenance and storage areas, and a data acquisition center will be located outside the tracks at the middle of one of the straightaways to facilitate antenna coverage for the radio links. The LIM vehicle will undergo an extensive test program at this facility.

It is anticipated that the ground station telemetry receiving and recording equipment described in this paper will serve for data collection from various vehicles sequentially. Separate on-board sensors, signal conditioning, data encoding and transmitting gear would be installed in each case. The data acquisition setup utilizes a small computer which can also be used on site for quick-look data reduction and analysis, thereby reducing the turn-around time for test results and shortening overall schedules.

LIM TEST VEHICLE DESCRIPTION

The general configurations of the vehicle are shown in Figs. 1 and 2. Overall dimensions are 54.5 feet long, 9.8 feet wide and 7.0 feet high, excluding the air scoop, with a total estimated weight of 42,000 lbs. Vehicle construction is a welded tubular steel space frame covered by a non load bearing aluminum skin with a low frontal area and minimum drag so that the design speeds can be achieved with the available power plant. Electric drive power for the LIM is generated on board the vehicle since a proven high speed wayside power collection system is not available at this time. The combination of a 3000 hp free spool turbine (G.E. T-64), reduction gear box, and power alternator

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allows the LIM to be operated in a variable voltage-variable frequency (constant volts per cycle) mode, developing essentially constant thrust over the operating speed range. To meet the 250 mph top speed, special rail trucks were built which are equipped with adjustable spring rates and damping factors for the various degrees of freedom. Research tests will be performed to check the ride quality and stability as the different parameters are varied.

A turbine powered auxiliary power unit (APU) mounted in the aft end of the vehicle is used to provide pneumatic and electric power for the ancillary systems. Bleed air from the compressor stage is used to start the T-64 engine and for the pneumatic systems. APU inlet air is drawn from the vehicle interior and thereby serves to ventilate and cool the engine compartment. Electrical power for the vehicle subsystems is obtained from two alternators driven from a single APU gearbox --- a 120 KVA 3ø 400 Hz 120/208Y volt machine and a smaller 12 KVA 1ø 60 Hz 120/240 volt unit. Each alternator is equipped with a voltage regulator, control and protection switchgear and meets the power requirements of MIL-STD-704. Plug-in provisions are incorporated to energize the vehicle systems through the same control and protection circuits, from a ground power source at the maintenance facility. The 400 Hz 3ø alternator supplies power for the high capacity fans used to cool the LIM and the main power alternator, as well as the phase delay rectifier which regulates the field current to the power alternator. The 60 Hz 1ø alternator is reserved primarily as the instrumentation "wall plug", although it is also used for the front compartment air conditioner. Several forms of d-c power are also utilized in the vehicle systems. A 24 volt lead-acid battery and charger/power supply (negative ground) is used for APU starting and loads which can tolerate a ground connection at the APU frame. Additional +12 volt and -12 volt power supplies (mid-point at signal ground) with lead-acid batteries in float service across each, are used to feed the regulated supplies for the signal electronics and critical protection circuits. All regulated supplies are transient voltage limited and short-circuit proof. A transformer-rectifier set (400 Hz 3ø) with a rating of 50 amperes at 28 volts d-c is used to power a number of vehicle auxiliary circuits.

Air conditioning is provided for the insulated front compartment of the vehicle which houses the operators and the on-board electronic systems. The air temperature is maintained at $74 \pm 5^{\circ}$F with automatic changeover from heating to cooling as required. This approach reduces the temperature drift requirements on the electronic gear and will result in more accurate data at lower system cost. The air conditioning system is operated from the 120/240 volt 60 Hz source which is also used to power most of the instrumentation electronics.

Line transients are kept to a minimum by running the fan and compressor motors continuously. Temperature modulation in the cooling mode is obtained by adding heat. Should the temperature drop further as in cool weather, the unit switches automatically to a heat pump configuration; additional resistance coil heaters (400 Hz 3ø) are mounted in the outlet duct for quick warm-up and ambient temperature extremes.

Linear Induction Motor (LIM)

A LIM with a double-sided three phase primary and an extruded aluminum alloy reaction rail secondary is used to propel the vehicle (Fig. 3). A linear induction motor can be considered to be derived by radially cutting and unrolling the primary and secondary members of a rotary induction motor. In the double sided design two primaries connected in a flux aiding mode serve to complete the magnetic path, each contributing half of the total magnetizing ampere turns. Induced alternating currents in the aluminum rail produce linear reaction thrust in the vehicle-mounted primary. From a performance standpoint the primary-to-primary gap should be as small as possible to increase the power factor, thrust and efficiency; mechanically this is limited by the minimum clearance necessary for high speed operation. Preloaded rubber tired guidance wheels with springs and dampers act to center the LIM on the reaction rail. The LIM itself is free to move transverse to the vehicle on linear bearings. Future development work on guidance systems may include air cushion pads or a high power active servo system capable of centering the stator at rapid rates to track the rail waviness.

VEHICLE OPERATION AND SAFETY

The vehicle is designed to be manned at low speeds only. An on-board console for the driver and co-driver contains all the necessary controls and monitoring functions for the main power package and the auxiliary power systems. The console also includes the controls for the propulsion, braking, vehicle auxiliaries and safety devices such as the remote fire extinguisher. Fig. 4 is a picture of the console panels mounted in a temporary cabinet during the turbo-alternator checkout in the test cell. At high speeds the vehicle will be unmanned and will be operated from a remote console with radio links for command and monitoring. The monitoring readouts on the two consoles are essentially in parallel, with a local/remote operation transfer switch on the vehicle. Initial checkout of remote operation will be made at low speeds with drivers on-board able to switch back to local control in case of malfunction. Loss of the r-f command link to the vehicle will result in an automatic safe shut-down and application of brakes.

The power control scheme for the T-64 engine is primarily open loop, similar to the throttle on a turbine-powered racing car. The driver monitors the critical parameters such as torque, power turbine temperature and others, and operates the throttle servo fuel control so as not to exceed the safe limits. Additional protection is provided by adjustable meter-relay settings, permanently set electronic limits and electromechanical overspeed devices, with redundancy in several cases. Under remote control the command loop is closed by telemetry monitoring of key parameters in real time, with the same protective and limit functions still applicable aboard the vehicle. Additional limit warnings are incorporated into the remote console for operator alert.

An analog computer simulation of the control system was performed to check the system stability as influenced by the time constants of the alternator field excitation, turbine fuel control servos and the effect of the various inertias.(3) Acceleration and speed control of the vehicle is accomplished by varying the throttle setting of the T-64 turbine, and by means of the alternator excitation which can be considered analogous to the automotive clutch. The T-64 is started with the field off and the alternator accelerates to a frequency of about 120 Hz, corresponding to turbine ground idle free wheeling speed. To start the vehicle rolling, the field is applied at a programmed rate with the throttle still at idle. Increasing the field current too slowly or too rapidly will result in excessive localized heating of the reaction rail. Field control then automatically reverts to the selected "manual" or "automatic" mode. The automatic mode has adjustable droop compensation as a function of current and frequency. A simplified block diagram of the vehicle control, monitoring and protective systems is shown in Fig. 5.

Numerous other safety features are incorporated for protection of the vehicle and the on-board systems. The design goal was to make the vehicle inherently fail-safe, with the major protective functions on-board and automatic. Operational interlocks and sequencing circuits are provided to prevent inadvertent unsafe operation of the controls (Fig. 6). Predetermined "high-low" parameter limits are built into the various systems which will automatically activate different levels of shutdown as follows:

(a) Warning only --- fault indicator energized

(b) Electrical System Fault --- T-64 turbine speed is reduced to idle and the alternator field is switched off

(c) T-64 Turbine Fault --- T-64 turbine is shut down and the alternator field is switched off

(d) APU Fault --- complete shutdown of T-64 and APU turbines

(e) Panic Shutdown --- complete shutdown of T-64 and APU turbines, plus braking systems applied automatically

(f) Fire (Manual or Automatic) --- Similar to panic shutdown plus operation of fire extinguisher system

Four types of braking systems are available to bring the vehicle to a stop with independent controls for each:

1. Dynamic braking whereby the LIM acts as an induction generator excited by the power alternator and the energy is dissipated in a resistance grid

2. Pneumatic friction brakes using two discs per axle (total of eight) and equipped with adaptive anti-skid control

3. Aerodynamic spoilers which are extended by actuators into the vehicle slipstream

4. Emergency braking consisting of an arrestor hook and aircraft type arrestor cable system

The 250 gallon fuel tank is located in the rear of the vehicle and is filled with open cell plastic foam which reduces the spillage rate in case of derailment and fire. Fuel is delivered to the APU and T-64 engines by electric pumps equipped with electrically operated normally closed shut-off valves in each line. Fuel level is sensed by a capacitance type gage with a warning light when a minimum safe low level is reached; excessive heat "soak-back" may reach the turbine oil and bearings if an engine under full power suddenly runs out of fuel.

On-Board Control

The on-board control console provides the vehicle with the capability of on-board local operation by qualified personnel. It will be used during low speed runs and for startup and checkout prior to high speed remote operation. Vehicle system parameters are monitored by means of meters and other devices as tabulated in Fig. 7. Multiposition switches can be used for location of faults in the propulsion and auxiliary power systems. An outline drawing of the on-board console revised layout showing the monitoring readouts, fault indicators, and operating controls is presented in Fig. 8.

Remote Control

The design of the remote control system provides for remote operation of a vehicle that has been manually started and checked out from the on-board console. Remote starting is not included in the interest of equipment safety and reduction in complexity and cost. System design integration of the on-board and remote consoles enables the two units to provide monitoring readouts in parallel when the telemetry system is in operation. Changeover to remote operation can be initiated on-board only by means of a local/remote switch which disables the mode not being used. From a human engineering standpoint the driver's section of the remote console is similar in appearance, functions and controls to the on-board unit, providing maximum familiarity of operation (Fig. 9).

