Maglev: A New Approach

The Inductrack promises a safer, cheaper system for magnetically levitating trains. The same technology can also be used to launch rockets.

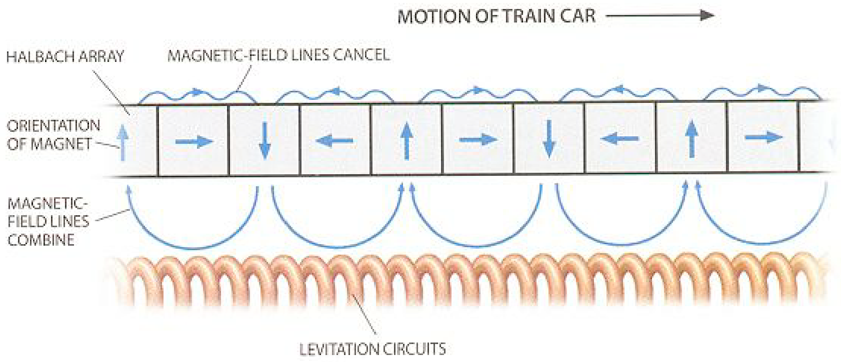
by Dr. Richard F. Post., Inventor of Inductrack Passive Magnetic Levitation, January 2000, Scientific America

The story "Prince Ahmed and the Fairy," one of the classic tales in The Thousand and One Nights, tells of a prince who flew from place to place on a magic carpet, supported by invisible forces. The modem version of the magic carpet is the magnetically levitated train, or maglev, which can travel faster and more efficiently than ordinary trains because it rides on air instead of steel rails. The concept took off in the late 1960s, when Gordon T. Danby and James R. Powell of Brookhaven National Laboratory proposed using superconducting coils to produce the magnetic fields that would levitate the trains. In the 1970s and 1980s demonstration maglevs were built in Germany and Japan. Yet despite the appeal of the technology, which promises smooth-as-silk train rides at speeds up to 500 kilometers per hour, no full-scale commercially operating maglev system has been constructed.

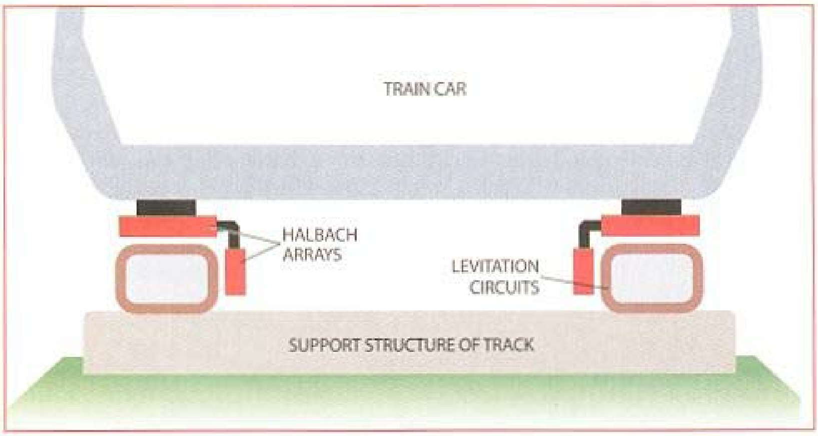
Why is this so? For one, the maglevs that have been demonstrated so far are much more expensive and complex than conventional railways. The Japanese system, for example, requires costly cryogenic equipment on the train cars to cool the superconducting coils, which must be kept below 5 Kelvin to operate efficiently. The German maglev uses conventional electromagnets rather than superconducting ones, but the system is inherently unstable because it is based on magnetic attraction rather than repulsion. Each train car must be equipped with sensors and feedback circuits to maintain the separation between the car's electromagnets and the track. What is more, neither system is fail-safe. A breakdown of the magnet control circuits or power systems could lead to a sudden loss of levitation while the train is moving. Careful design can minimize the hazards of such a failure but not without a further increase in cost and complexity.

