EDS Levitation and Guidance Using Sheet Guideways

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Abstract

Electrically conducting sheet guideways for levitation offer potential advantages over discrete coil guideways in construction cost and ride quality. Sheet configurations, however, have lower electromagnetic lift to drag ratios than some coil-based EDS (eg- null-flux systems). Sheet guideways can have a large operational clearance capability if superconducting coils are used, and they are sufficiently "soft" so that a secondary suspension is not necessary on the vehicle. To compensate for the low damping constant of the suspension, however, feedback control using the propulsion system, aerodynamic control sufaces or other means are required. The lift and drag forces are essentially constant at a given velocity for a sheet guideway as opposed to coil based EDS guideways in which the discrete nature of the coils necessarily results in time varying forces and, in turn, induced vibrations. Parametric results for sheet guideway levitation are presented for lift, drag, and minimum lift-off velocity, together with estimated spring constants for guidance in sample configurations. Design examples are presented and the potential advantages discussed. The latter includes lift per unit weight and drag per unit weight estimates for superconducting and permanent magnet levitation systems.

1 Introduction

The use of conductive sheets in guideways for Electrodynamic Levitation Systems (EDS) was the design basis for several of the early studies in the 1970's. Designs originating at Ford Motor Corporation [1], Stanford Research Institute [2], the University of Montreal [3] and MIT [4] all used sheet guideways. An overview of these early studies can be found in Moon[5]. The original Kolm and Thornton MIT design was updated by Magplane Technology in 1992, resulting in the vehicle and guideway concept illustrated in Figs. 1 and 2 [6].

Early studies in the 1970's, for example by Powell and Danby [7], pointed out the superior electromagnetic (em) lift to drag ratios obtainable with null-flux coil systems using coils in the guideway. Thus, null flux coil systems have dominated many maglev designs in the ensuing years, with little attention given to sheet systems. However, when a broad optimizing perspective is taken, for example, to include the details of operating cost, guideway capital cost, & maintenance, sheet guideways may prove to be a superior choice.

For example, while increased drag for a sheet system will add to the operating cost, reduced amortization costs on a lower capital cost system will reduce operating costs. Amortization costs will dominate total operating costs for any self-sufficient transportation system. In addition, electromagnetic (em) drag is only one factor effecting electrical power needs. Aerodynamic drag is comparable to electromagnetic drag at high speed, and constant demands for acceleration and deceleration to accomodate route alignment dominates over em and aerodynamic drag. Finally, in assisted space vehicle launch applications such as "Maglifter", the power required for em drag in a sheet guideway would be insignificant (1-3%) compared to the power for the required 2g's of acceleration.

2 Magplane System Description

The Magplane baseline vehicle employs superconducting magnets clustered fore and aft [6]. At full speed these coils provide sufficient lift to elevate the 25 tonne vehicle 15 cm above the top of the guideway sheet. At a speed of 150 m/s the lift to drag ratio is 40.

The semi-circular cross section of the quideway allows the vehicle to bank, provides both lift and lateral restoring forces, and couples the pitch and yaw stability modes. The top sheet and integral aluminum beam support provide all the structure necessary to span between support piers, which are at 9 meter intervals. A single guideway using the section shown in Fig. 2 would utilize 285 tonnes of aluminum per kilometer, 60 % in the levitation sheets, and 40 % in the integral aluminum structural support beams.

Recently updated Magplane designs include a lower speed intracity transit application where a similar weight vehicle would use permanent magnets rather than superconducting magnets and operate on the same guideway at a 5 cm operating gap rather than a 15 cm gap.

3 Design Issues for Sheet Guideways

3.1 Superconducting Magnet Systems

Some of the major sheet levitation design issues are associated with coil geometry and can best be illustrated with examples. Figs. 3 and 4 show simplified plan views for two different levitation modules. Fig. 3 was used for the 1992 Magplane design and consists of two oppositely excited coils that are relatively long in the direction of motion. Four modules of this type with 1.8x10^5 amp-turns per coil per module are sufficient for a 25 t vehicle and provide a 15 cm clearance at an operating speed of 150 m/s. Four of the modules in Fig. 4 can provide the same function with slightly less amp-turns per coil (about 1.7x10^5 AT) per module. Adjacent coils in Fig. 4 are oppositely excited and have a shorter "wavelength" in the direction of motion, but both modules have about the same footprint area.