Remote control is achieved by means of an FM/FM radio link operating on a carrier frequency of 406.8 MHz, 300 KHz bandwidth and using standardized IRIG subcarrier channels 2 through 13 with $\pm$ 7.5% deviation. All twelve channels are bipolar analog and the demodulated signals aboard the vehicle are utilized to operate the various control systems. Two spare slots are available to expand the link to 14 channels if required. The command functions to the vehicle are listed below:

1. Throttle control servo
2. Direction of travel
3. Alternator excitation
4. Electrical dynamic brakes
5. Aerodynamic brakes
6. Friction disc brakes
7. Instrumentation on/off/reset
8. High speed camera control
9. Emergency stop
10. Spare channels

The basic parameters that are monitored under remote operation are shown in Fig.7. In addition any 14 channels can be selected from the data stream, converted to analog and recorded on the light beam oscillograph providing extra monitoring information almost in real time.

INSTRUMENTATION REQUIREMENTS

Instrumentation is required to obtain test data from the LIM, vehicle, trucks and wayside for evaluation and performance analysis. In addition many measurements have to be made in order to control and monitor the operation of the test vehicle. The measured parameters fall into these general categories in terms of usage:

(a) Parameters that are monitored only in order to operate the vehicle and its subsystems safely; prime examples are the readouts for the turbo alternator and the auxiliary power systems

(b) Those parameters that require monitoring during test and which will also be recorded for performance calculations and analysis; LIM thermal readings and certain vehicle dynamics fall into this class

(c) The balance of test data parameters that will be recorded and used specifically for evaluating the performance and merit of various hardware

LIM Instrumentation

Essentially the LIM test objectives require the determination of:

Thrust	Thermal results
Horsepower	End effects
Efficiency	Flux distribution
Power factor	Equivalent circuit
Slip	Reaction rail variables

Effect of air gap on all motor parameters
Guidance system performance

Vehicle Instrumentation

Vehicle data is necessary for the evaluation of ride quality, stability and high speed aerodynamics and requires the measurement of:

Speed/Position	Air pressure distribution
Accelerations	Vehicle air speed

Truck Instrumentation

The trucks must be evaluated for stable safe performance at speeds up to 250 mph. Transducers are required to measure:

Vibrations	Bearing temperatures
Accelerations	Wheel velocities
Displacements	Air spring pressures

Wayside (Ground) Instrumentation

At present this consists primarily of the measurement of ambient temperature, humidity, pressure, wind conditions, vehicle noise and reaction rail heating. Test data will be needed for wheel-running rail-road bed interactions at high speeds; sensors for this purpose will be added when the test track is built.

INSTRUMENTATION CONSIDERATIONS

The vehicle instrumentation must operate in a "mobile" environment with reasonably stringent requirements for shock, vibration and ambient weather conditions, particularly for the truck mounted sensors A tabulation of performance specifications and environmental conditions for the various sensors is presented in Figs. 10a & 10b. General locations of the sensors are shown in Figs. 11, 12 & 13. The on-board electronics are housed in standard rack and panel cabinets which are fastened to shock mounted slides located in the front compartment of the vehicle just behind the two drivers' seats. (Fig. 2). The ambient temperature in this compartment is maintained at 74 ± 5°F, which reduces the temperature drift requirements on the circuitry. Relatively inexpensive IC operational amplifiers are used throughout the gain and active filter stages.

Electrical Noise

The most important factor that had to be considered in the choice of sensors, signal conditioning and cabling was the high level of electrical noise which was expected aboard the vehicle. The turbo-alternator power package will generate a maximum of 3 MVA of power. High leakage fields exist around the alternator, LIM, and the power cables which will carry nearly 2000 amperes at full load. In order to achieve satisfactory signal to noise ratios, the schemes listed below were incorporated:

Auxiliary and main power leads were kept towards the right side of the vehicle

Instrumentation (signal) leads were routed along the left side of the vehicle

Signal leads are shielded twisted pairs, grounded at the central signal conditioning point only

Magnetic shielding for signal leads is used in the form of steel raceways and flexible conduit

High level low impedance transducers received preference, or amplification at the sensor where it was deemed necessary. "Real world" accuracies and tolerances were specified; in some cases this allowed the usage of a less accurate but more noise immune sensor

All channels are individually amplified and gain normalized to ± 5 volts full scale before multiplexing. Differential amplifier stages are trimmed for maximum common mode rejection

Sources of RFI, such as the phase delay rectifier used for the alternator field regulator, are shielded and filtered

System grounding was optimized from a total system concept, wherein the integration of the subsystems is considered at the design stage

LIM Electrical Measurements

Initial tests of the LIM will occur when only a portion of the test track is completed and most of the operational time will be spent in acceleration or deceleration. Thus tests which would normally be run under steady state conditions will have to be conducted with transient velocity (and frequency) conditions. The voltage varies from zero to over 1000 volts, while the frequency increases from minimum slip value to nearly 200 Hz. The rated current (over the frequency range) is nearly 2000 amperes, with maximum values in excess of this. Due to the end effects, the magnetizing current (and hence power factor) in the three phases is not equal, and there is an additional variation between the leading and trailing ends when the unit is in motion. Since the leakage flux is in the order of 25%, an impedance variation occurs between the two primaries when the reaction rail is not centered in the air gap. The on-board 3 MVA alternator is from being a low impedance "infinite bus" and will tend to accentuate the voltage differences at the phases due to unequal impedances. The instrumentation should be able to measure the extent to which these variations exist and their effect on the performance of this developmental LIM. The selected method independently records the phase voltages and half-phase currents in correct time relationship (phase angle) to each other. A computer will be used to calculate the total power input, efficiency and other performance factors.

Truck and Vehicle Dynamics

Data is required to determine factors relating to ride quality, vibratory modes, stability and both translational and rotational movements of modern rail trucks during high speed operation. This data will be used to verify the analytical procedures developed by A.H. Wickens [4] and others. It is planned to extract the coefficients of the equations of motion from the recorded dynamic tests of the running rail-truck-vehicle interactions. The recorded signals from the various transducers must have the same time/phase relationship to each other that the actual displacements, velocities and accelerations had at the time the data was taken.

DATA SYSTEM CONSIDERATION

A basic choice had to be made between on-board or remote recording and whether the system would be analog or digital. All the factors listed below were a consideration in the final decision:

The vehicle has to be monitored in real time during remote operation, hence a bidirectional r-f link is already available

Data from many channels is to be recorded simultaneously; information rate is high due to frequency response requirements

Wayside and fround station data to be available in a format that is time correlated with the vehicle data

Safety of data and equipment and also the available space and environmental conditions aboard the vehicle

Accuracy in a noisy environment

Freedom from human errors in patching, calibration and interpretation

Use of a computer to edit and analyze the vast data output in order to reduce time and costs

Overall cost effectiveness, system flexibility and adaptability to usage with other vehicles

Proven state-of-the-art techniques and equipment to prevent early obsolescence

Preferred System

A technical review of the factors listed above resulted in a decision to use a PCM/FM digital telemetry system with ground station recording. Specific advantages include:

High accuracy and relatively immune to noise

Direct computer compatibility

Minimum data turn-around time

Real time availability for display

Recorded directly with wayside data for optimum time correlation

Very large channel capability

Safety of data and equipment

Minimum equipment in vehicle (space and environment)

Same ground station equipment can be used with other vehicles

A detailed explanation of the principles of PCM telemetry (5) is not included in this paper.

PCM DATA ACQUISITION SYSTEM

The main criteria in the design of the test facility PCM system was that it should have a very high capacity, consistent with the availability of proven hardware, and that the data was to be recorded in computer format directly on to digital tapes in real time. On this basis the limiting factor was the recording rate of the selected tape transports, which is 800 characters per inch at 120 inches per second. On a 9-track configuration each character becomes a data word by limiting to 7 bits plus sign plus parity, (accuracy is one part in 255 since last increment is $\pm$ 1/2 of least significant bit). Allowing a generous figure of 10% for the inter-record gaps, the maximum recording rate is still greater than 86,000 data words (or samples) per second.

Self-explanatory block diagrams of the on-board and ground station data acquisition and control systems are presented in Figs. 14 & 15. The features listed below are of particular interest:

The digital time code generator (oscillator) is on the vehicle, and is used to synchronously strobe the on-board and wayside multiplexers/ A-D encoders from a common time reference

Optical timing pulses are available to the high speed camera upon command; this time code is also recorded on the magnetic tapes allowing the correlation of picture frames with other events

A small computer complete with peripheral hardware is used on-line to format the tapes into a compatible configuration with interrecord gaps

A D-A channel selector and converters are used to strip out the required monitoring information from the data stream. Any 30 channels can be converted, each channel being updated at the original sampling rate

Software is available to record calibration data, create calibration tapes and load them into the disc memory

Software is provided to convert the recorded data to engineering units, complete with calibration corrections. Summary listings and validity checks can be performed on site before proceeding with further tests

Telemetry transmission is in the L-band at a temporarily assigned frequency of 1495.5 MHz with a power of 10w and a bandwidth of 2 MHz. A blade type antenna is mounted on the vehicle.

The ground station equipment is located in cabinets (Fig.16) and housed in a trailer as shown in Fig.17. The trailer will be used at the temporary 1/4 mile test facility where an end-to-end system checkout of the vehicle, control, instrumentation and telemetry will be performed.

TIME CORRELATION OF VARIABLES

In the previous section on LIM Electrical Measurements and on Truck and Vehicle Dynamics, the need for recorded data outputs that are uniform in gain and phase vs frequency was pointed out. The selected solution in the area of transducers, signal conditioning, presampling filters, and sample-and-hold amplifiers will be presented for each.

Transducers

The LIM potential and current transducers are calibrated for gain and phase versus frequency (Bode plots). In the case of the potential transformer the calibration is performed at several values of flux (volts/cycle) in order to establish the phase variations due to the magnetizing ampere turns.

The accelerometers are all "servo type" and are second order systems. The normalized damping factor is a nominal 0.65 with all units adjusted to $\pm$ 0.1 of this value. The normalized natural frequency is a nominal 60 Hz $\pm$ 10%, except the angular accelerometers where the natural frequency is slightly lower at about 40 Hz. Once the more difficult task of accelerometers had been settled, then the demodulated outputs of the LVDT displacement transducers (with 2 pole LC filter network) were adjusted to the same values (and tolerances) of damping factor and natural frequency. Individual calibration Bode plots for each transducer are supplied by the manufacturer of the accelerometers and the displacement sensors. The aerodynamic pressure transducers themselves have a natural resonant frequency of several hundred hertz; however the orifices in the skin are connected by means of flexible tubing to the transducers, mounted inside on the vehicle frame and other suitable locations. All tubing is the same diameter and lengths are standardized at 2 feet long resulting in a response of over 100 Hz which is about a decade above the 10 Hz required in the readings.

