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THE CONCEPT OF THE MECHANICALLY ACTIVE GUIDEWAY AS A NOVEL APPROACH TO MAGLEV

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Abstract:

A maglev system suitable for operation in the United States has to meet unique requirements which determine the major system characteristics. Maglev configurations presently developed in Germany and Japan are based on conventional maglev concepts and as such do not meet all of the requirements. A novel maglev guideway concept is introduced as a solution. This concept, the mechanically active guideway, is articulated in three degrees of freedom and assumes system functions which normally reside in the maglev vehicle. The mechanically active guideway contains spatially distributed actuators which are energized under computer control at the time of vehicle passage to achieve bank angle adjustment and ride quality control. A typical realization of the concept is outlined.

1.Introduction:

The United States represents a unique environment for a maglev system. The size of the country, the location and the nature of the population centers are different from other areas of the world, and travel in terms of passenger miles per capita, for both business and pleasure, is substantially higher than in any other nation. By far the largest amount of travel is done by automobile over short to medium distances, a fact which is becoming less desirable from both economic and environmental viewpoints. Longer distance travel is done primarily by air, which is energy intensive and also detrimental to the environment. Efforts are underway to curtail the dependence of transportation on oil imports by promoting mass transit, and by doing so to simultaneously reduce pollutants. Conventional rail based mass transit is limited by insufficient connectivity with other transportation modes and by relatively low speed, for short as well as long distance travel. Maglev promises to circumvent these limitations by offering an alternative mass transit mode.

A maglev system to be suitable to the United States has to meet a set of requirements which result from the uniqueness of the environment within which it has to operate. These requirements are the following:

(1) It must use existing right of ways, such as the median of interstate highways. The acquisition of new right of ways in highly populated areas would incur unacceptable initial capital cost.

(2) It has to be able to carry high passenger loads, on the order of 50000 per hour per track, to justify and amortize the high initial capital investment.

(3) It must be capable of high speeds, comparable to average block speed of air carriers, which is in excess of 300 miles per hour.

(4) It must be able to serve stations at less than 20 mile intervals.

(5) It has to be energy efficient, consuming less than 20 MW per mile, in bidirectional traffic.

(6) It must be connectable to other transportation systems, like rail, subways, and highways.

(7) It must have low construction costs, preferably 20 million dollars or less, per mile.

(8) It must offer superior ride comfort compared to other means of transportation

(9) It must be reliable and require low maintenance.

(10) It has to have low environmental impact and must be aesthetic in appearance.

Some of these requirements have a great degree of influence on system characteristics of maglevs suitable for operation in the United States.

The requirement of using existing right of ways (1), for instance, dictates that the maglev be capable of negotiating tight turns, with radii of about 1.5 miles, which are typical for the interstate highway system, and railroads. Adding the requirement of high speed (3) dictates that the turns must be made at substantial bank angles, to avoid excessive side forces detrimental to stability and passenger ride comfort.

High passenger loads (2) and short distances between stations (4) can only be met by provisions for off-track loading, so that the guideway is not occupied by parked maglevs, keeping other maglevs from transiting.

Energy efficiency (5), low construction cost (7), together with environmental and aesthetic considerations (10) require light weight cars, which in turn allow lighter guideway construction, but may compromise ride comfort (8).

Some of these requirements may be difficult if not outright impossible to meet with current maglev concepts upon which the maglev configurations presently developed in Germany and Japan are based. Meeting the requirements above becomes tractable, however, if conventional concepts, such as a fixed guideway, are abandoned.

The concept of the mechanically active guideway is introduced here. This guideway has limited articulation in three degrees of freedom and thus assumes functions which conventionally reside in the maglev vehicle. The concept of the mechanically active guideway was evolved from functions which the maglev system has to perform to meet the requirements listed above. Some of these functions will be analyzed below and the mechanically active guideway concept will be described.

2. Control of Bank:

To execute tight turns at high speed, the turning of the maglev vehicle has to be "coordinated". This is a term common in aviation with the meaning that the direction of the vector sum of gravity acceleration and centrifugal acceleration is perpendicular to the grand plane of the vehicle, resulting in new ride forces.

