FASTER THAN A SPEEDING

BULLET TRAIN

China is throttling up a 430-km/h magnetically levitated train to link Shanghai and its airport BY PHILIP HOLMER

SCALPING TICKETS TO A FOOTBALL or basketball game? Happens all the time. Scalping tickets for a 30-kilometer train ride? Now, that's unusual.

Ah, but what a ride it was. The train is the fastest by far on the planet, and it literally flies while suspended and propelled by magnetic forces. Built in China by a trio of German companies and the Shanghai Maglev Transportation Development Co., it reaches 430 km/h (268 mi/h)—130 km/h faster than Japan's famous bullet train. And even as it goes faster than any commercial vehicle without wings, the Chinese train is smoother and quieter than Amtrak's wheel-on-rail Acela—the state of the art in the United States—which pokes along when it can at a maximum 240 km/h.

Could this be the dawning, at last, of the long-awaited age of magnetic-levitation ("maglev") trains? After many false starts and the completion of full-scale experimental maglev systems in Japan and Germany in the 1980s, maglev in China will finally start shuttling passengers in October in a reasonably large-scale, commercial system. The trains will run from downtown Shanghai's financial district to Pudong International Airport, making an 8-minute run that will shave about 40 minutes off the typical trip time in a taxi. With three five-car trains, each carrying as many as 574 passengers, and trains leaving every 10 minutes, the US $1.2 billion system could carry more than 10 million passengers a year.

The Shanghai line is the first of several maglev projects planned for later this decade [see "Selected Maglev Projects," p. 34]. They include:

REN LONG/CHINA FEATURES PHOTOS

- A 37-km Munich-to-airport link in Germany.
- A U.S. regional maglev for either Pittsburgh or Baltimore, finalists in a competition for funding by the U.S. Department of Transportation's (DOT's) Federal Railroad Administration (Washington, D.C.).

A 78-km Düsseldorf-to-Dortmund link in North Rhine–Westphalia, Germany's most populous state, was cancelled only in late June because of a budget shortfall and political differences.

Another system was almost up and running, meant to carry students across the campus of Old Dominion University [see "Riding on Air in Virginia," *IEEE Spectrum*, October 2002, pp. 20–21]. But following its shakeout on a test guideway, the 1000-meter-long monorail, with a top speed of 64 km/h, provided a much bumpier ride on the real thing than expected. It sits unfinished, awaiting funds for further tweaking.

Passenger travel will not be the only beneficiary of maglev technology. NASA is considering it for assisting the launch of space vehicles, and the U.S. Navy wants it for catapulting its planes from the decks of aircraft carriers [see "Magnetic Takeoffs," p. 32].

Compelling advantages

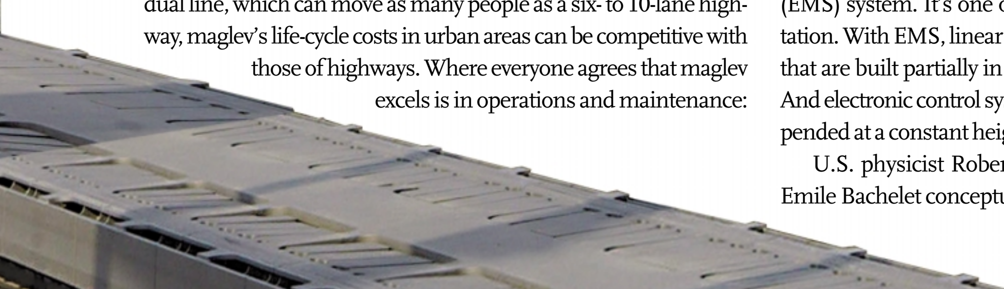
No question, maglev can move people quickly. It also accelerates and decelerates quickly—up to 1.5 meters per second per second. At this rate, a maglev train can reach 300 km/h in around 5 km, compared with 30 km for a high-speed train. Thus, on routes of less than 1000 km, a maglev train could match gate-to-gate air-travel times.

Maglev is less susceptible to weather delays than flying or driving. And it is relatively quiet. Vibration levels on Amtrak's Acela train at its top 240-km/h speed are much higher than on a maglev at 400 km/h, according to a DOT study.