Signal Conditioning

The front end of each signal channel consists of an IC amplifier which provides gain scaling, calibration inputs and a low impedance output. Phase shift contributed by the amplifier is negligible since the closed loop roll-off frequency is orders of magnitude higher than the signal frequency of the time correlated channels.

Sampling Rates

The sampling theorem states that an ideally band limited continuous signal of W cycles per second can be effectively reconstructed from a sampling rate of 2 W samples per second. Somewhat higher sampling ratios are required with practical filters in order to reduce aliasing errors within accuracy requirements.

LIM voltage and current signals have a maximum frequency of 173 Hz at 250 mph. The desired frequency response is 800 Hz in order to include the lower harmonics, and hence the sampling rate has been set at 2000 sps. Truck and vehicle dynamics channels have a required response of 0 to 30 Hz within specified accuracies on gain and phase. The sampling rate on these channels is 250 sps.

Presampling Filters

Presampling filtering is provided by active two-pole low pass filters which are second order systems and thus can be matched easily to the "second order" transducers. The selection of cutoff frequencies is based on signal-to-noise ratios, sampling rates and accuracy requirements. In this system the cutoff frequencies are set at 1600 Hz for the LIM channels and at 60 Hz for the dynamics channels. The filter configuration makes it possible to adjust the damping factor (and hence phase) with no effect on the d-c gain. Higher order filters would increase filter distortion (6); between the transducer and filter combination, and the higher sampling ratios, the aliasing error is insignificant.

Sample & Hold Amplifiers

When the first channel within a time-correlated group is gated through the multiplexer, all of the sample-and-hold circuits within that group freeze the value of their particular input voltage. This allows precise time correlation of all the channels in the group even though the signals are sampled sequentially, which would otherwise result in a time-skew error. The settling time of the sample-and-hold amplifier for a 10v input step is 5 microseconds to 0.1% accuracy; hence the tracking error at 2.4 KHz is 0.5%.

A-C Calibration

Two oscillators with frequencies of 800 Hz for the LIM electrical channels and 30 Hz for the dynamics channels are used for calibration purposes. Each channel in a group is normalized for phase angle by means of the presampling filter; the phase lag of the specific transducer associated with that channel is taken into account, using the value obtained from the calibration Bode plots supplied by the manufacturer. A future refinement being considered is a portable shaker/calibration system which would make possible an end-to-end check of each dynamics channel.

SUMMARY

This paper has described the implementation of sophisticated aerospace telemetry techniques to the control and instrumentation of a high speed rail vehicle. The system-level description discussed the LIM test vehicle, and overall system philosophy in the selection and integration of theinstrumentation.

FUTURE WORK

A follow-on paper is planned which will describe the PCM telemetry portion in detail, along with actual test results obtained with this system.

KEY WORDS

Instrumentation, control, test vehicle, rail vehicle, high speed, linear induction motor.

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The author wishes to acknowledge the contributions to the design of this system by R. Holland of Garrett Corporation and J. Stafford of Philco-Ford, WDL Division at Palo Alto, California.

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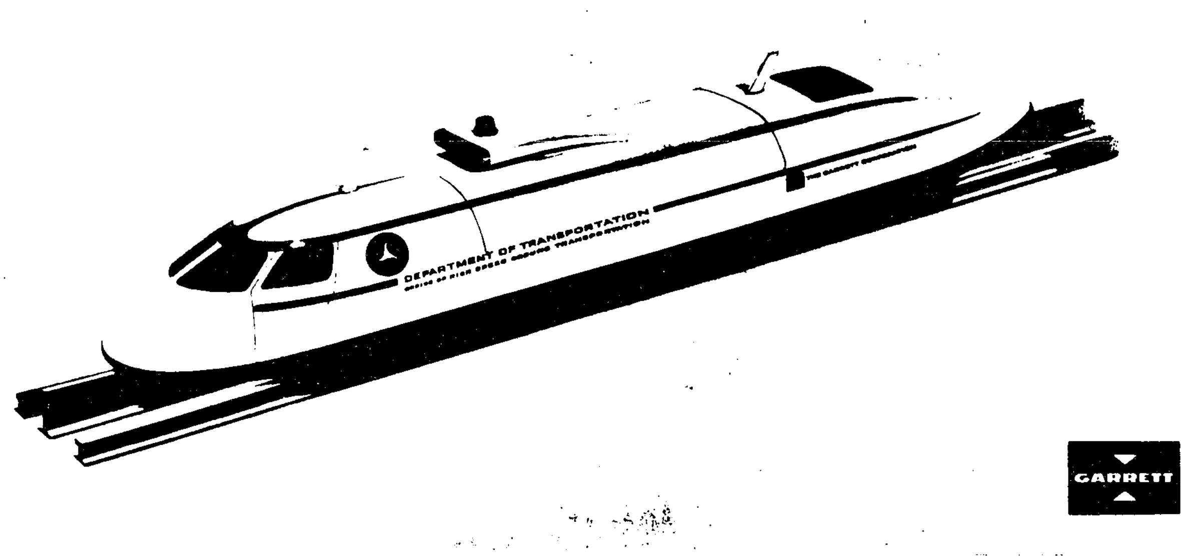