The centrifugal accelerations of a vehicle moving at a velocity v on a track with a radius of curvative R is

$$a_c = v^2/R \tag{1}$$

To achieve the new ride force condition the vehicle has to bank at an angle

$$\beta = \arctan(a_c/g) = \arctan(v^2/gR) \tag{2}$$

The total acceleration, the vector sum of centrifugal acceleration and gravity acceleration is then

$$a_t = (g^2 + a_c{}^2)^{1/2} \quad (3)$$

or

$$a_t = [g^2 + v^4/R^2]^{1/2} \quad (4)$$

This total acceleration is higher than the acceleration due to gravity, and the passengers of the vehicle will experience higher "g-forces" resulting in higher weight. While a small increase in weight may be hardly noticable, larger increases could result in physiological effects well known in military aviation.

From (2) and (4) we get the total acceleration as a function of bank angle

$$a_t = (1 + \tan^2 \beta) \quad (5)$$

This function is tabulated below

β	a_t
15°	1.035
30°	1.155
45°	1.414
60°	2.000
75°	3.864

Table 1

The radius of curvature of a coordinated turn negotiated at a given vehicle speed is obtained as

$$R = v^2/b \tan\beta \quad (6)$$

which is tabulated below for two speeds, 300 km/hr and 500 km/hr

ß	R(m)	
	300 km/hr	500 km/hr
15°	2442	7350
30°	1226	3411
45°	708	1970
60°	409	1137
75°	190	527

Table 2

Again, there is a strong dependence on bank angle.

The radius of a turn determined by a given rate of total acceleration, normalized to the acceleration due to gravity is determined from (2) and (5) as

$$R = v^2/g(\alpha^2 - 1)^{1/2} \qquad (7)$$

where α is the ratio of total acceleration to acceleration due to gravity. This radius is tabulated below as a function of percent acceleration increase over gravity.

ß	R(m)	
	300 km/hr	500 km/hr
10%	1545	4298
20%	1067	2969
50%	633	1762
100%	408	1137

Table 3

The minimum turn radius of a maglev vehicle is thus determined by the maximum acceleration tolerated by the passengers. Assuming that a 50% increase in perceived body weight is tolerable the corresponding minimum turn radius would be 1762 meters, or a little more than one mile, at the speed of 500 kilometers per hour, or 312 miles per hour.

Entering turns can be accomplished at a minimum discomfort for the passengers by gradually increasing the bank angle until the value corresponding to vehicle speed and the turn radius is reached. Exiting turns is accomplished in reverse order. If the bank angle is increased linearly (constant rate of increase) with time for turn entering and exiting, then according to (2) the instantaneous turn radius of the transition section is defined by the differential equation

$$d/dt\ \{\arctan[v^2/gR(t)]\} = \text{const} \qquad (8)$$

which, since $1/R(t) = K(t)$, the instantaneous curvature of the path, equation (8) then becomes:

$$d/dt\ \{\arctan[v^2K(t)/g]\} = \text{const} \qquad (9)$$

In Cartesian coordinates, with the directon of travel before turning aligned with the x-axis, and the incidence of turn centered at the origin, the path is defined by the differential equation

$$\frac{d}{dt}\left\{\arctan\left[v^2 y''(x)/g(1+y'(x)^2)^{3/2}\right]\right\} = \text{const} \qquad (10)$$

where the constant is equal to the rate of change of the bank angle. One has to assure that sufficient time is allocated to complete the turn.

The immediate conclusion which can be drawn from the above results is that the bank angles of maglev guideways has to be substantial if existing right of ways with their tight turn radii are to be used. Furthermore, for a given turn radius the bank angles of the guideway required for coordinated turns (zero side forces) is strongly dependent on the speed. Significant side forces would result causing unacceptable discomfort to the passengers if the maglev vehicle were to deviate from the optimum speed required for a given bank angle. Forced speed deviations have to be expected, however, as a result of a number of conditions like system congestion and meteorological effects. In addition, one would also have to account for system power failures which would result in loss of propulsion with the vehicles coming to rest in turns at a very high bank angle, a condition equally if not more unacceptable to passengers. Constructing maglev guideways on existing right of ways, with fixed, high bank angles is therefore an unrealistic proposition.