Maglev provides a quiet ride because it is a noncontact system. The usual noisemakers are gone. It has no wheels, rails, axles, gearing, or current collector riding on a high-voltage rail. They're replaced by electromagnetics in each vehicle and in the guideway [see "Moving on Air in China," p. 33]. One set of electromagnets elevates the vehicle above the guideway and then propels it along. A second set keeps the vehicle centered laterally over the guideway. Such a frictionless system also consumes less energy per passenger than high-speed trains and no more than one-fifth the energy of airplanes and one-third that of automobiles. The ride is smooth, and passengers can move about freely, although air friction, and its concomitant noise, becomes a factor at higher speeds.

Like high-speed rail, maglev has dedicated rights of way with no grade crossings. This should allow it to match the enviable safety records of the Japanese Shinkansen bullet trains (in operation since 1964) and the French Train à Grande Vitesse (TGV, since 1981), which have never had a passenger fatality.

Even at an estimated $20 million per kilometer and up for a dual line, which can move as many people as a six- to 10-lane highway, maglev's life-cycle costs in urban areas can be competitive with those of highways. Where everyone agrees that maglev excels is in operations and maintenance: one California project calculated it would cost 33–50 percent less to operate than high-speed rail. Studies have shown maglev construction costs to range from slightly to much higher than those for high-speed rail, and it can move up a 10-degree incline, compared with high-speed rail's 3 degrees, a factor in cost comparisons.



The system in China

Shanghai's system is being built jointly by Shanghai Maglev and three German companies in the Transrapid International consortium. The technology was developed by Siemens AG (Munich), the electrical equipment giant, and ThyssenKrupp AG (Düsseldorf), which applies its locomotive experience to the vehicles and guideways. In 1998, the two companies formed Transrapid International GmbH (Berlin) to develop maglev transportation. A demonstration system, on which China's maglev is based, has operated in Emsland, Germany, since 1984.

Siemens Transportation Systems Group (Munich) built the propulsion, control, and safety systems, and ThyssenKrupp Transrapid GmbH (Kassel and Munich) built the vehicles and motors. Shanghai Maglev, itself a joint venture of Chinese government-funded enterprises, fabricated more than 2700 25-meter-long concrete-and-steel sections for the elevated guideways at its Shanghai factory. The guideways were completed last summer, with a pair of stations at the ends of the line, a repair center, and transformer substations ready earlier.

On New Year's Eve 2002, Zhu Rongji, then premier of China, and chancellor Gerhard Schroeder of Germany were aboard for the first demonstration ride that reached 430 km/h. For Zhu, the ride must have been of particular interest: he is an electrical engineering graduate of Tsinghua University in Beijing. Some years earlier, he rode the demo maglev in Germany. He liked it, which could have played a role in the choice of a maglev for Shanghai.

"So far, the system is running with no technical problems," Hartmut Heine, ThyssenKrupp's representative in Beijing, told *IEEE Spectrum* in late May. Its practice runs on weekends were so popular that people were even buying the $6 and $9 tickets on the black market. In the first 10 weeks of test runs this year, 83 000 people rode the maglev. By the May Day holiday, though, the rides were halted because of the SARS epidemic.

The Chinese are indeed serious about high-speed ground transportation, and maglev is a contender. Heine expects a decision "in the near future" on whether the Shanghai line will be extended to the nearby cities of Hangzhou and Wuxi. At 30 km, the Shanghai line is relatively short, on flat terrain; it has yet to prove economically viable for long distances.

One of two systems

Transrapid's maglev system for Shanghai (and elsewhere) relies on magnetic attraction in what's called an electromagnetic suspension (EMS) system. It's one of two basic approaches to magnetic levitation. With EMS, linear synchronous motors had to be developed that are built partially in the vehicle and partially in the guideway. And electronic control systems were needed to hold the vehicle suspended at a constant height above the guideway as it zooms along.

