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Some Applications of Cryogenics to High Speed Ground Transportation

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CONTENTS

SOME APPLICATIONS OF CRYOGENICS TO HIGH SPEED GROUND TRANSPORTATION

Vincent D. Arp, Alan F. Clark and Thomas M. Flynn

The current status (December 1972) of worldwide research on high speed ground transportation techniques is reviewed. Particular attention is given to studies of magnetic levitation using superconducting magnets, including comparison with alternative magnetic techniques and with air suspension systems. Superconducting levitation appears to be a strong contender in the U.S. Department of Transportation hopes to select in the late 1970's the best of the possible levitation techniques for subsequent advanced development. Cryogenic engineering research needed in support of major development of a superconducting levitated system is identified.

Key words: Levitation; magnetic suspension; materials fatigue data; refrigeration; superconducting magnets; transportation.

1. INTRODUCTION

The status of transportation in this country was summarized by Senator Vance Hartke (1972), Chairman of the Senate Surface Transportation Subcommittee: "We have regretably allowed our transportation network to grow in an unplanned, uncoordinated, fashion. We have expended too little effort in integrating - fusing - the development of our various modes of transportation. We have given too little thought and attention to how transportation might be planned to structure regional or national development in a practical manner. We have, in short, created a crisis."

The changing balance of transportation use in this country is seen directly in table 1.

Table 1. Intercity Passenger Traffic

	Lift to Drag Ratio*	1950	1955	1960	1965	1969
		Percent of intercity passenger-miles				
Private auto	20	86	89	90	89	87
Airway	20	2.0	3.2	4.3	6.3	9.8
Bus (excludes schoolbus)	20	5.2	3.6	2.5	2.6	2.2
Railroad	150	6.4	4.0	2.8	1.9	1.1
Canal Barge	1000	0.23	0.24	0.34	0.34	0.34

*An index of merit, the ratio of the weight of the vehicle to the force required to keep it moving at a given speed.

Mass ground transport, and railroads in particular, have suffered dramatic decreases in passenger miles of travel, while air travel has risen correspondingly. At the same time, auto transport has only just about held constant on a percentage basis, probably due in part to the 60 billion dollar Federal Highway Assistance Program, which is now 77% complete. Airlines have been assisted by local, state, and federal support. Rail travel, on the other hand, has fallen in the quantity of passenger train-miles available. In principle, however, rail service should be about the most efficient way of moving people and goods, as judged by the lift-to-drag ratios for various types of transport shown in figure 1 (Gudenjahn and Wipf, 1971).

It is important to note that successful operation of the high speed Tokaido Line in Japan has resulted in measurable decrease in the