3. Suspensions:

One of the most important characteristicsof maglev systems is the stiffness of the primary suspension, which is primarily related to the weight of the maglev vehicle (including the bogies, if present) and the maximum permissible levitation gap variation, which should not exceed a small fraction (about 10-15%) of the levitation gap.

The electromagnetic maglev system has the highest primary suspension stiffness. At the typical maglev vehicle loaded weight (such as the German TR-07) of 53 metric tons distributed over sixteen levitation magnet sections, and a maximum levitation gap variation of about one millimeter (12.5% of the levitation gap), the stiffness of the individual levitation magnet section is about 32.5 Mega Newtons per meter.

Electrodynamic maglev system primary suspensions with their larger gaps have proportionally smaller stiffness. In this case, however, one has to further distinquish between repulsive bottom suspension and null-flux sidewall suspension. Contrary to the former, the stiffness of the latter is dependent on vehicle speed. Vertical stiffness component values for bottom suspension of 2.7 Mega Newtons per meter have been reported for the Japanese maglev system. The reported null-flux sidewall suspension stiffness values range between 3.82 and 7.05 Mega Newtons per meter over the speed range of levitation.

Even smaller stiffness values are expected for the Magneplane system, primarily as a result of the very large levitation gap of 25 centimeters and the commensurately larger allowable relative gap variations, which could be as large as 50% of the levitation gap width. The stiffness in this case is also nonlinear, which reflects the behavior of the electrodynamic forces over these large relative levitation gap excursions.

The stiffness of the suspension together with the mass of the portion of the car supported by it determines the natural frequency of the system. This natural frequency is given by

$$w_n = (\sigma/M)^{1/2} \tag{11}$$

where σ is the stiffness of the suspension element and M the mass supported by it. For the electromagnetic maglev system the natural frequency of the primary suspension is thus about 16 Hertz, while for the electrodynamic maglev system and the Magne Plane system, the natural frequencies are in the ranges of 4.5-7.3 Hertz and 1.2-1.7 Hertz respectively. The natural frequency of a suspension system has direct bearing on ride comfort as a result of the vibrational components transmitted to the passengers due to the guideway irregularities. Generally speaking, the higher the frequency components (the sharper the bumps) the more unpleasant the ride.

The primary suspension characteristics of the various maglev systems are summarized in Table 4 below.

System	Levitation Gap (m)	Stiffness (Nm^{-1})	Frequency (Hz)
EMS			
TR-7	8.5×10^{-3}	3.25×10^{7}	16.0
EDS			
Sheet	1.0×10^{-1}	2.70×10^{6}	4.5
Null Flux		3.82×10^{6} - 7.05×10^{6}	5.3 - 7.3
Magne Plane	2.5×10^{-1}	1.90×10^{5}	1.2

Table 4

With the possible exception of the Magne Plane described by KOLM[1], the primary suspensions of the listed maglev systems are too stiff. Either massive, highly accurate and thus expensive guideway structures will be required, which will also be aesthetically unattractive, or the maglev vehicles will have to be equipped with secondary suspensions. The latter would increase the complexity of the maglev vehicles substantially, and thus be counter to the maglev vehicle design philosophy of simplicity.

4. Realizations:

The mechanically active guideway is, in principle, compatible with both electromagnetic (EMS) and electrodynamic maglev concepts. Only an elctrodynamic realization will be discussed in the following.

Such a possible realization of the active guideway makes use of a box beam track (guideway) of triangular cross section, shown in Figure 1. The beam is hollow, open to the bottom for access, and could thus contain the various power and signal cables needed for the operation of the system. A similar concept employing a beam of rectangular cross section has been proposed by THORNTON[2] The propulsion magnets are flush mounted in the box beam. The box beam is extruded from aluminum alloy in sections which are welded together on site to form a continuous track. Curvatures for turn sections could be built in during the manufacturing process. Such curvatures would only amount to about 0.07 degrees per meter deviation from straightness, at the minimum turn radius.

