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Flying Land Vehicles using Superconducting Magnets

R. G. Rhodes, BA, MS, PhD., B. E. Mulhall, BA, PhD, and E. Abel, BSc (Engineering Science)

Department of Engineering, University of Warwick

SYNOPSIS

The possibility of both suspending and propelling a land vehicle completely free of its guideway at a height of 20 to 30 cm represents an entirely new concept in transportation. Resiliently supported by magnetic forces and propelled at speeds up to 500 km/h or greater, a vehicle such as this bears a closer resemblance in both its streamlined shape and behaviour to a wingless aircraft than to the more conventional train riding on wheels along steel rails. Unlike the aircraft, however, from an environmental point of view it is almost noiseless and pollution-free.

This is only one of several novel modes of land transport using magnetic suspensions and linear motor propulsion which are being actively developed both here and abroad. These can be roughly divided into (1) the electromagnetic small-gap suspensions and (2) the electrodynamic large-gap systems. The former is based on the magnetic attraction faces developed between conventional electromagnets on the vehicle and steel guide rails along the track, while the latter so-called magnetic levitation (maglev) system utilises the repulsion forces developed between superconducting coils on the vehicle and induced currents in an aluminium guideway. It is this latter development which is being investigated at the University of Warwick, and, with the help of a grant from the Wolfson Foundation, a linear test facility and a model vehicle is being designed.

The essential feature on which the feasibility of this basically simple system depends is the superconducting magnet. These cryogenic magnets are being commercially produced with field strengths many times higher but with weights many times less than their conventional copper-iron counterparts. Furthermore, since there is virtually no resistance to the flow of current in the superconducting coils, there is negligible power consumption during their operation (mainly the relatively small amounts of refrigeration power required to replenish the supply of liquid helium coolant in the cryostat).

In its simplest form the guideway for the maglev vehicle would be a continuous strip of aluminium conductor having a suitable cross-section to provide both the lift and guidance forces for the vehicle. Analyses of the ride quality of such a maglev vehicle have indicated that the surface roughness of the track need be no better than that of an average motorway. By comparison with small-gap magnetic systems for which accurate and very smooth tracks are essential, the maglev guideway would have considerable advantages both in initial capital costs and in subsequent maintenance.

The stringent requirement of maintaining a small air gap between primary and secondary would tend to preclude the use of a linear induction motor drive for the maglev system since this would partially nullify the advantage of the large gap suspension. Apart from the excessive weight of present designs having the primary winding on the vehicle, a major disadvantage of the LIM is the difficulty of power collection in the very-high-speed range up to 500 km/h. Most of these drawbacks can be overcome by a linear synchronous motor propulsion system utilising a powered track winding interacting with the superconducting magnets on the vehicle. The possibility of integrating the propulsion and the suspension using the same set of magnets is being investigated.

In this paper the basic specifications for a magnetically levitated test vehicle using superconducting magnets and linear synchronous motor propulsion along a powered guideway will be discussed.

Introduction

What is required to succeed the 'motorway and jet' age of the present is not just a railway revival, although this is long overdue, but a completely new public transport system which is environmentally 'clean' and capable of much higher speeds of travel. With all our worsening social and environmental problems directly linked with present inefficient and inadequate transport modes, already aggravated by a serious oil shortage, the time scales for the introduction of the novel high-speed railway of tomorrow will be much shorter than previously thought. Although supplies of fuel will become less plentiful and their cost increased, the underlying demand for transport is such that no one expects cars, trams and aircraft to disappear. However, this very demand is strong justification for a high-speed ground transport (HSGT) system intermediate between the car and the aircraft which would be more efficient and environmentally acceptable than either.

From the point of view of average inter-city distances in Europe and the advanced countries in the world it is considered that 500 km/h (300 mph) is the speed to aim for. This allows the business man, for example, to travel from one major centre to another and return in a day, with ample time to complete his job of work.

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Although any ground system operating in this speed range would be expensive to develop and to construct initially, it will not necessarily be expensive to operate. A 500 km/h system is not likely to cost three times as much as a 170 km/h one, either to build or to run. Yet it would be capable of making three times as many journeys in a given period and hence could earn three times as much revenue. The traffic is already there on many of the world's busier inter-city corridors and at the present rate of increase it will have a calamitous effect on the more desirable aspects of our present life style unless something is done to relieve the present transport chaos. A fast and efficient public transport system for the inter-city transport of both passengers and goods, using 'clean' electric motor propulsion, makes more sense than our present reliance on cars and aircraft with their inefficient, polluting, and noisy internal combustion engines, using oil and petrol fuels which are already becoming more scarce and costly.

