

Maglev vehicle design for permanent magnet levitation electro-dynamic suspension (EDS) system

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Abstract

Specific aspects of maglev vehicle technology development for urban alignment are discussed. The design approach conforms to permanent magnet Halbach array levitation, guidance, and Linear Synchronous Motor (LSM) propulsion for electronically coupled consists, while meeting the requirements of urban transit. Non-dynamic service and emergency braking is performed via a half-caliper design that obtains braking force by magnetic attraction to a steel plate, thus making the braking force independent of vehicle weight. The optimal vehicle is designed for mass production, as part of a noiseless and relatively unobtrusive mass transportation system that is made possible by the selected technologies.

1 Introduction

The U.S. Urban Maglev program, sponsored by US Department of Transportation (DOT), Federal Transit Administration (FTA) and led by General Atomics, is currently in the detail design phase of test articles, after completing an 18 month study which included system and subsystem conceptual design, and levitation proof-of-concept. The Urban Maglev vehicle (Figure 1) is lightweight, quiet, low maintenance, durable, low cost, delivers excellent ride quality, can operate in dense urban environments, is adaptable to a variety of alignments, is flexible and extendable, meets safety standards, and is aesthetically pleasing.

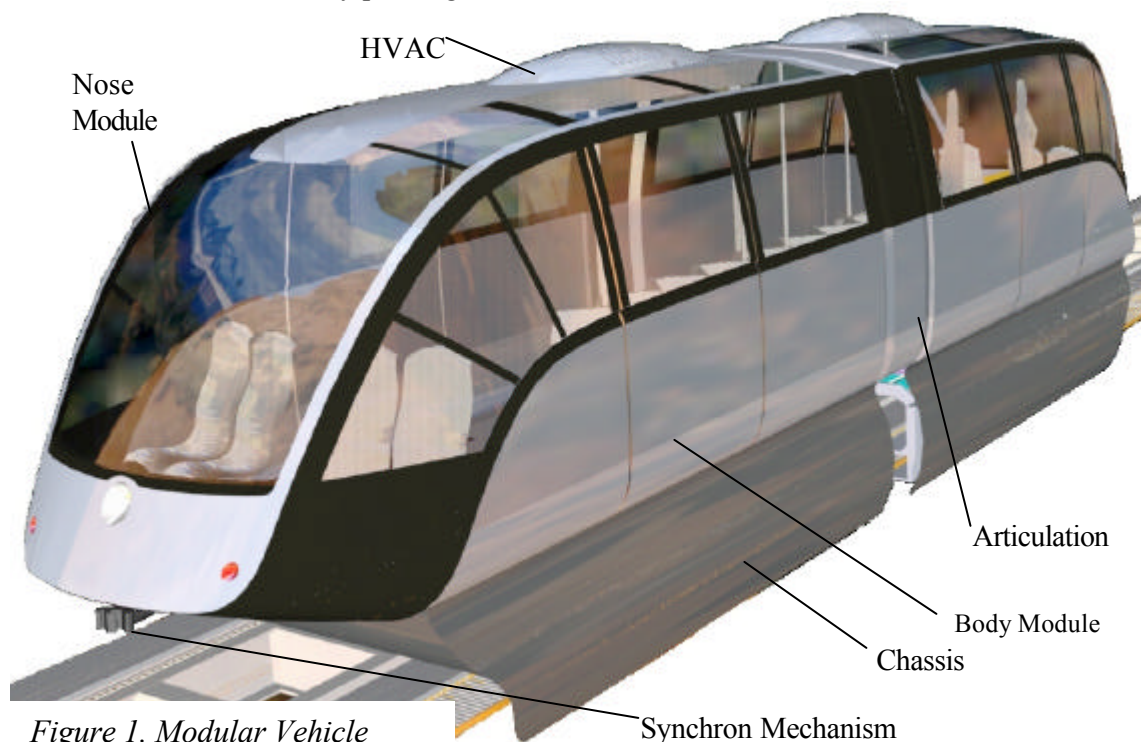


Figure 1. Modular Vehicle

These attributes are designed into the vehicle in order to have a competitive, deployable system that is attractive to riders and transit providers. The vehicle is designed to take maximum advantage of the enabling technologies: robust and simple permanent magnet (PM) double sided Halbach array levitation, Linear Synchronous Motor (LSM) propulsion, and PM guidance that provides inherently stable levitation from ~ 2 m/s.