FIG. 1 ARTIST'S DRAWING OF LIM TEST VEHICLE

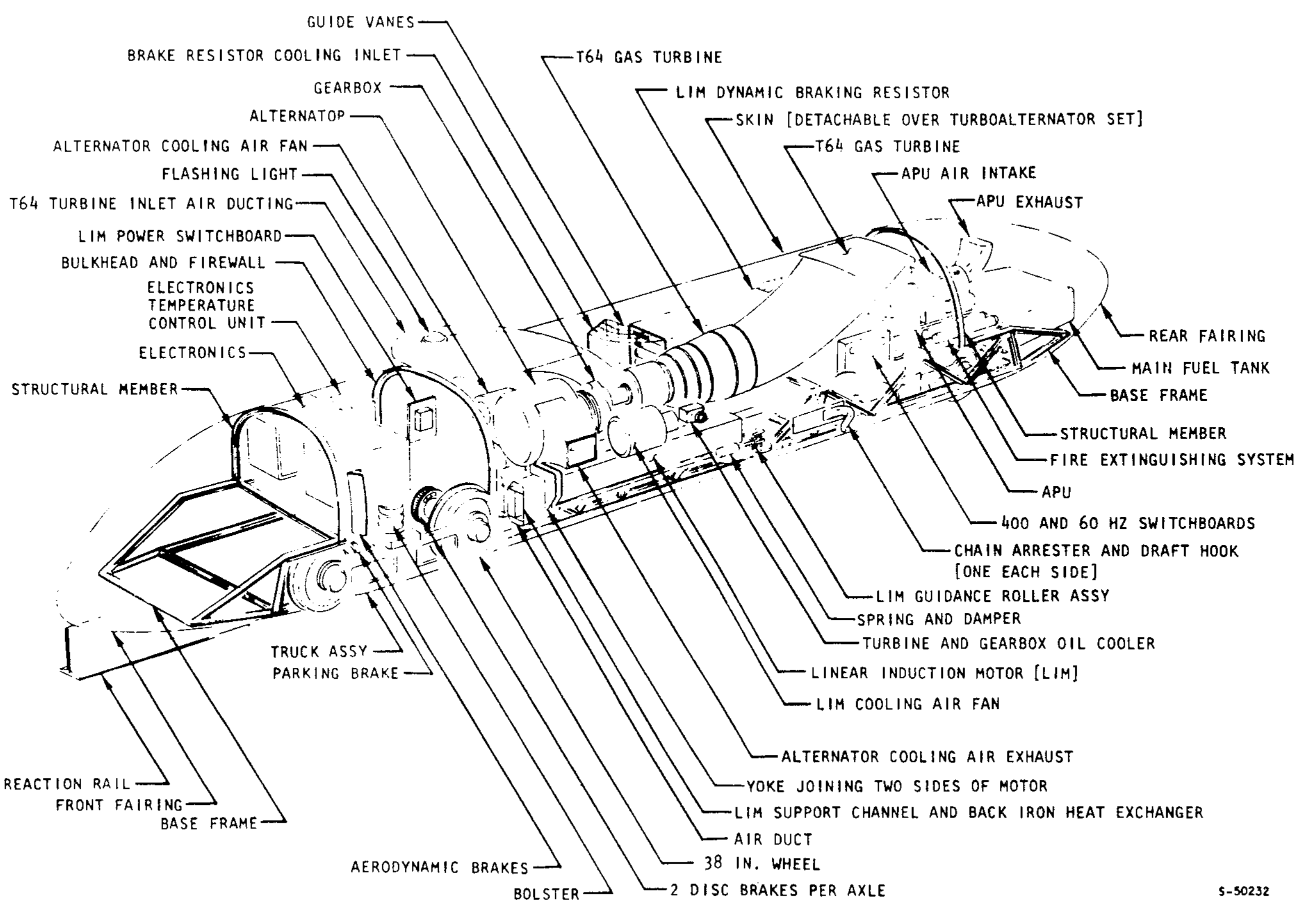

FIG. 2 GENERAL ARRANGEMENT OF HARDWARE IN LIM TEST VEHICLE

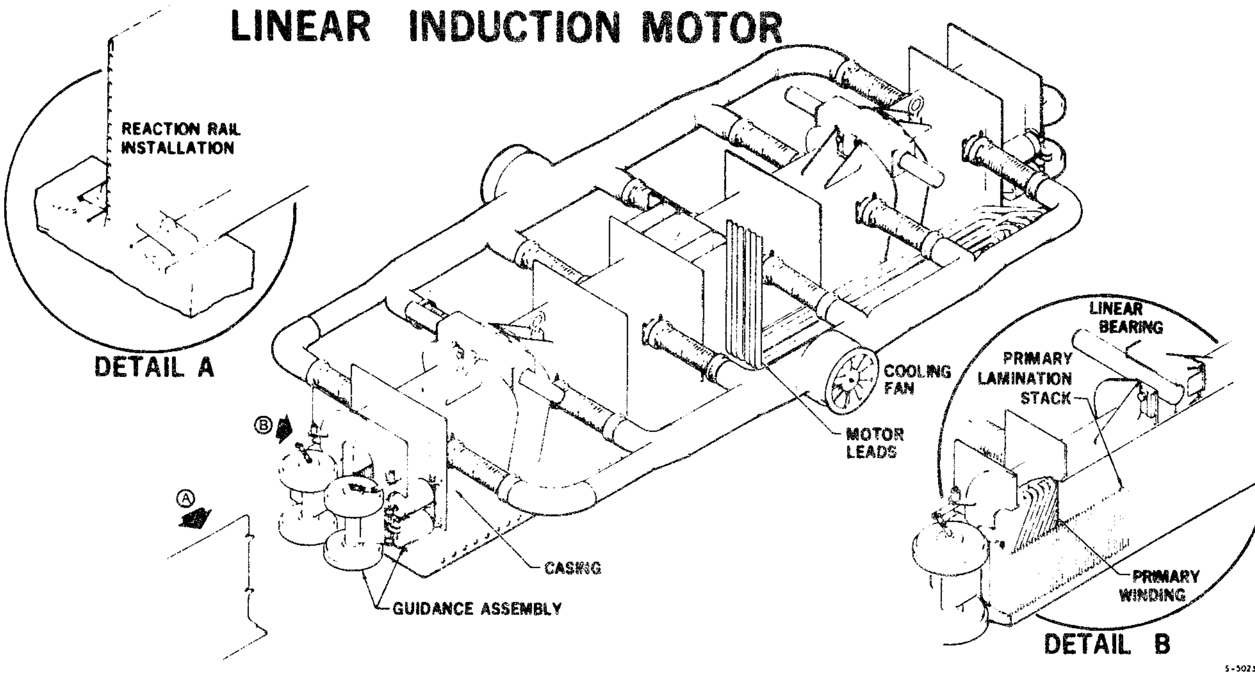

FIG. 3

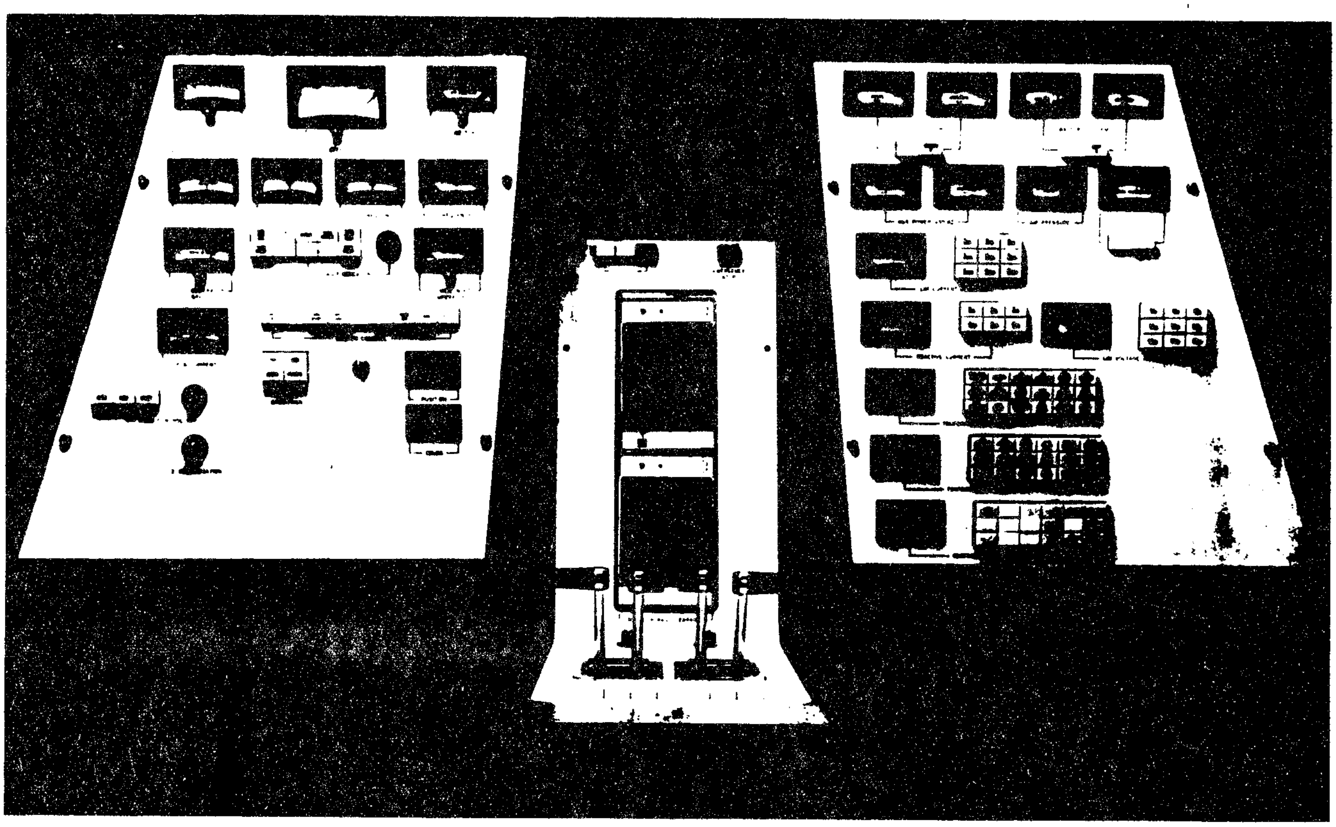

FIG. 4 TEST CELL ARRANGEMENT OF ON-BOARD CONSOLE

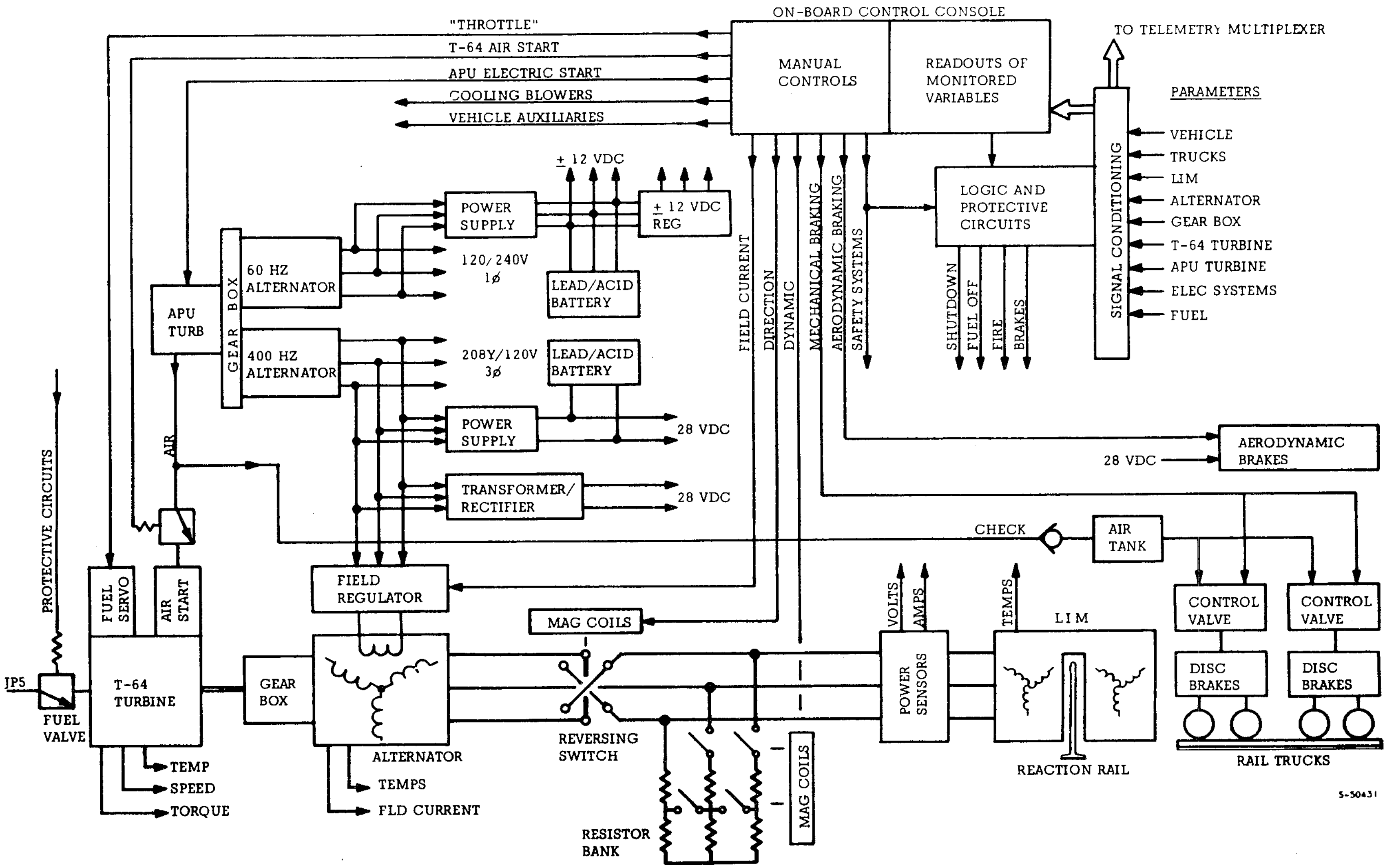

FIG. 5 SIMPLIFIED CONTROL SYSTEM DIAGRAM

SUMMARY OF INTERLOCKS

1. MASTER CONTROLS

GRND PWR	APU FUEL	APU START	APU LOAD	TURB FUEL	TURB START	TURB IGN	FANS	FIELD

Indication: RED (R) ---- OFF
GREEN (G) - ON

Note: The GREEN indication denotes the condition of the switch only. If the control switch is operated out of sequence (as described below) the indication may change from RED to GREEN but the remote function will remain OFF.

However, the converse condition (i.e. switch in OFF position and remote function ON) cannot occur.

2. VEHICLE OPERATION

FWD	REV
LOC	REM

Indication: NONE (N) ---- OFF
WHITE (W) -- ON

3. FIELD CONTROL

AUTO	MAN	START

Indication: NONE (N) ---- OFF
WHITE (W) -- ON

4. FAULT INDICATORS

LOW FUEL	GAS GEN SPEED	VEH SPEED	TURB TEMP ALARM
TURB FAULT	TURB TORQ		ELEC FAULT

Indication: NONE -- Normal
RED --- Limit Exceeded

Note: All buttons are indicators only with the exception of "TURB FAULT" and "ELEC FAULT".