All Aboard the Inductrack

At Lawrence Livermore National Laboratory, we are exploring a different approach to magnetic levitation, one that could be simpler and less expensive to implement. The idea arose from earlier research on an electromechanical battery for cars and trucks. Such a battery stores kinetic energy using a flywheel, which requires nearly frictionless magnetic bearings to minimize energy loss. The bearings developed at Livermore employed cylindrical magnet arrays to stabilize the levitation of the flywheel. We soon realized that if we unrolled these stabilizers, we would have the basis for a new type of maglev.



PERMANENT MAGNETS under an Inductrack train car are arranged in a Halbach array (above) so that the magnetic-field lines reinforce one another below the array but cancel one another out above it. When moving, the magnets induce currents in the track's circuits, which produce an electromagnetic field that repels the array, thus levitating the train car. Halbach arrays can also provide lateral stability if they are deployed alongside the track's circuits (below).



Called the Inductrack, the new system is passive in that it uses no superconducting magnets or powered electromagnets. Instead it uses permanent room-temperature magnets, similar to the familiar bar magnet, only more powerful. On the underside of each train car is a flat, rectangular array of magnetic bars called a Halbach array. (It is named after its inventor, Klaus Halbach, a retired Lawrence Berkeley National Laboratory physicist.) The bars are arranged in a special pattern, so that the magnetic orientation of each bar is at right angles to the orientations of the adjacent bars [see top illustration on this page]. When the bars are placed in this configuration, the magnetic-field lines combine to produce a very strong field below the array. Above the array, the field lines cancel one another out.

The second critical element is the track, which is embedded with closely packed coils of insulated wire. Each coil is a closed circuit, resembling a rectangular window frame. The Inductrack, as its name suggests, produces levitating force by inducing electric currents in the track. Moving a permanent magnet near a loop of wire will cause a current to flow in the wire, as English physicist Michael Faraday discovered in 1831. When the Inductrack's train cars move forward, the magnets in the Halbach arrays induce currents in the track's coils, which in turn generate an electromagnetic field that repels the arrays. As long as the train is moving above a low critical speed of a few kilometers per hour-a bit faster than walking speed-the Halbach arrays will be levitated a few centimeters above the track's surface.

The magnetic field acts much like a compressed spring: the levitating force increases exponentially as the separation between the track and the train car decreases. This property makes the Inductrack inherently stable-it can easily adjust to an increasing load or to acceleration forces from rounding a bend in the track. Thus, the system would not require control circuits to maintain the levitation of the train cars. All the train would need is some source of drive power to accelerate it.

In the past, engineers believed permanent magnets could not be used in maglev systems, because they would yield too little levitating force relative to their weight. The Inductrack's combination of Halbach arrays and closely packed track coils, however, results in levitation forces approaching the theoretical maximum force per unit area that can be exerted by permanent magnets. Calculations show that by using high-field alloys-neodymium-iron-boron, for example-it is possible to achieve levitating forces on the order of 40 metric tons per square meter with magnet arrays that weigh as little as 800 kilograms per square meter, or one fiftieth of the weight levitated.

In a full-scale Inductrack system, the track would consist of two rows of tightly packed rectangular coils, each corresponding to one of the steel rails in a conventional track. The main levitating Halbach arrays would be placed on the underside of the train car so that they would run just above the rows of coils [see the second illustration on this page]. Smaller Halbach arrays could be deployed alongside the rows of coils to provide lateral stability for the train car. Such a configuration would somewhat resemble its counterpart in an ordinary train-namely, a flanged wheel rolling on a steel rail. In the Inductrack the role of the "flanges" is played by the small side-mounted Halbach arrays, whereas the role of the "wheel" is fulfilled by the main levitating arrays.