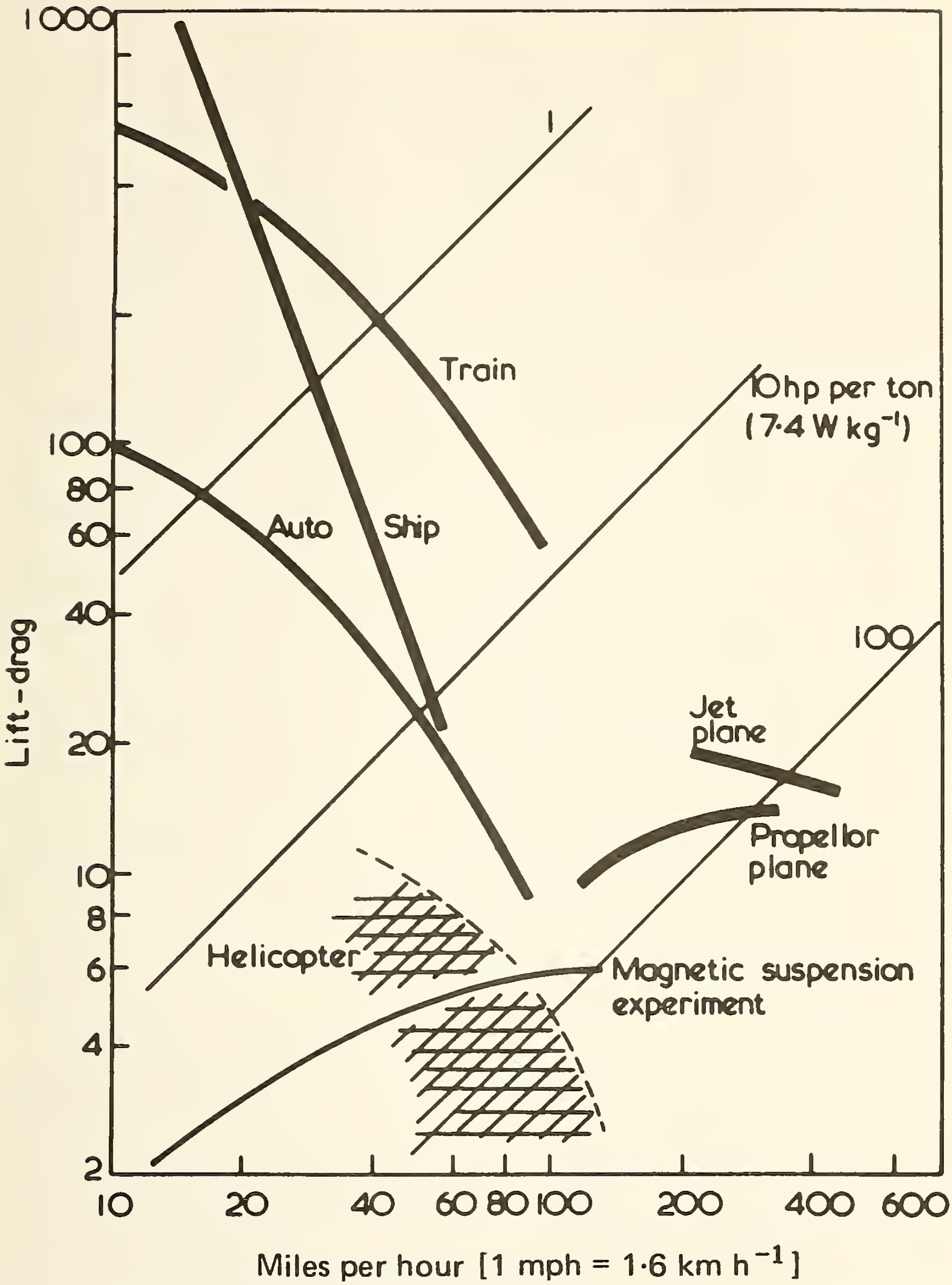

Figure 1. Lift to drag ratios as a function of speed for various types of transportation (Guderjahn and Wipf, 1971).

localized air traffic. In recognition of these and related facts, the Office of Research, Development and Demonstration (ORDD)* in the Federal Railway Administration (FRA) is investigating new methods of ground transportation, with speeds of up to 500 mph (800 km/hr) under consideration for intercity travel. However, even at speeds above about 125 to 150 mph (200 to 250 km/hr) wheels become impractical. This is the case because the suspension system, upon which the vehicle weight is concentrated, becomes incapable of absorbing or accommodating to the high frequency shocks from residual irregularities in the wheels, roadbed, or track. Accordingly, there is no question that contact between the train and the track must be eliminated by either air cushion or magnetic suspension for speeds in the range of 250 to 500 mph (400 to 800 km/hr) which are becoming a national goal for intercity ground transportation. Air cushion technology currently has a development lead, but magnetic suspension potentially has a much higher efficiency and lower adverse environmental impact.

Magnetic levitation, floating one magnet above another on the simple principle that like poles repel one another, has become really practical and dependable for very large magnets only in the last few years with the advent of workable superconductors. Superconductivity is found only at very low temperatures, and this forges an indispensable link between cryogenics and transportation. The remainder of this paper focuses primarily on the essential role of cryogenics in magnetic levitation. However, if a cryogenic system were an integral part of a train for levitation purposes, it might be expedient to exploit the benefits of cryogenics for superconducting generators and propulsion motors as well. This latter topic is touched upon but briefly.

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* formerly known as the Office of High Speed Ground Transportation (OHSGT).

2. WAYS OF LEVITATION

2.1 Air Cushion

The ORDD of the Federal Railway Administration of DoT has sponsored the development of Tracked Air Cushion Vehicles (TACVs) since 1967, with maximum speeds targeted at 300 mph (500 km/hr), limited by vehicle wind resistance. The TACV is both supported and guided in a concrete guideway by air cushions provided by on-board compressors.

Outside of the USA, England and France have major demonstration programs underway on TACV, with tentative plans for usage in airport shuttle service. The top speed reached by the French propeller-driven Aerotrain was 265 mph (430 km/hr) on January 22, 1969, but its noisy propeller creates a severe environmental impact problem. At present, TACV research enjoys a comfortable lead on magnetic vehicle levitation research. Its potential disadvantage as compared to superconducting magnetic levitation includes: (1) high track cost because of the small vehicle to roadway clearance (1 to 2 cm), and (2) the necessity for a heavy and somewhat noisy on-board mechanical power source to provide the air flow.

2.2 Magnetic Levitation/Suspension

Magnetic fields can be employed for magnetic "cushions" analogous to the way that air is used to support and guide an air cushion vehicle.

Proposals embodying this general concept date back to the early 1900's, but have been given serious attention only in the past few years as high field superconductivity has come of age. The required magnetic fields can be generated by permanent magnets, electromagnets (generally superconducting), or eddy currents in a conducting sheet or loop due to relative motion with an opposing magnet. Often, some sort of magnetic propulsion by linear electric motors is considered in addition to the magnetic levitation, and it is possible in principle to use the same magnets for both operations (Richards and Tinkham, 1972). The various possible levitation systems are outlined in table 2, with one exception: Clark (1971) has suggested that to conserve rights-of-way, the track might be built in conjunction with a superconducting power line to provide a track-based magnetic field which could levitate either a passive eddy current shield on the bottom of the vehicle or a superconducting magnet on board the vehicle. It is not certain that the possibly disparate requirements of power transmission and vehicle levitation could simultaneously be satisfied, and it appears that tests of this suggestion will have to wait for further superconducting power line development.