Both module types use superconducting coils and would operate in a constant flux condition, which is close to constant current at higher speeds, but not at low speeds. Fig. 5 shows the radically different height vs.. low speed performance for the two module types which both operate at a height from coil center to sheet surface of 20 cm at 150 m/s. Five cm are necessary from coil center to vehicle surface, so the actual clearance to the guideway for h= 20 cm is 15 cm, and there is no clearance when h=5 cm. The coils operate under constant lift and constant flux conditions, and the height decreases as the speed decreases until wheels make contact. The short horizontal lines in Fig. 5 represent options for wheels holding the height constant at a clearance of 3, 5, or 7 cm when the speed is sufficiently low. From that point to zero speed, the electromagnetic lift decreases to zero approximately linearly. The type 1 module has "lift-off" speeds of 9, 11 & 13 m/s for these three options, whereas the type 2 module shows lift off at less than 3 m/s in all cases.

Fig. 6 shows the EM lift to drag ratio characteristics for the two module types. At low speeds both modules have similar em lift/drag performance, but at higher speeds, the "long wave" character of module type 1 continues to increase the lift/drag ratio vs. velocity at a higher slope compared to the "short wave" character of type 2.

The explanation for this divergence is implied in 1970's work, which used two dimensional analyses; for example, Woodson & Melcher [8] or Reitz & Davis [9]. They showed that lift/drag for a sinusoidal current sheet travelling over a guideway is proportional to a magnetic Reynolds number, $\mu\sigma$ Vf, for low values of this parameter (μ= permeability of the sheet, σ = conductivity, V = velocity, f = sheet thickness). Velocity, conductivity and sheet thickness can, therefore, be traded off at low speed and obtain the same lift/drag performance, but at high speed, the asymptotic lift to drag performance can be shown to be proportional to the square root of a magnetic Reynolds number where the length dimension, f, is not the sheet thickness, but the wavelength of the current sheet excitation. In essence, at high enough speed, all guideway sheets appear to be thick so the thickness is not important. The short wavelength character of module type 2 causes the guideway sheet to appear thick at lower speed and allows lift off at lower speed, but then impedes the further increase of lift/drag ratio compared to module type 1 because of the shift to a square root dependence on velocity.

The 3 dimensional nature of the modules brings in another dependence on the ratio of characteristic wavelengths in the two directions in the plane of the coils; this is included in the numerical calculations underlying the results in this paper.

The drag for a 25 t vehicle using 4 modules, either type 1 or type 2, at speeds below 15 m/s is shown in Fig. 7. Both module types operate under constant lift-constant flux conditions above the lift off speed. Below the lift off speed, the drag is dependent on the selected constant height (3 values are shown) above the guideway. One advantage of the type 2 module is the lower lift off speed, but a disadvantage is the significantly higher drag force at lift off. For example, for a lift off height of 12 cm, a vehicle with type 1 modules would have a maximum em drag of about 7.5x10^4 N, whereas a vehicle with type 2 modules would have a maximum em drag of about 3.9x10^5 N, but at a lower lift off speed. The maximum drag power in both cases is almost the same at about 1.2-1.5 MW.

The total mechanical power input to the vehicle must provide for aerodynamic drag and "inertial" drag (for acceleration), as well as the em drag discussed so far. The aerodynamic drag is proportional to the velocity squared and, for Magplane, exceeds the em drag between 100 and 150 m/s. For an acceleration of 0.15 g, the inertial drag will exceed the em drag at about 50 m/s. A comparison of the required mechanical power input for a vehicle with either type 1 or type 2 modules as a function of speed is shown in Fig. 8. The requirement for type 2 modules is higher than for type 1, but comparable. Both cases allow for a 0.15 g at acceleration at any speed, however, this is not necessary at the higher speeds where, for example, the power required could be reduced by about 3 MW if the acceleration requirement were dropped to 0.05 g at high speeds. The total mechanical power required would then be about 7 Mw for a vehicle with either type 1 or type 2 modules, respectively.

