Overview of the 2004 Magplane Design

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Abstract:

The Magplane uses on-board permanent magnets that interact with levitation sheets on the guideway to provide lift above an 18 km/hr velocity and a 10 cm gap. A linear synchronous motor in the guideway provides propulsion. The lift pads are mounted on an active secondary suspension to provide damping of external disturbances. The vehicle can freely bank by +/- 10 degrees in curves. The intra-city version of the vehicle, with a maximum speed of 160 km/hr uses a standard transit vehicle body and under nominal loading carries 315 standing and sitting passengers. The higher speed intercity vehicles utilize aerodynamic shaping and aerodynamic control surfaces for enhanced external disturbance damping capability.

Introduction

The engineering basis of the basic Magplane configuration was extensively analyzed in the 1992 “Concept Definition Studies” commissioned by the US Federal Railway Administration [1]. Since that time, the design has evolved to result in greater simplicity and wider market applicability [2].

The most significant technology change from the 1992 design involves the replacement of the superconducting systems with permanent magnet systems. This reduces the vehicle operational complexity and reduces the number of potential failure modes, but results in some compromises: (1) To limit the weight of the permanent magnet systems, the operating gap has been reduced from 15 cm to 10 cm. The gap remains large enough however, to remove accuracy and stiffness of the guideway as a cost driver. (2) The weight of the permanent magnets in the baseline case is 40 % greater than the weight of the previous superconducting system.

The 1992 design studies focused on performance at a cruise speed of 500 km/hr in an inter-city high speed application. The current design has been modified to serve the much larger “intra-city” travel market and satellite city interconnections. This market can be readily met with speeds below 160 km /hr, allowing the use of less costly vehicle technology.

With the 10 cm operating gap, the magnetic suspension remains relatively resilient. It is also under damped, requiring that additional damping be supplied. In the 1992 design, damping was supplied at high speed by active aerodynamic control surfaces, and at low speed by Linear Synchronous Motor phase control. In the new baseline design, damping is supplied at all speeds by mounting the lift pads from an active secondary suspension.

The “take-off velocity “of the lift pad system is 5 m/s (18 km/hr). Below takeoff speed, the vehicle is supported on rubber tires. To avoid the electromagnetic “drag peak” and minimize take-off thrust requirements, the lift pads are withdrawn into the vehicle body prior to take-off and only deployed when take-off speed has been obtained.

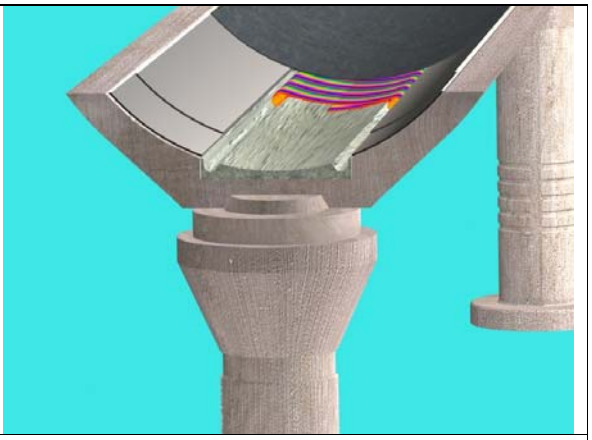
The Magplane system guideway in the 1992 design was an open semi-circular aluminum trough, with radius of 2.1 m and width of 4.5 m, consisting of three parts: a center linear synchronous motor winding flanked on each side by curved aluminum levitation plates; and supported by integral aluminum box beams. The 2004 baseline design span structure is largely concrete. The levitation surface sheet is retained, but all structural support for the 30 m span is derived from the pre-cast trough-like span.