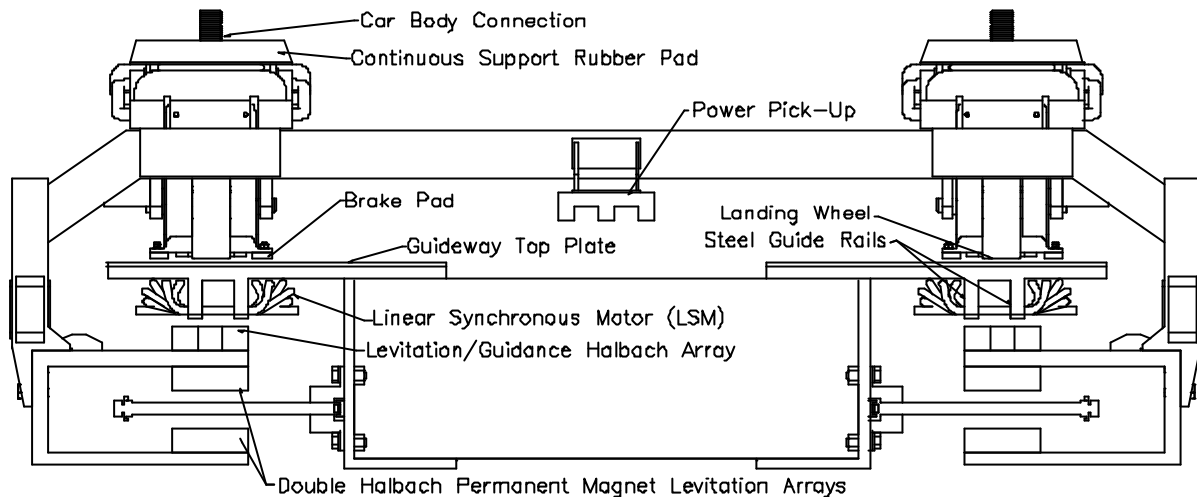


Figure 2. End view of chassis and guideway module: functional arrangement

The nature of LSM propulsion coupled with the tight super-elevated turns (Radius 18.3 m) necessary to negotiate a dense urban environment requires a unique solution to the issue of consist formation, namely non-contacting electronic coupling. A safety coupler, which transmits zero force between vehicles in normal operation, is provided to maintain consist integrity in case synchronization is lost. It also restores proper vehicle spacing after non-synchronous (non-LSM) emergency stops, and is able to damp unwanted longitudinal oscillations between vehicles.

To enable the vehicle to negotiate tight turns with a long ski-like levitation pad, a non-rotating 'flexible' chassis is designed consisting of two chassis sections that are elastomerically connected, which 'continuously' supports self-contained lightweight FRP body modules connected by articulation joints. The modular approach, utilizing body and nose modules, enables rapid, cost effective production and deployment of a vehicle that can serve equally well in a high capacity transit system that outperforms the subways and Light Rail (LRV), and in a Group Rapid Transit (GRT) system that can attract automobile users with a short, hassle free downtown commute. The baseline two module vehicle weighs in at $\sim 12,500$ kg AW0, can hold 100 passengers, and utilizes two plug slide doors per body module to allow rapid ingress and egress. It is fully automated and driverless, utilizing fixed block control architecture, in harmony with the block architecture of the LSM.

The non-contacting levitation, guidance, and propulsion also requires a unique solution to guarantee reliable secondary service braking and fail-safe emergency braking. There are two operationally and physically separate $\frac{1}{2}$ caliper friction brakes on the vehicle, which provide braking force through development of pressure, via magnetic attraction, between the brake pads and the steel guideway top plate. The plate (Figure 2) also shields the magnetic fields generated by the Halbach arrays such that no additional shielding is required on the vehicle. The resultant field in the passenger compartment caused by the permanent magnets is below 1 Gauss, lower than most light rail systems.

2 Maglev Specific Design Challenges

The selected levitation, propulsion and guidance technologies pose unique challenges to the vehicle design. Levitation is achieved with an inherently stable double Halbach arrangement, consisting of two arrays of permanent magnets facing each other, interacting at a nominal 25 mm gap with a low drag Litz wire reaction rail, as shown in Figure 2. The propulsion array is located above the levitation arrays, and interacts with the LSM coils that are attached to the underside of the ferromagnetic guideway top plate. The levitation approach, using permanent magnets arranged in a Halbach array with an optimum wavelength (λ) of 408 mm, is able to operate without the closed loop feedback controls that burden EMS Maglev technologies. The LSM operates by forming a variable frequency traveling magnetic sine wave that ‘locks’ into the magnetic sine wave on the vehicle, and thus propelling all vehicles within the same circuit in unison. Synchron spacing is when each vehicle in a consist is spaced such that each vehicle is synchronized with the LSM. Guidance is obtained through attraction of the propulsion Halbach arrays to two iron rails that are collinear with the LSM. The double Halbach arrangement results in a very stiff vertical primary suspension of $\sim 2 \times 10^7$ N/m (including guideway stiffness), which therefore provides excellent vertical and roll stability. The lateral primary spring constant provides ~ 25 kN of restoring force at a displacement of 25 mm. Levitation, guidance, and propulsion is provided by factory built guideway modules, where close tolerances can be held.