2.2.1 Attraction Between Electromagnets and Steel Rails

In the attraction system, a servo-controlled electromagnet is carried on the vehicle. The attraction between the electromagnet and steel guide rails provides lift and guidance. A gap of about 0.5 in (12 mm) can be maintained between magnet and rail at a power expenditure of about 1 kW per metric ton of suspended weight. This small gap has to be monitored and controlled by a very fast acting and reliable servo-system, since this suspension technique is inherently unstable.

Two attractive-rail test vehicle programs are being explored by the German Ministry of Transport. In the system developed by Krauss-Maffei (KM), the gap is held nearly constant and the unavoidable irregularities of the guide rails must be cushioned by a secondary suspension system. In the Messerschmitt-Bolkow-Blohm

Table 2. Features of Various Suspension Systems

Roadbed Magnetic Field	Vehicle Magnetic Field	
	Permanent Magnets	Electromagnets (generally superconducting)
Permanent Magnets (very expensive; difficult to keep track clean).	Small lifting force. Small vehicle clearance. Stability problems require additional control. Very low magnetic drag (Pohlgreon, 1966).	Would provide greater lift and clearance than the all permanent magnet system.
Induced Eddy Currents in Conducting Sheets or Loops.	(Same as above). (Has never been seriously proposed).	Can support high loads with high clearances at speeds above about 40 to 80 km/hr using superconducting magnets. Being studied in USA, Japan, Germany, Canada.
High Permeability Magnetic Rail.	Impossible: inherently unstable and uncontrollable attraction between the magnet and the rail.	Fail-safe operation is difficult to achieve. Two test trains are running in Germany, using conventional electromagnets. Small vehicle clearance. Very low magnetic drag. Inherently unstable but can be controlled.

(MBB) system, the gap is allowed to vary, and no secondary suspension is used. An additional difference between the two schemes is that Krauss-Maffei has dispensed with the vertical steel rail and derives both lift and guidance from each electromagnet. Schematic drawings are given in figure 2. Both of the German vehicles achieved successful demonstration in barely one year's time, and are impressive evidence that the technique is within the state-of-the-art. Because of relatively short lengths of test tracks, top speeds to date have been about 60 mph (100 km/hr). The track must be constructed and maintained to very tight tolerance in order to obtain good ride quality at 300 mph (500 km/hr). Because of the inherent instability in this type of suspension, however, the feedback-controlled levitation system must have a high degree of redundancy and protective circuitry built into it to assure safe operation in the event of every conceivable possible component failure or failures. The tests in Germany are being watched very carefully, since the system has had no major development problems to date. Whether appropriate redundancies can be built into the control system to guarantee safe daily operation is not known at this time.

2.2.2 Repulsion Between Permanent Magnets

The recent development of rare-earth cobalt permanent magnets possessing high intrinsic coercivity gives new impetus to the old idea of using the repulsion between like poles to support and guide a vehicle. This technique is by now quite well known, having been demonstrated years ago by Westinghouse in a single-passenger vehicle (Kerr and Lynn, 1961) and lately by Hitachi in the small-scale magnetically suspended train displayed at EXPO 70. Pre-rare-earth cobalt materials provided gaps of less than a centimeter and were subject to self-demagnetization. The advantages of permanent magnets for suspension