Interlocks: None

When "TURB FAULT" and "ELEC FAULT" shows a RED indication an alarm has occurred and the faulty system will shutdown. The horn will also sound. By depressing the fault indicator the horn will be reset. The fault may be analyzed and reset in the automatic fault finder panel.

	ACTION	CONTROLS INHIBITED UNDER THE FOLLOWING CONDITIONS	INDICATION	
1.	Energize "GRND PWR"	(a) Ground Power not connected	R	G
		(b) "APU FUEL" ON	R	G
2.	Energize "APU FUEL"	(a) APU not connected	R	G
		(b) "GRND PWR" ON	R	G
3.	Energize "APU START"	None	R	G
4.	Energize "APU LOAD"	(a) "TURB FUEL" ON	R	R
		(b) "FANS" ON	R	R
		(c) "FIELD" ON	R	R
		(d) APU frequency or voltage incorrect	R	R
5.	Energize "TURB FUEL"	None	R	G
6.	Energize "TURB START"	(a) APU not running	R	R
		(b) "FANS" ON	R	R
		(c) "FIELD" ON	R	R
7.	Energize "TURB IGN"	(a) "FANS" ON	R	R
		(b) "FIELD" ON	R	R
8.	Energize "FANS"	(a) No supply from APU or Ground Power	R	G
9.	Energize "FIELD"	(a) "FANS" OFF	R	G
10.	Energize "FWD" ("REV" control is mechanically bailed)	(a) "FIELD" ON	N	W
		(b) Vehicle moving	N	W
11.	Energize "REV" ("FWD" control is mechanically bailed)	(a) "FIELD" ON	N	W
		(b) Vehicle moving	N	W
12.	Energize "LOCAL" ("REMOTE" control is mechanically bailed)	None	N	W
13.	Energize "REMOTE" ("LOCAL" control is mechanically bailed)	(a) "FIELD" ON	N	W
14.	Energize "AUTO" ("MAN" control is mechanically bailed)	None	N	W
15.	Energize "MAN" ("AUTO" control is mechanically bailed)	None	N	W
16.	Energize "START"	(a) "AUTO" ON	N	W

FIG. 6

		On-Board Console: Meter Readouts	On-Board Console: Switch Positions	On-Board Console: Fault Indicator	Remote Console: Meter Readouts	Remote Console: Fault Indicator
LINEAR INDUCTION MOTOR	LINE & PHASE VOLTAGES	A	9			
	PHASE & HALF PHASE CURRENTS	A	9			
	HALF PHASE REACTIVE CURRENTS	A	6			
	FREQUENCY	A		P	A	
	SLIP FREQUENCY	A			A	
	THRUST	A			A	
	TEMPERATURES	A	24	P		
	REACTION RAIL CLEARANCE - FRONT	CR		P	CR	
	REACTION RAIL CLEARANCE - REAR	CR		P	CR	
VEHICLE	SPEED	AL		I	AL	I
	ACCELERATION	A			A	
	ODOMETER	D				
	POSITION OR TRIP MILES	D			D	
	TRUCK BOLSTER SPRING PRESSURE	A	2			
TURBO-ALTERNATOR POWER	POWER TURBINE TORQUE	AL		P	AL	I
	POWER TURBINE TEMPERATURE	AL		P	AL	I
	TURBINE GAS GENERATOR SPEED	AL		P	AL	I
	FUEL GAUGE	AL		I	AL	I
	THROTTLE POSITION	A	1			
	OIL PRESSURES	A	3	P		
	ACCESSORY TEMPERATURES	A	6	P		
	TURBINE FAULT OR FIELD FAULT			P		I
	ALTERNATOR FIELD CURRENT	A		P	A	
	ALTERNATOR TEMPERATURES	A	12	P		
	PHASE CURRENT UNBALANCE			P		
AUXILIARY POWER SYSTEMS	APU TURBINE TEMPERATURES	A	1	P		
	APU PERCENT SPEED	A	1	P		
	PNEUMATIC SYSTEM PRESSURE	A	1	P		
	400 HZ VOLTS	A		P		
	400 HZ AMPS	A		P		
	60 HZ VOLTS	A	2	P		
	60 HZ AMPS	A	2	P		
	BATTERY SYSTEMS VOLTS	A	3	P		
	BATTERY SYSTEMS AMPS	A	3			
	ADDITIONAL SWITCHED READOUTS	A	6		A	
	ELECTRICAL FAULT			P		I

Key:
A = Analog meter movement
AL = Analog meter-relay limit
CR = Cathode ray tube
D = Digital readout
I = Indication - visual and/or audio
P = Protected automatic shutdown