The use of LSM propulsion along with PM double Halbach levitation, while offering many advantages, in a tight urban environment restricts some aspects of the vehicle design. Synchronization requires that for a vehicle composed of many self-contained, self-supporting modules (see section 3), the spacing of each chassis be driven by the wavelength (see Figure 3). This is critical for operation, since loss of synchronization means a loss of dynamic braking and propulsion. Small deviations from the spacing, such as 10 mm to provide the split chassis, do not significantly affect system performance and efficiency.

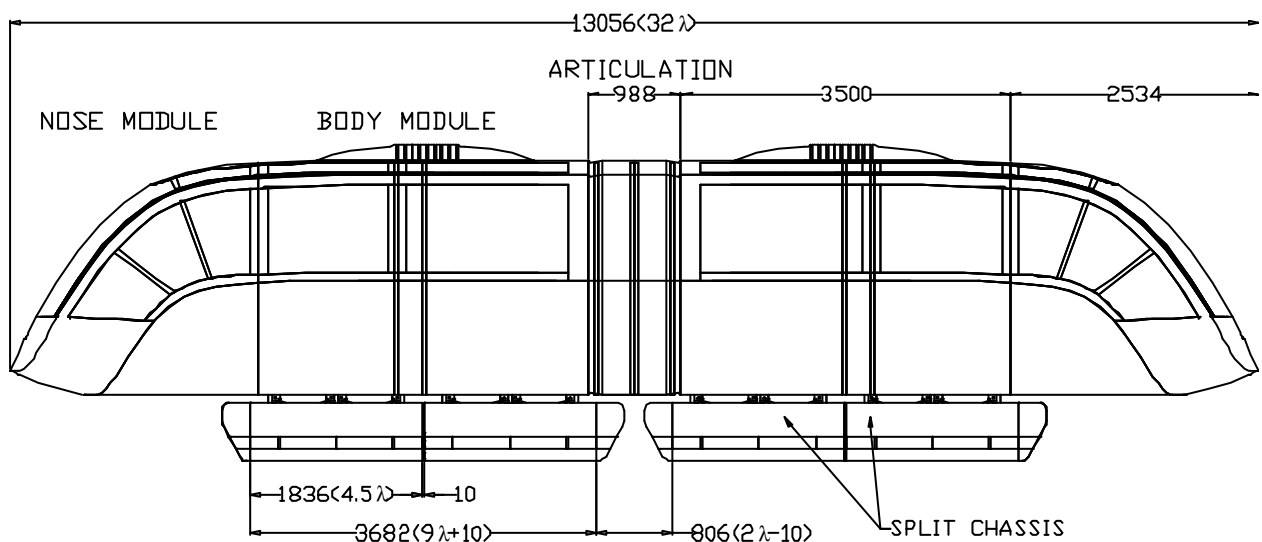


Figure 3. Two body module articulated vehicle. Layout driven by LSM wavelength ($\lambda = 408$)

In order to maintain synchronization on small radius turns with minimal effect on performance, the LSM wavelength must be shortened on the inside ‘rail’ and lengthened on the outside rail, due to the difference between arc and chord length. Figure 4 shows the different wavelengths required for an 18.3 m 6° superelevated curve. A consequence of the synchronization requirement and the tight turns is that a vehicle can consist of a maximum of 5 body modules connected by articulations before some significant de-synchronization of the end chassis occurs. This limitation is alignment geometry

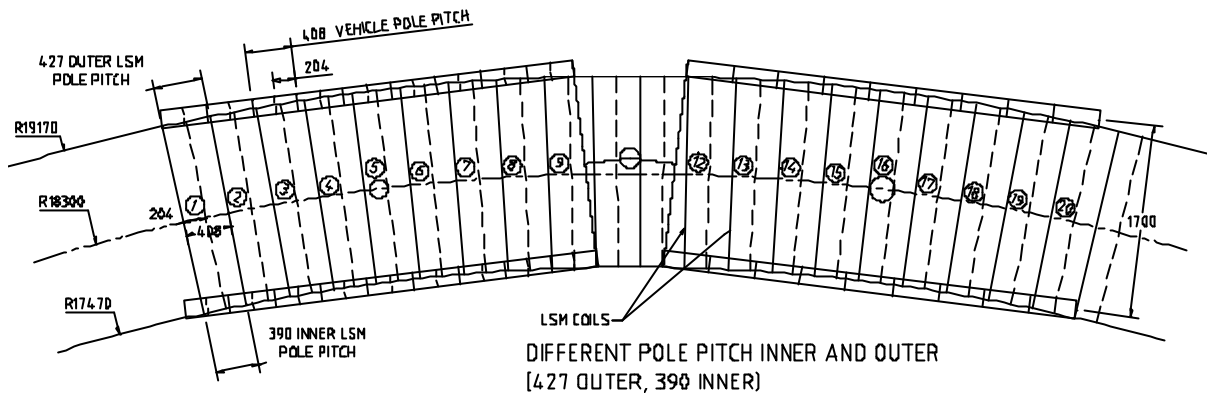


Figure 4. Linear Synchronous Motor layout on 18.3 m radius turn: Wavelength variation

dependent, and must be reevaluated for each proposed alignment. Another consequence of the synchronization and tight turn requirements is that vehicles cannot be ‘hard’ coupled together to form consists, like traditional rail vehicles.