But although the growing fuel shortage gives cause for serious concern and makes transport one of the first targets for economising on its consumption, the real necessity for HSGT systems is to relieve the intolerable congestion levels which many of our cities will be experiencing in the 80's if road traffic is allowed to grow at its present rate. Although trains have dominated our society and our economy for well over a hundred years, in more recent times they have given way to the dominance of the motor car and its big brother, the juggernaut. The hardening of public opinion against further deterioration of living standards which is now reinforced by the economic pressures created by the fuel shortage, are clear signs pointing to a revival of the railway age as one solution to our problems. But tomorrow's trains will bear little resemblance to the familiar strings of coaches suspended on steel wheels running on steel rails, and certainly speeds will be very much higher.

Conventional railway have had a good run since their invention over 140 years ago and the steel wheels with flanges for guidance are little different from those which supported Stephenson's Rocket in 1830, although now the wheels are coned to enable them to negotiate curves more easily.

It is a widely held opinion that speeds of 200 km/h or so represent a practical limit on the existing rail system and that higher speeds, although technically feasible, nevertheless require considerable investment in new track or radically improved rolling stock or both. The history of railway technology abounds with methods for improving the wheel-on-rail concept and considerable effort is still being put into the development of high-speed trains.

In the UK, British Rail are concentrating on the development of an entirely new rolling stock, the advanced passenger train (APT), with a maximum design speed of 250 km/h on existing track, and trains having a similar speed are being developed in half a dozen other countries in Europe.

In Japan, too, the now famous New Tokaido line from Tokyo to Osaka, a distance of 515 km, was the earliest example of an effort to push the technology of the 'steel-wheel-on-steel-rail' concept beyond the conventional limits. Inaugurated in 1964, the Tokaido line has proved to be both a commercial and a technical success; trains run every 20 minutes (more often during rush hours) at an average speed of 170 km/h and reaching top speeds of 210 km/h. The success has been considered so great that this line has now been extended to form the New San-Yo line and plans have been approved to build additional trunk lines which would allow average speeds of 200 km/h with peak speeds of 250 km/h.

However, even with new track and advanced developments in the equipment, there would appear to be limits as to how far one can push the steel-wheel-on-steel-rail technology. The problem of attaining the necessary adhesion between the wheels and the rails at speeds beyond 200 km/h has led to doubts about the reliability of propulsion and braking. There is also concern about the ability of coned wheels to resist the lateral forces which would be encountered at these high speeds as well as their stability in operation. The cost of achieving and maintaining the very high accuracy of track alignment that would be necessary is also thought to be prohibitive since technical and safety problems multiply rapidly beyond about 250 km/h.

Although this speed may represent a practical limit of adhesion, for wheel traction systems developments for linear motor propulsion will enable the speed of trains to be pushed well beyond this, ie, in excess of 300 km/h. However, very high accuracy of rail alignment would be essential, requiring new straight, level track and rights-of-way so that considerable development lies ahead in this field.

The other main competitor for inter-city transport is the aeroplane. However, because of the formalities of take-off and landing and the waiting times of incoming and outgoing aircraft at airports, short air journeys over land would seem to have no great future in competition with a HSGT system, which is in addition virtually independent of weather conditions. The difficulties of the expansion of air transport, however, are much more serious. The present policy of building new airports or extending the existing ones has clearly shown up the adverse effects of pollution and the spoiling of the environment in the neighbourhood of cities. The situation has been further aggravated by the future landing and take-off of supersonic aircraft.

That domestic air transport is declining in competition with the railways is shown by statistics, — for example, during the period 1962—1972 the number of passengers travelling by air between New York and Washington increased by 3% compared with an increase in rail passengers of 19% during the same period. A similar pattern is being repeated in the UK and in Europe and there now seems little doubt that the introduction of very-high-speed trains will pose a serious threat to the airlines. A new regime is emerging in the sphere of intercity transport for the greater good of the travelling public.

Magnetic suspension systems

The magnetically-levitated train, maglev, is a serious contender for the new high-speed era which seems inevitable for the 80's. It will bear little resemblance to trains as we know them and instead of wheels it will be levitated several inches above an aluminium guideway by magnetic forces. Propelled at 500 km/h it will resemble a wingless aircraft in size and shape, flying at an altitude of 20 to 30 cm along its trough-shaped guideway. Unlike the aeroplane, however, with its jet propulsion, the electric maglev vehicle will be virtually noiseless and pollution-free. The basic principles of its design are well understood but it is only in the last few years that the technology has been developed to the stage when a practical vehicle now seems feasible (refs 1–6).

The possibility of supporting a vehicle by magnetic forces extends back for over a century and numerous inventions involving both permanent magnets and electromagnets have been proposed. For many reasons, including the cost and weight of permanent magnets, such as the ceramic ferrite materials, and the weight and power requirements of electromagnets if operated with a reasonable suspension height, none of these has hitherto proved economically successful. However, with recent technological developments, particularly in the case of the solid-state control of electromagnets, a new impetus has been given to this form of suspension (refs 7,8). Also, with the development of stable superconducting magnets within the last few years, the engineer now has a relatively light-weight source of magnetic field strength hitherto unobtainable by conventional means.

