# Overview of the General Atomics Low Speed Urban Maglev Technology Development Program

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**Abstract**

The overall objective of the Urban Maglev Program, sponsored by the Federal Transit Administration, is to develop magnetic levitation technology that offers a cost effective, reliable, and environmentally friendly option for urban mass transportation in the United States. Maglev is a revolutionary approach in which trains are supported by magnetic forces without any wheels contacting the rail surfaces. The program is funded under the Transportation Equity Act for the 21st Century (TEA-21). An innovative approach for the General Atomics Urban Maglev has emerged that involves an entirely passive, permanent magnet levitation system with an efficient linear synchronous motor powering the guideway to provide propulsion. The studies show that the Urban Maglev system offers many attractive benefits, including very quiet operation, the ability to operate in challenging terrain with steep grades and tight turns, all-weather operation, low maintenance, and rapid acceleration and the potential for high speed.

## 1 Introduction

Significant progress has been achieved in the areas of system studies, base technology development, route-specific analysis, and full-scale system concept development (including costs, schedule and commercial planning) [1].

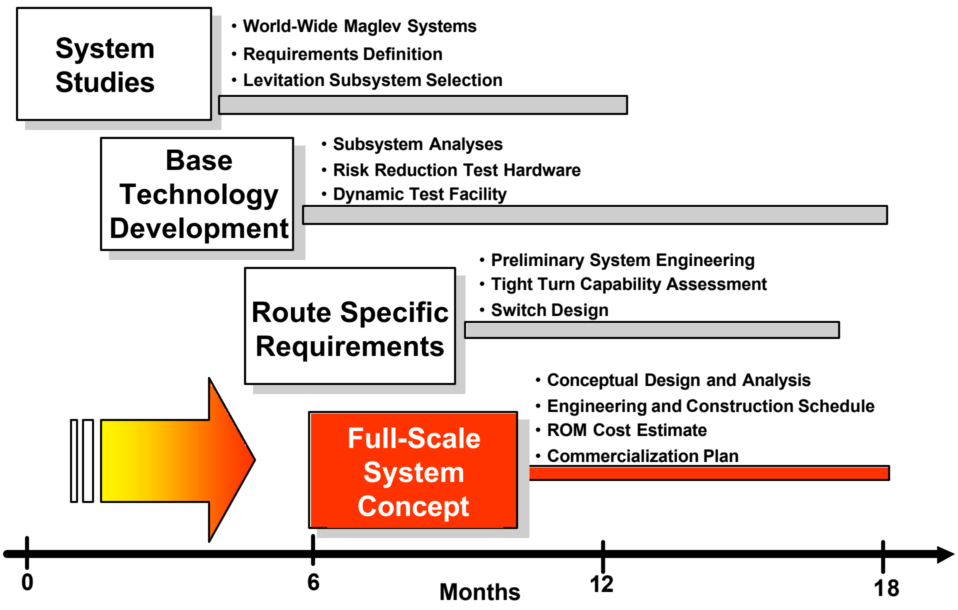


Figure 1. The General Atomics Team Plan

"System Studies" started with review of the state of maglev systems built around the world, followed by preparation of a detailed system requirements document. The system requirements document is divided into three sections: general requirements, alignment description, and specific requirements. A summary of key system parameters is presented in Table 1. This task also evaluated four different levitation subsystems, as well as comparing linear induction motor (LIM) propulsion with linear synchronous motor (LSM) propulsion. The design flow logic for the process which culminated in the selection of an electrodynamic (EDS) levitation system with a LSM propulsion system is schematically represented in Figure 2. The capability of a maglev system to operate with a "large air gap", in the range of 2.5 cm, provides potential benefits, such as its ability to operate in all weather conditions, as well as being less sensitive to guideway construction tolerances. The result was the selection of permanent magnet Halbach arrays for levitation [2,3], and a guideway-mounted LSM for propulsion.