2.1 Electronic Coupling

The LSM synchronization and the tight turn requirement does not allow consist formation via traditional ‘hard’ couplers, since LSM de-synchronization would occur. A fixed coupler length between two pivot points pulls the connected vehicles together, causing de-synchronization of one of the vehicles. As required in order to have a system that can still provide frequent service at non-peak hours without excessive unused capacity (via consist formation), non-contacting electronic coupling is utilized. Nominally, this system relies on the operational characteristics of the LSM, which acts like the cable in a ski lift, to hold a consist together via the generated traveling sine wave magnetic fields of the LSM and the on-board magnetic fields of the permanent magnet Halbach propulsion arrays. In the consist, each vehicle automatically maintains an integer number of wavelengths between neighboring vehicle chassis.

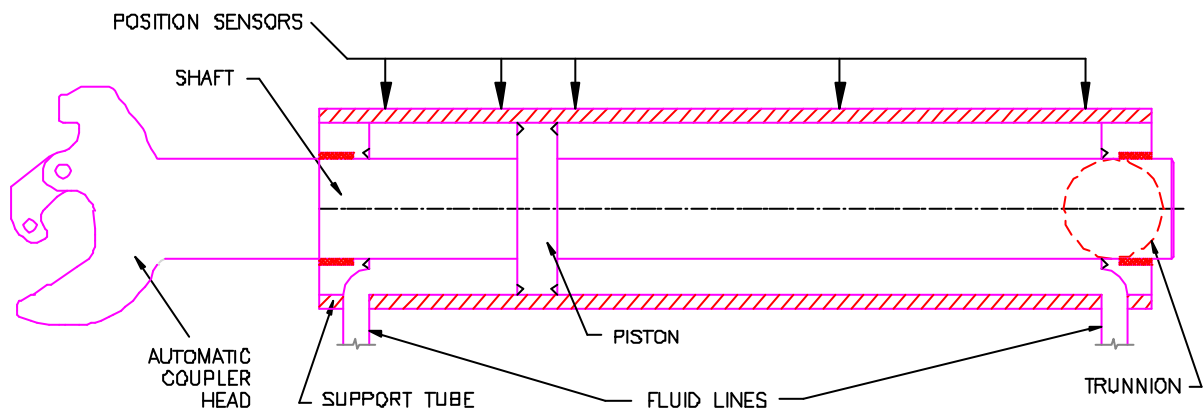


Figure 5. Top View: Safety Coupler

To minimize service interruptions and provide a high level of safety for electronically coupled consists, a safety coupler is provided. It is a device that connects the vehicles together to maintain consist integrity in extreme situations, yet transmits ‘zero’ force between vehicles during normal operation. It is also used to restore proper vehicle synchron spacing after non-synchronous (non-LSM) emergency stops. Resynchronization is performed using the safety coupler because resynchronization via the LSM is more time consuming, and is not consistent with the 99.9% availability goal. Figure 5 shows how the safety coupler works. It is a double acting hydraulic cylinder with a modified conventional automatic

coupler head, which allows unrestricted motion when a valve permitting free movement of the fluid is open. However, even passively it provides a maximum and minimum spacing between vehicles, and by pressurizing one side or the other, can accurately achieve synchron spacing of a consist.

The nature of LSM propulsion is such that control of longitudinal oscillations can only be performed on one vehicle in a circuit. So when operating in consists with full and empty vehicles, some will not be optimally controlled to minimize these motions. As an option, the safety coupler provides an additional function of longitudinal damping between vehicles. This is obtained by restricting the flow between sides of the cylinder. If magneto-rheological fluid is used as the active fluid, the level of damping between vehicles can be controlled electronically, which may have a more beneficial effect on overall ride quality.

2.2 Braking Systems

While the LSM and the magnetic drag (minimum 0.05 g) serve as the primary dynamic brake which provides full zero speed braking for the consist on challenging terrain (10% grade), an electromagnetic secondary service brake and fail-safe emergency brake provide full redundancy and safety. As a rule, three different braking systems are required, separated both physically or operationally. The nature of a levitated vehicle requires the mechanical brakes to pull themselves down onto the brake surface (in our case the guideway top plate), rather than relying on the vehicle weight, since it varies considerably and destabilization of the levitation could occur. Thus, the brake surface is specified to be a ferromagnetic material (steel), and the brakes achieve deployment and the proper pressure through the use of magnetic attraction. The surface pressure of the brakes will break up ice, and a sand system will be used to increase friction when low friction conditions (rain, snow, ice, and black ice) are present on the guideway.