MAGNETIC SUSPENSION - Attractive

THE ELECTROMAGNETS ON THE TRAIN ARE ATTRACTED TO AN IRON PLATE IN THE GUIDEWAY

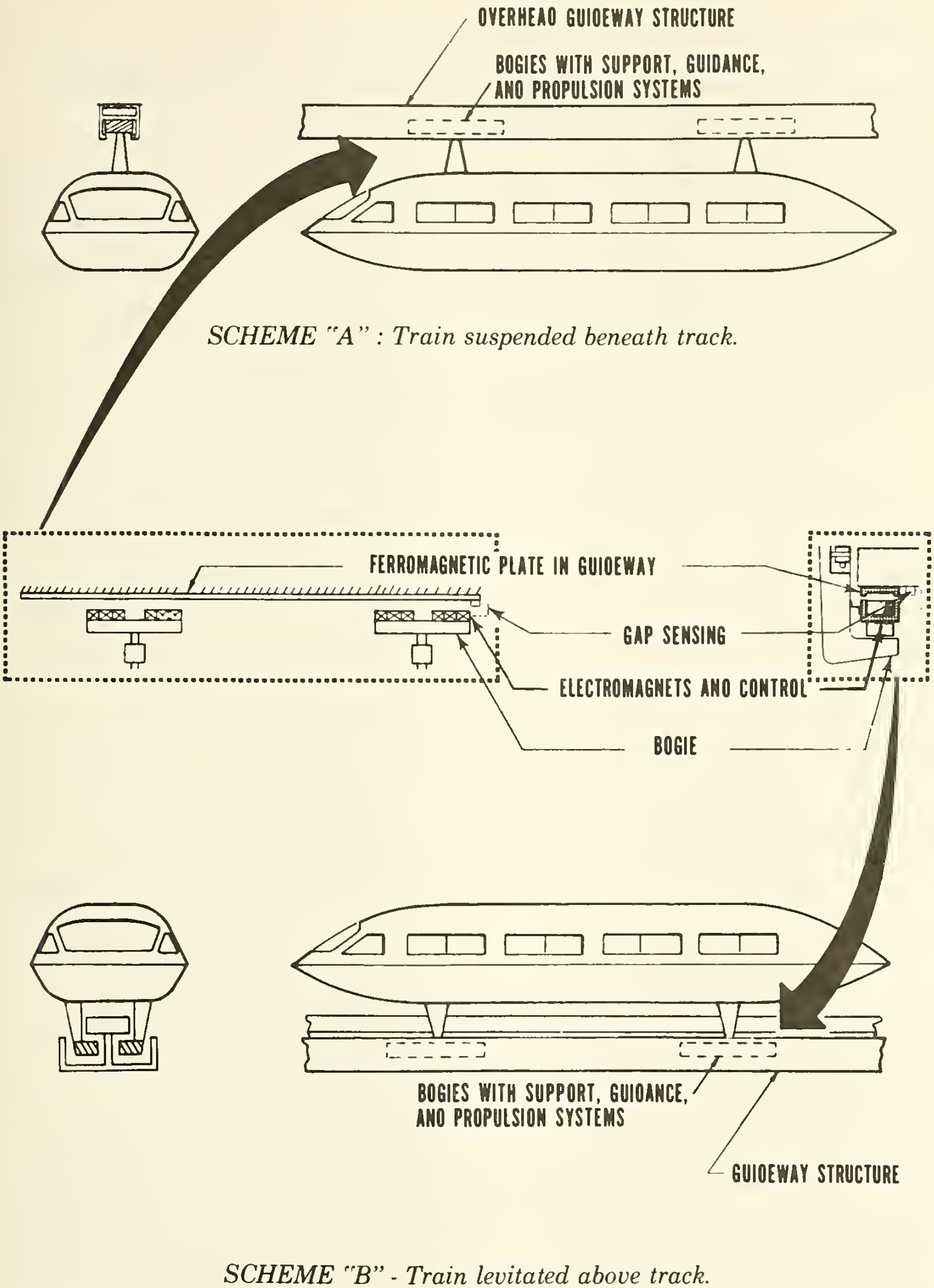

Figure 2. Schematic diagram of two possible attractive-suspension systems.

are that there is no induced drag and no power is required for levitation. The cost of the guideway is probably the most overwhelming drawback. Estimates range from \$4.5 to \$9 million per kilometer, and this is based on a very optimistic projection of ultimate RCo_5 magnet costs of \$33/kgm, or little more than the cost of the raw materials. Finally, the problem of maintaining a clean track, smooth and free of magnetic litter, would be significant.

2.2.3 Repulsion Between a Superconducting Train Magnet and Conductors in the Guideway

The first suggestion for vehicle levitation with superconducting magnets came from Powell in 1963, subsequently improved and made more detailed by he and Danby in 1966. Later they developed the "null flux" suspension idea. The history of this development, along with a concise technical summary, is presented in their 1971 paper.

As superconducting magnets began to prove themselves in high energy physics applications, more attention was given to this magnetic levitation. Consideration was given to magnetic suspension for a high speed rocket test sled and other studies appeared by Guderjahn and Wipf (1969) at Atomics International, and Coffey, Barbee, and Chilton (1969) at the Stanford Research Institute (SRI). Guderjahn and Wipf (1971) and Powell and Danby (1971) have since published excellent reviews. Richards and Tinkham (1972) have summarized technical features of magnetic lift, drag, and propulsion systems.

The essence of the superconductive repulsion system is the use of superconducting magnets in the vehicle which induce eddy currents in the aluminum guide-way when the vehicle is moving. These guide-way currents react with the moving magnetic field in the vehicle to produce a repulsive supporting force. Guidance is obtained by the same techniques and by designing the aluminum guideways to produce lateral forces on the vehicle. It may prove possible to shape the guideway in such a way that the same superconducting magnet in the vehicle can be used for both suspension and guidance. Two schemes are shown in figure 3.

An important feature of the eddy-current-track levitation systems is that the magnetic drag rises to a peak in the low speed region, nominally at about 50 km/hr and then decreases, being proportional to $(\text{velocity})^{-1/2}$ in the high velocity limit. Magnetic lift, on the other hand, rises to a maximum somewhere in this same speed range and then remains constant as the speed increases. Since operating costs for a given cargo weight will tend to scale inversely with lift to drag ratio, there is considerable interest in providing very high speed magnetic levitation systems. Aerodynamic drag is proportional to $(\text{velocity})^2$ and becomes comparable with magnetic drag somewhere in the neighborhood of 200 km/hr. This leads to the suggestion that perhaps the train should run in an evacuated or partially evacuated tunnel to reduce aerodynamic drag and take advantage of the high lift-to-drag ratios obtainable at high speeds.

The optimum configuration of the eddy-current track structure remains to be determined. Powell and Danby (1966) have suggested a "null flux" scheme giving lift to drag ratios in the range 100 to 500 and allowing reasonable clearance ($\approx$20 cm) between the vehicle and track structure, but requiring a fairly complex track structure and giving a rather stiff suspension. Kolm (1972) favors a much simpler, trough-like continuous-sheet track giving a suspension much less sensitive to minor track irregularities, but lift-to-drag ratios not

MAGNETIC SUSPENSION - Repulsive

THE SUPERCONDUCTING MAGNETS ABOARD THE MOVING TRAIN
ARE REPELLED BY EDDY-CURRENTS IN THE TRACK CIRCUITS.

