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Fast Track

The high-speed magnetic levitation rail line now in operation in Shanghai—the first of its kind in the world—demonstrates that this extraordinary technology can move people in a way that is fast, reliable, and cost effective. **By Walter Antlauf, Dipl.–Ing., François G. Bernardeau, P.E., and Kevin C. Coates.**

The Shanghai maglev system traverses 30 km in just eight minutes. Because right-of-way restrictions ruled out a straight alignment, the planners chose a gently curving S shape to take full advantage of the system's speed. *Transrapid International–USA-all photos*

Extending 30 km above a sparsely populated alluvial plain in southeastern China is a high-tech concrete bridge that at first might not attract one's notice. But this is no ordinary bridge. It is the elevated dual-track guideway for the world's first high-speed commercial magnetic levitation, or maglev, transportation system. In addition to linking the city of Shanghai to Pudong International Airport, which is 30 km away, this new system bridges the technological and time gap between conventional rail and air travel and opens a new era of reliable, energy-efficient, and low-maintenance high-speed ground transportation.

Supervised by engineers from the Shanghai Maglev Transportation Development Company, Ltd. (SMTDC), of Shanghai, and German engineers from Transrapid International AG (TRI), of Berlin, CDM Consult AG, of Bochum (a subsidiary of CDM, based in Cambridge, Massachusetts), Max Bögl, of Neumarkt, Siemens AG, of Munich, and ThyssenKrupp AG, of Düsseldorf, the Shanghai maglev project is an example of international cooperation in engineering, manufacturing, and construction.

Limited commercial operations began in early 2003, and since then the SMTDC, which owns the system, has shuttled nearly 2 million passengers between Shanghai's Long Yang Road station, at the southeastern edge of the city, and the airport at speeds up to 430 km/h. The 464-seat maglevs depart every 10 minutes during peak travel periods, arriving at the airport less than 8 minutes later. According to a report published by the SMTDC in July of this year, computerized operations have resulted in arrivals and departures that are on time to the second 99.7 percent of the time, a remarkable feat for any transportation system. At present the system operates from 8 am to 5:30 pm, but service is to be expanded to 18 hours a day in the near future.

Engineers chose a hybrid girder design that combined the rigidity, noise absorption, and low cost of concrete with the precision manufacturing offered by steel. The system's reinforced-concrete support piers are designed to withstand the seismic forces of earthquakes measuring up to 7.5 on the Richter scale.

With an acceleration force only a 10th that from gravity, the maglev's ride is so smooth that travelers would be unaware that they were leaving the station if they did not look out the window. It takes just four minutes for the cars to attain their operational cruising speed of 430 km/h, which is held for 52 seconds prior to the three-minute deceleration ending the trip. As the cars near their maximum speed, there is some detectable vibration, but the ride is still smooth enough for passengers to easily walk the aisles without bracing themselves. Despite the speed, the ride is comfortable and the interior noise is significantly less than what one experiences in the cabin of a turboprop traveling at the same speed.

The system cuts the trip from the Long Yang station to the airport from 45 minutes—via a six-lane highway that runs adjacent to the maglev line—to just 8 minutes and offers other, less tangible advantages to the city of Shanghai as well. Because a maglev consist can comprise as many as eight vehicles, the potential passenger capacity of the system is several times greater than the highway, negating any immediate need for additional highway expansion to handle the city's ever-increasing traffic. Since the entire maglev route is elevated, there are no at-grade crossings, eliminating any interference with vehicular traffic and providing a high degree of safety for maglev travelers.

What is more, the elevated guideway is visually integrated with the nearby highway infrastructure. In areas where the guideway deviates from the alignment of the highway, the land beneath is used for such other purposes as farming, industry, and commerce. Plans exist to expand the line farther into the city and beyond, and as this expansion occurs it is expected that real estate development will increase around the maglev stations, just as it has in countries where high-speed rail has been implemented.

During a presentation in January 2004 in Washington, D.C., at the annual meeting of the Transportation Research Board, Wu Xiangming, who was the president of the SMTDC during the design and construction of the line, pointed out that China's limited domestic oil supply figured prominently in the deliberations. Consideration was also given, he said, to other high-speed rail options that rely on electricity, the intent being to eschew highway expansions and modes of travel that depend on oil. He said that as China modernizes, its energy consumption per capita will inevitably rise and raise the demand for oil. (To support this point, he noted that the average energy consumption per capita in the United States is presently 11 times that in China.)