Hence the two systems with the most promise which are actively being developed on a significant scale, are (1) the attraction system using controlled electromagnets (refs 7,8) and (2) the repulsion system using superconducting magnets (maglev) (refs 1–6).

It is this latter type of magnetic suspension that is being investigated at the University of Warwick and financed by the Wolfson Foundation.

In the following the maglev system is discussed from the point of view of the lift and drag forces, guidance and linear motor propulsion.

Induced current suspension

A repulsion force can be produced between a coil carrying alternating current and a metal conducting plate, ie, eddy currents are generated in the plate by the time-varying field. Using this principle, Emile Bachelot (ref 9) in 1912 demonstrated a model vehicle carrying an aluminium plate that was suspended and propelled above a continuous row of coils along the track. More recently (ref 10, 1971) a similar system was demonstrated in Germany. A proposal which is in many ways similar, to put the field winding of a linear induction motor on the vehicle, has been made by Professor Laithwaite of Imperial College and is discussed in another paper in this conference. With the aluminium reaction rail on the tracks the capital costs for this arrangement should be very much reduced and on-board control becomes more feasible.

Following the development of the high-field superconducting magnet in the past ten years, another method of vehicle suspension based on induced eddy currents is being re-examined. We now have a relatively lightweight source of dc magnetic field of high intensity requiring little or no power during operation, so that some of the objections to the previous schemes, namely excessive weight and large power consumption, can be overcome. Thus another variant of Bachelet's basic ideas can be reconsidered for the levitation of high-speed trains. In contrast to the schemes mentioned above, the superconducting magnet only produces a dc field, and hence it must be moved relative to the conducting sheet in order to produce the time-varying fields necessary to generate the eddy currents which provide the lift force.

The essential features of eddy current suspension are easily understood and the flux line patterns of the real magnet and an imaginary image magnet of equal and opposite strength are shown in Fig 1. As the vehicle magnet moves over the aluminium sheet, eddy currents are induced in the thin surface layer so as exactly to prevent the magnetic flux lines from penetrating the sheet. The interaction of these induced currents with the magnetic field gives rise to a magnetic pressure or lighting force on the vehicle. As illustrated in the figure, the magnetic flux pattern is the same as if an 'image' magnet were produced on the other side of the sheet in a similar position and with an equal strength but oriented to produce a repulsion force on the real magnet. If, for example, the magnetic field strength at the surface of the guideway is 1T, which is easily attainable with superconducting magnets, the lift is equivalent to a pressure of 4×10^5 N/m^2 or 4 atmospheres over the guideway and the levitation of a 100-passenger vehicle having a typical weight of 30 tons becomes entirely feasible.

Speed dependence of the lift and drag forces

In general, the lift force produced by a current-carrying coil accelerating at a constant height above a conducting sheet guideway, increases sharply at low speed, ie, proportional to V^2, but eventually approaches asymptotically to a high speed limit (Fig 2).

However, since the aluminium sheet, and indeed all metal conductors at normal temperatures, have only a finite conductivity the induced eddy currents give rise to a power dissipation in the form of Joule losses which appear as a magnetic drag force on the vehicle. It is as if the image magnet were smaller and displaced forward of the real magnet. The dissipated power must be supplied ultimately by the propulsion system, ie, linear motor, and appears as a drag on the vehicle motion. This drag force at first increases rapidly with speed, being proportional to V, but it then passes through a peak value (at around 20–40 km/h) and decreases as $V^{-1/2}$ at high speeds (Fig 2). The drag decreases more slowly in the high-speed range because of this "skin" effect whereby the induced eddy currents are prevented from penetrating into the aluminium sheet and flow only in a thin surface layer called the "skin depth", ie, the aluminium appears to have a lower conductivity. This decreasing drag force with increasing speed, unlike aerodynamic drag, is one of the remarkable advantages of this form of electromagnetic levitation. For a practical guideway take-off becomes possible at around 40 km/h and the limit of lift is essentially reached at approximately 100 km/h.

The lift/drag ratio, F_L/F_D, is a measure of the quality of the conducting sheet suspension since it determines the propulsion power necessary to overcome the drag force. It has been shown (refs 1, 2) that

$$F_L/F_D = \frac{v\,\mu_o \sigma d}{2} \text{ (low speed)}$$

$$= \frac{v\,\mu_o \sigma \delta}{2} \text{ (high speed)}$$

where μ_o is the permeability of free space, σ is the conductivity of the aluminium guideway and d is its thickness; in the high-speed range the eddy currents are limited by the skin depth, δ which is proportional to $1/\sqrt{v}$ From calculations and experiments it has been found that, in general, increasing the length of the rectangular magnetic coils in the direction of vehicle motion and increasing the suspension height improves the F_L/F_D ratio (ref 2). Proposed magnet design parameters for a conducting sheet suspension are shown in Table 1.