In a levitation system using a sheet guideway and for a given coil geometry in the levitation modules, the lift capability of a module can be shown to be proportional to the square of the amp-turns in the coils. This is a significant advantage for superconducting coils. Magplane is able to use essentially the same module geometry for a 145 passenger vehicle at twice the weight (50 t), because the superconducting coils require only a 41% increase in amp-turns, which, in turn, requires only a 20% increase in the linear cross-sectional dimensions of the coils. The coils are a small part of the lift module weight, which is dominated by the cryostat and refrigerator, hence, the fractional weight of the levitation system becomes more favorable as the payload requirement becomes larger.

3.2 Permanent Magnet Systems

Magplane also offers the possibility of using permanent magnets in the levitation modules. In this case it is necessary to consider the limited ability of permanent magnets to increase the equivalent amp turns that can be provided locally. For example, the superconducting coils considered above easily provide about 1.8x10^5 amp turns (or more) around the boundary of a coil. A permanent magnet with a residual induction of about 1.25 T, can provide the equivalent around its boundary of about 1 x 10^6 amp per meter of height. To be effective, the height must be limited to 2-3 cm, so the equivalent ampere turns is 2-3x10^4 amp. As a result, it can be expected that the operating clearances must be smaller than with superconducting coils and that lift modules with significantly larger footprint areas will be necessary.

As an example of using permanent magnets for Magplane, consider the type 2 geometry of Fig. 4 as the boundaries for permanent magnets with a residual induction of 1.25 T. Furthermore, consider a type 3 geometry (not shown) which has the same amount of material as in type 2, but in which the sections are cut in half in the “2A direction” to provide 10 sections (each 0.2 x 0.9 m) rather than 5 sections in a module of essentially the same length.

Figs. 9 & 10 show estimates for the lift per module and drag per module, respectively, vs. clearance to the guideway for a speed of 20 m/s. Curves are given for type 2 and type 3 modules using permanent magnets with thicknesses of either 2 or 3 cm. Fig. 9 shows that increasing the permanent magnet thickness increases lift, but at a rate that is less than proportional to the square of the equivalent current, because each successive increment of magnet produces an equivalent incremental current further from the sheet. The shorter wavelength type 3 modules are more effective in lift capability for the smaller clearances than the longer wavelength type 2 modules, but less efficient at large gaps. Fig. 10 shows the drag relationship for the same cases. The lift to drag ratio is essentially the same for all corresponding points over the range shown, and has a value of 6+ at the 20 m/s velocity.

The permanent magnet configurations represented by type 2 and type 3 have not been optimized. However, as an example, consider using type 3 with permanent magnets for a 25t Magplane. Allowing for the 36 degree inclined angle of the lift magnets above the trough, the total lift required to support the vehicle is 3.0 X 10^5 N. Referring to Fig. 9, a type 3 configuration with 3 cm build permanent magnets, can supply a lift of 1.5 X 10^4 N per module at a gap of 8 cm. It would therefore require 20 modules to supply the full lift. Twenty modules is also the maximum number that can be accommodated on the underside of the vehicle.

Figs. 9 and 10 are based on 2-D analytical approximations. A more accurate 3-D model for the same geometry (type 3) indicates that the lift is somewhat smaller. To obtain a lift of 1.5 X 10^4 per module requires reducing the gap to 7 cm.

The weight of the 20 modules would be approximately 8.7 tonnes. The 8.7 tonnes of magnets in the 25 tonne vehicle are lifting a “payload” of 16.3 tonnes, a payload to magnet weight ratio of 1.9. By way of comparison, the superconducting magnet system used in the 1992 Magplane design for the same vehicle had a total weight of 7 tonnes including the lift magnets and cryostats (2.5 tonnes), refrigeration (2.5 tonnes) and magnetic shielding system (2.0 tonnes). The latter is needed only for the higher field superconducting system. The payload to magnet system weight ratio is thus 2.6 for the superconducting system. More importently, the superconducting system has this ratio at a clearance gap of 15 cm, two times the operating gap of the permanent magnet system. To compare the two systems on an equal weight basis, we can reduce the number of permanent magnet modules to bring the magnet weight down to 7 tonnes. The operating gap would then be reduced to 5 cm, one third that of the superconducting system.

The lift to drag ratio for the type 3 configuration permanent magnet system is approximately 6 at 20 m/s, 8 at 50 m/s, 12 at 100 m/s and 14 at 150 m/s. Configuration 2 would have someway higher lift to drag ratios, for example 17 at 150 m/s, but would have a lower lift capability, resulting in a loss of about 1 cm in gap for a similar weight of magnet. These can be compared with the lift to drag ratio for the type 1 module superconducting system, where the ratio is 15 at 50 m/s, 27 at 100 m/s and 40 at 150 m/s.