FIG. 7 TABULATION OF MONITORED PARAMETERS

S-50430

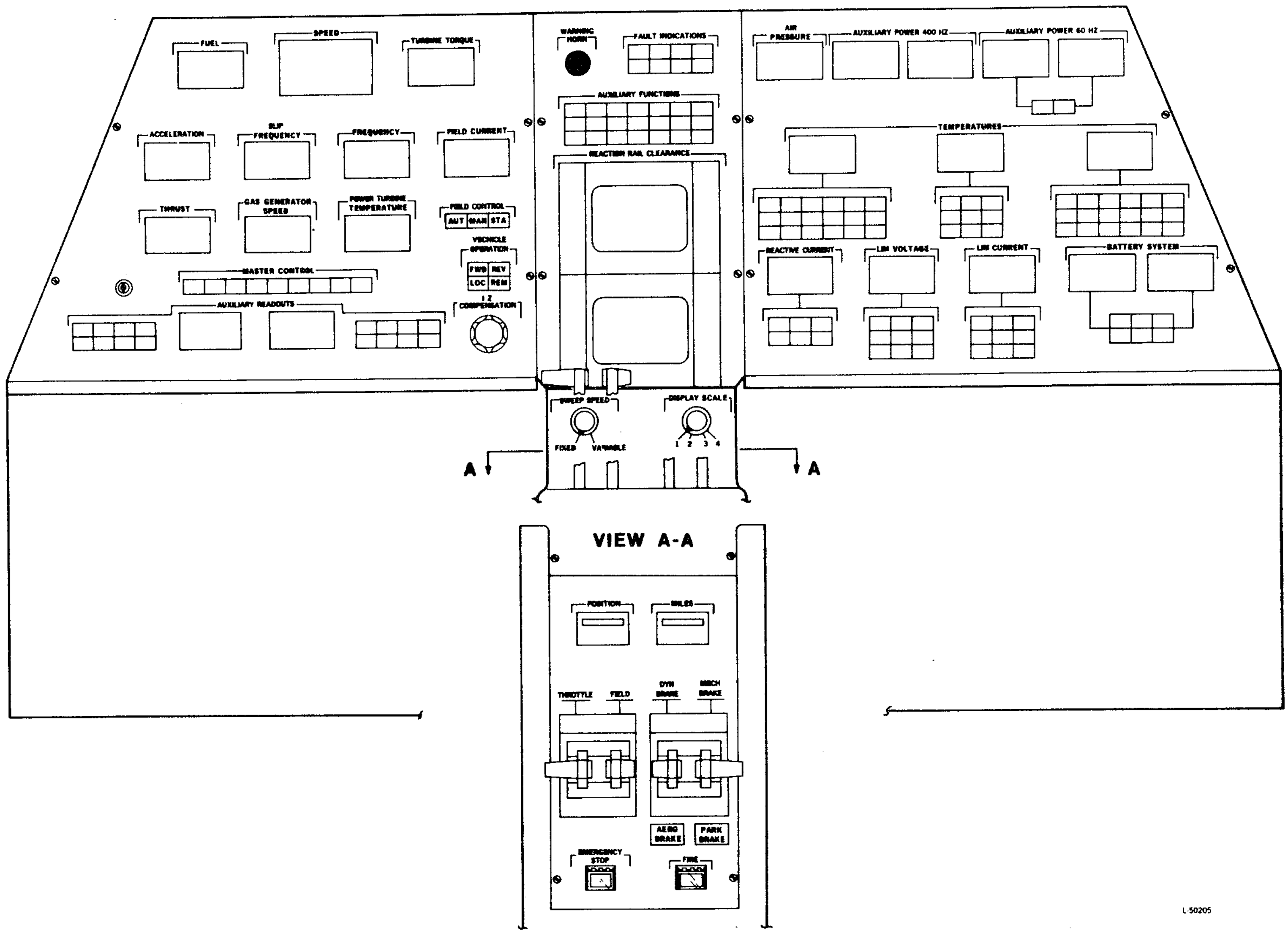

FIG. 8 ON-BOARD CONSOLE ARRANGEMENT

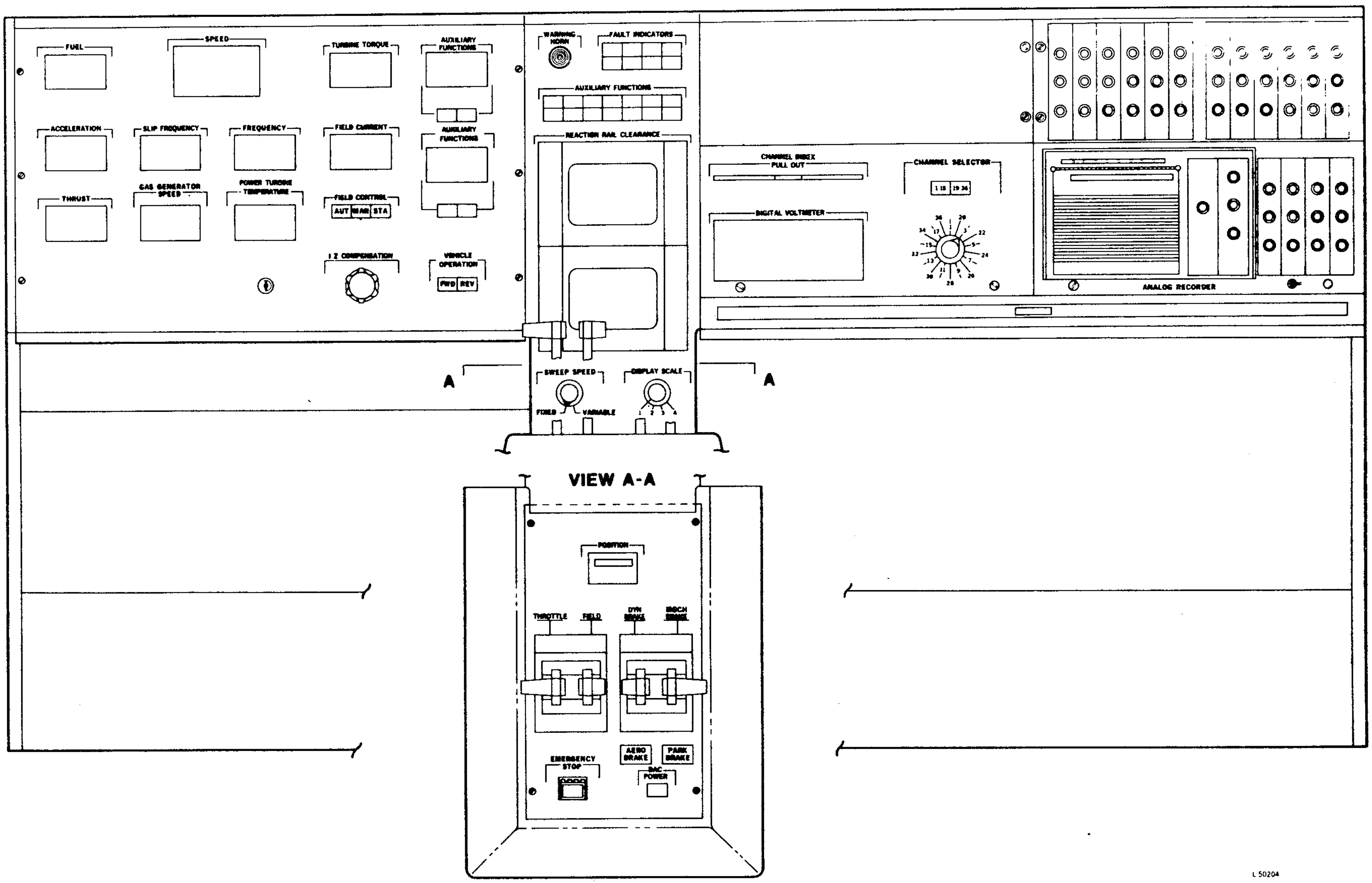

FIG. 9 REMOTE CONSOLE ARRANGEMENT

PERFORMANCE SPECIFICATIONS FOR SENSORS

	Item No.	No. of Sensors	Sensor Description	Measured Parameter	Param. Range	Param. Prop.	Acc'y ±% of F.S.	Desired Freq. Resp.	Desired Time Const.	Temp. Range	Environmental Conditions: Relative Humidity	Vibration	Shock
LINEAR INDUCTION MOTOR	A1	3	Potential transf.	LIM line voltages	1200 vac	10 to 200 Hz	1	800 Hz		0-150°F	90%	10 g - 20 to 100 Hz	20 g for 11 msec
	A2	6	Potential transf.	LIM phase voltages	700 vac	10 to 200 Hz	1	800 Hz		0-150°F	90%	10 g - 20 to 100 Hz	20 g for 11 msec
	A4	3	Current transducer	LIM phase currents	3000 aac	10 to 200 Hz	1.5	800 Hz		0-150°F	90%	10 g - 20 to 100 Hz	20 g for 11 msec
	A5	6	Current transducer	LIM half phase currents	1500 aac	10 to 200 Hz	1.5	800 Hz		0-150°F	90%	10 g - 20 to 100 Hz	20 g for 11 msec
	A6	24	Resistance thermometer	LIM temp	0-500°F		2		1 sec	0-600°F	90%	10 g - 20 to 100 Hz	20 g for 11 msec
	A7	12	Search coils	Mag. Flux distribution		10 to 200 Hz	5	10 Hz 10 khz		0-600°F	90%	10 g - 20 to 100 Hz	20 g for 11 msec
	A8	4	Microsyn	Guidance syst. position	±6°	±1 in.	5	0-40 Hz		0-140°F	100% & splash	10 g - 20 to 100 Hz	20 g for 11 msec
	A9	-		LIM lateral thrust	1000 lb		10	0-40 Hz		0-140°F	100% & splash	10 g - 20 to 100 Hz	20 g for 11 msec
	A11	1	Torsion spring and microsyn	LIM thrust	±5000 lb	±4°	3	0-10 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	A12	6		Spare ckts				10 Hz					
VEHICLE	B1	1	Accelerometer	Veh. Acc'n Longitudinal	±0.5 g		5	to 30 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	B2	1	Accelerometer	Veh. Acc'n Vertical	±1.0 g		5	to 30 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	B3	1	Accelerometer	Veh. Acc'n Lateral	±1.0 g		5	to 30 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	B4	1	Angular Accelerometer	Veh. Roll	4 rad/sec^2	±5°	5	to 30 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	B5	1	Angular Accelerometer	Veh. Pitch	2 rad/sec^2	±1°	5	to 30 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	B6	1	Angular Accelerometer	Veh. Yaw	2 rad/sec^2	±1°	5	to 30 Hz		0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	B7	48	Pressure Transducers	Veh. Aero-dynamic	±1 psi d		8	0-10 Hz		0-150°F	Outdoor Weather	10 g - 20 to 500 Hz	20 g for 11 msec
	B8	1	Pressure Transducers	Veh. Air Speed	300 mph	440 fps	4	0-10 Hz		0-150°F	Outdoor Weather	10 g - 20 to 500 Hz	20 g for 11 msec
	B9	-	Position System	Veh. Position on track	0 - 24 miles	Digital (500 ft)	0.2		2 msec		Outdoor Weather		
	B10	1	Switch	Aero Brakes Response					0.1 sec				
	B11	1	Switch	Chain Brakes Response					0.1 sec				
	B12	12		Spare ckts				10 Hz					
TRUCKS	C1	1	Triaxial Accelerometer	Truck Journal Brg. Acc'ns.	±20 g		5	to 30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C2	2	Displacement Sensor	Veh./Bolster Vert. Pos'n.	±4 in.		5	0-30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C3	2	Displacement Sensor	Veh./Bolster Lat. Pos'n.	±4 in.		5	0-30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C4	1	Displacement Sensor	Truck Yaw	±1 in.	1°	5	to 30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C5	1	Accelerometer	Truck Frame Vert. Acc'n.	±10 g		5	to 30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C6	1	Accelerometer	Truck Frame Lat. Acc'n.	±10 g		5	to 30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C7	8	Resistance Thermometer	Truck Brg. Temperatures	0-300°F	Outer race	10		1 sec	0-300°F	100% & splash	50 g - 40 to 2000 Hz	100 g for 3 msec
	C8	-		Wheel Rim Temperatures	0-600°F		10		1 sec	0-600°F	100% & splash	2600 g centrifugal	100 g for 3 msec

FIG. 10a

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PERFORMANCE SPECIFICATIONS FOR SENSORS (Cont.)

Group	Item No.	No. of Sensors	Sensor Description	Measured Parameter	Param. Range	Param. Prop.	Acc'y ±% of F.S.	Desired Freq. Resp.	Desired Time Const.	Temp. Range	Environmental Conditions Relative Humidity	Vibration	Shock
TRUCKS	C9	4	Tachometers	Veh. Speed	250 mph	Avg. Rdg.	1.5			0-150°F	100% & splash	5 g - 10 - 100 Hz	20 g for 11 msec
	C10	-		Wheel Unloading			10						
	C11	4	Displacement Sensors	Truck Axle Displacement	±.25 in.		5	0-30 Hz		0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C12	2	Pressure Transducer	Bolster Spring Pressures	100 psig		5		2 sec	0-150°F	100% & splash	10 g - 20 to 500 Hz	20 g for 11 msec
	C13	3		Spare ckts.				10 Hz					
WAYSIDE	D1	12	Resistance Thermometer	Reac. Rail Temp Rise	0-200°F		10		1 sec	0-200°F	Outdoor Weather	10 g - 20 to 500 Hz	20 g for 11 msec
	D2	1	Anemometer	Wind Velocity	60 mph		10						
	D3	1	Vane	Wind Dir'n.	360°		10						
	D4	1	Thermometer	Loc. Temp	-40 to 120°F		2°F		5 min				
	D5	1	Hygrometer	Loc. Rel. Humidity	10% to 100%		10		30 min				
	D6	1	Barometer	Local Air Press.	30 in. Hg		2						
	D7	1	Microphone	Noise Level	130 db		3 db	20 Hz to 15 KHz		0-120°F	95%		
	D8	1	Switch	Vehicle approach									
	D9	16		Spare ckts				10 Hz					
	D10	50		Spare ckts				50 Hz					
TURBO ALTERNATOR SET	E1		Cr-Al Thermocouples	Turbine T5 Temperature	1400°F		2		1 sec				
	E2	2	Electromagnetic Pulse Pickups	Turbine Torque	1200 ft-lb	Phase angle	3			Mounted on T-64 turbine			
	E3	1	a-c Tachometer	Gas generator speed	18000 rpm	4430 tach rpm	2			Mounted on T-64 turbine			
	E4		Various	Protective Functions					.5 sec				
	E5	1	Current Transducer	Alt. Field Current	250 ADC	3ø PDR	2			0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	E6	1	Capacitance Cell	Tank Fuel Level		JP4 JP5	10		2 sec	0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	E7	2	Resistance Thermometer	Oil Temperatures	0-300°F		10		1 sec		90%	10 g - 20 to 500 Hz	20 g for 11 msec
	E8	3	Pressure Transducers	Oil Pressures	0-100 psig		10		1 sec	0-150°F	90%		
	E9	1		Spare ckt.				2 Hz					
AUX. POWER SYSTEMS	F1		Cr-Al Thermocouple	APU Turbine Temperature	1400°F		3		1 sec				
	F2	1	Pressure Transducer	Pneumatic Pressure	50 psig		5		1 sec	0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	F3	3	Potential Transformers	400 Hz Volts	250 vac		3			0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	F4	3	Current Transformers	400 Hz Amps	500 aac		3			0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	F5	2	Potential Transformers	60 Hz Volts	150 vac		3			0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec
	F6	2	Current Transformers	60 Hz Amps	100 aac		3			0-150°F	90%	10 g - 20 to 500 Hz	20 g for 11 msec