Table 1 Design Parameters of Typical Vehicle

Fuselage	Lightweight aircraft construction length 30 m width 4 m weight 30,000 kg
Suspension height	200–300 mm
Track	aluminium sheet (25 mm thick) (double L section)
Superconducting magnets (filamentary wire)	four per vehicle length 3 m width 0.5 m current 4 x 10^5 A-turns winding cross-section 100 x 50 mm max. field 3 Tesla
Magnet + cryostat	600 kg
Lift-to-drag ratio	20

At speeds below about 30 to 40 km/h the eddy currents in the guideway exclude so little of the magnetic flux that the lift force falls below the vehicle weight and therefore an alternative low-speed suspension, such as rubber-tyred wheels, must be provided. This can in fact be turned to advantage, since maglev vehicles may be designed to run on standard gauge track and hence use existing city termini. Lateral stability and guidance are obtained by the appropriate guideway configuration, such as, for example, two L-shaped guide rails. The stability of the maglev suspension and guidance is similar to a spring, in that the lift force increases rapidly with decreasing lift height.

Supported by superconducting magnets distributed essentially over its entire length the maglev vehicle offers the possibility of guided land flight at an elevation of 30 cm. On bends, the aluminium guides might be curved in section to allow the vehicle to assume a coordinated 'bank' angle in a similar manner to an aircraft or bicycle (ref 5).

The distributed lift forces, combined with a lightweight construction, provide the possibility of an elevated guideway of a strength and cost very much less than that required for conventional trains (Fig 3). With the large vehicle guideway clearance, the track need not be very smooth or accurate, and an ordinary roadway or airfield surface would suffice. Furthermore, small debris or snow and ice would not in any way be a problem.

At the higher speeds, the aerodynamic drag, which increases as V^2, tends to dominate so that 500 km/h is considered to be an economic limit for the maglev vehicle under normal conditions. However, the possibility exists of operating in tunnels at reduced atmospheres (evacuated) and speeds up to 1000 km/h then become possible. For other reasons also, such as weather-free conditions and the fact that some tunnelling is essential for any high-speed system depending on the terrain, a tunnel system should be seriously considered.

Propulsion

The choice and design of propulsion machinery is of major importance in the design of high-speed magnetically levitated vehicles. Having eliminated the need for mechanical contact between vehicle and ground for suspension, it is undesirable to reintroduce it for propulsion, either in the primary means of transmitting the propulsive force, or in ancillary power collection mechanisms. This is proposed not merely on aesthetic grounds, but for reasons already discussed above. It should also be noted that the absence of the wheel/rail current return path accentuates the power collection problem.

Modern conditions dictate that environmental effects shall be minimised — hence the power unit should be non-polluting (at least locally), quiet, and, in view of future energy costs, should form part of a system of the highest possible overall efficiency. Clearly linear electric motors must be considered, since they possess all these qualities in varying degrees, and indeed many types of linear motor have been proposed for traction purposes. In principle a linear equivalent of any type of rotating machine can be developed (though the resulting end effects may introduce quite profound differences in behaviour between linear and rotating versions). The following discussion is by no means exhaustive. The main points are summarised in Table 2, though again it must be emphasised that these machines are at such an early stage of development that a comparison can only be in very general terms.

The machine which has received most attention to date is the linear induction motor. In its originally developed form a relatively short primary (on the vehicle) generates a moving wave of magnetic flux, which interacts with eddy currents set up in the reaction rail (along the track) to produce tractive force. The reaction rail requires a backing of iron to complete the magnetic circuit, but this can in fact be made as a second primary, giving the double-sided machine. The reaction rail assembly of the single-sided machine is expensive, while the double-sided machine has the disadvantage that for good efficiency the air gap must be small, and hence the reaction rail is narrow and mechanically very weak. For high-speed applications the main problem is that either a high frequency supply (perhaps up to 400 Hz) must be available or the pole pitch must be so long that the core thickness and winding resistance would become excessive. These difficulties are to some extent overcome by the 'transverse' flux machine of Laithwaite and Eastham (refs 11-13). However, in all induction machines the primary is the only powered winding, and hence is ultimately the source of all magnetic fluxes and electric currents in the machine. The net result is that for reasonable efficiency and power factor the air gap should be small and induction machines are incompatible with the large gap possible with super-conducting magnet suspensions. A further problem with the linear induction motor is that for lowest capital cost the primary should be on the vehicle, but this introduces the problem of high-speed power collection, as well as significantly increasing the weight to be levitated.