Rather than adopting a system based on one of the high-speed rail technologies now found in Japan and Europe, officials with the SMTDC favored maglev, which they saw as a low-maintenance way of quickly moving passengers across vast distances in comfort. Prior to the construction of the maglev line, the six-lane highway was Shanghai's only link to Pudong International Airport. Faced with increasing congestion and the prospect of continual highway expansion, planners ultimately decided that a maglev line would be the fastest and most reliable way of delivering travelers to the airport. It also required less energy than other options and offered the lowest life-cycle cost. Looking to future line expansions, the officials saw that longer maglev routes would allow routine operating speeds of up to 500 km/h, making it possible for business travelers, for example, to attend meetings 1,000 km away and return in a single day. By constructing this "demonstration" line, the owners would be able to accumulate and analyze data from a commercial application of this electronic transportation system.

In the summer of 2000 the Chinese prime minister, Zhu Rongji, an electrical engineer by training and a man with a strong interest in maglev technology, arranged for the SMTDC engineers to visit a 30 km long maglev test facility in the Emsland region of Germany. The TVE (Testversuchsanlage Emsland) was built in the early 1980s near the village of Lathen, about 10 km from the Dutch border. The engineers took this opportunity to observe operations, evaluate guideway systems, and review operational data.

While in Germany, the engineers met with representatives of the firms involved in maglev development—Siemens, ThyssenKrupp, CDM, Transrapid, and Max Bögl. All of these firms signed contracts with the SMTDC to design and construct the Shanghai system. Max Bögl was selected as the main guideway engineering consulting firm because its hybrid guideway girder was deemed the best system for the project.

Essentially, Transrapid maglev passengers ride inside a vehicle that forms part of an electric linear synchronous motor. The guideway, which contains the stator broken into segments called stator packs, magnetically propels passengers riding inside a vehicle, which acts as the rotor. Vehicle levitation is effected via onboard computer control units that sample and adjust the magnetic force of a series of onboard electromagnets as they are attracted to the guideway. The vehicles feature cast aluminum support arms that wrap around the top cantilevers of the guideway. The support arms' upward facing suspension magnets are attracted toward the stators, which are underneath the cantilevers—a design that also makes derailment virtually impossible at any speed. (See figure below)

Regardless of load and speed, the onboard control system maintains a 10 mm gap with a ±2 mm tolerance between the vehicle's support magnets and the guideway's stators and between the guidance magnets and the steel guide rails. Three-phase cables run the length of the guideway through both sides' stator packs. When the control center—located in the Long Yang Road station—applies current to these cables from strategically located trackside substations, the resulting magnetic waves cause the maglev vehicles to accelerate, cruise, decelerate, or brake. Power is delivered to the maglev vehicles through linear generators at speeds above 80 km/h and through power rails that are in contact at lower speeds in and near stations. Onboard batteries provide redundant power to maintain vehicle levitation in the event of guideway power failures.

The particular alignment of the Shanghai system was chosen because it had relatively few right-of-way obstacles and because its point of origin—the Long Yang station—offered access to the Shanghai metro. From this metro station passengers can reach downtown Shanghai in less than 15 minutes. Because right-of-way restrictions ruled out a straight alignment, the planners chose a gently curving S shape—the radii of curvature being 2,257 and 4,502 m to take full advantage of the maglev's speed.

A short construction schedule dictated by political considerations was adopted for the project. Zhu Rongji was stepping down as prime minister in early 2003 and had planned a December 31, 2002, inaugural ride with Gerhard Schröder, the German chancellor. In response, the German companies marshaled their resources to meet this tight schedule.

The site's periodic seismic activity and weak alluvial soil, with the possibility of liquefaction during an earthquake, made it less than ideal for the stable support of the heavy concrete and steel infrastructure. The solution to these instability problems lay in building elevated guideways sitting atop support piers. The reinforced-concrete support piers, 1.8 by 1.8 m in plan and typically 8 m high, are designed to withstand the seismic forces of earthquakes measuring up to 7.5 on the Richter scale. Each support pier sits atop a pile cap 2 m deep and 10 to 12 m on a side. The caps cover 20 to 24 piles, each 60 cm in diameter, that are driven to depths reaching 70 m to counter seismic forces and liquefaction.