4 Stability

A vehicle traveling over the trough-like guideway of Fig. 1 will be first order stable. That is, when the vertical or horizontal gap between the vehicle and the guideway is reduced, the lift or centering force increases.

The spring constant of the type 3 configuration permanent magnet system at an operating gap of 7 cm would be negative 8.3 x 10^4 N/cm. The type 1 configuration superconducting system used in the baseline design has a spring constant of negative 2.8 X 10^4 N/cm at a clearance gap of 15 cm, 33 % that of the smaller gap permanent magnet system.

While it is first order stable, the vehicle will develop under damped, significant amplitude, oscillations in heave, pitch, yaw and roll in response to disturbances [10]. Some roll and yaw stability is imparted to the vehicle from the slot in the guideway which accommodates the LSM. There is a significant restoring force on the vehicle attitude when the propulsion magnets on the vehicle encounter the edge of the slot, the so called "keel effect."

In general, however, it is necessary to utilize some form of active feedback to keep the oscillations within an envelope that does not impact on rider comfort. In the Magplane concept, feedback can be introduced by phase changes in the LSM excitation, by aerodynamic control surfaces, and by local magnetic pads with controllable lift. A six-degree of freedom simulation has been done for the baseline Magplane design, and demonstrated an ability to meet all recommended passenger comfort requirements [11].

5 Conclusion

The best "wavelength" magnetic configuration to use for lift depends on the operating gap. The smaller the gap, the shorter the wavelength.

Shorter wavelength magnetic configurations provide higher lift at lower velocities, but exhibit larger drag at higher velocities.

Longer wave length magnetic configurations can have higher lift to drag ratios at high velocities than short wavelength systems.

Superconducting systems of comparable weight to permanent magnet systems can provide at least 3 times the operating gap.

Permanent magnet systems are capable of providing operating gaps of at least 5 cm for a 25 tonne vehicle. The same vehicle, when equipt with superconducting coils, travelling over the same guideway, can increase the operating gap to 15 cm, and increase the lift to drag ratio by a factor of three at high velocity. This suggests the strategy of initially deploying the low technology permanent magnet modules on vehicles for moderate speed service, and upgrading to the advanced technology, superconducting modules on higher velocity vehicles at a later time.

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Fig. 1: Model of Magplane 25 tonne vehicle on aluminum sheet guideway

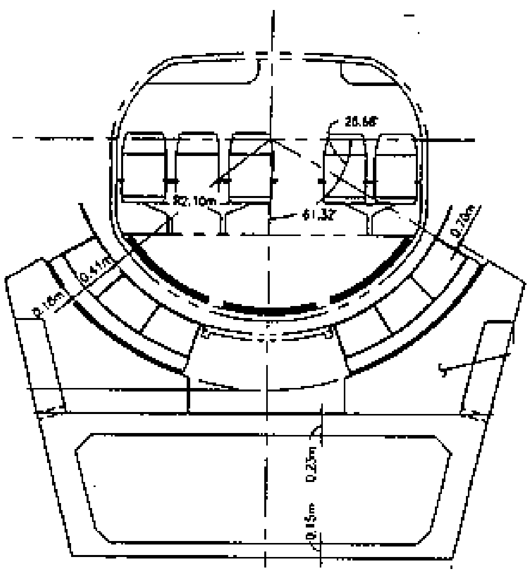

Fig. 2: Cross-section of vehicle, reinforced aluminum guideway and auxiliary long-span pre-tensioned concrete beam support