A possible answer to the inherent problem of the induction machine is to provide part of the magnetic flux by means of another winding, viz, a superconducting winding. Since this source of flux is light in weight (involving no iron) and consumes little power the efficiency and power factor of the machine should be capable of improvement. A further attraction is the possibility of using for the propulsion the levitating magnets already on the vehicle, ie, combining the lift and propulsion for levitation. Several suitable types of machine have been proposed, including homopolar (ref 14), synchronous (ref 6) and commutation machines. Homopolar machines (Fig 4) can be dismissed as they necessarily entail severe problems of high-speed current collection, which are solved only with difficulty even in the environment of experimental machines. Synchronous and commutation machines are similar, in that each has a nominally dc field winding, reacting with a second powered member. In the synchronous machine (Fig 5) the powered member is a multiphase winding which produces a travelling magnetic wave onto which the field winding locks. Power pick-up problems are avoided if the multiphase winding is on the track, and though a normal type of machine winding (but with no steel yoke) is possible it appears that for high-speed transport a simple wave winding may be sufficient, and would represent only a rather small fraction of capital cost of the track.

The main disadvantage of the synchronous machine is that it can only provide thrust when running synchronously so that some alternative method of acceleration and

Table 2 Characteristics of Linear Motors

	LIM, wound track	*LIM, reaction rail on track, narrow gap*	*LIM, reaction rail on track, large gap*	*LSM, wound track*	*LCM, wound track*	*LHM, on-board power control*	*LHM, trackside power control*
Gap	narrow (40 mm)	narrow (40 mm)	wide (40 mm)	wide	wide	wide	wide
Efficiency	70%	70%	poor	70%	70%	60%	60%
Power factor	0.5	0.5	poor	0.2	good	good	good
Capital cost	high	low	low	moderate	moderate-high	low	high
Weight of onboard equipment	low	moderate-high	moderate-high	low	low	high	low
Power collection problems	none	h.v.a.c.	h.v.a.s.	none	none	severe	severe
Starting performance	good	good	good	poor	good	good	good

deceleration is required. The several possibilities for doing this are (1) a variable frequency supply, (2) variations in the pitch of the track windings, or (3) auxiliary windings for the machine to operate as an induction machine for starting. A further problem is that, if at any time a long length (say 1 km) of track is powered, the efficiency and more particularly the power factor are seriously degraded. The alternative of powering short track lengths poses a switching problem, though as discussed below, this may prove to be quite tractable.

The requirements of good starting torque and the ability to operate efficiently over a widespread range are already met in traction service by rotating commutator machines. Series connected they may be fed with ac or dc, though in the former case the frequency is usually low (e.g. 16⅔ or 25Hz). As a linear machine, with separate field excitation (from the superconducting magnets on the vehicle) the supply must be unidirectional — ie, dc or rectified ac, and the track winding will in many ways resemble that of a linear synchronous machine. It is the switching action of the commutator which controls the currents thus setting up the travelling magnetic wave, and as the commutator is synchronised to the vehicle (in a rotating machine it is, of course, on and fixed to the rotor) the machine can run at any speed. Clearly the major problem lies with the commutation mechanism. One solution is to use thyristors (Fig 6) switched on by signals transmitted from the vehicle, for example, by light-duty mechanical contacts, or by optical or magnetic induction methods, and switched off by supplying the power as ac. Since any one switch only operates for the short time the vehicle is passing (which may be a few or only one half cycle(s) of power frequency) they can be appropriately overrated and hence keep costs within reasonable limits. Such a scheme is of particular interest for the track sections where the vehicle must be accelerated.

Levitating motors

The radial forces that exist in rotating electric machines are well known, and indeed Laithwaite has pointed out that the corresponding vertical forces in a linear induction motor can provide lift. It is also known that in an induction machine, with iron return yokes for the magnetic flux, the force has an attractive component arising from the iron components and a repulsive component arising from the interaction of the armature currents and currents induced in the reaction member; the net force varies from being repulsive at low speeds (high slip) to attractive at high speeds, (low slip). Clearly the same possibility of obtaining lift and thrust from one machine exists for other types of motors. Indeed, the magnetic drag discussed above can be regarded as another aspect of the subject, and illustrates that the problems are not those of setting up currents (and their associated losses) of the magnitudes needed to provide both lift and thrust, but rather of devising a stable and controllable system. The advantages of using superconductors arise firstly from the elimination of iron, which, apart from cost savings, eliminates the attractive forces, and secondly from the high excitation available for negligible power dissipation, which allows the track currents to be relatively small even at large vehicle-track clearances. The design of such a machine is one aspect of the research now in progress at Warwick.

Experimental programme at Warwick University

From the preceeding discussion it is clear that the use of superconducting magnets in high-speed ground transport offers quite remarkable advantages. It is also clear that there are many aspects to a transport system, each of which it is difficult to study in isolation. Thus the University of Warwick, with generous funding from the Wolfson Foundation, is building an experimental vehicle and track.