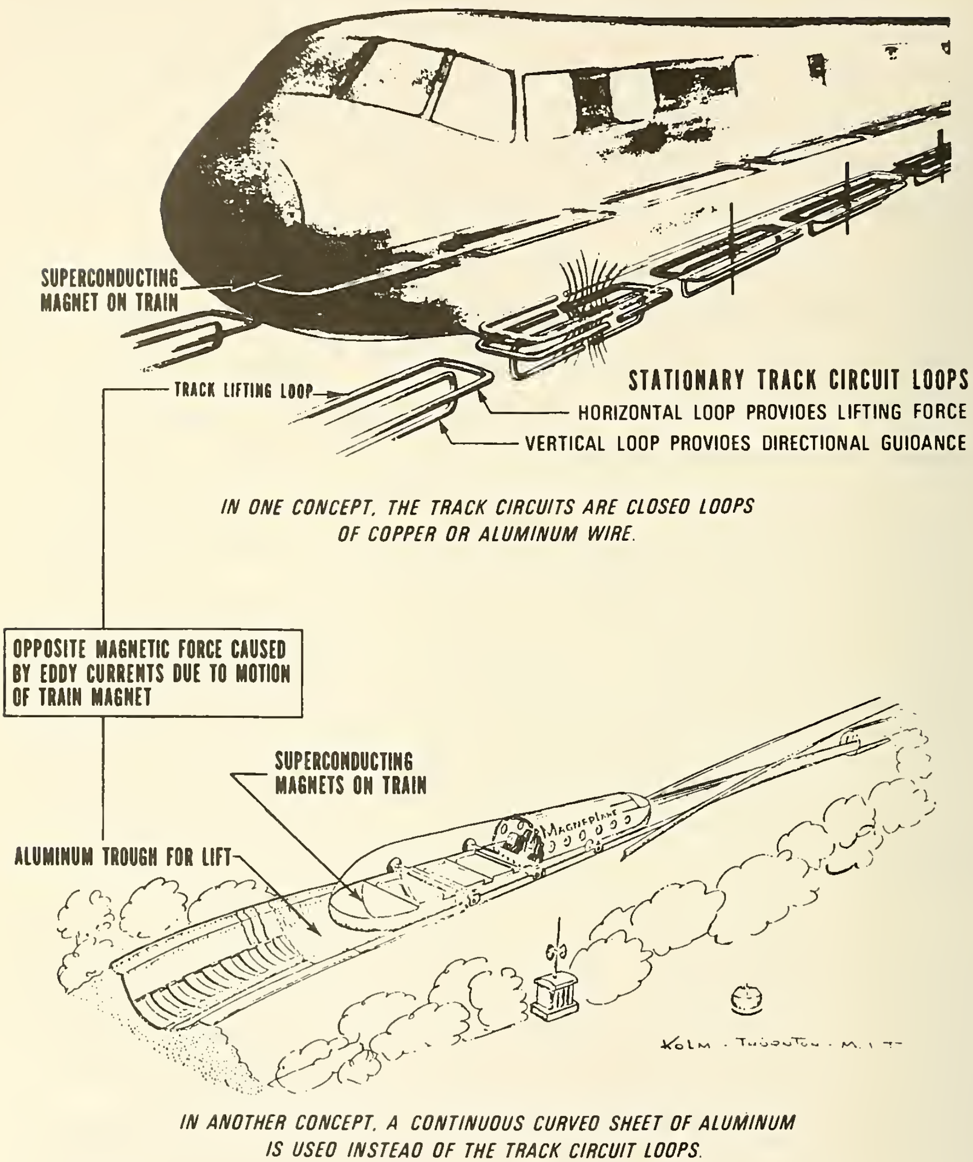

Figure 3. Schematic diagram of two possible repulsive-suspension systems employing superconducting magnets.

much more than 10 or 20. The Japanese are experimenting with a "ladder-track" which gives lift-to-drag ratios comparable with the sheet track. Guderjahn and Wipf (1971) suggest that a hybrid system employing some iron in the eddy current track may be advantageous. The lift-to-drag ratios obtainable with the null-flux system at high speed in an evacuated tunnel would be truly remarkable: Powell and Danby estimate that such a vehicle with a lift-to-drag ratio of 500 would coast (without propulsive power) 640 kilometers while its speed dropped from 960 to 800 km/hr. This is equal to the distance from Washington, D.C. to Boston, and more than the length of the Tokaido high speed rail line. One can conceive of using this fact to minimize the propulsive requirements of an active-track system. A further advantage of high lift-to-drag ratios comes from the reduced total energy requirement for transportation on a national scale--an important factor. Selection of an optimum track configuration depends on a wide number of system and operational parameters.