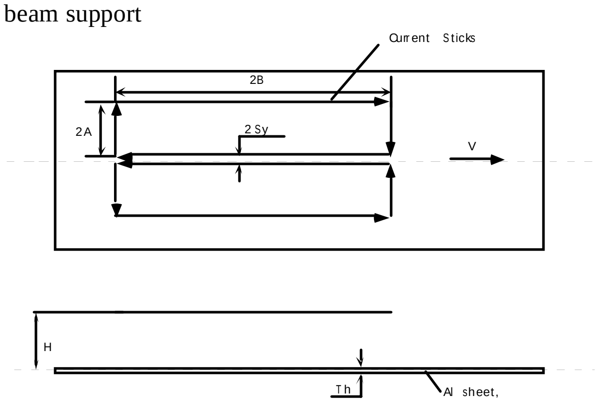

Fig. 3 Module Type 1 –
2A=0.40 m, 2B=2.25 m, 2Sy=0.10 m

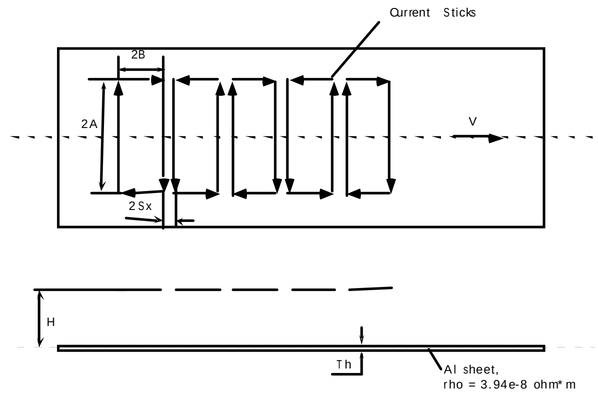

Fig. 4 Module Type 2 –
2A=0.90 m, 2B=0.40 m, 2Sx=0.06 m

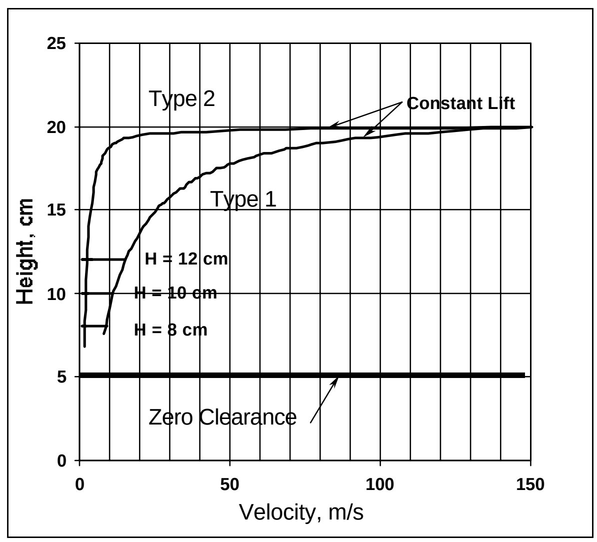

Fig. 5 Height vs. Speed Performance for Module Types 1&2

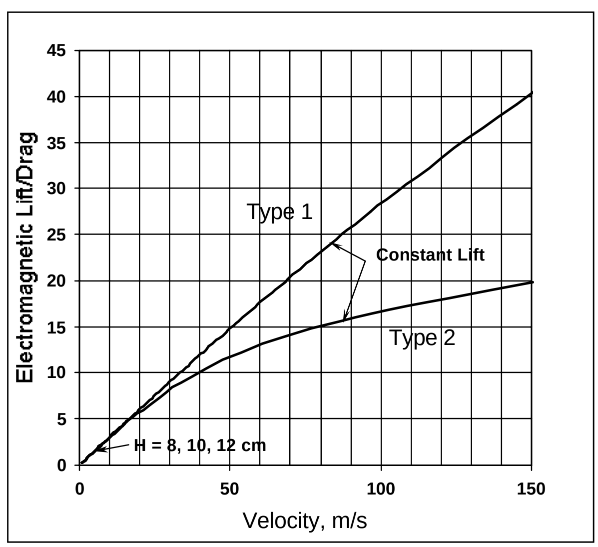

Fig. 6 Ratio of EM Lift/Drag for Module Types 1&2

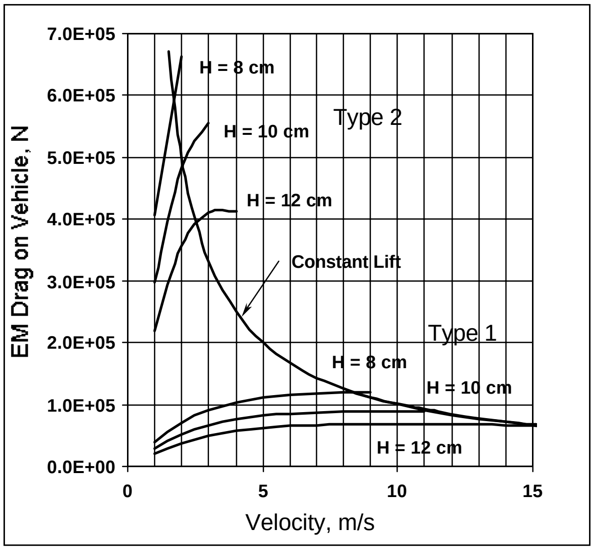