FIG. 10b

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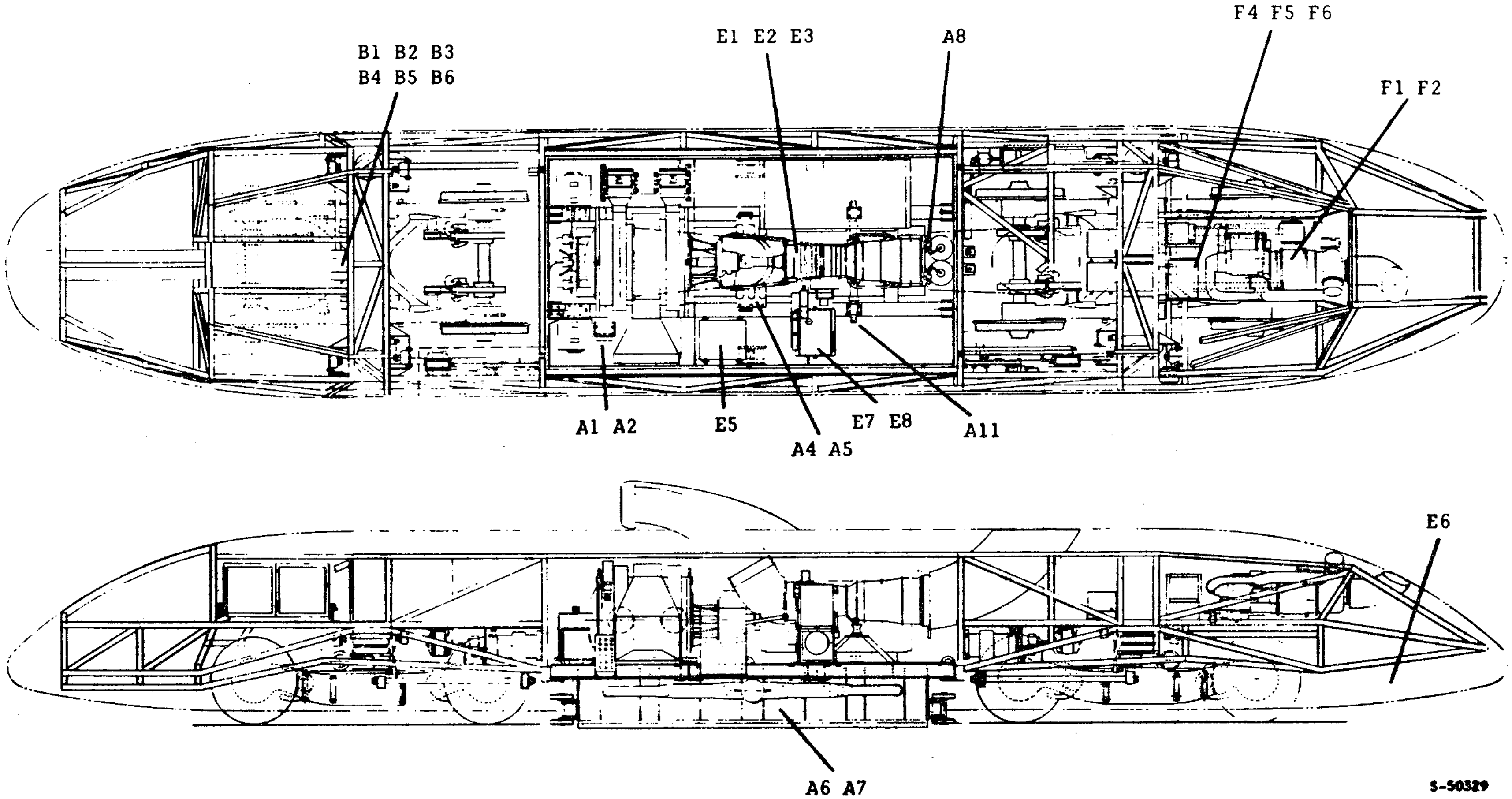

