Shanghai's maglev project

– levitating beyond transportation theory

by Kevin C Coates

SHANGHAI is growing fast. To the periodic visitor, it seems as if new gleaming glass and steel skyscrapers pop up someplace new every week.

Shanghai also moves fast. Running 30km from Shanghai's new Pudong International Airport to the Longyang Road subway station at the southeastern edge of the city is a new high-tech concrete and steel elevated dual-track guideway for the world's first high-speed commercial magnetic levitation, or maglev, transportation system.

In the next few years when this 30km demonstration line is finally extended another 7km closer to the centre of Shanghai, trips from the airport to downtown will take only 10 minutes, regardless of traffic or weather conditions – trips that routinely take over an hour by taxi. This new system essentially bridges the technological and travel-time gap between conventional rail and air travel, and launches an entirely new era of ultra-reliable, energy efficient and low maintenance high-speed ground transportation.

The Shanghai maglev project is an example of international cooperation in engineering, manufacturing and construction. It was supervised by engineers from the Shanghai Maglev Transportation Development Company (SMTDC) of Shanghai, 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.

SMTDC, the system's owner, began limited weekend commercial operations in early 2003. By January 2004, SMTDC started daily operation of the demonstration line between 8am to 5.30pm. As of February this year, the maglev has shuttled over 2,500,000 passengers and travelled over 1,287,000km at speeds up to 430km/h, with the 464-seat maglevs departing every 10 minutes during peak travel periods. The 30km trip takes only 7½ minutes and costs about US$6. With so many international flights arriving after 5:30pm, it is obvious that passenger numbers will inevitably rise when the system eventually extends its operations to 18 hours per day. At Longyang Road station, maglev passengers have access to the #2 subway line that provides 14 minute access to the inner city (US35¢ fare) or they can grab a taxi for the 30-45 minute ride to downtown (about US$6). A taxi from the airport to downtown typically takes more than an hour and costs between US$18 and US$24, depending on the destination.

According to a report published by the SMTDC in July last year, computerised operations have resulted in arrivals and departures that are on time to the second 99.7% of the time, a remarkable feat for any transportation

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A gently curving 30km dual-track "S" route was selected for Shanghai's maglev system to maximise its high-speed performance potential.
PHOTO: TRANSRAPID INTERNATIONAL GMBH & CO KG.

Over 2,500,000 passengers have taken advantage of Shanghai's maglev system, which cuts the 45 minute taxi trip from Longyang station (pictured) to the airport to less than 8 minutes. PHOTO: TRANSRAPID INTERNATIONAL GMBH & CO KG.

system. Even more remarkable, the latest reports state that performance levels have since improved to 99.9%.

With an acceleration rate of only 0.1 g, passengers would be completely unaware the maglev is leaving the station without outside visual references. It takes just under 4 minutes for the maglevs to attain top operational speeds of 430km/h, which are held for 52 seconds before beginning the 3 minute deceleration. Near maximum speed, there is some detectable vibration aboard the maglev vehicles, however the ride is still smooth enough for passengers to easily walk the aisles without holding on. As the scenery whizzes by, the ride is comfortable and the interior noise is significantly less than what one experiences in the cabin of a turbo prop travelling at the same speed. The whole trip is over before a cup of coffee can cool off.

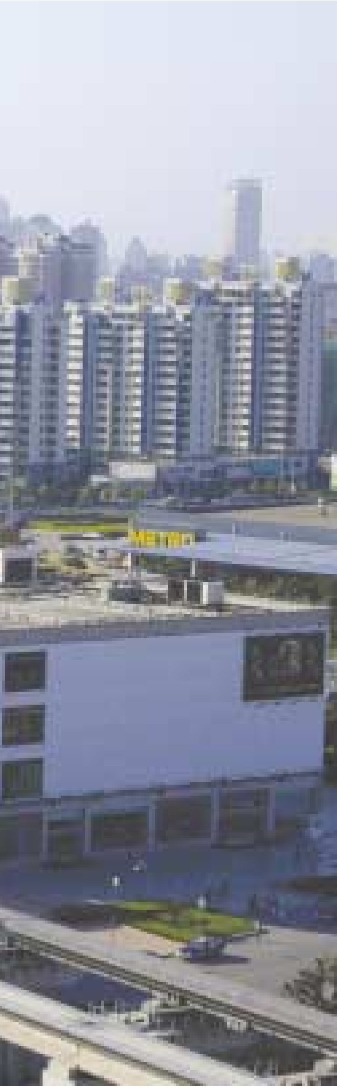
Aside from the obvious trip-time advantages, the maglev has other less visible advantages for Shanghai. Because up to eight vehicle sections can form one maglev consist, the potential passenger throughput capacity of the system is several times greater than the adjacent six-lane airport highway, negating any immediate need for additional highway expansion. Since all 30km of the route are elevated guideway, there are no at-grade crossings. This removes any interference with automobile traffic and provides the highest degree of safety for maglev travellers, along with enabling near perfect trip-time reliability.