Table 1 Key System Parameters

| System Parameter | Value |
|---|---|
| Accessibility standards | Americans with Disabilities Act (ADA) |
| Weather | All-weather operation |
| Levitation | Permanent magnet Halbach array, passive |
| Propulsion | Linear synchronous motor |
| Operation | Fully automatic train control (driverless) |
| Safety | Automated train control, wraparound feature on the guideway, and restricted access to elevated guideway |
| Speed, maximum operational | 160 km/hr (100 mph) |
| Speed, average | 50 km/hr (31 mph) |
| Vehicle size | 12-m (39.4-ft) long x 2.6-m (8.5-ft) wide x 3-m (9.8-ft) tall |
| Average power consumption | 50 kW |
| Grade, operating capability | 7% (design capability >10%) |
| Turn radius, design minimum | 25.0 m (82 ft), design capability 18.3 m (60 ft) |
| Size of vehicle (passenger capacity) | AW3 (crush load) capacity: 100 passengers total |
| Aesthetics philosophy | Guideway will blend with and enhance the environment |

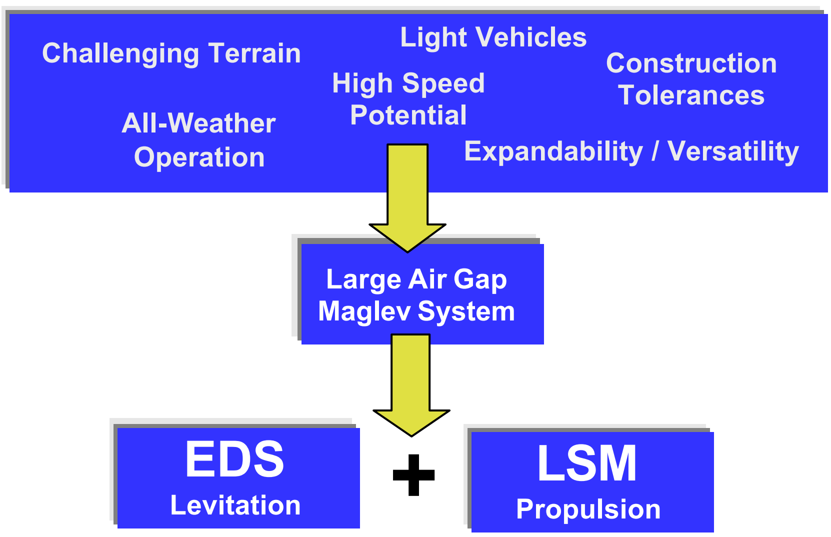


Figure 2. Design Flow Logic Used in Selecting Key Levitation and Propulsion Subsystems

"Base Technology Development" included a number of risk reduction analyses, as well as building several test articles. Examples of some of the test articles built for reducing technology development risks includes a subscale and full-scale test wheel to verify levitation physics.

Based on route specific requirements a full-scale system concept has been developed.

General Atomics (GA) in San Diego, California manages the General Atomics Urban Maglev project, backed by a team consisting of companies and organizations with unique strengths and capabilities, particularly suited for a Maglev project, as shown in Table 2.

Table 2. Urban Maglev Team Members

| **Urban Maglev Team Member** | **Responsibility** |
|---|---|
| General Atomics | System Integration and Magnetics |
| Carnegie Mellon University | Magnetic Shielding |
| Hall Industries | Vehicles |
| Mackin Engineering Co. | Guideway Design and EIS |
| Pennsylvania Department of Transportation | Transportation Studies |
| PJ Dick | Guideway Construction |
| Sargent Electric Co. | Power Distribution |
| Union Switch & Signal | Communication and Controls |
| Western Pennsylvania Maglev Development Corp. | Commercialization |
| Booz-Allen Hamilton | Transportation Studies |
| Lawrence Livermore National Laboratory | Magnetics |

This paper presents an overview of the technical progress to date. Related papers at this conference address additional details [4, 5, 6].

## 2 Requirements of an Urban Maglev

A thorough requirements document was prepared during the initial stage of the program. This document creates a common set of guidelines, which is intended to keep the design team focused during the design/development process. Included are requirements for the system and major subsystems to assure the performance, ride comfort and safety of the passengers. Key requirements are listed below.

| **Key Requirements** | | | |
|---|---|---|---|
| Speed, Max | 160 km/hr | Jerk, Max | 2.5 $m/s^3$ |
| Throughput | 12000/hr/direction | Noise Level Inside | < 67 dBA |
| Acceleration, Max | 1.6 $m/s^2$ | DC Magnetic Field in Car | < 5 Gauss |
| Curve Radius, Min | 18.3 m | Availability | > 99.99 % |
| Grade, Max | 10% | Ride Quality | ISO 2631 (1987) |

Levitation and Guidance Systems

The levitation system uses vehicle mounted permanent magnet double Halbach arrays. The orientation of the magnetization of the magnets in the Halbach array is arranged such as to concentrate the field lines below the array while nearly canceling the field above the array. This results in a system which requires no active magnetic shielding of the passenger compartment. In a double Halbach array, the strong sides of two Halbach arrays oppose each other with the track in between. The guidance force is provided passively by the propulsion magnets (on the vehicle) interacting with the laminated iron core of the LSM winding (on the guideway). The guideway and vehicle chassis cross section are shown in Figure 3.