FIG. 11 GENERAL LOCATIONS OF SENSORS

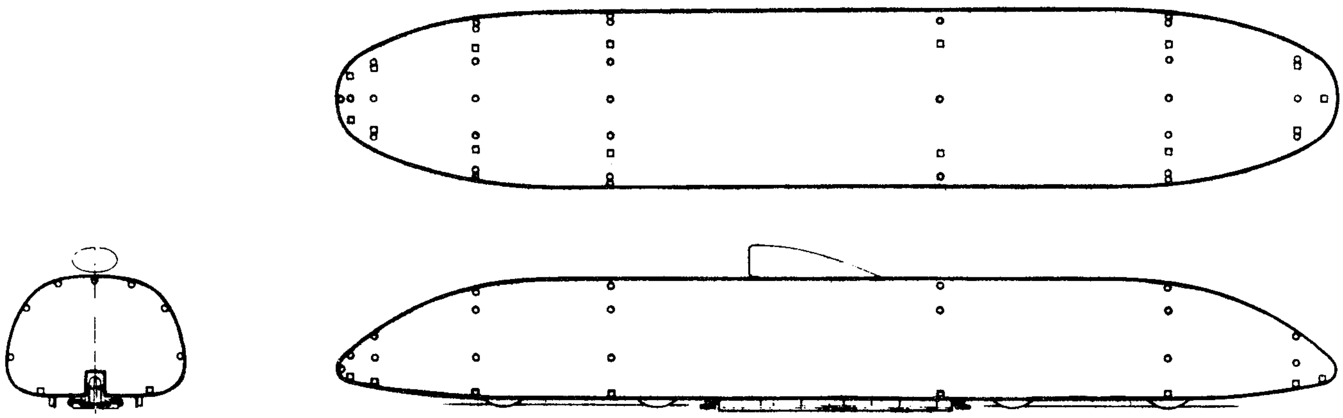

FIG. 12 LOCATIONS OF AERODYNAMIC SENSORS

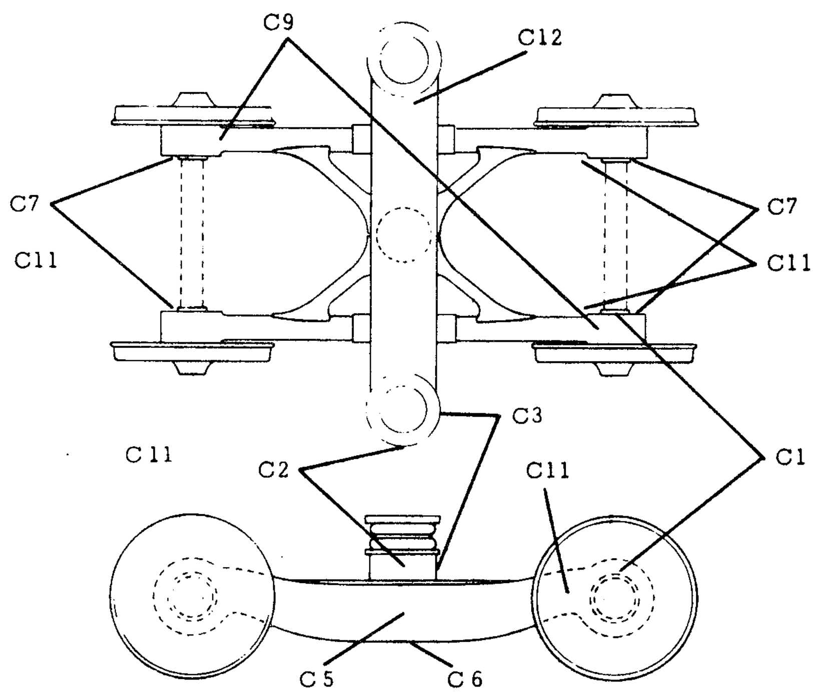

FIG. 13 LOCATIONS OF TRUCK SENSORS

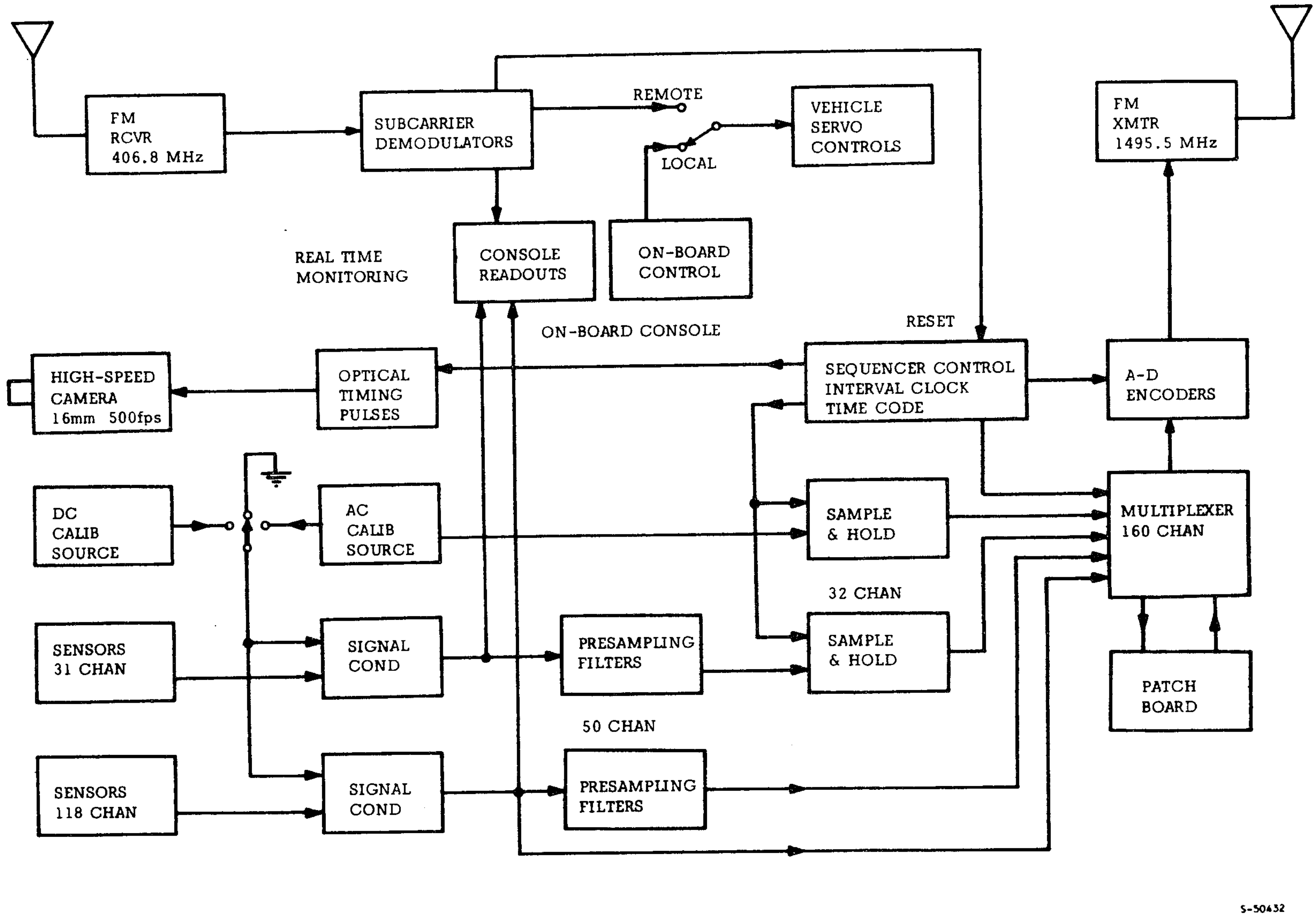

FIG. 14 ON-BOARD DATA ACQUISITION & CONTROL

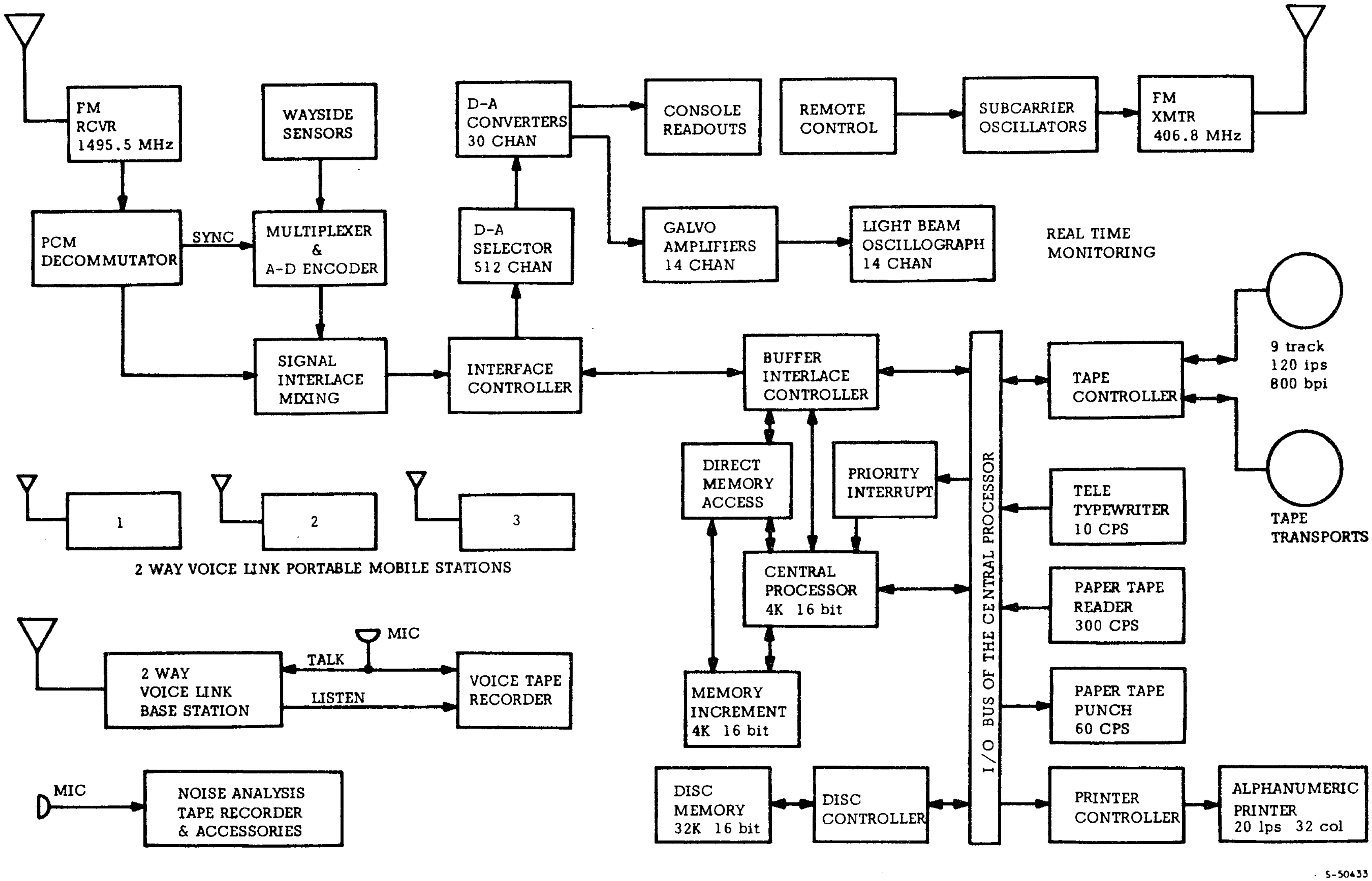

FIG. 15 GROUND STATION DATA ACQUISITION & CONTROL

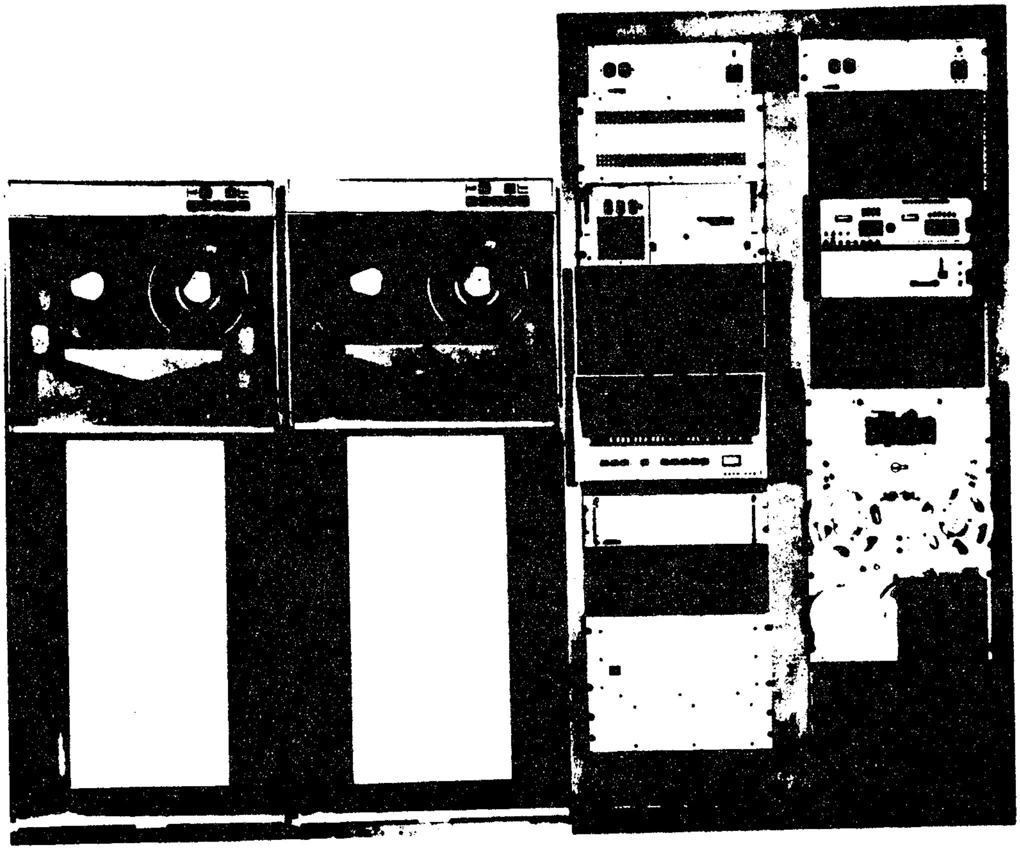

FIG. 16 GROUND STATION EQUIPMENT CABINETS IN ASSEMBLY

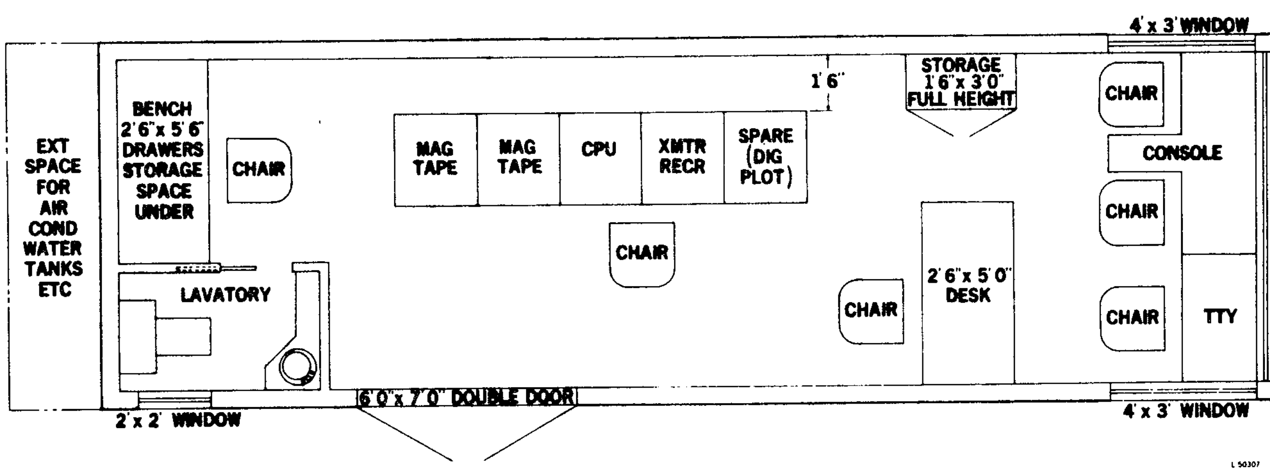

FIG. 17 GROUND STATION TRAILER LAYOUT