The vehicle is planned to be running in 1975, on a straight track of over 600 m length to be built on the campus. Speeds of over 180 km/h will be possible, and though this does not allow a comprehensive study of the vehicle's dynamic behaviour (the time of any run, less than a few tens of seconds, will be too short for many modes of instability to develop), it will both demonstrate the feasibility and essential characteristics of magnetic levitation and serve as a test bed for linear synchronous motors.

To focus attention on the engineering problems, as opposed to the conceptual ones (which have in any case already been extensively studied) the vehicle will be of passenger-carrying size — that is, it will be about 3m long by 1m wide by 1m high, and weigh up to 600 kg fully loaded. Thus it will not be a scale model of a revenue vehicle.

The maximum speed desired will only be attained with accelerations approaching 1*g*, and thus the propulsion equipment will have a short-term rating of about 400 kW. The development is planned in two stages; in the first the chassis and superconducting magnets will be towed by a winch, while the second will be the addition of the linear motor. To facilitate modification the track is a simple concrete roadbed with a flat top 1m wide. The aluminium L-shaped sections to provide the lift and guidance surfaces, and the propulsion winding, will be bolted on at the appropriate stage.

Present studies are devoted to choosing and designing the propulsion/levitation system. It is however already clear that the superconducting magnets will have ratings well within the limits already reached by the technology. The peak magnetic field at the coils is about 1T, with the coil riding about 20 cm above the guideway (the actual track-vehicle clearance will be 10 cm, because of the thermal insulation around the coils). The vehicle will carry sufficient liquid gases for several hours' operation, after which re-filling from trackside storage will be a relatively simple routine. The feasibility of such a system for a full-scale design will also be investigated.

References

1. Coffey, H. T., Chilton, F., and Hoppie, L. O., 1972. SRI Report DOT-FR-10001, PB-210505.
2. Reitz, J. R., Borcherts, R. H., Davis, L. C., and Wilkie, D. F., 1972. Ford Report DOT-FR-10026, PB-210506.
3. Rhodes, R. G., and Eastham, A. R., 1971. *Hovering Craft and Hydrofoil,* Vol. **11** no.3, p.12. (see also Final SRC Report, Oct 1971 – Oct 1972).
4. Alston, I. A., Hayden, J. T., and Clark J. M., 1972. *Hovering Craft and Hydrofoil,* Vol. **11** no.11, p.9.
5. Kolm, H. H., and Thornton, R. D., 1972. Proc Applied Superconductivity Conference, Annapolis, Md.
6. Thornton, R. D., 1973. Proc IEEE Vol. **61** no.5, p.586.
7. Meisenholder, S. G., and Wang, T. C., 1972. TRW Systems Group, Report FRA-RT-73-1.
8. Jayawant, B. V., and Kaplan, B. Z., 1961. J. Phys. E., **4** p.301.
9. Bachelet, E., 1912. *The Engineer,* Vol. **114**, p.420.
10. Hockhausler, P., 1971. *Elektrotechnik Z.* Vol. **23**, no.13, p.311.
11. Laithwaite, E. R., Eastham, J. F., Bolton, H. R., and Fellowes, T. G., 1971. Proc IEEE Vol. **118** no.12, p.1761. (See also discussion in ibid **119** no.12, p.1727).
12. Laithwaite, E. R., and Eastham, J. F., 1973. Proc IEE Vol. **120**, no.3, p.337.
13. Laithwaite, E. R., 1973. *Electrical Review,* Vol. **193**, p.566.
14. Polgreen, G. R., 1966. *'New Applications of Modern Magnets', Macdonald, London.*