A geotechnical investigation was performed by Chinese consultants to provide subsurface data at each pile location along the alignment. The study included 359 standard penetration drill holes and 230 cone penetration test holes, as well as split spoon and undisturbed Shelby tube sampling, groundwater sampling, and a site survey. The exploratory work was performed in 2000 between October 7 and November 12. CDM reviewed the soil data and chose foundation design parameters in such a way as to ensure smooth and reliable operation. This information was also used to evaluate the possibility of short- and long-term settlement along the track alignment and deformations of the piles.

The geotechnical challenges peculiar to maglev included exacting deformation limitations and the need for long-term stability of the foundations under dynamic loads. Thus an analysis of the support that would be provided to the girders was called for. The maximum allowable total deformation of the guideway is 10 mm. This deformation can come from settlement caused by consolidation, plastic settlements resulting from secondary consolidation or creep, settlements caused by the dead load, settlements caused by cyclical loads from the vehicles, elastic settlements caused by dynamic loads, and settlement during operation. CDM developed an analytical methodology to study the resulting settlements and maintains a soil database expressly for maglev and high-speed rail that provides relevant information on settlement for any type of soil. This database was used in conjunction with data from the site to produce a comprehensive deformation analysis that made it possible to precisely position the guideway.

To meet such a tight schedule, the right material had to be chosen for the guideway. Three basic types of guideway girders had been installed at the TVE: concrete, steel, and a hybrid girder. The T-shaped hybrid girder, a reinforced-concrete center girder to which steel cantilevers are bolted, is 62 m long, 2.8 m wide, and 2 m high and weighs 290 Mg. Following a thorough evaluation of the three guideway types with respect to ride, wear, noise, cost, handling, and heat expansion characteristics, the SMTDC engineers selected the hybrid design because it combined the advantages of concrete (rigidity, noise absorption, and low cost) with those of steel (precision manufacturing). It was felt that the concrete girders lacked the long-term durability and precision in the critical grouted areas where such steel components as the stator packs and guidance rails would be affixed, raising questions about long-term maintenance costs. The steel girder was seen as offering the precision needed but was rejected because of the irregular expansion characteristics that can result when one surface is subjected to prolonged exposure to the sun. What is more, the steel girders exhibited undesirable oscillation effects when multisection vehicles passed over them, some undesirable lift-bearing forces, and some strong vibrations. These problems could have been overcome, but higher costs aside, they would have required greater amounts of steel and longer lead times for manufacturing. These considerations tipped the scale in favor of the hybrid guideway.

The maglev system has carried nearly 2 million passengers between the Long Yang station, right, and Pudong International Airport at speeds up to 430 km/h.

To increase rigidity, engineers from SMTDC and Max Bögl redesigned the shape of the hybrid girder from a T to an I that would be 2.2 m high and 2.8 m wide. To facilitate handling during construction, the designers also shortened the girder to 25 m. Although the modified design improved passenger comfort, it also increased the overall weight of the girder and reflected noise upward.

The hybrid girder design evolved from Max Bögl's considerable experience with steel fabrication and with elements of precast, prestressed concrete. The girders were milled to a precision of 0.2 mm, enabling the completed cantilever assemblies to satisfy a total tolerance criterion of 1 mm for the entire length of the guideway. Adhering to all of Transrapid's specifications, which are dictated by considerations of deflection, dynamic strength, and thermal expansion, engineers evaluated the girder with respect to as many as 14,000 load cases. It is believed that no transportation infrastructure project of this magnitude has ever been built to such exacting deflection or expansion design specifications. The hybrid design was also considered the best for quickly and economically moving from prototype guideway to commercial mass production. When the contract between SMTDC and Max Bögl was signed, on January 26, 2001, no manufacturing infrastructure for such guideways existed anywhere in the world. One month later, however, construction began on a 1.8 km long, climate-controlled facility that would have laser-guided milling machines for the mass production of guideways.