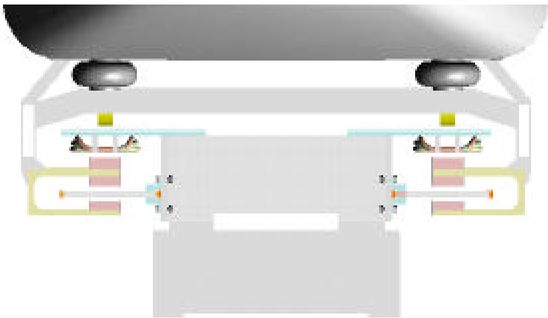

Figure 3. Guideway and Vehicle Chassis

The vehicle is supported on wheels when stationary, but levitates as it reaches the lift-off speed of about 2.5 meters per second. The air gap increases gradually as the vehicle speed increases, with a nominal levitation gap of 25 mm at a cruising speed of 80 km/hr. Minimization of the magnetic drag was a primary consideration for urban applications with frequent starts and stops. The magnetic drag shows a peak at around the lift-off speed and decreases very rapidly with speed. Figures 4 and 5 show the gap and drag force, respectively, as a function of vehicle speed.

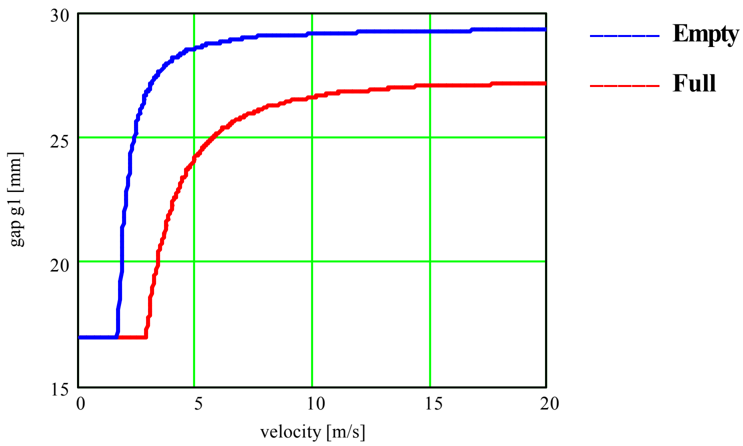


Figure 4. Gap vs. Velocity

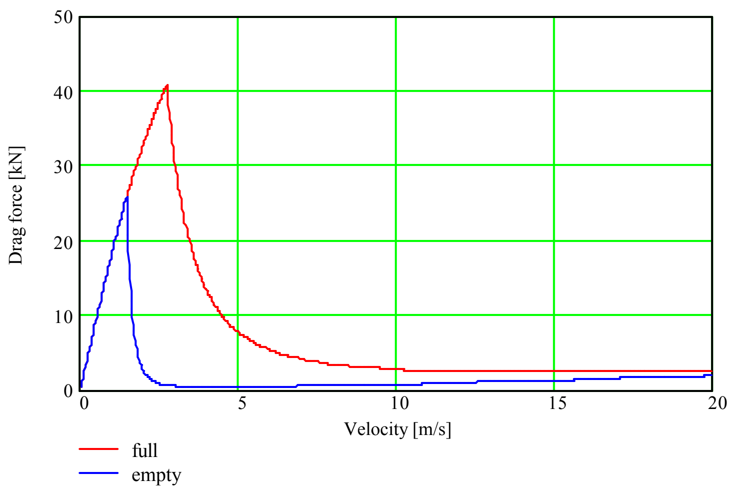


Figure 5. Magnetic Drag vs. Velocity Including the Effect of Wind Resistance and Eddy Currents