Of all the proposals and work on superconducting levitation systems, the superconducting coils themselves receive relatively little attention since their use seems straightforward. The ambient magnetic fields experienced by the magnet windings will be in the neighborhood of 3 T (30 kilogauss), somewhat lower than those generally met in other superconducting magnet applications. Current densities in the coils are in the range 2×10^4 to 5×10^4 A/cm^2, higher than standard practice for high field magnets, but consistent with the smaller ambient fields expected for this application. The magnets would be operated in the persistent current mode, so that the levitation would not fail if an external power supply were to fail; such persistent mode operation is also within the state of the art. In order to hold the weight of the magnet to a reasonably low value, the modern dynamically-stabilized, twisted multifilament NbTi conductors without too much copper would probably be used. If track irregularities should cause too high an a.c. ripple at the magnet, these could be shielded out by an eddy current shield so that operational losses would be low.

A concise summary of the present situation comes from Dr. John Harding (1971) of the ORDD: "All aspects of the repulsive superconducting suspension have by now been evaluated in sufficient depth that it can be stated that the system is technically feasible. It cannot be faulted on any single factor, such as cryogenics, superconductivity, or magnetic shielding. If the superconducting magnetic suspension is abandoned, it will have to be because of a combination of factors and not any particular shortcoming."

3. STATE-OF-THE-ART IN THE U.S. OF MAGNETIC SUSPENSION

The U.S. Department of Transportation has a strong, long range interest in magnetic levitation through its Office of Research, Development and Demonstration (ORDD). In early 1971, Ford and SRI were the successful bidders for an ORDD contract oriented to determine whether magnetic levitation is a practical alternative to wheels or air cushions for suspending and guiding high speed ground vehicles. These companies are contributing funds approximately matching those of ORDD to their projects for a total effort of about one-half million dollars. Ten different bids for these contracts were received by ORDD.

These contracts at Ford and SRI were renewed in March 1972 at about the same funding rate. In 1972, also, Kolm and Thornton of MIT recieved funding from NSF for studies of what they call the Magnaplane. This is a rather specific system intending to utilize superconducting magnets moving above a sheet aluminum track and linear synchronous propulsion.

A small private company was formed about a year ago to try to build a small full-scale system, but it has given up this approach at this time.

4. FOREIGN PROGRAM PLANS

The ORDD maintains close contacts with these various national high speed ground transportation programs, and there is every reason to believe that technical information exchange is unimpeded.

Work is going on in Japan, Germany, and Canada. The Japanese effort is the largest, amounting to $10 million per year, most of which will be for construction and operation of a 400 meter superconducting magnetic levitation test track. They had a small (four passenger size) vehicle in operation on the track in October of this year (1972), levitated by superconducting magnets running above discreet coils in the track. They are considering primarily active track propulsion, which avoids the problem of pickup of electrical power by the fast moving vehicle. Future tests of linear synchronous propulsion are anticipated as an alternative to the linear induction motor.

In Japan, the decision is of some urgency inasmuch as capacity on the New Tokaido Line (NTL) between Tokyo and Osaka is expected to reach saturation by 1980. In 1970, 85 million intercity passengers were carried on the NTL express trains at a profit of over $300 million. During the busiest hour, nine NTL expresses with a combined capacity of 10,460 passengers leave Tokyo for Osaka. Rather than expand the present system for additional capacity, the Japanese National Railways (JNR) is directing its research toward magnetically levitated trains which can convey passengers from Tokyo to Osaka in just over one hour.

The German Ministry of Transport is funding both attractive and repulsive magnetic suspension vehicle programs. The attractive rail program, utilizing conventional electromagnets and a very small magnet-to-rail clearance, has produced two test vehicles, one at Messerschmitt-Bolkow Blohm (MBB) and the other at Krauss-Maffei (KM). Similar conceptually, these vehicles differ in the techniques chosen to provide guidance, stability, and vibration isolation of the passenger compartment. The repulsive suspension program, utilizing superconducting magnets, has been funded more recently at Seimans, and has not yet produced any models comparable with the MBB and KM vehicles.

The Canadian Department of Transport has just initiated a study of superconductive systems for high speed ground transportation. The activity will be conducted at the Institute for Guided Ground Transport at Queens University in Kingston, Ontario. The Canadian program will concentrate on superconducting magnet design, the cryogenics problems, and the development of a linear synchronous motor concept deriving thrust from switched powered coils in the guideway.

Tests and decisions made outside of the USA will undoubtedly have an influence over our own decisions scheduled in the late 1970's. The Japanese test track studies will undoubtedly be an important input to the U.S. decision-making process. The Japanese are currently about two years ahead of the U.S. towards the goal of a working system, though the U.S. appears to have a broader base of studies of system alternatives. The Japanese are putting larger sums of money into their studies than the U.S., and they hope to have a superconducting levitated train running between Tokyo and Osaka by 1980.

5. PROPULSION

Possible propulsion systems to be used with magnetic levitation are summarized in table 3. Only the linear electric motors are being seriously considered by any of major world-wide studies at this time, though the aerodynamic propulsion systems have been mentioned as possibilities. The linear electric motors have the great advantage of being quiet and pollution-free, and capable of operation in an evacuated tunnel. Vehicle-mounted superconducting coils for a linear induction motor could conceivable provide both propulsion and lift, even at zero speed. This can be done through the use of a.c. powered superconducting coils (Richards and Tinkham, 1970), or rotating d.c. coils providing a magnetic paddle wheel or propeller effect (Borcherts, 1972). Alternating current losses in superconducting coils would have to be decreased by a dramatic factor before the a.c. system becomes feasible. Linear synchronous propulsion requires only that power be fed into stationary coils in track in the immediate vicinity of the vehicle, such that the field of these stationary coils pushes on the superconducting magnets in the vehicle. Power must be supplied to each succeeding track coil in synchronism with the vehicle movement, and variable frequency power supplies will have to be developed to make this scheme practicable.