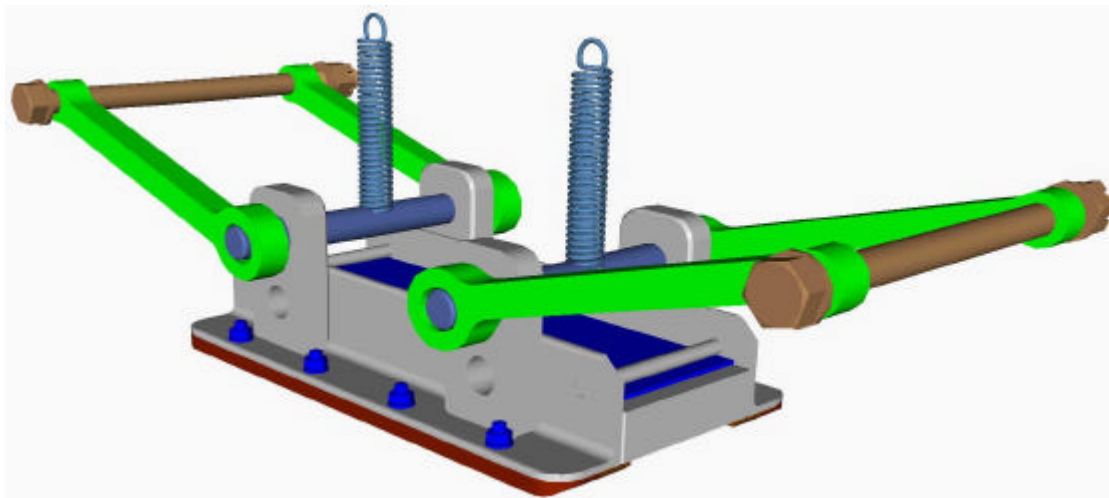


Figure 6. Electromagnetic secondary service brake

Required braking performance for an AW3 vehicle on level track is: dynamic– 0.21 g, secondary service– 0.26 g, fail-safe emergency– 0.15 g. The requirements are designed to provide full braking performance, even down 10% grades, while minimizing the weight and complexity of the emergency brake. Both the service and emergency brakes can be used as parking brakes. Since each body module is a self-contained fully functional unit, each chassis will have two of each brake. In normal operation, the dynamic brakes provide all braking function, and are able to stop a consist while maintaining vehicle spacing. If the emergency braking rate is required, the secondary service brake will act with the dynamic brake to deliver the full 0.36 g deceleration even down a 10% grade. Since both brakes are controlled, jerk is controlled to maintain acceptable ride quality, and LSM synchronization is maintained. Under power failure conditions, the service brake provides full service braking, even down a 10% grade, while maintaining synchron vehicle spacing and ride quality. If,

under power failure conditions, the emergency braking rate is required, the secondary service and fail-safe emergency brake are both deployed to provide full performance, and maintain acceptable ride quality. If a power failure occurs, and the battery systems fail at nearly the same time (they are continuously monitored and taken out of service if failure is detected), the fail-safe emergency brake is deployed for non-synchronous braking. Consistent integrity is still maintained via the safety coupler.

The secondary service brake is an electromagnetic ½ caliper friction brake that utilizes brake pads mounted to an external housing that reacts against the top of the ferro-magnetic steel LSM support plate, as shown in Figures 2 and 6. The brake is a single integrated structure that minimizes maintenance and maximizes reliability. The only moving parts are the swing arms, which transmit braking force to the vehicle and the retraction spring. Anti-wear back-up pads are provided 5 mm above the surface of the brake pads to protect the electromagnet in case of improper maintenance. Since wear is infrequent (emergencies) and the brake pads will last for ~20,000 applications, it is expected that they will never need to be replaced over the 30 year expected lifetime. The braking force is varied by changing the current flowing to the electromagnet, which in turn varies the pressure of the brake pad on the steel plate. The current is controlled by a closed-loop feedback system that considers the vehicle deceleration rate, yaw, grade, velocity, and spacing between vehicles. Approximately 2.5 kW of power is required to develop the 25 kN attractive force required for full