The Issue of Efficiency

A primary concern for any maglev is the efficiency of the levitating system. Unlike the German and Japanese maglevs, the Inductrack requires no power to produce its magnetic field, because it uses permanent magnets. Therefore, this particular source of inefficiency is not an issue. To levitate the train car, though, currents must be induced in the track's circuits, and electrical resistance in the circuits will dissipate some of the power, converting it to heat. This power loss, coming as it does from the motion of the train relative to the track, will result in drag forces. These drag forces are the magnetic counterpart of the frictional drag associated with wheels and bearings in a conventional train. In the Inductrack, the magnetic drag forces vary inversely with the train's velocity, becoming very low at typical maglev speeds (250 to 500 kilometers per hour). These drag forces thus behave in an opposite way to wheel-frictional drag forces or aerodynamic drag, both of which increase with rising speed.

In aircraft, a common way to gauge the performance of an airfoil is to calculate its lift-to-drag (L/D) ratio-the ratio of its lifting power to its aerodynamic drag. At typical flying speeds, the L/D ratio of the wing of a jet aircraft is about 25 to 1 and does not vary much with velocity. In the Inductrack system the corresponding ratio relates magnetic lift-the levitating force-to magnetic drag. We were able to find a formula for the Inductrack's L/D ratio by performing a detailed theoretical analysis of the system. Much help came from my coworker at the Livermore laboratory, Dmitri D. Ryutov, formerly at the Budker Institute of Nuclear Physics in Novosibirsk, Russia. Ryutov is recognized internationally for his contributions to the theory of magnetically confined plasmas for fusion, and he applied techniques from that discipline to his analysis of the Inductrack.

We found that the Inductrack's L/D ratio is directly proportional to the speed of the moving Halbach arrays. When the train is at rest, there is obviously no levitating force, and the L/D ratio is zero. But as the train begins to move, the levitating force rises quickly, reaching half its maximum value at a speed between two and five kilometers per hour. We call this the transition speed-at this velocity, the magnetic lift and drag are equal. At twice the transition speed, the levitating force reaches 80 percent of its maximum value and the L/D ratio rises to about five. Thus, we see that the Inductrack's levitation becomes effective when the train is moving very slowly. If the cars are equipped with auxiliary wheels, the train can run on rails until it reaches the transition speed, at which point it would begin levitating. Furthermore, the system's efficiency continues to improve as the train gathers speed-the L/D ratio can reach values as high as 200 to 1 at a velocity of 500 kilometers per hour. And if the drive power suddenly fails, the train cars would remain levitated while slowing down to a very low speed, at which point the cars would come to rest on their auxiliary wheels.

Another way to evaluate the efficiency of the Inductrack maglev system is to measure the power loss from magnetic drag and compare it with other power losses. With a 50,000-kilogram train car running at 500 kilometers per hour, about 300 to 600 kilowatts of power would be dissipated in the track's levitating circuits. In contrast, the aerodynamic drag on the train car at that speed would cause a power loss of nearly 10 megawatts. In other words, the power needed to keep the train car levitated is less than one tenth of that required to overcome wind resistance.