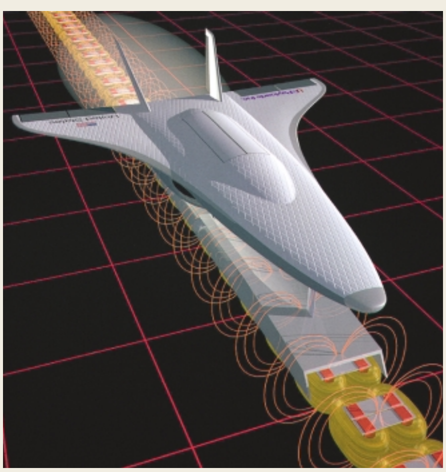
U.S. physicist Robert Goddard and French émigré inventor Emile Bachelet conceptualized frictionless trains using magnetic

Magnetic Takeoffs

Both the British and U.S. navies are investigating maglev propulsion to launch aircraft from carriers. Not only does a maglev system occupy less space than a conventional steam catapult, but it's easier to tailor the catapult's propulsive force to the weight of an aircraft, which is done at every launch. Maglev is also more energy efficient. It converts stored energy to aircraft kinetic energy with an efficiency of 40–70 percent, compared to 5 percent for steam.

General Atomics (San Diego) and Northrop Grumman (Sunnyvale), both in California, are building competing systems for the U.S. Navy's US $373 million Electromagnetic Aircraft Launch System. Later this year, prototype catapults based on linear synchronous motors will be tested at the naval facility, Navair, in Lakehurst, N.J. (General Atomics is also working on a maglev train being developed in Pennsylvania.)

NASA wants maglev as a booster-assist to lower the cost of space launches [see illustration]. Marshall Space Flight Center (Huntsville, Ala.) is studying a launcher on a 17-meter-long outdoor test track, built by PRT Advanced Maglev Systems Inc. (Park Forest, Ill.). The agency's visionaries foresee a maglev-assisted launch accelerating a space vehicle to over 965 km/h on a 2.4-km-long track. Rocket engines would kick in once this speed is reached. The assist might consume 200 kWh, or about $75 worth, of electricity. With less fuel and other efficiencies, launch weight could be lowered by 20 percent.



NASA

The space shuttle has cost about $4500 per kilogram to overcome Earth's gravity and enter space orbit. Maglev could drop this cost down to $450 per kilogram or less. Launches would also be safer and more reliable, with less environmental impact and much lower vibration levels. —P.H.

fields about 100 years ago. Maglevs have been on the drawing boards since Hermann Kemper received a maglev patent in Germany in 1934. In 1994 a decision was made to build a Berlin-to-Hamburg line, but the project and others later were put on hold at different times by one political party or another. Another confrontation, instigated by the Green Party, halted the Düsseldorf system. However, the Christian Democrats in the Frankfurt area now seem interested in considering a maglev.

The turning point could be now. Shanghai's system is soon to go into operation, and in fiscal year 2003, the German government budgeted €550 million (US $638 million) out of €1.6 billion for the Munich system to link to the nearby international airport, the country's second busiest. Traveling at a top speed of 400 km/h, the system will turn a 45-minute rail trip into a 10-minute hop. The project is in the "public legal planning process," as it's called, leading to environmental impact statements and final design. Construction is to begin around 2005–2006. When given the go-ahead, Transrapid International will build the vehicles and electronics, while local industry will build the guideway and other structures.

Magnetic expectations

The other basic system—electrodynamic suspension (EDS)—depends on repulsive magnetic forces and is being pursued by the Japanese, as well as by Maglev 2000 Corp. of Florida, in Titusville. Such a system has a larger air gap between the vehicle and guideway, a plus in earthquake-prone Japan. The larger gap also means that components can be built with wider tolerances. But stronger magnets are needed to maintain the gap, which is being achieved with superconducting electromagnets. (Guideway components in the Shanghai system are machined to higher tolerances—hundredths of millimeters—to keep the cars from hitting the guideways.)

Relying on liquefied helium and nitrogen, EDS consumes less energy than the German EMS, and lets a train reach higher speeds. However, the system is further from commercialization, although the Japanese built a test track in 1975. Presently, they have an 18-km-long track near Yamanashi, on which passengers have been enjoying demonstration rides since 1997. Trains there have set a speed record of 552 km/h.