6. SOME CRYOGENIC TECHNICAL PROBLEMS

Cryogenic technology will be essential to the superconducting levitation system. This technology is well in hand for the purposes of laboratory and test model development. However, a full-scale working transportation system will demand a degree of reliability and serviceability of the cryogenic components which is beyond present standards,

Table 3. Propulsion System

Method	Advantage	Disadvantage
Aerodynamic: propellors or jet engines.	Requires no development; works independently of vehicle clearance.	Noise and fumes: very high vehicle weight since fuel must be carried. Could not be used in evacuated tunnel.
Linear induction motor in the vehicle.	Does not require variable frequency input power; allows easy control of starting and stopping (not true, however, if used also for levitation: Richards and Tinkham, 1970) compact propulsion unit. Works in vacuum if necessary; no noise.	Requires small vehicle to track clearance (1-2 cm); transmission of power from a line to the high speed vehicle is very difficult.
Linear synchronous motor in the track.	Allows high vehicle clearance (20 cm), and lower vehicle weight; appears to permit safe operation of closely spaced vehicles; no power transmission to the vehicle is required. Works in vacuum if necessary; no noise.	Requires variable frequency power services and complicated controls to activate that section of track which the vehicle occupies, and make a smooth transition to the next section.
Aerodynamic: partially evacuated tunnel ahead of the vehicle.	Power source can be conveniently separated from the vehicle or track; may be required in any case for speeds above 500 km/hr.	Low efficiency: difficult to control precisely or with multiple units; requires low vehicle to tunnel clearance. Requires alternate technique for starting from an unevacuated station.
Impulse-jet: track-based air jets are activated as the train passes. (Mouritzen, 1972)	Convenient location of conventional power sources (turbo-compressors) at intervals along the track. Can utilize schemes of energy storage in compressed air. High vehicle-to-track clearance.	Could not be used in an evacuated tunnel. Noisy, though not as much so as propellers or jet engines. Low efficiency, 20-25%.

and must be considered carefully. There is no reason to believe that the scale-up in technology cannot be done successfully, but there are areas where additional knowledge must be developed in order to do the job with assurance. These are discussed here briefly.

6.1 Helium Refrigeration

Maintenance of the superconducting magnet at 4 K for weeks or months on end will be a necessity for superconducting levitation. Some suggest that a liquid helium supply be simply replenished from a central storage reservior at convenient intervals, much as one now puts ice on a train. However, the drain on the earth's helium resource would be very large if the boil-off helium were not collected, assuming a large national train and track system. It is likely that on-board refrigeration will be superior from an operational standpoint. However, refrigerator reliability would have to be extended over that available at this time. This would call for a substantial effort, especially to increase the mean time between failure of room-temperature refrigeration compressors. The Refrigerator Sub-Task of the DoC-NBS Presidential Initiative in Cryogenics for the Electrical Industry has as its goals increasing refrigerator reliability and optimizing refrigerator efficiency. Thus, this technology is directly transferable from the DoC program.

6.2 Materials

The availability of reliable superconducting coils, which was initially thought to be the major drawback of the induced levitation schemes, is now considered to be well within the present state-of-the-art. Nonetheless, there are unknown problems of building, supporting, and maintaining the superconducting coils in daily operation. For instance, the forces on the superconducting magnet at 4 K must be transmitted to the vehicle by some sort of solid connection which must not increase the helium heat load to unworkably high values. Composite materials, such as the fiber reinforced plastics, seem to excel for this application, and in fact have been suggested in one form or another by all the superconducting levitation papers which have touched this topic.

A major problem which this brings up is the almost total lack of fatigue studies on materials of all kinds at low temperatures, as well as more general lack of properties data: expansion coefficients (generally anisotropic with oriented fibers), complete stress-strain data as a function of temperature, sensitivity to notches or cracks, aging effects for extended service, thermal conductivity, etc. Completely unknown at this time is the effect of fatigue upon the electromagnetic properties of the system. These material problems are congruent with those of the DoC-NBS program on superconducting generators.

7. FUTURE DEVELOPMENT

The late 1970's appear to be the U.S. target date for selection of the optimum levitated-vehicle system for major development in this country. Tests and evaluations of all potential systems - TACV, attractive rail, repulsive superconducting, and possibly even advanced wheel concepts - should be complete by then. No one system has a clear advantage at this time, in that all except the wheel appear to be able to provide vehicle transportation at speeds up to 300 mph (500 km/hr) without relying on yet-to-come technological breakthroughs. It appears most probable that selection will be based upon combinations of system parameters, using criteria which are not clearly defined and ranked at present. Examples of such criteria include cost, safety, ease of switching, control of close-spaced vehicles, the need for speed as compared to the need for convenient stop and start service operation, possible extension to speeds higher than 300 mph (500 km/hr), on-board vehicle power requirements, liquid helium service requirements, freedom from noise adjacent to the track, freedom from fuel combustion products along the track, allowable development time scale, availability of large blocks of electric power, etc.