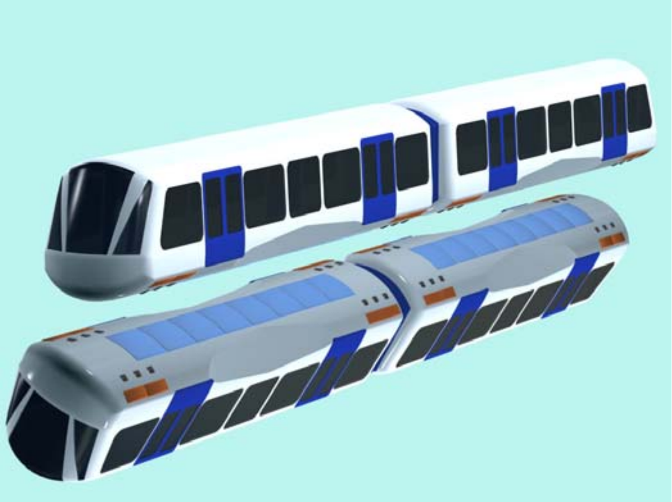
Magplane Configuration

The general Magplane configuration is illustrated in Figures 1 through 4.

The conducting levitation structures are two half thickness laminated sheets with displaced joints. No electrical conductivity is required between sheets or across gaps. The sheets are attached to the span structure by edge clamps that allow for differential expansion. The surface of the conducting sheets and the Linear Synchronous Motor are covered by an asphalt protective layer. The guideways will carry walkways (not shown) for emergency exit mounted from the upper lip of the trough. The guideway incorporates appropriate drainage for rain water. A nominal depth of snow or ice coverage is allowed, but larger accumulations would be removed by a special snow-blower vehicle.

Large radius of curvature horizontal and vertical curves in the guideway would use straight spans, but smooth out the span-to-span discontinuities by using on-site assembly tooling to compound bend and fit the levitation sheets with appropriate structural interface to the concrete span. Small radius of curvature curves would use special pre-cast spans with appropriate curvature.

	
Figure 1: 30 meter trough-like concrete span with surface mounted levitation sheets and a motor winding directly below the vehicle.	Figure 2: Expanded view illustrating the motor winding and structural insert. The emergency exit walkways and water drainage details are not shown.

	
Figure 3: End-on view illustrating the large operating gap.	Figure 4: Transit vehicle illustrating lift pads, propulsion magnets and wheels.

Lift Magnets

The onboard lift and propulsion permanent magnets use neodymium-iron-boron materials. The magnets are arranged as “Halbach arrays” which result in the maximum magnetic field at the guideway for a given weight of magnets, and at the same time result in the minimum magnetic field in the passenger cabin.

The maximum lift for a given weight of magnet is achieved when the magnets are concentrated over relatively limited areas, but with significant array height. With a near optimum wavelength of 1 m and an array thickness of 0.2 m, sufficient lift can be achieved with 4 pads that are each 2 m long (two wave lengths), and 0.48 m wide. With a lift pad magnet weight of 5.9 tonnes, and a loaded vehicle weight of 32 tonnes, the lift to magnet weight ratio is 5.4

The magnet portion of one wavelength of a typical lift pads is illustrated in Figure 5. The surface field at the pad is 0.85 Tesla, and 10 cm distance at the guideway surface, is 0.45 T. The baseline design uses a somewhat wider pad measuring 48 cm.

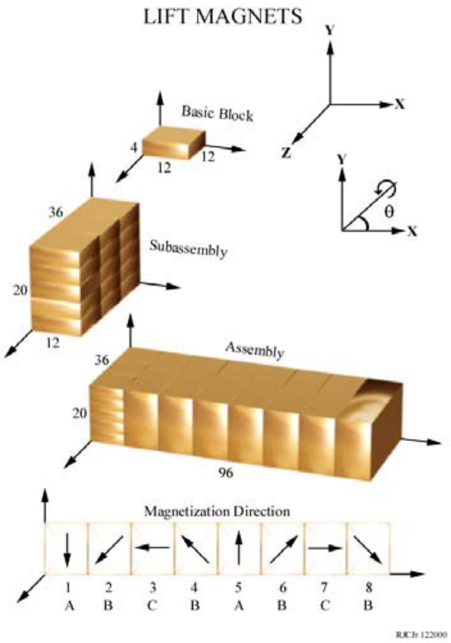


Figure 5: Lift Pad magnetic structure built from magnetized unit blocks.