In the United States, surface transportation efforts, including maglev, are receiving funds from the Federal Railroad Administration (FRA) under the 1998 Transportation Equity Act for the 21st Century (TEA-21). In May 1999, the agency funded seven studies in different parts of the country involving market analysis and construction planning for maglev systems. Two years later, the two most promising projects—in Pittsburgh and Baltimore—received follow-on awards to consider environmental factors, total costs, and revenue projections over 40 years. The two projects are now vying for an all-or-nothing award expected this year of up to $950 million, about one-third of estimated costs.

Pennsylvania plans a 76-km link joining Pittsburgh to its international airport and two other cities. Maryland wants a 60-km-long line from Baltimore to Baltimore-Washington International Airport in Linthicum, Md., and on to Union Station in the nation's capital, where it will join Amtrak, regional rail lines, and the subway. Travel time over the entire route could be a short 18 minutes.

California, which failed to win a federal award, has been pursuing maglev projects on its own. For example, in May 2002, the Southern California Association of Governments (Los Angeles), an authority of 165 cities and six counties, awarded a $16 million contract to a team from Lockheed Martin Corp. (Bethesda, Md.) to assess four possible maglev corridors. Among these is a seven-station 171-km line between Los Angeles International Airport and Palmdale Regional Airport.

In October 2002, the San Bernardino (Calif.) Associated Governments, another regional planning group, approved funds for feasibility and precon-

Moving on Air in China

Each vehicle developed by Transrapid International GmbH, in Berlin, for Shanghai's maglev train is supported in the air above the guideway by an electromagnetic suspension system. Levitation depends on attractive magnetic forces. Individually controlled electromagnets positioned along each side of a vehicle "arm" are slung under the guideway, and ferromagnetic "long-stator" packs are on the underside of the guideway itself [see figure].

At rest, the vehicle sits on skids [not shown] that settle on top of the guideway. Powered from on-board batteries, which also supply the vehicle electronics, support electromagnets on the arm are attracted to the underside of the guideway, at A. This lifts the vehicle and creates a 15-cm gap, B, between the bottom of the vehicle and the top of the guideway.

There then ensues an electronic *pas de deux* between the vehicle's weight and the attractive force of the electromagnets. The gap between each arm and the guideway is measured 100 000 times per second. This distance is fed to a control system that continually adjusts the current in the support magnets to reach an equilibrium point at which the weight of the vehicle is supported by the magnetic attraction. The result: the vehicle hovers so the gap between each vehicle arm and the underside of the guideway is 10 mm ± 2 mm.

The propulsive "engine" is called a long-stator linear synchronous motor. Its components are shared by both the vehicle and the guideway.

Think of a conventional motor whose stator and copper windings have been cut open, flattened, and placed on the guideway just above where the vehicle's arm wraps underneath. The stator pack is of ferromagnetic material wound with the motor's three-phase windings. Packs are bolted on in sections along the entire length of the guideway, which is why it's called a long-stator motor.

The equivalent of the motor's rotor—in this case, the vehicle magnets—are placed along the vehicle arms below the stator packs so that levitation and propulsion occur along the vehicle's entire length.

Once the vehicle is elevated off its skids, a current is applied to the three-phase cable windings braided into the stator packs to produce a traveling electromagnetic field along the guideway, instead of the rotating field of a conventional motor. This traveling field draws the vehicle electromagnets along synchronously, propelling the vehicle.

Linear motors are not new. They're used, for example, to move industrial conveyor belts and in textile looms and, more recently, for thrill rides in amusement parks.