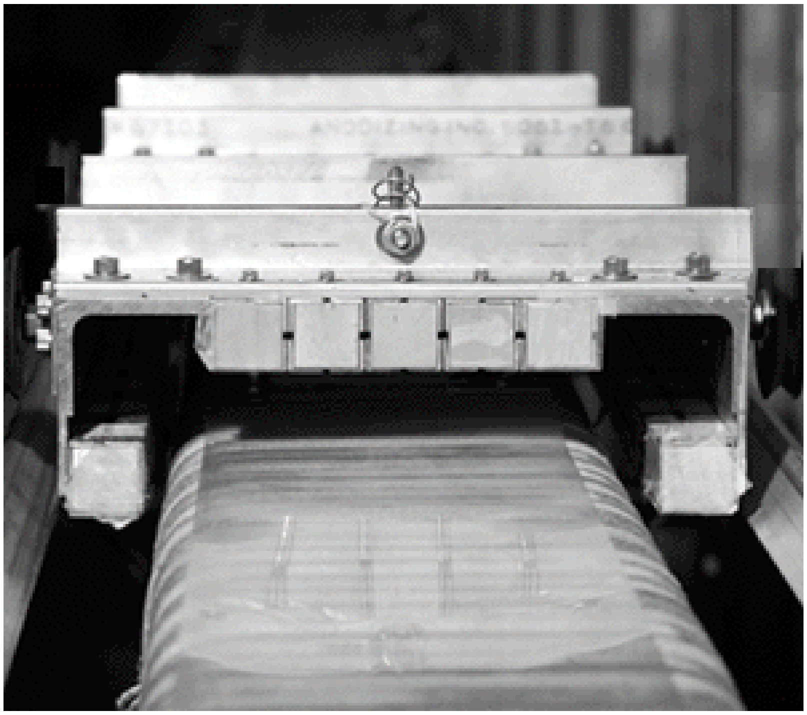
Drive Systems for the Inductrack

Thus far I have described only one type of Inductrack circuit-namely, a row of rectangular coils. The track, however, might take many other forms, depending on the performance that is desired. For example, the track could consist of stacks of thin sheets of aluminum, with insulating films placed between the layers. When the Halbach arrays move above these stacks, the magnetic fields would induce electric currents in the aluminum sheets. A series of parallel slots would be etched into each sheet to create the optimal path for the electrons, minimizing eddy currents that would increase power losses. Such a track would exert a greater levitating force than a row of rectangular coils would, and it might also be cheaper to manufacture.

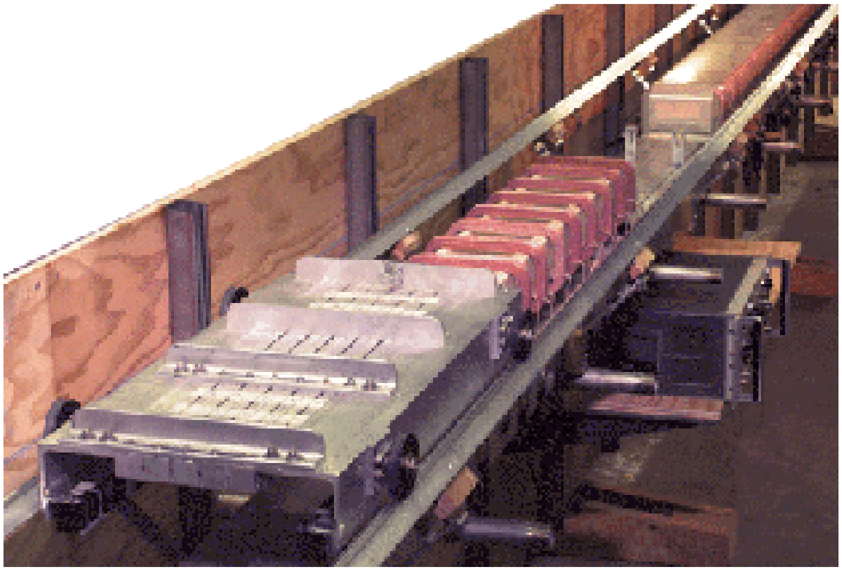
Another alternative is to increase the track's efficiency through a method called inductive loading. It can be applied to the rectangular circuits by placing tiles of ferrite-a magnetic ceramic containing iron oxide-around the bottom section of each coil. This change would decrease the current induced in the coils by the Halbach arrays and hence cut the power loss caused by electrical resistance. Because the magnetic drag would be lower, the magnetic lift would overcome it more easily, and the train would begin levitating at a lower transition speed. Inductive loading involves a trade-off, though: it would reduce the system's maximum levitating force below the 40 metric tons per square meter that is possible with the simpler track construction.