The lift and drag as a function of velocity is illustrated in Figure 6 for the case of a 2 cm thick sheet of copper.

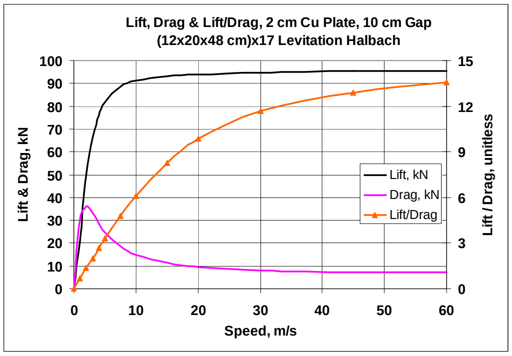


Figure 6: Lift, Drag, L/D (3-D analysis)

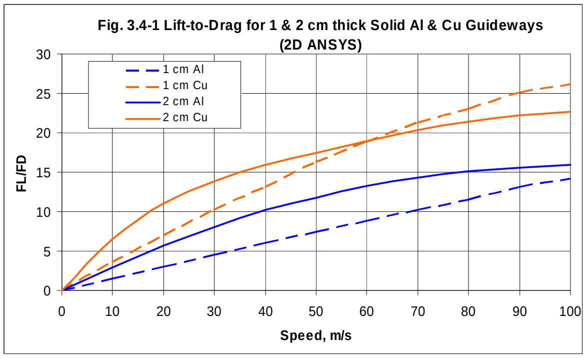


Figure 7: L/D ratio (2-D analysis)

For cases of equal lift, the drag at a given velocity is dependent on the guideway conductivity. Figure 7 illustrated the lift over drag ratio for copper and aluminum and as a function of sheet thickness. At velocities of 20 m/s, a 2 cm copper sheet has 50% the drag of a 2 cm aluminum sheet. At 100 m/s, the difference is smaller, the drag of a copper sheet being only 30 % less than the aluminum. More apparent from the figure at high velocities, is that 1 cm thick sheets are as effective as 2 cm thick sheets for both materials. The figures suggest that copper should be used at a minimum in the lowest speed portions of an intercity guideway, for example at the station platform exits where the vehicle is accelerating to cruise velocity. They also suggest that intracity systems, where speeds are likely to always be less than 40 m/s, copper can profitably be used throughout. The increased capital cost of copper is offset by the reduced electrical cost.

Propulsion Magnets

Unlike the lift magnets, which optimize for relative thick arrays of limited frontal area, the maximum motor thrust for a given weight of propulsion magnet is achieved by maximizing the area of the engagement of the onboard magnet with the LSM winding. The magnets are therefore optimally distributed along the largest practical fraction of the vehicle length. The thicker the magnet array over the vehicle length, the greater will be the field at the guideway winding, and the lower the current and resistive power necessary to achieve a given thrust. On the other hand, the thicker the array, the heavier and more costly will be the on-board magnets. The baseline design uses a propulsion array thickness of 0.08 m over a 1 m width and a ten wave length, 10 meter length. The propulsion magnets weigh 5.6 tonnes.

Shaping the thickness of the array rather than using a fixed 8 cm thickness can further optimize the propulsion magnet as shown in Figure 8. Such a magnet cross-section produces the maximum thrust for a given weight of magnet. The field at the surface of the magnet is 0.47 Tesla, and 10 cm away at the surface of the winding, is 0.25 Tesla.

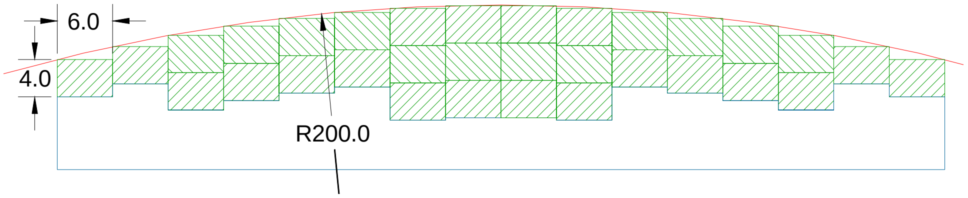


Figure 8: Optimized Cross-section Propulsion Magnet

Linear Synchronous Motor

The Linear Synchronous Motor propulsion winding wavelength is 1 meter. The winding is a "helical winding" with six flat conductors bundles (3 phases outgoing and 3 phases returning). The motor modules are 10 meters in length, requiring 3 modules in series to match the guideway spans. The helical winding is formed to fit and bonded to a structural insert which is subsequently transported to and installed in the guideway span beam.