# 3 Ride Quality

Ride quality and damping are provided by an entirely passive secondary suspension system. This, coupled with the relatively stiff primary (magnetic) suspension provides excellent ride quality and only minimal changes in ride height with passenger load. Six degree of freedom dynamic simulations performed to date have shown no instabilities. Existing models of rail track roughness were used. Actual test track measurements, when available, will be valuable in verifying the vehicle dynamics, and projecting performance to higher speeds. The long (3.6 m) levitating arrays provide a means for minimizing the effects of track perturbations. Calculations show expected passenger compartment accelerations well below the ISO 1-hour comfort limit set forth in the requirements. In fact, the passenger compartment accelerations were below the 8-hour limit (Figure 6).

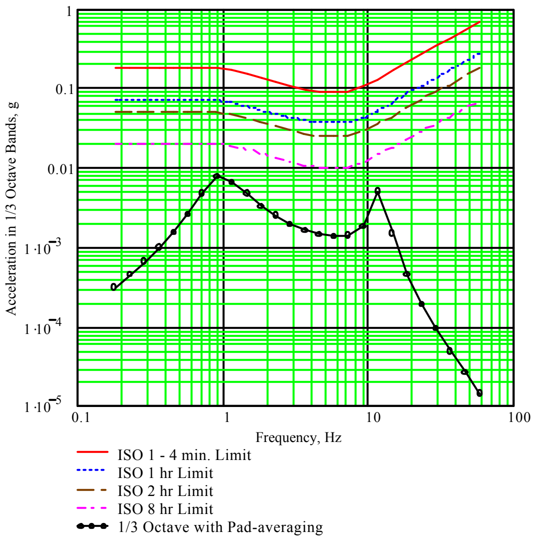


Figure 6. Predicted RMS Acceleration of the UML Passenger Compartment in 1/3 Octave Bands

# 4 Propulsion System

One of our first design decisions focused on selecting the propulsion system. We compared a LIM on the vehicle with a LSM mounted to the guideway. Because of the large operating air gap, a LSM is fundamentally better suited to the needs of an EDS suspension system. It was also found that a LSM is more cost-effective for a high capacity transportation system, which requires many vehicles on the alignment. The LSM configuration chosen also provides the required guidance force as well as additional passive levitation force (~70 kN at nominal air gap).The motor design optimizes the iron geometry to achieve the combined passive guidance and added levitation forces. This additional levitation force helps to reduce the drag force, which in turn reduces the operating power. The LSM design utilizes a simple three-phase winding with solid copper cables, chosen for low cost manufacturing. The LSM winding and propulsion magnets are shown in Figure 7.

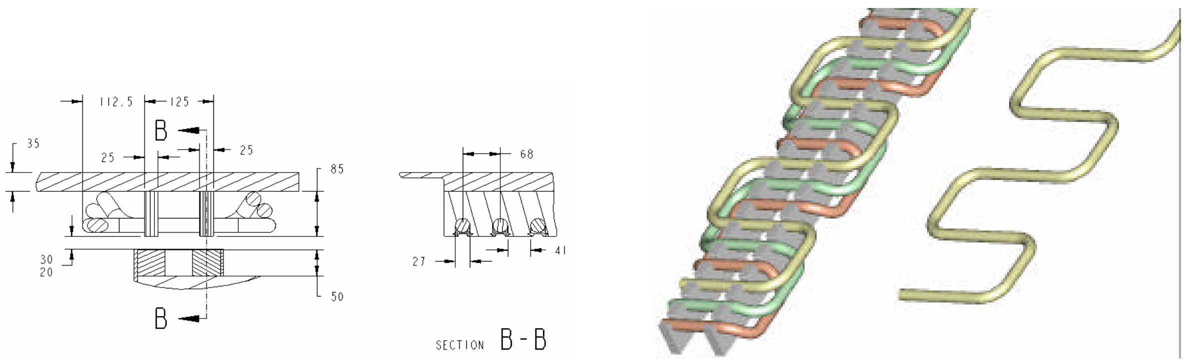


Figure 7. Simple Three Phase LSM Winding and Propulsion Magnets

# 5 Vehicle and Guideway

The technology choices of EDS and LSM result in a very simple and lightweight (9.5 Metric tons empty) vehicle. The vehicle consists of two modular sections connected via an articulation. The length of the levitation pads (per module) was limited to 3.6 meters to allow tight turn capability (18.3 meters). The vehicle and guideway are shown in Figure 8.