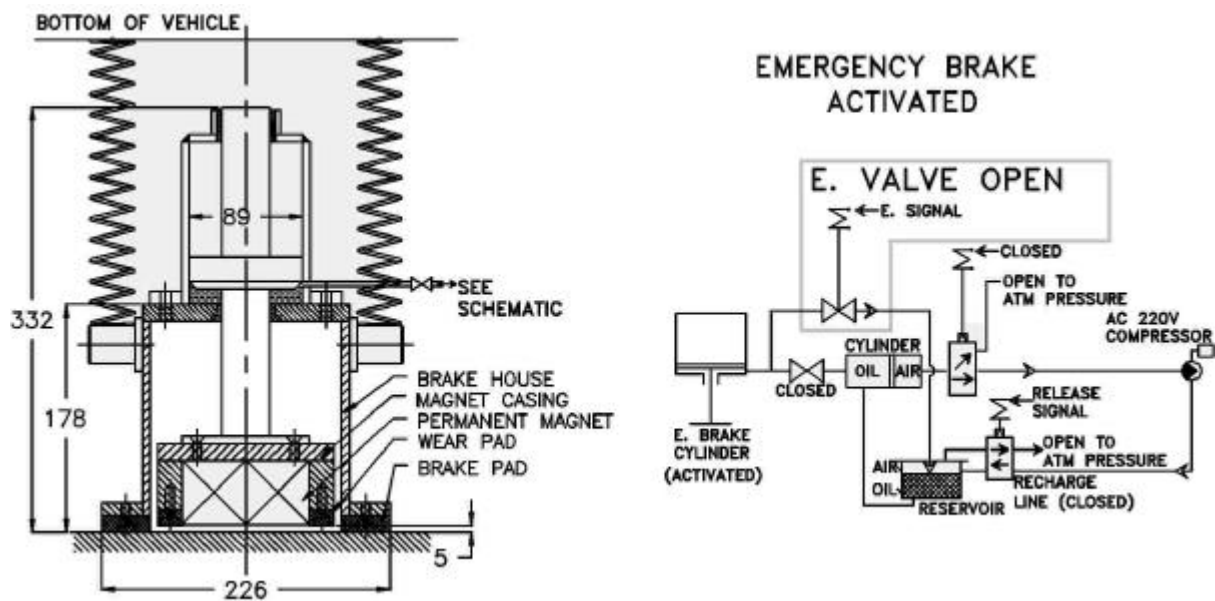


Figure 7. Fail-safe permanent magnet emergency brake

braking, and can be supplied by a back up battery.

The permanent magnet half caliper fail-safe emergency brake (Figure 7) utilizes the ever-present attractive force of permanent magnets in a Halbach array to deploy and provide braking force. Because of the constant attractive force, a holding/retraction cylinder is used to prevent the brake from deploying. Fail-safe deployment is possible because holding the retracted position relies on a normally closed (NC) solenoid, which when the power is interrupted in an emergency, the solenoid opens to allow the hydraulic fluid in the retraction cylinder to quickly drain into a reservoir. Then gravity and the magnetic attraction work together to ensure full deployment onto the brake surface for non-synchronous braking. When retraction is required, the hydraulic fluid is pumped back into the cylinder, lifting the inner magnet housing ~100 mm above the guideway such that the retraction springs are then able to overcome gravity and the magnetic attraction. Note that the braking portion of the system is very simple and robust, such that any failure in the system causes brake deployment. The rest of the system is provided for the retraction and holding function.

2.3 Ride Quality

In order to attract ridership, the maglev system should provide ride quality (noise, vibration, and trip time) that exceeds that of any existing public transportation modes. Several design choices were made in order to meet the challenging turn radius (18.3 m) and maintain maximum ride quality by minimizing unpleasant vibrations caused by gap invasion due to the geometry of a long magnetic ski and the curvature of super-elevated turns. The module lengths and widths are optimized for the capacity requirement while carefully minimizing the required clearance envelope. An articulation joint is used in conjunction with the body modules to minimize the clearance envelope and allow use of a ‘continuously’ supporting non-rotating chassis, and the chassis units are split into two sections in order to minimize gap invasion. The invasion caused by the curvature of an 18.3 m 6° super-elevated curve is ~ 10 mm for a 3.6 m long magnetic pad. This level of gap change would cause a change in lift and drag, thus affecting ride quality, and lowering the safety margin before physical contact occurs. By splitting the chassis into two sections that are elastomerically connected to allow $\sim 1^\circ$ of rotation, the curve invasion is lowered to ~ 2 mm, as shown in Figure 8. The split ‘flexible’ chassis is shown in Figure 9. The nature of a levitation system, utilizing numerous sets of magnetic pads, naturally leads to use of a non-rotating chassis that is able to support, ‘continuously’, individual body modules that are connected together with articulation joints to negotiate tight turns. The chassis design and modular articulated vehicle concept allow for trouble-free, noiseless negotiation of tight super-elevated curves, thus minimizing any self-induced motions. However, the guideway and vehicle still have tolerances that affect ride quality.