In these days of concern over environmental problems, it appears that the magnetic levitation systems may be favored for being more pollution-free than the TACVs. Some DoT engineers believe that the superconducting system could prove superior to the attractive rail system even if low-cost reliable control systems are developed for the servo-controlled electromagnet system. The major cost in a total system will be in the production, installation and maintenance of the guideway, they believe. Because the superconducting system works with a larger gap between vehicle and guideway, it would allow for lower costs in manufacture, installation and maintenance.

The need for advanced forms of ground transportation seems compelling as evidenced by government-sponsored research programs in four major countries including ours. The U.S., which may make the largest use of such a system in the long run, may be contributing a disproportionately small share of the research and development cost for magnetic levitation, about $0.5 million out of a world wide spending of over $10 million per year.

A high speed ground transportation system represents a gigantic capital investment. The 515 km New Tokaido Line, a high speed conventional rail link between Tokyo and Osaka, had cost about $1.1 billion when service was initiated in October 1964. The estimated cost of a proposed Tracked Air Cushion Vehicle system offering 2.3 hour travel time for the 650 miles (400 km) between Washington and Boston is $2.7 billion.

The degree of interest, as measured by the international scale of the research on the problem to date, suggests strongly that a positive decision to proceed with a full scale program will be made in the U. S. in the late 1970's, when comparative merits of the alternative systems will have been evaluated. Superconducting levitated vehicles are in contention, but lagging over other levitation systems in the degree of development work to date. The chances that a superconducting levitation system will be selected and developed in the U. S. are impossible to assess, being dependent on complex technical, economic, and social forces, but it is not unreasonable to believe that they are in the 10% to 50% range.

A decision to proceed with a full-scale superconducting levitation system would have major impact in the cryogenics industry. At the present time, annual sales in this diverse industry are about $1.5 billion, of which only a very small fraction is derived from superconducting and liquid helium temperature components. In order to service a large transportation system with many superconducting levitated vehicles running continuously over a wide geographical area, it is not unreasonable to believe that annual sales of superconducting components and support equipment could reach the neighborhood of several hundred million dollars. It would be appropriate to tackle the major developmental research in the cryogenics program at an early stage.

8. REFERENCES

Borcherts, R. H., "Mathematical Analysis of 'Permanent' Magnet Suspension Systems," J. Appl. Phys. 42, 1528 (1971).

Borcherts, R. H., to be published (1972).

Clark, A. F., "Combination of power transmission line and an active track for a magnetically suspended high speed train," to appear in J. Appl. Phys. (Aug 1972).

Coffey, H. T., Barbee, T. W., and Chilton, F., "Magnetic suspension and guidance of high speed vehicles," Conf. on Low Temperatures and Electric Power, IIR Annexe, p. 311 (1969).

The Economist, p. 55 (May 8, 1971).

Guderjahn, C. A., and Wipf, S. L., "Magnetic Suspension and guidance for high speed trains by means of superconducting magnets and eddy currents," Adv. in Cryogenic Eng. 15 (1969).

Guderjahn, C. A., and Wipf, S. L., "Magnetically levitated transportation," Cryogenics 11, 171 (1971).

Harding, J. T., "Progress in magnetic suspension applied to high speed ground transportation," presented at the 17th Annual Conf. on Magnetism and Magnetic Materials, Chicago, Illinois (Nov 1971).

Hartke, Senator Vance, "Replacing our hodge-podge transportation," reported in Astronautics & Aeronautics, 10, 52 (Feb 1972).

Kerr, C., and Lynn, C. "Roller road", Westinghouse Engineer (Mar 1961).

Mouritzen, G., "Impulse-jet transportation system," Mech. Eng., p. 12 (Feb 1972).

Pohlgreen, G. R., "Guided land transport," Proc. Inst. Mech. Engrs. 181, 145 (1966).

Powell, J. R., "The magnetic road: a new form of transport," paper 63-RR4, ASME Railroad Conference (Apr 1963).

Powell, J. R., and Danby, G. T., "High speed transportation by magnetically suspended trains," ASME paper 66-WA/RR-5, Winter Annual Meeting of ASME, New York (1966), also published in Mech. Eng. 89, 30 (1967).

Powell, J. R., and Danby, G. T., "Magnetic suspension for levitated track vehicles," Cryogenics 11, 192 (1971).

Richards, P. L., and Tinkham, M., "Magnetic suspension and propulsion systems for high speed transportation," J. Appl. Phys. 43, 2680 (1972).

Strobridge, T. R., "Refrigeration for superconducting and cryogenic systems," IEEE Trans. Nucl. Sci. NS-16 (Proc. 1969 Particle Accelerator Conf., Washington D. C. (Mar 1969).

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The current status (December 1972) of worldwide research on high speed ground transportation techniques is reviewed. Particular attention is given to studies of magnetic levitation using superconducting magnets, including comparison with alternative magnetic techniques and with air suspension systems. Superconducting levitation appears to be a strong contender in the U.S. Department of Transportation hopes to select in the late 1970's the best of the possible levitation techniques for subsequent advanced development. Cryogenic engineering research needed in support of major development of a superconducting levitated system is identified.

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