Remarkably, the guideway system blends in with the nearby highway infrastructure. In areas where the guideway deviates from the highway, the land underneath is used for other purposes, such as farming, warehouses or other commercial purposes. As this demonstration line extends and expands into a well connected transportation network, it is expected that real estate development will blossom around the future maglev stations, just as it has in countries where high speed rail has been implemented.

Chinese vision

The Chinese interest in maglev transportation is rooted in their leaders' acute awareness that they are transforming a country of 1.3 billion people into a modern nation. As China modernises, its energy consumption per capita will inevitably rise and further strain limited domestic and imported energy supplies. By comparison, the average US energy consumption per capita is presently nine times that of China, revealing China's huge potential demand.

During the January 2004 Transportation Research Board (TRB) Annual Meeting in Washington, DC, the Chinese project manager for the maglev project, chief commander Xiangming Wu, pointed out in his presentation that China's limited domestic oil supply was a key consideration for building the Shanghai maglev demonstration project. Since oil has a questionable future as a general transportation fuel source, Chinese leaders decided to embark on a plan to use electric-powered high-speed rail and



high-speed maglev as the backbone of their new national transportation system. These modes are fast, energy efficient, and can easily handle high passenger volume. By selecting electricity as the source of power for most intercity transportation, the Chinese (and Europeans) are intending to make themselves less dependent on the world's prime mover of choice – oil.

Rather than just deploying the high-speed rail systems of Japan or Europe to shorten long distance travel times, the Chinese decided to investigate the possibility of leap-frogging existing high-speed rail technology by first deploying the German-designed Transrapid maglev system as a demonstration line. This way, the Chinese engineers could accumulate and analyse data from actual commercial operations of a new electronic transportation system.

Wu also pointed out that China's vast expanse can be quickly bridged by a maglev system capable of cruising at 500km/h and stated that from the "perspective of human body fatigue, a trip time of three hours is the turning point of travel comfort". With such a system in place, a business meeting 1000km away would be within comfortable travel distance for a day's roundtrip, regardless of weather conditions.

In May of 1998, after the German government invested fully 30 years and an estimated US$2 billion into maglev development, Siemens AG and ThyssenKrupp AG set up the consortium Transrapid International AG (TRI), in Berlin, Germany, to further develop and market their maglev technology. However, when a 1999 change in Germany's leadership eroded political support, a long planned Berlin-Hamburg Transrapid maglev line was cancelled on 5 February 2000, just six months before construction was scheduled to begin.

By mid 2000 and in spite of this political setback for TRI, Zhu Rongji, the Chinese prime minister and a trained electrical engineer, was intrigued enough by maglev technology to arrange for Chinese engineers to conduct due diligence on the maglev technology at the 20 year old TVE (Testversuchsanlage Emsland) test track facility located outside Lathen, in rural northwest Germany.

By 23 January 2001, TRI had its first successful contract, not for a German intercity line, but for an airport connector in Shanghai, China. Once the contract was signed, a tight construction schedule was driven by some powerful political considerations. Rongji was stepping down as prime minister in early 2003 and wanted a New Year's Eve inaugural maglev ride for himself and German chancellor Gerhard Schröder set for 31 December 2002. German companies rapidly responded to meet the ambitious Chinese construction schedule.

While in Germany, the Chinese met with the companies involved with maglev development (Siemens, ThyssenKrupp, Transrapid International) and the two companies designing and building guideways (ThyssenKrupp and Max Bögl). Because of their geotechnical experience at the TVE, as well as their preparatory work for the Hamburg-Berlin line, the German branch of Camp, Dresser & McKee, Inc (CDM) was hired to assist the Chinese with support structures. The construction and design engineering company Max Bögl, was selected as the main guideway engineering consulting firm because its hybrid girder design was considered best suited for meeting the project's rapid production schedule.

Meanwhile, back in China, other engineering teams and planners were mapping out the best route between Pudong International Airport and Shanghai. Longyang station was chosen because it lies at the southeastern edge of the congested metropolis and had the fewest obstacles to overcome. A gently curving 30km dual-track "S" route was selected for maximising high-speed performance potential (the radii of curvature for the route ranging being 2257m and 4502m) and for dramatically cutting the 45 minute taxi trip from Longyang station to the airport to less than 8 minutes by maglev.