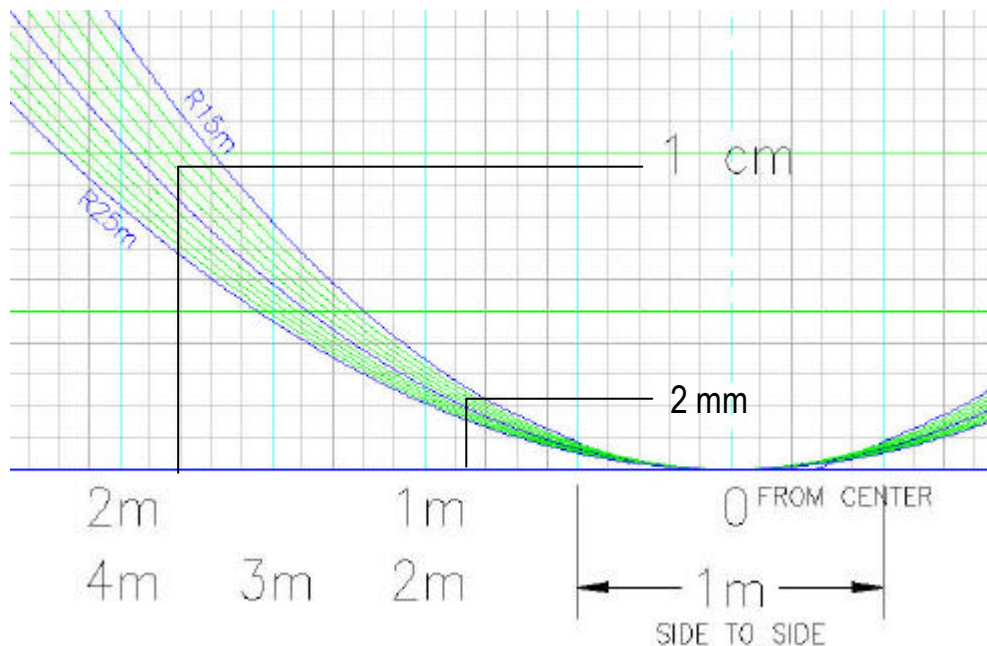
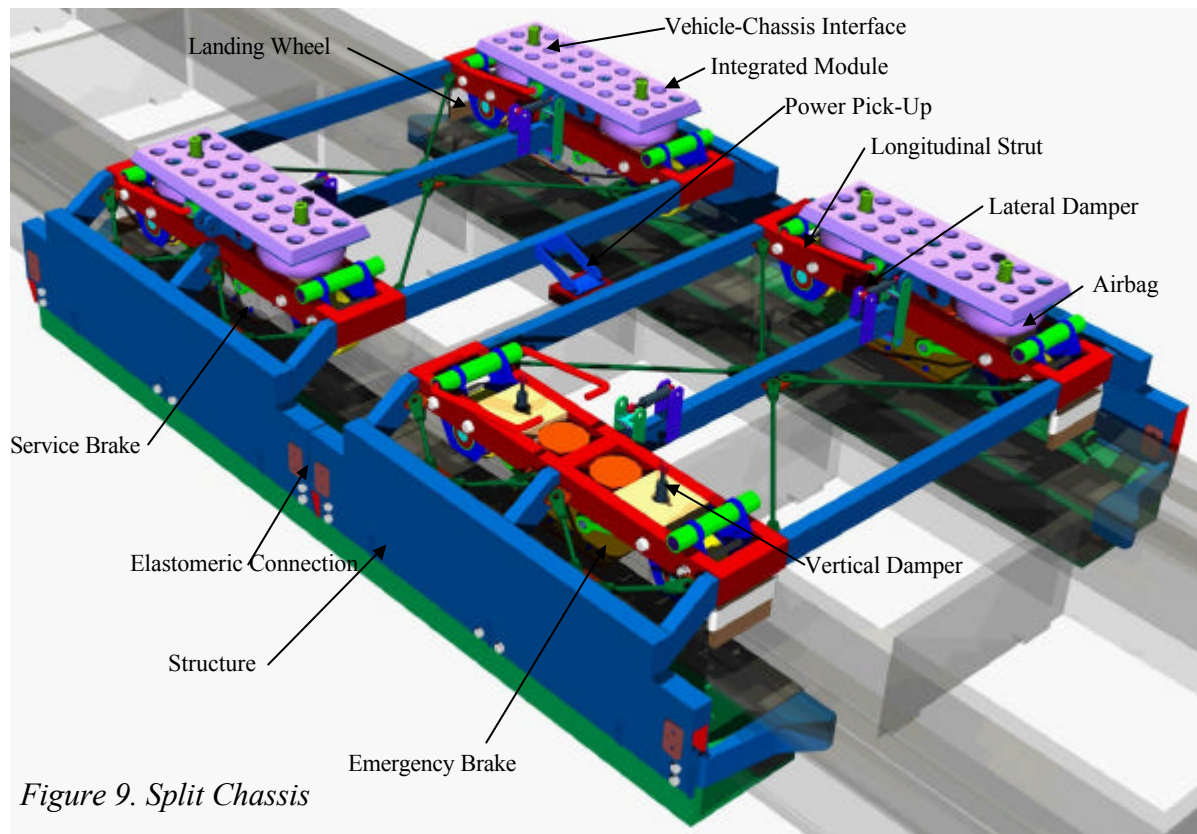