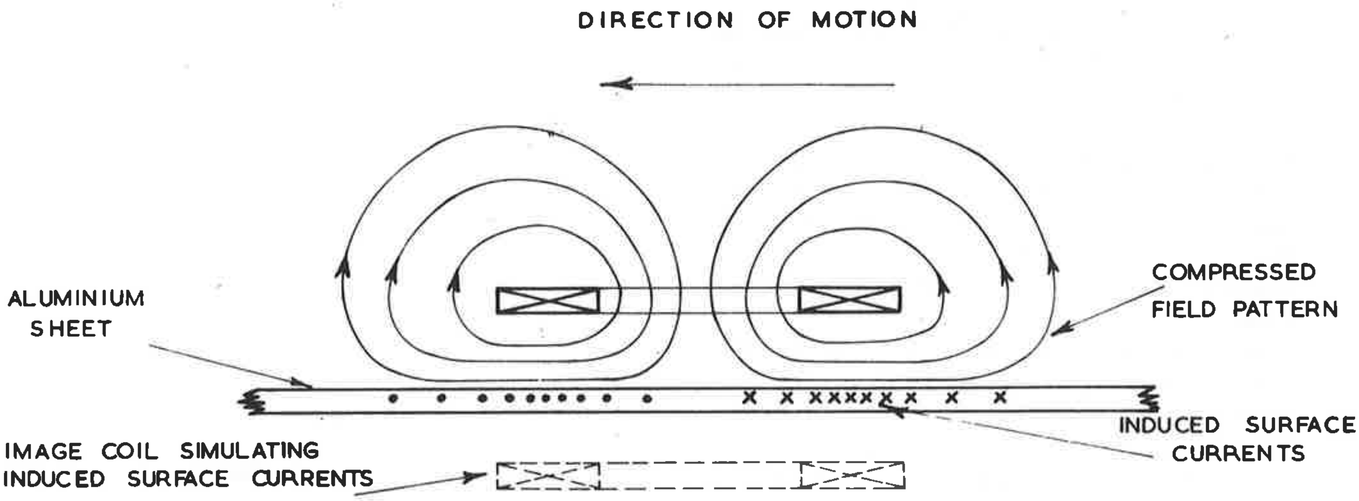

Fig. 1 Magnetic field and induced current distribution produced by a dc coil moving over a conducting sheet

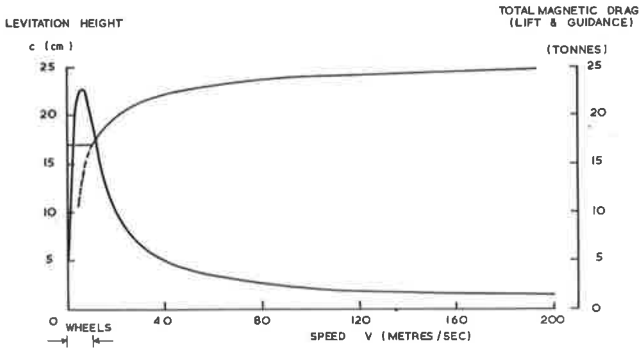

Fig. 2 Levitation height and total drag force as a function of speed for a conducting sheet suspension