Prior to the maglev line, the six-lane highway was Shanghai's only link to the airport. Faced with increasing congestion and a future of costly highway expansion projects, planners ultimately decided that a maglev line offered the fastest, most energy efficient and reliable method of delivering travellers to the airport, while also providing the lowest life cycle cost of any proposed transportation solution.

Design and construction

Essentially, TRI maglev passengers ride inside a vehicle that is part of an electric linear synchronous motor: the I-shaped guideway (containing the stator) propels passengers riding inside a vehicle (rotor). Vehicle levitation is achieved via onboard computer control units sampling and adjusting the magnetic force of a series of onboard electromagnets as they are attracted to the underside of the guideway cantilevers. Vehicles ride along the guideway with their cast aluminium support arms wrapped around the top cantilevers of the guideway's I-shaped cross section. The support arm's upwardly facing suspension magnets are attracted towards stator packs attached underneath the cantilevers – a design that also makes derailment virtually impossible and safe at any speed.

Regardless of load and speed, the onboard control system maintains the 10mm gap with a ±2mm tolerance between the vehicle's support and guidance magnets and the guideway's stator packs and steel guidance side rails, respectively. Along the entire length of the guideway, three phase cables run through stator packs that are attached underneath the top guideway cantilevers on both sides. When the centrally controlled operations centre located in Longyang station applies current to these cables from strategically located track-side substations, the resulting magnetic waves cause a direct and immediate reaction by the maglev vehicles to accelerate, cruise, decelerate or brake. At speeds above 80km/h, power is delivered to the maglev vehicles through noncontact linear generators. Power is delivered via contact power rails for lower speeds in and near stations. A series of onboard batteries provide redundant backup power to maintain vehicle levitation in case of any guideway power failures.

In Shanghai, the site's periodic seismic activity and weak alluvial soil, along 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 daunting geotechnical challenges lay in building elevated and rigid guideways sitting atop support piers, a design better suited to difficult geotechnical conditions than a continuous at-grade system. Any 30km long at-grade ballasted rail system on this site with its long exposed surface area would experience constant settling, be more costly to maintain and likely suffer more damage as a result of even a moderate earthquake.

The reinforced-concrete support piers, 1.8m by 1.8m in plan and typically 8m 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 2m deep and 10m to 12m on a side. The caps cover 20 to 24 piles, each 60cm in diameter, that are driven to depths reaching 70m to counter seismic forces and liquefaction.

A geotechnical investigation was performed by engineers 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 7 October and 12 November. CDM reviewed the soil data and chose foundation design parameters in such a way as to ensure smooth and reliable maglev operations. This information was also used to evaluate the possibility of short- and long-term settlement along the track alignment and deformations of the piles.

Since the maximum allowable total deformation of the guideway is 10mm, the geotechnical challenges peculiar to maglev are formidable. These challenges included highly demanding deformation limitations, long term stability of foundations under dynamic loads, analysis of the entire foundation-support-beam system and optimisation of the foundation systems for cost effective design. Deformation considerations included immediate settlement, primary settlement due to consolidation, plastic settlements resulting from secondary consolidation or creep, total plastic settlements due to dead load, total settlements due to cyclical loads from vehicle operations, elastic settlements due to dynamic loads, and total anticipated 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 the 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 centre girder to which

steel cantilevers are bolted, is 62m long, 2.8m wide and 2m high, and weighs 290t. 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 required volumes of steel and the longer lead times for manufacturing. These considerations tipped the scale in favour of the hybrid concrete/steel guideway.

To increase rigidity, engineers from SMTDC and Max Bögl

I-shaped hybrid girders – reinforced-concrete centre girders with steel cantilevers – were chosen to support the guideway as they offered the best rigidity, ride, wear, noise, cost, handling and heat expansion characteristics. PHOTO: TRANSRAPID INTERNATIONAL GMBH & CO KG.

redesigned the shape of the hybrid girder from a T to an I that would be 2.2m high and 2.8m wide. To facilitate handling during construction, the designers also shortened the girder to 25m. 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 0.2mm, enabling the completed cantilever assemblies to satisfy a total tolerance criterion of 1mm 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 26 January 2001, no manufacturing infrastructure for such guideways existed anywhere in the world. One month later, however, construction began on a 1.8km long, climate-controlled facility that would house some very impressive laser-guided milling machines for the mass production of guideways.