Choosing a hybrid girder design facilitated the deployment of the tooling machines needed to form and mill the girders, which were designed in three lengths. Those referred to as type I girders were approximately 24.8 m long and weighed approximately 190 Mg. The type II girders were 12.4 m long, and those for the maintenance facility, located near the airport, were 3.1 m long. Logistical and manufacturing approaches developed by Max Bögl led to fast, efficient, and economical mass fabrication. The company also provided special software to route the digital tracking data automatically to the CAM (computer-aided manufacturing) tooling machines, giving operators of the plant real-time reports on fabrication. Additionally, a sophisticated quality management system guaranteed quality control from production and storage to delivery and installation.

The precast plant produced an average of 10 girders a day, seven days a week, and sustained a reserve capacity sufficient to support the project schedule and meet the needs of any future expansion of the line. A large storage field adjacent to the plant was used to cure the high-strength concrete girders (34,475 kPa) for between 45 and 60 days to minimize long-term creep and shrinkage.

The SMTDC's vision for developing a larger maglev network demanded that the girders be suitable for use in—and transportation to—multiple locations. To provide flexibility in future guideway construction while maintaining the strict deflection requirements, all of the single-span girders designed for the Shanghai project can be coupled to form double-span girders.

Once the right-of-way was cleared in March 2001 and construction of the guideway manufacturing facility—located near the midpoint of the line—began, pile driving commenced along the entire route. Contractors drove groups of piles for the foundation piers every 25 m at a very rapid pace, completing the entire 30 km route in less than nine months. The pile caps were then poured atop the pilings.

The German and Chinese engineers and construction crews manufactured, delivered, installed, and aligned a total of 2,777 guideway girders to the system in less than 18 months. The majority of the girders (2,497) were the larger (type I) versions, and to facilitate installation a temporary rail line was laid along either side of the maglev route to support specially designed gantry cranes. In addition, some 70 type II beams and 210 maintenance facility girders were manufactured and delivered.

Installed between the guideways and their support piers are three-way bearings designed to allow alignment corrections in response to the settlement that will occur during normal operation.

While construction in Shanghai progressed, ThyssenKrupp was transforming a construction facility in Kassel, Germany, originally intended for a prototype maglev vehicle (the TR-08) into a full-fledged manufacturing plant. The SMTDC ordered 15 vehicles to constitute three 5-vehicle consists. Once the Kassel plant was up to speed, it produced one section per month. The completed vehicles were then shipped to a facility constructed at the end of the maintenance spur for final assembly. In addition to the maglev vehicles and guideway stator packs, ThyssenKrupp designed, fabricated, and shipped the eight bendable steel guideway switches for the system and supervised their installation.

Route Map

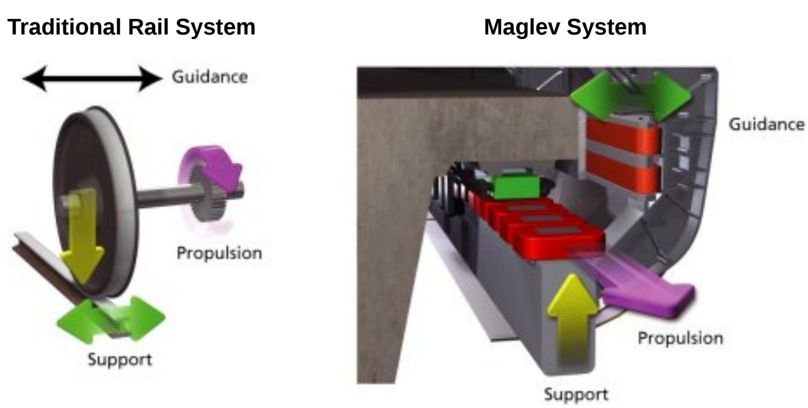
Siemens designed, manufactured, and delivered all the power electronics for the digitally controlled and operated system, including the two propulsion substations, the control center, several miles of specialized power cables, and 62 microwave data towers. At least one of these towers has a line of sight at all

times to one of the two antennas on the maglev's end section (one on each end). A steady stream of data between the vehicles and the control center makes for safe and efficient operation, with no need for a human operator. The data transmitted include information on guideway deviations detected by the vehicles during normal operation, along with exact coordinates to aid speedy corrections. Siemens supervised the installation of these systems.