One of the virtues of the Inductrack is that it could accommodate a wide variety of drive systems for the trains. If the track can be hooked up to a power grid, the train cars could be propelled by "drive coils" interspersed among the track's levitating circuits. Supplied with current from the grid, the drive coils would generate electromagnetic fields that would interact with the fields from the Halbach arrays. Pulsing the drive coils in synchronization with the train's motion will result in accelerating or decelerating forces on the train cars. In situations where electrification of the rail line could be too expensive-for example, in rural areas between distant cities the maglev train could be equipped with a shrouded propeller driven by a gas turbine. Because wind resistance would be the only significant drag force on the train, a single propeller would be sufficient to accelerate the maglev to high speeds.

WORKING MODEL of the Inductrack constructed at Lawrence Livermore National Laboratory to test the system's performance. The first section of the 20-meter-long track contained electrically powered drive circuits to accelerate a 22-kilogram cart (below). Once set in motion, the Halbach arrays on the underside of the cart allowed it to coast over the 1,000 levitating coils in the second section of the track (inset).



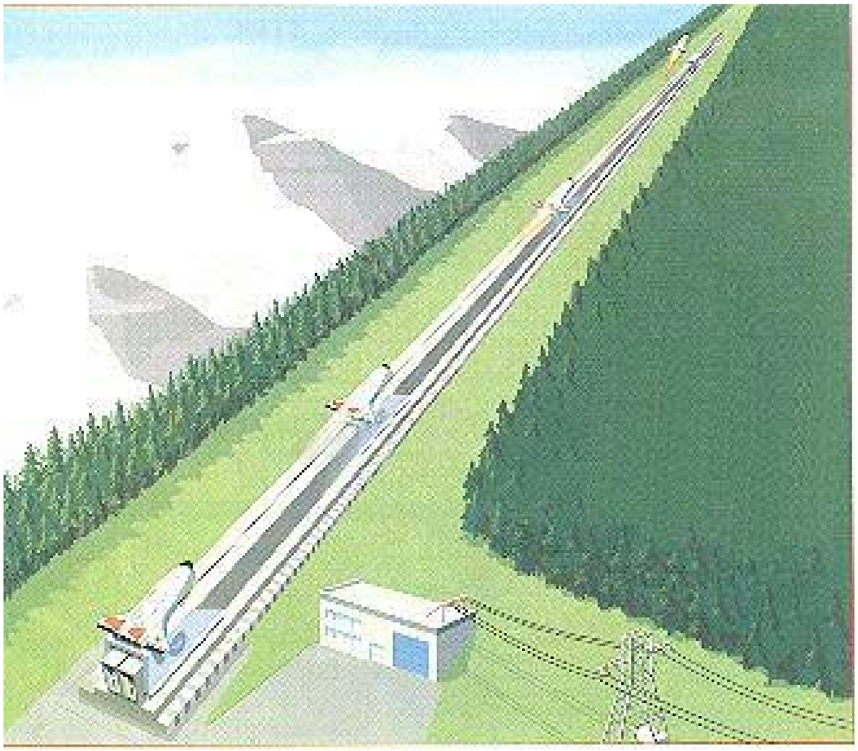
After we completed our theoretical analysis of the Inductrack, our team proceeded to the next logical step: building a small working model of the system. Its purposes were to check the theory's predictions and to demonstrate stable levitation. The 20-meter-long test track was designed to levitate a 22-kilogram cart equipped with Halbach arrays on its underside. The first section of the track contained electrically powered drive circuits; the second section consisted of 1,000 thin, rectangular levitating coils, each about 15 centimeters wide.



At the start of each test run, the cart rolled on its auxiliary wheels over the drive circuits, which accelerated the vehicle to a speed of 12 meters per second. This was sufficient to allow the cart to levitate above the rectangular coils (the track's transition speed was only four meters per second). The cart coasted over nearly the whole length of the track before settling on its wheels at the far end. We measured the cart's velocity and oscillations using two pointer-type lasers that were mounted on the cart at a slight angle to each other, like a pair of crossed eyes. The lasers illuminated spots on a white screen at the end of the track; analysis of a video-camera record of the spot separations and locations yielded plots of the cart's position and its pitch-and-yaw motions.