Figure 8. Super-elevated curve invasion versus magnet assembly length

The tolerances on the relevant portions of the guideway are ± 3 mm vertically and laterally (surface tolerance). Since it is easy to line up the ends of the guideway modules, step inputs are not expected to be present in a regular, periodic fashion. More likely is the presence of some slight amount of warping of the 15 m modules, thus presenting an gentle curving input that can be modeled as a periodic sinusoidal input. The results of these analyses are presented in Maglev 2002 conference paper 5302, “Ride Quality of an Urban Maglev”. To meet the ISO 8 hr discomfort criteria, the secondary vertical suspension consists of 16 low pressure airbags and gas pressurized (GP) dampers. The lateral suspension consists of the lateral spring constant derived from the airbags and 50/50 GP dampers. For the test chassis, magneto-rheological (MR) electrically controllable dampers will be used both vertically and laterally to simplify suspension optimization and, if required, provide a semi-active suspension.



The split chassis (Figure 9) allows use of fixed, instead of deployable, landing wheels, minimizing cost and complexity while increasing safety and reliability. The landing wheels are shop adjustable in 0.25 mm increments to account for wear and assembly tolerances. They are manufactured with an integral ring of polyurethane between the tread and hub to minimize noise and vibration at stations. In addition, a noise mitigating rubber/steel-landing plate is placed at the stations. The plate is concave to mate with the crowned wheels to provide the lateral guidance required to meet the station/vehicle gap requirement.

3 A Modular Approach

A modular approach to the vehicle construction is used which minimizes cost, provides a lightweight vehicle, allows negotiation of tight turns (18.3 m sufficient to serve urban areas) via split non-rotating chassis and articulation joints between modules, and offers maximum deployment flexibility. Two types of modules, nose and body, can be combined along with an articulation joint between body modules to form a variety of vehicle configurations to best meet system operational requirements. In addition, the length of the self-contained body modules can also be varied, depending on the capacity requirement, clearance envelope, alignment minimum turn radius, and propulsion wavelength. The baseline 100 passenger capacity vehicle (Figure 3), when operated in a 4 car consist, meets a 12,000 passengers per hour per direction (pphd) throughput requirement with ~120 second headways. The fundamental modular vehicle design approach provides unmatched deployment flexibility, because a single design effort and manufacturing setup can be used to produce vehicles that can be configured for a wide variety of system types, from short headway GRT to high capacity commuter. The advantage of vehicle size variability coupled with the advantage of extremely low noise generation due to the frictionless magnetic propulsion and absence of physical contact gives unmatched freedom to the alignment designer to go nearly anywhere in a dense urban environment with very minimal population disturbance.

The modular vehicle approach and freedom of alignment are powerful tools for cost reduction, permitting reinvestment of the savings to provide a system that is capable of moving people from

4 Conclusions

Several unique concepts are utilized in this maglev vehicle design. Electronic coupling is used to allow consist operation without causing LSM de-synchronization. A safety coupler is furnished to minimize service interruptions and mitigate unknown factors. The safety coupler offers safety, operational, and ride quality advantages of: consist integrity, synchron recovery, and longitudinal damping between vehicles. Electronic coupling offers the potential advantage of consist formation/division at speed, depending on the system configuration and switch capabilities, and thus the ultimate in operational flexibility.

Unique $\frac{1}{2}$ caliper friction service and emergency brakes are provided such that full braking of an AW3 vehicle is possible anywhere on a given alignment, up to 10% grade. In normal operation the LSM provides up to zero speed braking, at which time the friction service brake acts as a parking brake.

To fully utilize the advantages of the magnetic levitation and propulsion and meet the challenge of tight turns in an urban environment, a vehicle concept was developed consisting of:

1. Non-rotating flexible chassis that provide
2. 'Continuous' support of lightweight, individual body modules that are then
3. Connected together with articulation joints and/or nose modules to form the required capacity lightweight vehicles
4. That operate in electronically coupled consists.

This design approach results in an ultra-lightweight carbody (~5,000 kg for ~12 m vehicle) that can be mass produced economically using FRP molding technology. Since each module is supported by a chassis that provides full levitation, guidance, and propulsion, various length vehicles can easily be manufactured to meet a wide range of transit needs without excessive retooling.

It is obvious that this low-maintenance robust design will provide significant operational flexibility and cost savings for the system operator. When building a fleet, one only has to use identical and economically mass-producible modules to obtain a variety of car sizes, that can be operated in consists, to best fit both alignment characteristics and throughput requirements and fluctuations. It is our hope that this design approach will provide a higher level of satisfaction for both system operators and the ultimate users, the riders who only care about getting from one point to another as quickly, safely, and comfortably as possible.