Fig. 7 EM Drag for a 25 t Vehicle Using either Type 1 or Type 2 Modules at Speeds below 15 m/s

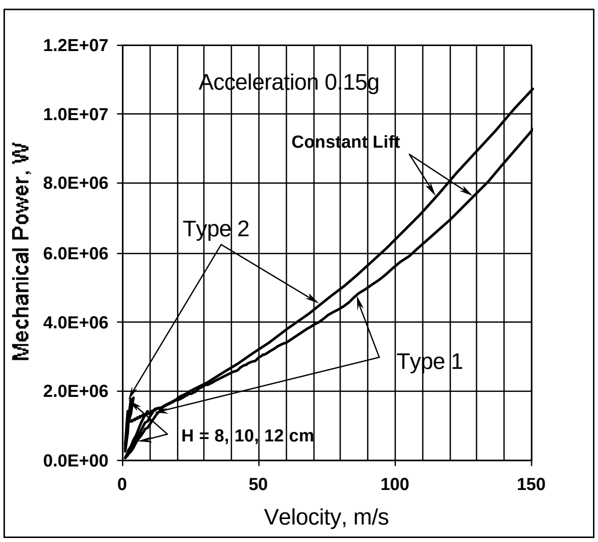

Fig. 8 Mechanical Power for a 25 t Vehicle Using either Type 1 or Type 2 Modules

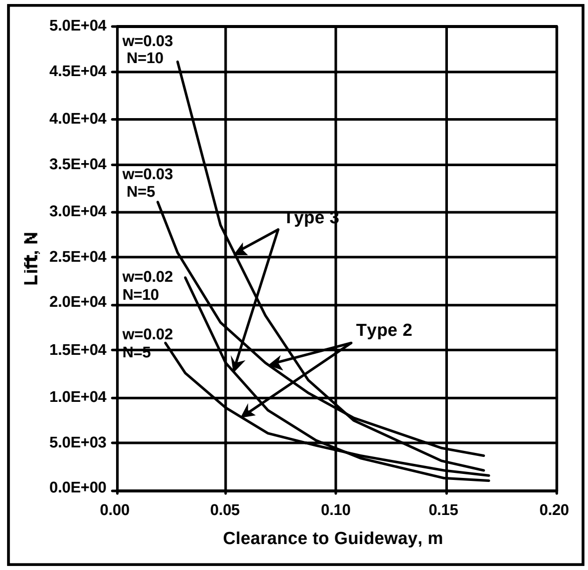

Fig. 9 Lift per Module vs. Clearance above Guideway

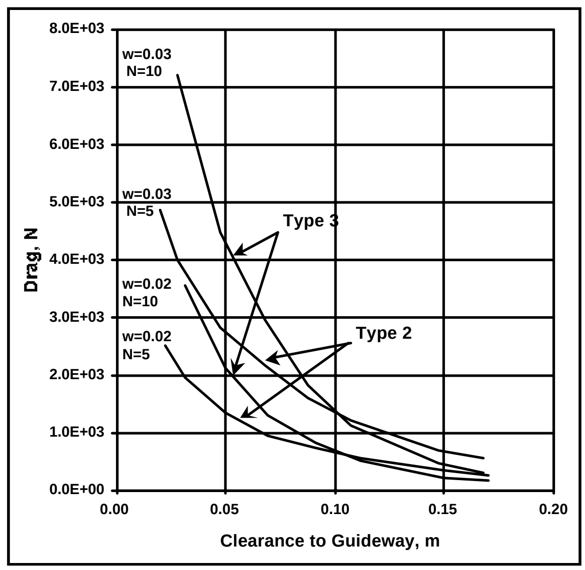

Fig. 10 Drag per Module vs. Clearance above Guideway