The tests verified our predictions of the Inductrack's performance and proved that the concept is workable. What is more, a preliminary feasibility study conducted in 1997 by the consulting company of Booz-Allen & Hamilton concluded that a full-scale Inductrack system would be less expensive to build and operate than the German maglev. For example, the study estimated that a train car equipped with Halbach arrays would cost between $3.2 million and $4.2 million, whereas a car in the German maglev would cost more than $6 million. (The estimated cost of a Japanese maglev car has not been made available.) The Inductrack vehicle would be more expensive than a conventional railcar, which costs between $2 million and $3 million, and building the system's track could cost as much as 80 percent more than constructing an ordinary track. The study noted, however, that the Inductrack's energy usage and maintenance costs would be significantly lower than those of a conventional railway.

Other Applications: Launching Rockets?



INDUCTRACK LAUNCHER could provide the initial boost for future spacecraft. The craft could be mounted on a levitation "launch cradle" that would glide up a sloping one-kilometer-long track. Unimpeded by wheel friction, the cradle could accelerate the spacecraft to 950 kilometers per hour. The craft's engines would then ignite and propel it into orbit.

After the construction of the test track at Livermore, officials at the National Aeronautics and Space Administration became aware of our work. As a result, the space agency awarded the laboratory a contract to build another model, aimed at demonstrating a very different application of the Inductrack concept. Studies by NASA have shown that if their rockets could be accelerated up a sloping track to speeds on the order of Mach 0.8 (950 kilometers per hour) before the rocket engines were fired up, it could substantially cut the cost of launching satellites. Such a system could reduce the required rocket fuel by 30 to 40 percent, thereby making it easier for a single-stage vehicle to boost a payload into orbit. Our Inductrack model, which will have a track about 100 meters long, will be designed to accelerate a 10-kilogram "launch cradle"-the rocket's platform-to speeds of about Mach 0.5 (600 kilometers per hour). Because of the shortness of the test track (compared with the kilometer-or-so length of a full-scale system), the electrical drive circuits for the NASA model must achieve 10-g acceleration levels. In a full-scale system the acceleration levels, limited by the strength and weight of the rocket itself, would be more modest, on the order of 3 g's.

Another possible application of the Inductrack was conceived by California inventor and entrepreneur Douglas J. Malewicki. His proposed maglev system, known as SkyTran, would transport small, two-passenger cars at up to 160 kilometers per hour. The podlike cars would be suspended from a monorail-type track that would support the levitating circuits. The cars would be available, on call, at each station in the system. After the passengers board a car, it would glide up to the main track and merge with the traffic speeding by the station. As a car approached its destination, it would switch to an exit track, dropping down to the station to allow the passengers to disembark.

As with any new technology aimed at improving or supplanting an older one, only time will tell how the Inductrack will be employed. In making the transition from theory and models to a fullscale system, several technological issues will have to be addressed. For example, to make the Inductrack's ride more comfortable, the system must damp out motions caused by aerodynamic forces. Another challenge would be clearing the track of any metallic junk that might be attracted to the Halbach arrays. (To accomplish this, the train's lead car could conceivably be equipped with the magnetic equivalent of a cowcatcher.)

In addition, the Inductrack's designers face the economic challenge of keeping costs low enough to provide a compelling advantage over conventional railways. I believe, however, that the essential simplicity and flexibility of the concept will ensure that it finds many applications-not only for high-speed rail systems but also for uses that we have not even imagined.

The Author

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Further Information

More information on the Inductrack system is available at www.llnl.gov/str/Post.html on the World Wide Web. The home page of the Railway Technical Research Institute, developer of the Japanese maglev, is at www.rtri.or.jp/index.html on the World Wide Web. The home page of the Transrapid System, the German maglev, is at www.maglev.com/english/index.htm on the World Wide Web.