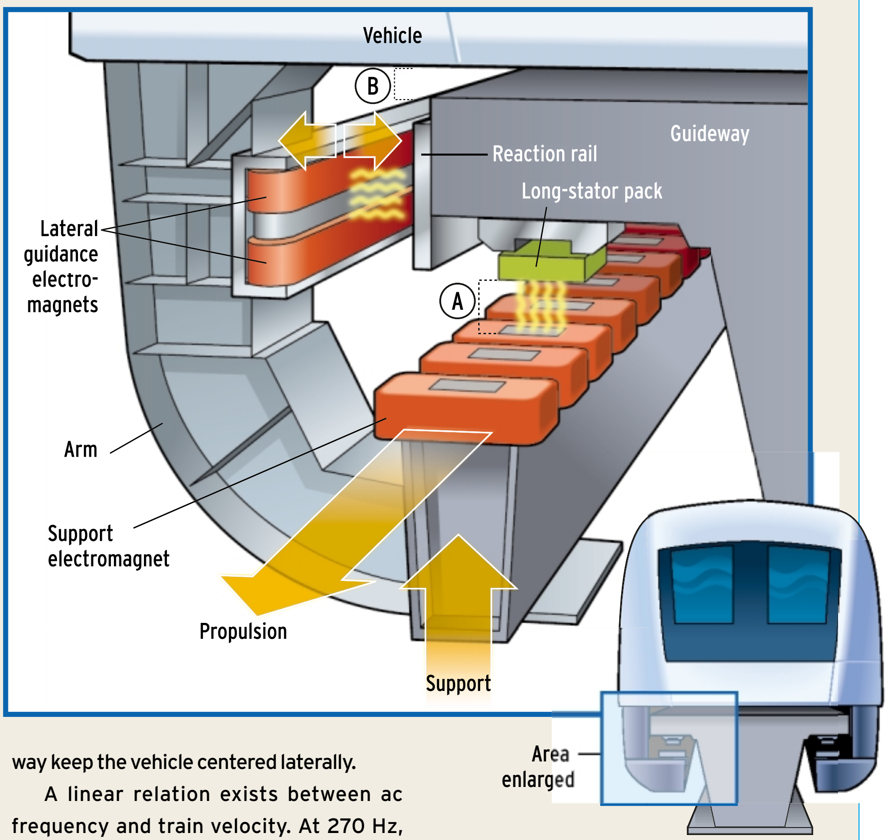
Guidance magnets in each vehicle arm and a reaction rail on both sides of the guideway keep the vehicle centered laterally.

A linear relation exists between ac frequency and train velocity. At 270 Hz, for example, the vehicle would move at 500 km/h. What's more, linear generators, integrated into the levitation magnets, derive power from the traveling electromagnetic field when the vehicle is in motion. This contactless energy exchange supplies power for the on-board equipment, levitation, and battery recharging.

Accomplishing this combination of levitation and propulsion required a great deal of applied research and testing on a real track. Handling turns and high speeds in the face of crosswinds while maintaining the 10-mm air gap is critical and difficult.

A big advantage is that the guideway is energized in sections as the vehicle passes. This avoids the inefficiency of always powering the entire route. More power is required for the air conditioning than to hover an empty maglev vehicle. Current ranges from 1200 to 2000 amps during acceleration and decreases to one-third full current when the vehicle cruises at a constant speed. At stations, 400-Vdc power rails are built into the guideway so the vehicle need not use its on-board batteries, a detail that reduces the size and weight of the batteries by three-quarters.

To slow the vehicle, the frequency is reduced. The vehicle magnets induce current in the guideway, essentially turning the vehicle's kinetic energy back into electricity, and the vehicle brakes. Train and guideway are monitored and controlled centrally via a 38-GHz datalink. The speed and location of the train on the guideway and the status of its equipment are transmitted from the vehicles to the control room. The datalink has reserve bandwidth to handle other transportation security needs, such as video of the passenger areas and driver's seat. A train operator still sits on the train to monitor the safety equipment and take over in an emergency. —P.H.