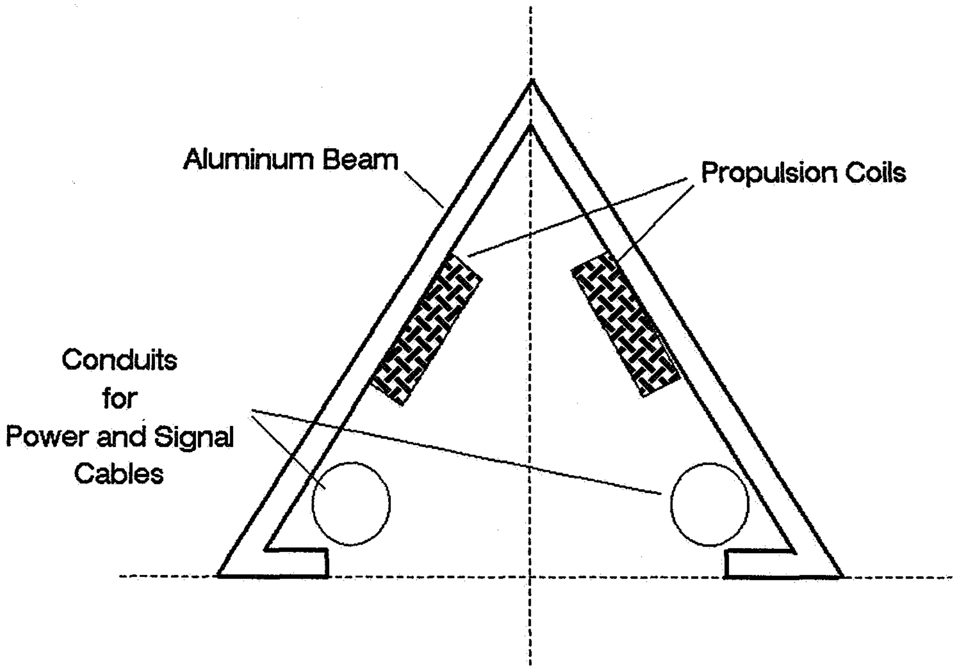

Figure 1
Guideway Box Beam

The metal beam track is secured to the concrete structure by means of actuators which would effect elastic deformations of the track for horizontal and vertical alignment and also for bank angle control. A typical cross section of such an arrangement is shown in Figure 2.

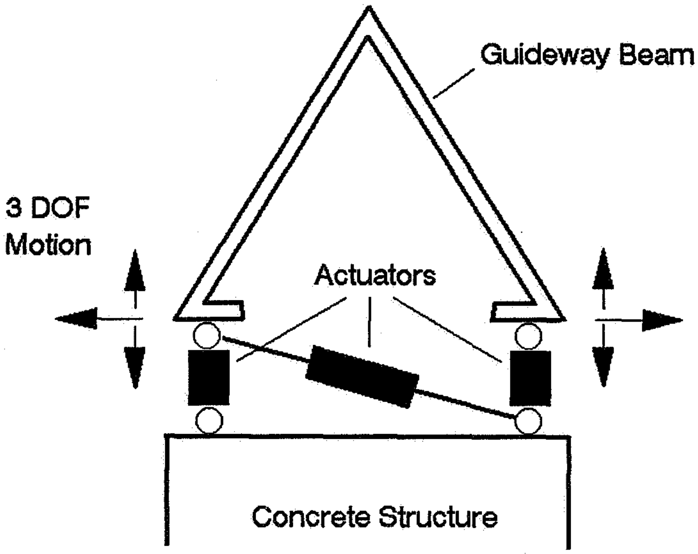

Figure 2
Guideway Beam Mounting

There are several advantages to a triangular cross section. The most important one is the greatly reduced stiffness of the suspension by the particular vector summation of the forces. Another advantage is that this cross section is easily deformable by twisting, requiring minimal actuator forces, while maintaining good mechanical stability in the vertical and horizontal directions. Furthermore, this profile makes efficient use of material. Additional advantages are incurred in the design of the vehicles riding such beams in terms of stability, efficient utilization of space, and better containment of stray magnetic fields. Better access and maintainability of guideway and vehicles are yet further benefits. Finally, there is one more very important consideration. A guideway of a triangular cross section of this kind would not permit debris to accumulate on its surface. A typical maglev car cross section on a triangular guideway is shown in Figure 3.