Buoyed by the success of the inaugural ride on December 31, 2002, the owners decided to operate the system for visitors on weekends while work proceeded on weekdays in connection with commissioning, safety certification, and overall regulatory approval. Full-scale daily maglev operations officially began in April 2004. The system's operating reliability is extremely high and its maintenance costs are reported to be 33 percent lower than those of traditional low-speed steel-wheel-on-steel-rail systems and half those of traditional high-speed rail systems. (Even the fastest of the latter are 130 km/h slower than the maglev system.)

Because the entire system is computer operated and controlled, the SMTDC requires only a small labor force. In fact, even large increases in passenger traffic will not require that the staff of 10 guideway and 20 vehicle maintenance workers be expanded. The low maintenance and labor costs, combined with the advantages the system confers in the areas of speed, reliability, and safety, mean that the owner can expect a steady and rapid return on investment and even a profit. Wu reported in July that even with its daily volume of 7,000 passengers, which was lower than expected, the system was already able to cover its operating costs.

Not long after service began on the maglev line, a 2 mm settlement of one pier was detected and corrected. Variable settlement of the guideway piers had been expected, analyzed, and planned for by all parties involved. When necessary, adjustments can quickly be made to the appropriate bearings to compensate for any deviation, even during operation.



The two stations built at either end of the route and the indoor maintenance facility were designed and constructed by Chinese firms. The maintenance facility is accessible from the main line via a bendable steel switch that leads to a single spur. Bendable steel switches at either end of the line allow the trains to be routed to either side of the stations' platforms as needed.

The greatest challenge confronting maglev deployment over the past 12 years has been political, not technical. The technology is radically different from that of other high-speed rail systems, and it will probably take time for decision makers to learn enough about maglev to include it in their deliberations. To be sure, it takes some time to absorb maglev's technical details, but once this has been accomplished the technology's many operational and financial advantages reveal themselves.

The SMTDC views its maglev airport connector as an immense success and believes its many advantages more than justify its $1.2-billion price tag. According to Wu, this figure includes the costs incurred in designing and constructing the guideway; purchasing the 15 vehicles; constructing the substations, the maintenance spur, the maintenance facility, and the bendable steel switches; purchasing auxiliary equipment; and meeting interest payments during the construction phase. If this total is applied to the 30 km main line, the price works out to $39.759 million per kilometer. The per-kilometer price of the guideway construction itself, exclusive of ancillary items, is naturally lower and is expected to drop as new construction and manufacturing techniques evolve. It should also be noted that guideway costs depend on the site and the project and that this first project was built to extremely high standards. Moreover, its price tag reflected the premium for an expedited construction schedule.

By comparison, says Wu, Shanghai's four-year-old Mingzhu (Pearl of the Orient) elevated rail line cost $44.578 million per kilometer, and the per-kilometer costs of maglev are just half of those of many subways. Other traditional high-speed rail lines, for example, the one being built in South Korea from Seoul to Pusan, the line being constructed in Taiwan from Taipei to Kaohsiung, the recently completed German line between Frankfurt and Cologne, and the line under construction in the Netherlands, all cost approximately $40 million per kilometer, according to Wu, and in some cases that figure does not include the vehicles. These costs are much higher than those for the Shanghai line.

This year Wu was appointed to lead the newly formed National Maglev Transportation Engineering and Development Center, a clear sign that China intends to expand the application of this technology. Plans and negotiations are moving forward to extend the initial operating segment 7 km into the city, with an eventual connection to the city's central rail station. There are also plans to link Shanghai to the city of Hangzhou, 163 km to the southwest, which would create the world's first intercity maglev line.

Maglev technology is also being considered in the United States. Congress established the Maglev Deployment Program in 1998 as part of the Transportation Equity Act for the 21st Century (TEA-21) with the express purpose of building a maglev demonstration project. While several environmental impact statements are nearing completion, no project has yet received construction funding from the federal government. Six projects are being considered: two in Southern California; one from Las Vegas to Anaheim, California; one from Atlanta to Chattanooga, Tennessee; one from Baltimore to Washington, D.C.; and one linking Pittsburgh International Airport to the surrounding region.

The Shanghai maglev system validates the technology and confirms its cost-effectiveness and is a significant achievement for the German and Chinese engineers. The system clearly represents a new standard for high-speed ground transportation.

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