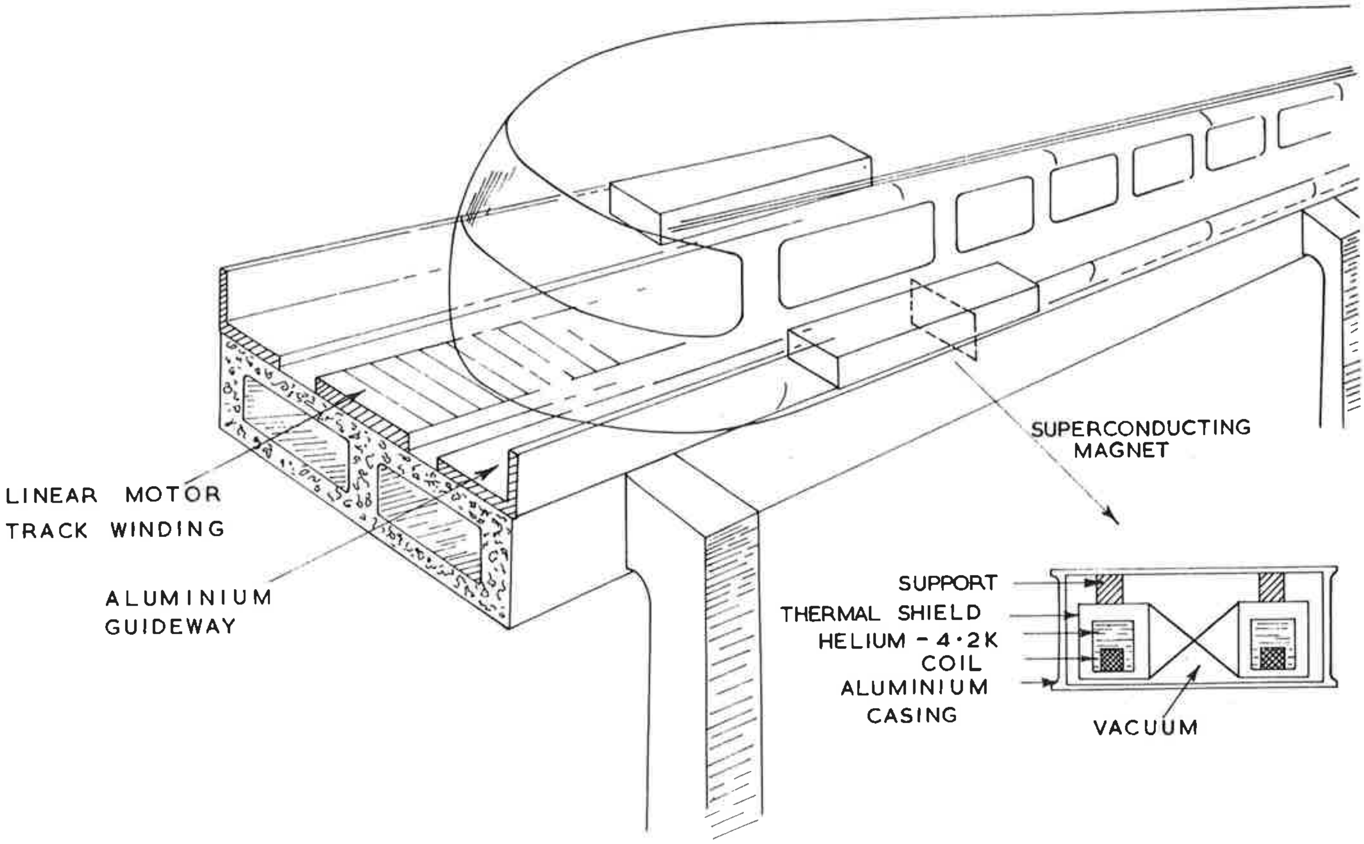

Fig. 3 Artists conception of maglev vehicle showing the levitating superconducting magnets

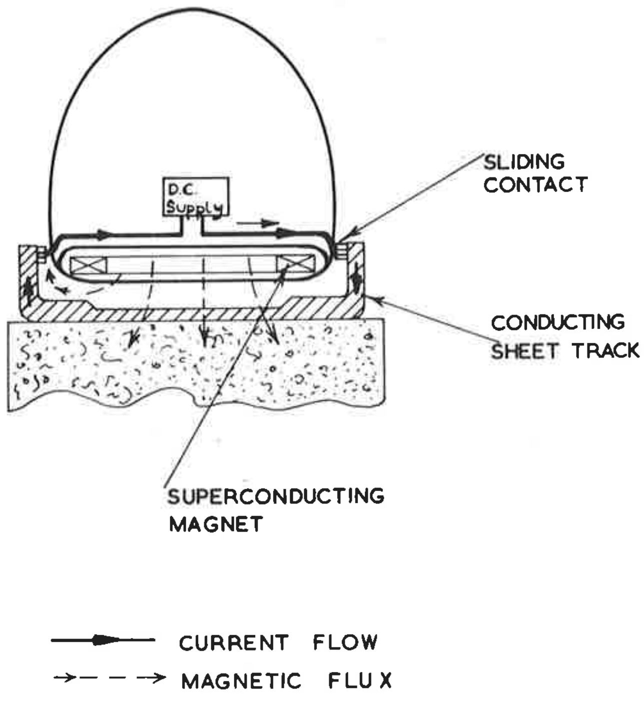

Fig. 4 Scheme of linear homopolar motor (LHM)
(section through track)

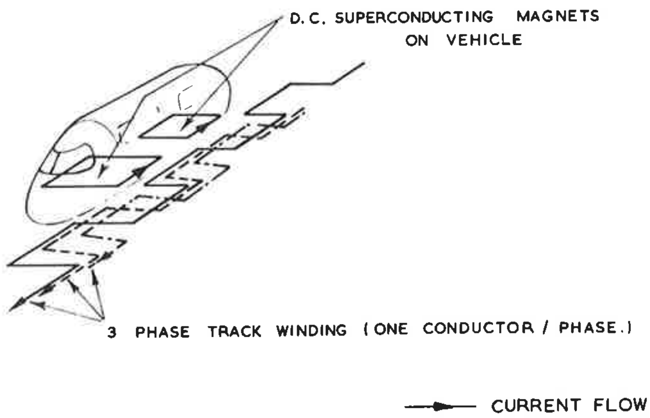

Fig. 5 Scheme of linear synchronous motor (LSM)

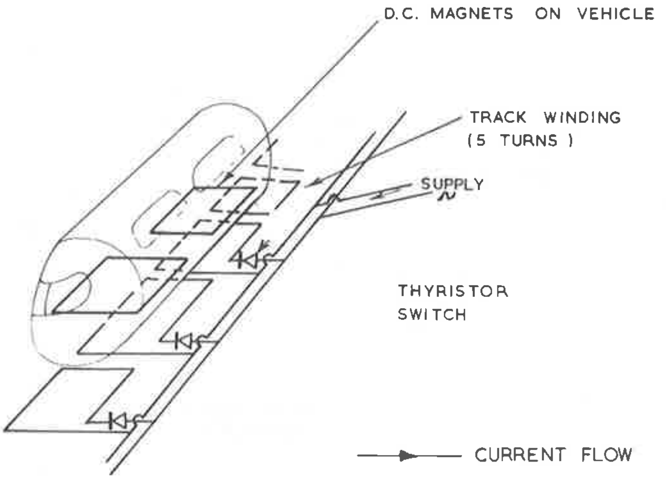

Fig. 6 Scheme of linear commutator motor (LCM)