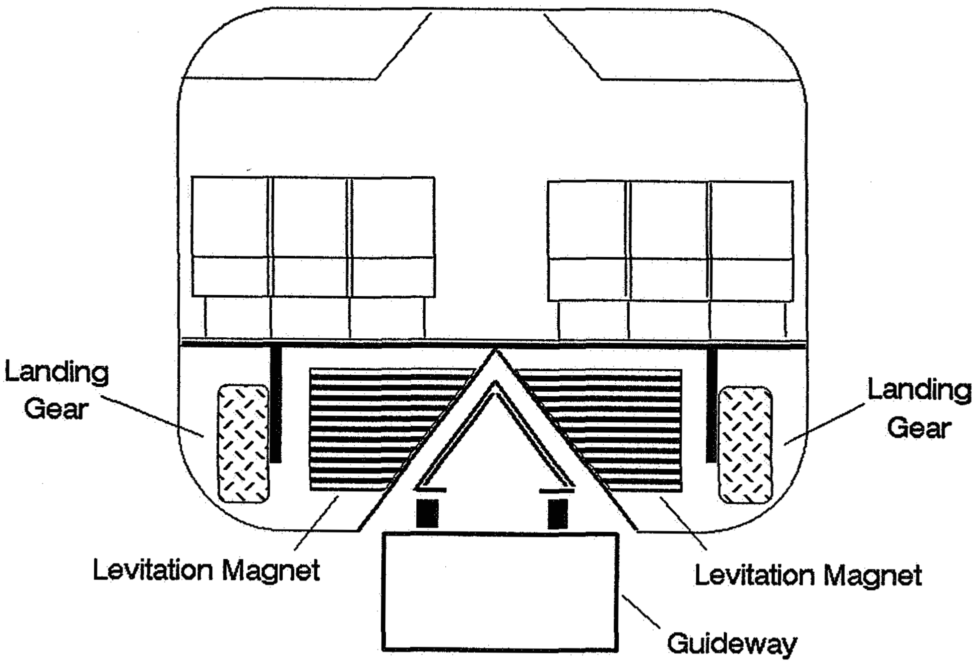

Figure 3
Typical Maglev Car

While two axis alignment would only require slight deformations, bank angle control appears to be significant at first. After all, the high speed turns at the minimum turn radii require bank angles of about 50 degrees. These bank angles, however, are achieved gradually. For a 30 degree course change, the length for the curved guideway at the minimum turn radius of 2000 meters would be about 1050 meters. Since the turn will commence with gradual change of bank angle, 500 meter long lead sections will be added for roll in and roll out. The distance over which the full bank angle will have to be established (and disestablished) is 1000 meters. The maximum torsional distortion (twisting) of the box beam required is 0.05 degrees per meter. The torque required to affect such a small deformation would be about $2x10^4$ Newton meters. This would be well within the elastic range of the material. Figure 4. shows such a maglev turn.