The construction of the motor will follow that used in the Magplane tube transport project built for IMC Agrico to demonstrate phosphate ore transport from the mine to the processing plant [3].

The length of control blocks for the Linear Synchronous Motor need to be approximately half the length of the separation of vehicles. There can be only one vehicle per control block, and at least one empty block needs to be located between vehicles to satisfy the overall position control logic that prevents a vehicle from entering the block until the previous vehicle has exited the block.

Control blocks can be subdivided to minimize resistive loses by exciting only that portion of the motor in the immediate vicinity of the vehicle. These sub-blocks are sequentially energized by local switches that connect the sub-blocks to the control block motor drive. Sub-blocks in the Magplane Baseline design are 300 m in length. Control block lengths are dependent of the vehicle spacing, which in turn is dependent on speed and frequency of stations.

A minimum of one motor drive is required for each vehicle in operation. A second motor may be required in each control block to assure a smooth transition between blocks and sub-blocks. The motor drives are based on commercial rotary motor drive units

Table 1: LSM Motor Drive Characteristics for the Coupled Pair of Vehicles in Figure 1.

Block length: 300 m **Acceleration: 0.15 g** Speed: 50 m/s Drive Frequency: 52 Hz RMS current per phase: 5820 A RMS current/cable: 485 A Inductive RMS voltage: 1517 V Resistive RMS voltage: 509 V EMF RMS Voltage: 438 V Total RMS Voltage: 1796 V Total RMS volt ampere: 10.5 MVA	Block length: 300 m **Acceleration: 0 acceleration (cruise)** Speed: 50 m/s Drive Frequency: 52 Hz RMS current per phase: 3168 A RMS current/cable: 264 A Inductive RMS voltage: 826 V Resistive RMS voltage: 278 V EMF RMS Voltage: 438 V Total RMS Voltage: 1098 V Total RMS volt ampere: 3.5 MVA

Under power failure conditions, the motor drives loose the capability to control deceleration. However, the windings can be automatically shorted and will decelerate the vehicle through drag. The drag currents generated are a function of the length of the sub-sections shorted as indicated in Table 2. In the shortest length shown, a shorting switch has been placed at the end of each 30 meter module.

Table 2: Emergency Braking in the Event of Power Loss to the AC Converters

Initial Velocity (m/s)	Deceleration (g)	Distance Traveled (m)	Shorted Winding Length (m)
80	0.129	2584	300
50	0.137	955	300
20	0.190	111	300

Vehicles

The intercity high speed Magplane vehicle is designed to require that all passengers be seated and utilizes a five-across aircraft-type seating arrangement. An average passenger density of 2 passengers/m^2 is achieved in the seating area.

The Magplane intra-city vehicle uses a car body similar to the conventional transit vehicle. The two vehicle set is articulated in the middle, and allows accommodation to smaller minimum radius curves than would be possible without articulation. The intra-city vehicles assume 4 passengers/m^2 under normal loading, and up to 8 passengers/m^2 for “crush load” conditions and provide for full standing height throughout the car except where there is a minimal seating of 32 seats per car.

The trough-like geometry allows the Magplane vehicles to bank naturally in the guideway by up to +/- 10 degrees and in doing so, eliminate the lateral acceleration when traversing curves. Larger bank angles can be used, but they introduce the complexity in the curves that special guideway sections be used exhibiting motor windings that are rotated relative to their orientation in the straight sections. The minimum radius of curvature in the exit ramps is 100 m.