Choosing a hybrid beam design enabled the fastest possible deployment of the necessary tooling machines to form and mill all the project's straight and curved beams in lengths of 24.8m down to only 3.1m. Max Bögl developed the logistics and manufacturing concepts that allowed for the simplifying of beam manufacturing that resulted in fast, efficient and economical mass fabrication. The company also provided special software to transfer the digital track data automatically into the CAM-tooling machines for providing real time project fabrication reports. In addition, a sophisticated quality management system was developed to increase awareness and guarantee control of material supply from production and girder storage to delivery and installation.

When the machining plant began operations in the northern autumn of 2001, a pair of specially designed five-axle CNC (computerised numerical control) milling and boring machines were processing hybrid girders. Lasers guided the synchronised machines down the length of each concrete girder to provide final shaping and precise boring for installation of the so called "functional sections," comprising of stator packs, slide rails and lateral guide rails. In addition, eight other special guideway machine tools were designed, manufactured, installed and successfully commissioned by the joint Shenyang China-Czech Friendship Machine Tool Factory in only six months.

The precast plant produced an average of 10 girders a day, seven days a week, and supplied ample reserve capacity to maintain the project schedule, as well as for any future network expansions. Adjacent to the girder plant, a large storage field was used to cure the high-strength concrete girders (34,475kPa) for between 45 and 60 days to minimise long-term creeping and shrinking.

Commanders Wu's vision for developing a maglev guideway network demanded suitable girders for transportation and handling. A major improvement was accomplished with the transition from a double-span design, into the more practical to handle single-span hybrid beam. However, to provide additional flexibility for guideway construction while maintaining the strict deflection requirements, all single-span girders can be coupled to form double-span girders. Based on the success in Shanghai, future projects will have the option to choose between double- or single-span girder designs.

Once the right of way was cleared in March 2001 and construction of the guideway manufacturing facility started near the mid-point of the line, pile driving commenced. Chinese engineers, world class experts with pile driving technology, drove groups of piles every 25m along the entire 30km route in less than nine months – a pace that amazed their German counterparts. Atop the pilings, 4m thick caps were poured. These caps provided the foundation for the reinforced concrete support piers.

German and Chinese engineers and construction crews manufactured, delivered, installed and aligned a total of 2,777 precision guideway girders, curved and straight, to the system in less than 18 months. The majority of the girders (2497), the so-called Type I beams, were approximately 24.8m in length and weighed approximately 190t. To assist in the careful installation of the Type I beams, a temporary rail line was laid along either side of the maglev route to support specially designed gantry cranes. There were 70 Type II beams 12.4m long and 210 maintenance facility beams 3.1m in length.

Installed between the guideways and the top of the support piers are three-way stepless adjustable bearings, designed to enable alignment corrections for eventual settlement. These corrections can be made during daily operations without disturbing maglev service.

While construction in Shanghai progressed, ThyssenKrupp was transforming what had only been a prototype TR-08 maglev vehicle construction facility in Kassel, Germany, into a full-fledged manufacturing plant. The SMTDC ordered 15 vehicles to constitute three five-vehicle consists. Once the Kassel plant was fully converted to mass production, it produced one vehicle per month. The completed vehicles were then shipped to a facility constructed at the end of the Shanghai 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.

Siemens designed, manufactured and delivered all the power electronics for the digitally controlled and operated system, including the two propulsion substations, the central operations control centre in Longyang Road station, the kilometres of specialised power cabling and the 62 microwave data towers along the route. At all times at least one of these towers has a line of sight view of the antennae located atop the maglev's end sections (one on each end). A steady stream of data between the vehicles and the control centre 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 also supervised the installation of these systems.