Figure 8. Vehicle Design is Modular with a Passive Secondary Suspension

Important design parameters are as follows:

| Design Parameters | |
|---|---|
| Vehicle Weight | |
| Empty | 9500 kg |
| Full | 16500 kg |
| Vehicle Dimension | |
| Length | 12 m |
| Height | 3 m |
| Width | 2.6 m |
| No. of Vehicles per Train | 4 |
| Speed, max | 160 km/hr |

# 6 Theoretical Studies and Alternative Designs

As a part of the Urban Maglev team effort, theoretical studies and examinations of alternative levitation and propulsion designs have been carried out at the Lawrence Livermore National Laboratory. Computer codes have been developed to analyze the present "baseline" configurations, as well as to scope out alternative configurations. Where possible, these codes have been bench-marked against the results of the Dynamic Test Facility (DTF) (see Section 8), finding good agreement. An example of such a comparison is the prediction of the improvement in levitation and Lift/Drag that can be expected in changing the track design from a litz-wire, "ladder" track to a laminated track. The specific comparison that was made was between the code predictions for the litz-wire-based "ladder" track as it is presently configured in the DTF, when operated with a double Halbach array that is five magnets in width on the top array and 3 magnets on the lower array. Still using the same magnet array and the same fixed-gap, the code was then programmed to calculate a 0.01 m. thick (copper) laminated-track configuration. Comparisons were made between such parameters as the levitated weight, L/D, and transition speed. It was found that the laminated track, because of its much higher conductor packing fraction and its smaller thickness (0.01 m. vs. 0.014 m. for the present litz-wire track) can be expected to yield markedly improved performance. Table 3 lists some comparisons between the "fixed-gap" code predictions for the present test facility track and a laminated track having the same transverse width as the present track. Also shown in the table (last column) is the further improvements that can be expected if the width of the laminated track is reduced to 0.3 m from the 0.5 m width of the present (test facility) track. The code predictions for the laminated track are to be bench-marked by measurements obtained using a linear-track test-rig now being constructed at LLNL specifically for that purpose.

Table 3

| | 0.5 m litz track | 0.5 m lam. track | 0.3 m lam. track |
|---|---|---|---|
| **Levitated weight, kg** | 600. | 1000. | 1800. |
| **L/D at 20 m/sec** | 6.0 | 12.5 | 15.0 |
| **Transition Speed, m/sec** | 6.4 | 2.8 | 2.8 |

The code that was used to predict the above results has also been modified to calculate the effect of introducing a shift in phase of one of the Halbach arrays relative to the other array. This shift has the effect of modifying the "generator action" of the vertical magnetic field component. The phase-shifting operation is accomplished by displacing the leading edge of one of the arrays relative to the other, and could either be performed as a fixed "trimming" of the levitation force, or could be incorporated into a levitation control circuit if required. The effect of applying such a phase-shift to a double Halbach array in which the upper and lower arrays have the same width as the upper array in the DTF, and with ratio of thickness of the arrays (lower relative to upper) of 0.8 as in the DTF is shown on the plot of Figure 9. As can be seen, even a small positive phase shift can result in a substantial increase in the levitation force. The down side of using a large phase shift is, however, a substantial decrease in the stiffness relative to the unshifted case. Note also that, initially, a negative phase shift results in a decrease in the levitation force relative to the unshifted case, owing to the introduction of anisotropy as a function of direction of motion that is implicit in the operation of shifting the phase. At higher speeds this anistropy is reduced as the electrical phase shift approaches its asymptotic value of 90 degrees.

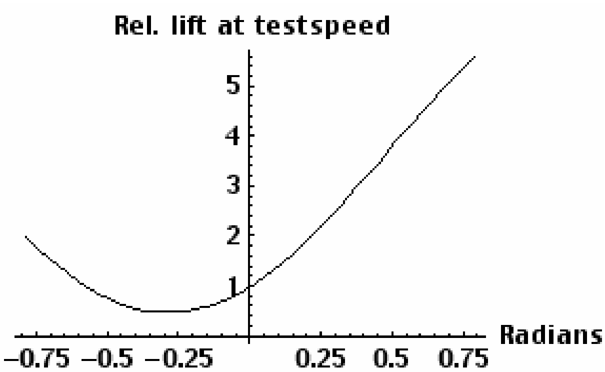


Figure 9. Relative lift force as a function of phase shift at 10 m/sec.