Figure 9: Passive banking in curves of +/- 10 degrees

Radius	Angle (deg)	Speed (km/hr)
2000	10	210
1500	10	182
1000	10	149
500	10	106

Table 2: Coordinated turn bank angle

The vehicle wheels are oriented at an angle of 20 degrees and are permanently deployed to protrude 3 cm beyond the vehicle skin. Permanent deployment provides an important safety feature in eliminating all failure modes connected with failure to deploy.

Vehicle Dynamics

While inherently stable, the suspension is very resilient, and oscillations around the stable point are under-damped. To maintain passenger comfort it is necessary to provide active damping by a combination of three techniques [4].

(1) At low speed the primary damping mechanism is by mechanical control of the position of the lift pads relative to the guideway surface. The lift pads are mounted to the vehicle body through an “active secondary suspension” system. Analysis indicates that this secondary suspension can use conventional rail or truck air springs and dampers, but will require a servo controlled electromagnetic actuator in parallel with the air spring and damper to control the relative displacement of the car body and lift pad surface. The active suspension isolates the vehicle from high frequency guideway irregularities, and the low frequency car body displacements when traversing curves or when encountering strong wind gusts. The active suspension control will have a frequency response in the 5 Hz range. Non-linear springs and end-stop limits will be used to limit maximum excursions of the car body relative to the lift pads.

(2) Attitude control damping of all modes at speeds above ~70m/s can also be supplied by relatively small aerodynamic control surfaces. This is more energy efficient than lift pad position control at these higher speeds and aerodynamic surfaces will therefore be used on the higher speed intercity vehicles.

(3) Attitude control damping at all speeds of “heave” oscillations can also be supplied by varying the thrust angle on the LSM to vary the lift component of thrust. Since all modes are coupled in the trough-like guideway, controlling heave modes will damp all modes. Use of the LSM to provide heave damping was the principle method used on an early 1/25th scale model experiment [5]. Use of the LSM for damping overlaps with (1) and (2) and offers some system redundancy.

System Capacity

The transit vehicles have a nominal passenger capacity of 315 seating and standing passengers. At 90 second headway, the vehicles will carry 12,500 passengers per hour in each direction. Coupling two such permanently coupled pairs of vehicles raises the capacity to 25,000 passengers in each direction. Crush load capacity of such a coupled set would be 40,000 passengers per hour. A minimum separation of 90 seconds is used to match the current state-of-the-art of commercially available transit-industry automatic control system.

Guideway Switches

The trough-like geometry allows a no-moving-parts magnetic switch as illustrated in Figure 10 showing the high speed vehicle part way through a switch section. The lift and guidance that would normally have come from the right-hand lift pad is replaced in the wide section of the switch by lift produced by the interaction of the propulsion magnets with lift and guidance magnetic structures below the vehicle. A mechanical switch alternate option is illustrated in Figure 11.

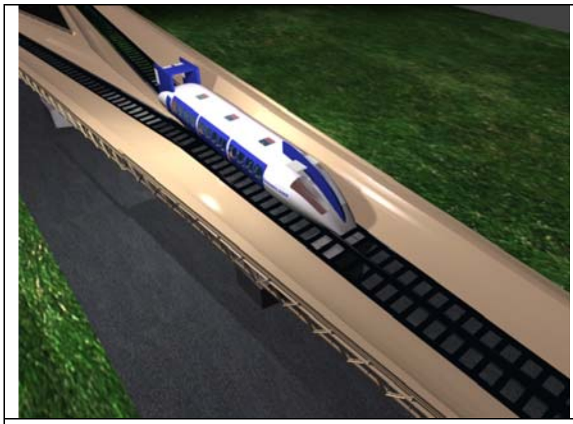


Figure 10: Magnetic Switch	Figure 11: Mechanical Switch

Prototype Test Facilities

A 500 m long full-scale test track will be built in 2005 in the US along a straight section of unused railway right of way. The principal use of the test track, where peak vehicle speeds of 80 km/hr can be achieved, will be to demonstrate the integration of the control systems.

A 2,000 m long test track will be built in China to be operational in 2006 in an oval configuration. The principle use of the test track, where peak speeds of 160 km/hr can be achieved, will be to demonstrate component life and to obtain preliminary system safety qualification.

Acknowledgement

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