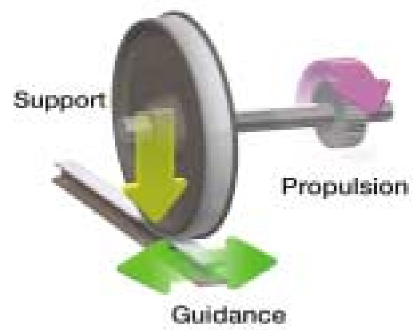
Operation

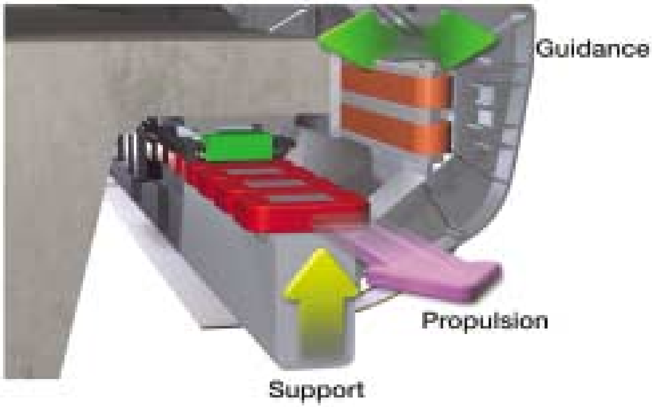
Based on the success of the inaugural ride on 31 December 2002, SMTDC decided to operate the system for visitors on weekends while work proceeded on weekdays in connection with commissioning, safety certification and overall regulatory approval. Daily maglev operations officially began in April 2004, but only during the day, since this remains a demonstration project. The system's operating reliability is now at 99.9% and its maintenance costs are reported to be 33% 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 high speed rail systems are 130km/h slower than this maglev system.

Because the entire system is computer operated and controlled, the SMTDC requires only a small labour 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 labour costs, combined with the advantages the system confers in the areas of speed, reliability and safety, mean that SMTDC can expect a steady and rapid return on investment and even a profit. Wu reported last July that even with a daily volume of only 7000 passengers, which is lower than expected, the system was already able to cover its operating costs. This is significant. No transit system in the world could make that claim based on such low passenger numbers. Even with much higher volumes of passengers, few train or transit systems can survive without government operational and maintenance subsidies.

Not long after service began on the maglev line, a 2mm settlement of one pier was detected and corrected. Contrary to some overblown newspaper accounts of a "sinking maglev guideway", variable settlement patterns of guideway piers was entirely expected, analysed and planned for by all parties involved. When necessary, adjustments can quickly be made to the appropriate bearings to compensate for any deviation.

The two stations built at either end of the route and the indoor





A comparison of the fundamental properties of a traditional rail system (left) and a maglev system (right).

GRAPHIC: TRANSRAPID INTERNATIONAL GMBH & CO KG.

maintenance facility near the airport were designed and built by Chinese companies. The maintenance facility is accessible from the main line via a bendable steel switch that leads to a 3km single spur line. Bendable steel switches at either end of the line allow maglevs to be routed to either side of the station 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 dedicated time to absorb maglev's technical details before the many operational and financial advantages reveal themselves.

In spite of premature claims by some "experts" who claimed the Shanghai project was "expensive", "unworkable" and "unproven technology", the system was built on budget, on time, is ultra-reliable, safe and works. Chinese view their SMTDC maglev airport connector as a huge success and believe its many advantages more than justify the price tag. According to the final financial statement approved by the SMTDC board at the end of April 2004, the total costs of the Shanghai Transrapid line were US$1.198 billion. This figure includes building the guideway, purchasing 15 vehicles, substations, the 3km single guideway maintenance spur line, the maintenance facility, the bendable steel switches, auxiliary equipment and interest during the construction phase. If this total is applied to the 30km main line, the average per-kilometre price is US$39.759 million. The per kilometre price of the guideway construction, exclusive of ancillary items, is naturally lower and expected to drop as new construction and manufacturing techniques evolve. It should also be noted that guideway costs are also site and project specific, and that this first ever project was built to extremely high standards and with a price tag that reflects a premium for an expedited construction schedule.

By comparison, according to Wu, Shanghai's four-year-old Mingzhu (Pearl of the Orient) elevated rail line cost US$44.578 million per kilometre, and the per-kilometre 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 US$40 million per kilometre, Wu said, and in some cases that figure does not include the vehicles.

Future of maglev

Last 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 both extend the initial operating segment 7km into the city and to link Shanghai to the city of Hangzhou, 163km to the southwest, which would create the world's first intercity maglev line. Nanjing, about 300km to the west of Shanghai, is also being considered for a maglev route.

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, DC; and one linking Pittsburgh International Airport to the surrounding region.

One thing is perfectly clear from this project, the Chinese have gained valuable technological experience building the world's first commercial maglev and will continue to do so. What is less clear in this new world environment of tightening world oil supplies, is when countries with transportation systems that are almost totally dependent upon oil wake up and begin to rebuild their transportation systems to run on eletricity. As the most fuel efficient high-speed transportation ever invented, intercity high-speed maglev travel can only become more attractive as oil prices rise.

The Shanghai maglev system now validates the vision, effort and resources expended over the last 30 years by all who worked toward making this technology a reality. This engineering marvel now stands as a stirring symbol of achievement for both German and Chinese engineering and represents the new standard for high-speed gound transportation.