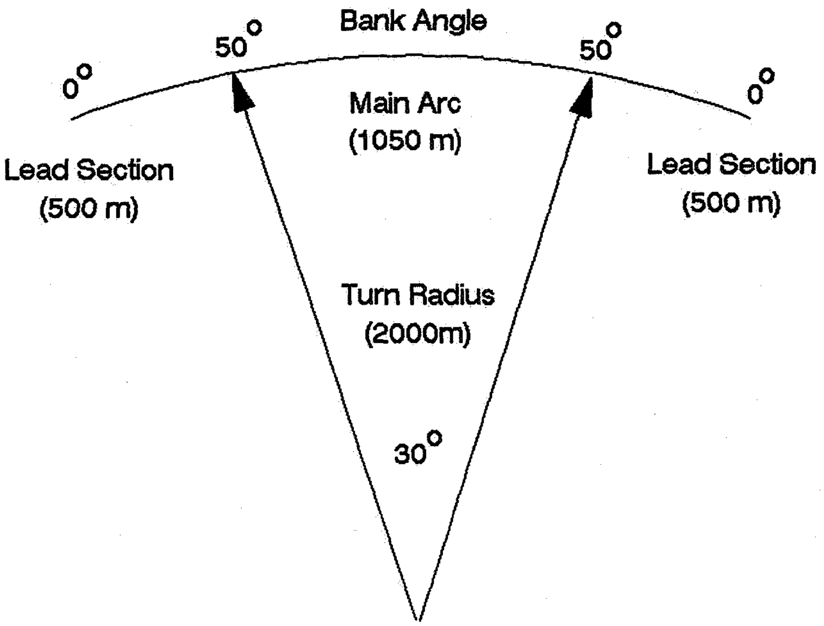

Figure 4
Typical Maglev Turn

The above example of transitioning from a level, straight section guideway to a maximum turning rate of about 50 degree bank angle is, of course, an extreme. The actuators will not have to exercise the full excursion of 50 degrees but only a fraction of this angle, since the guideway will be prebanked for some nominal speed, typically above minimum speed for levitation. The actuators would only have to fine-adjust this already existing bank angle to assure maximum coordination of the turn. The torsional stresses in the guideway sections as a result of actuator movements would therefore be less than in the example given above.

Electromechanical, as well as hydraulic actuators, could be employed to affect the required deformations of the track. Both types are very reliable. Electromechanical ones have the slight advantage that they could be powered directly from the electrical power feed and do not require the added complexity of hydraulic lines.

The actuators would be controlled globally as well as locally. Globally, from a central computer, in response to system wide parameters such as vehicle speed, traffic density, and environmental variables such as temperature, which can cause distortions of the guideway, and also tectonic activity which may occur in rare circumstances. Local control variables would be derived from sensors on the vehicles measuring vertical and lateral acceleration levels, turn coordination, and load.

The large number of actuators distributed along the guideway would assure high tolerance to individual actuator failures. Graceful degradation of the active guideway control process would be a direct result of this high degree of system redundancy. Single actuator failure would hardly be noticeable in system performance but could readily be detected by self diagnostics provisions built into the actuator control process.

Power distribution to the guideway will be similar to other maglev systems. Typically meandering windings will form the propulsion coils which will be fed by power supply and conditioning units from wayside stations. The separation of these stations will be nominally about one mile. These wayside units will be fed by the power grid. The output voltage and frequency of these units will be set locally by computer control, in response to sensors located in the passing vehicles, and also in accordance with overall system commands given by a central control computer.

5. Conclusions

The mechanically active guideway deviates from the conventional maglev concept because it is not fixed and rigid in its installation. It is articulated in three degrees of freedom and accommodates vibration damping, bank angle control, and responds to load variations as well. This latter point may result in substantial cost savings in guideway construction in spite of greater system complexity since the capability of dynamic adjustments will allow less massive and thus less expensive concrete structures.

The mechanically active guideway concept may be paramount to making maglev a viable transportation system in the United States because of its adaptability to existing right of ways. It will further offer superior ride confort, low environmental impact, and aesthetically pleasing appearance.

Finally, the mechanically active guideway concept represents a new design philosophy for maglev. This design philosophy recognizes the importance of coordinated turns, which are essential to tight turning radii at high speeds. It transfers many functions such as suspension, propulsion, control, and system monitoring from the vehicle to the guideway. This novel thinking, together with abandonment of a fixed, rigid guideway, severs maglevs traditional ties to its railroad heritage and establishes it as a new mode of transportation in its own right. It recognizes that maglev is not just another railroad.

6. References:

(1) H. H. Kolm, Scientific American Vol 229, No4 (Oct 1973)

(2) R. D. Thornton, Technology Review, April 1991