STEVE STANKIEWICZ

Selected Maglev Projects

	IN TEST	AWAITING APPROVAL			UNDER STUDY		
Location	Shanghai, China	Munich, Germany	Pittsburgh	Baltimore, Md.–Washington, D.C.	Las Vegas, Nev.–Los Angeles	Los Angeles–Palmdale, Calif.	Atlanta, Ga.
Purpose	Airport to subway in city	City to airport	To cities and airport	Cities to airport	Las Vegas airport to Primm, Nev. (Phase 1)	Cities to 2 airports	Airport to northern suburbs (Phase I)
Distance	30 km	37 km	76 km	64 km	56 km	115 or 171 km	51 km
Stations	2	2	4	3 or 4	2	5 or 7	4
Trip time	8 min.	10 min.	23 min.	18 min.	12 min.	Various	23 min.
Operational/ max speed (km/h)	430/500	350/400	400 max	430 max	500 max	400 max	400 max
Estimated annual ridership (millions)	10-36	8	33+	12+	14.3	30	7.5
Cost estimate (billions)	US $1.3	€ 1.6	US $3.3	US $3.5	US $1.5	US $8.2 or $11.9	US $2.2
Operational	Fall 2003	2007–08	2012	2012	2007–10	2007–10	2007–10

TRANSRAPID INTERNATIONAL-USA INC.

struction studies for a 433-km Anaheim-to-Las Vegas maglev line with several stations along the way. Project supporters hope to begin construction in mid-2007.

A compelling rationale for such projects is found in the U.S. Federal Aviation Administration's (FAA's) Aviation Capacity Enhancement Plan. An analysis of Los Angeles International's (LAX's) air traffic in 2000 found that only 2 percent of the passengers on short flights within California were responsible for 47 percent of LAX flight delays. And delays at LAX ripple out to keep aircraft from taking off at airports around the country. Getting to the airport by high-speed rail or maglev could save LAX about $515 000 per day in delay costs, notes the study.

Maglev projects slow to energize

Although maglev was popularized in the press decades ago, a host of technical problems first had to be solved. Only when full-scale prototypes were built and tested with Japanese and European government support did the technology mature and appear practical.

The Europeans and Japanese saw the value of high-speed ground transportation first. They built extensive, wheel-on-rail systems with speeds of up to 300 km/h. These include not only Japan's Shinkansen bullet train and the French TGV but the German InterCity Express (ICE) lines and the Eurostar trains of the English Channel tunnel. All these speedy trains depend on new signaling systems and dedicated rights of way. Their tracks are off limits to heavy freight trains with their wear and tear, although the fast trains can use ordinary rail lines at lower speeds.

Europe is also developing the Trans European Network, a transportation, telecommunications, and energy infrastructure. It includes 865 km of new—and 2000 km of upgraded—high-speed rail lines. The Europeans are particularly keen on intermodal transportation—that is, points where rail, plane, and highway systems come together and passengers may switch from one to the other. With Europe's high-speed rail infrastructure, adding a widespread maglev network offers little advantage. Rather, the greatest interest for maglev lies in regional and intermodal applications, such as airport-to-railroad or -city connections.

In the United States, high-speed ground transportation has made little headway. Amtrak, the national railway authority, has had financial and technical problems and has cut passenger connections to some cities. The condition of the rails lets the high-speed Acela train reach its top 240-km/h speed for only an 18-minute stretch; on most of the track between Washington, D.C., and Boston it travels at 216 km/h. Unusual for the United States, the line has an intermodal connection, at Newark International Airport in New Jersey.

Maglev in the United States has had a shaky existence. Federal funds for research were doled out to universities and aerospace companies in the early 1980s, and a "national initiative" to evaluate maglev for intercity travel lasted from 1990 to 1993. But funding was never constant, and public policy deemphasized high-speed ground transportation in favor of subsidized air and highway travel. ●

To Probe Further

Transrapid International offers photos, descriptions, and even videos of its systems on the Web at http://www.transrapid.de.

For three U.S. regional programs, see http://www.calmaglev.org (California), http://www.maglevpa.com (Pennsylvania), and http://www.bwmaglev.com (Baltimore-Washington, D.C.).

Japan's efforts can be found at the Japanese Railway Technical Research Institute, at http://www.rtri.or.jp.

Technical reports on noise, vibration, and electromagnetic fields are at the U.S. Department of Transportation's (DOT's) Volpe Center, http://www.volpe.dot.gov/enviro/pubs.html. The Federal Railroad Administration of the DOT presents its views on maglev at http://www.fra.dot.gov/rdv/maglev/index.htm.