# 7 Magnetic Levitation Test Wheel

In advance of a full-scale test track, considerable model validation can be done on bench and partial component test apparatus. At present, the device we have built to measure levitation characteristics of the vehicle is a 3 m diameter rotating wheel having a full-scale track at its perimeter. This wheel simulates the magnetics of the double Halbach array moving with respect to the guideway. It uses two wavelengths of the full-scale levitation magnets to demonstrate the levitation and drag forces as a function of speed. The footprint area of the test magnets corresponds to ~1/18$^{th}$ of a complete vehicle levitation magnet system. Testing began in January 2002 and has produced data essential to validating our modeling predictions. Figure 10 shows the test wheel facility, which consists of a programmable powered wheel having a full-scale ladder track around its perimeter. The simulated 1/18th scale car mass is affixed to a load cell that restricts movement in all directions except the vertical (levitation).

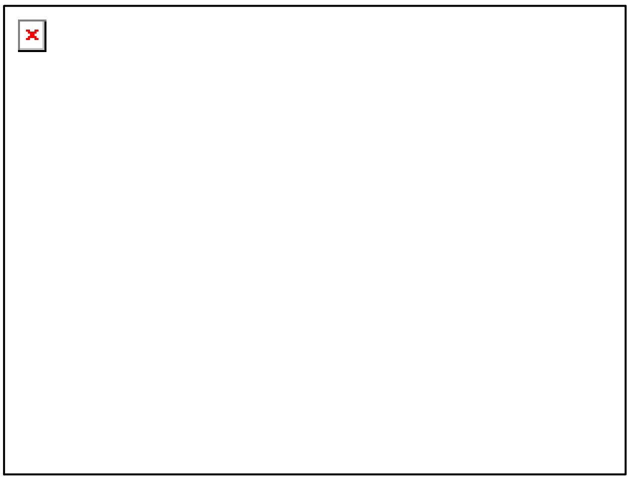

Figure 10. Magnetic Levitation Test Wheel

Figure 11 shows the measured and predicted lift and drag forces for a 25 mm fixed gap as a function of speed. The observed lift-off speed is ~2.5 m/s, and a final air gap of 25 mm is achieved at a speed of 20 m/s. These test results confirm levitation predictions. Oscillations in the data are due to radial tolerances in the dimension of the test wheel.

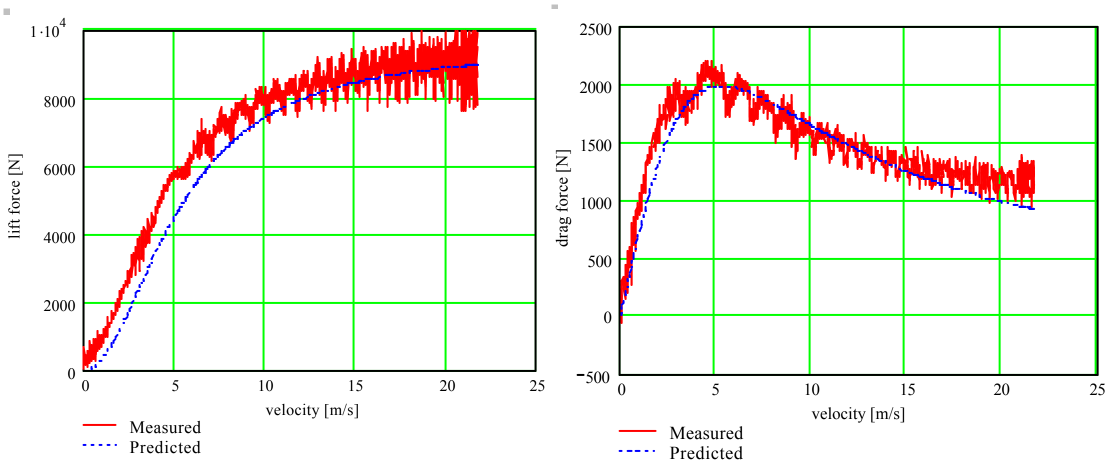


Figure 11. Lift and Drag Forces for a Fixed Gap on Test Wheel

## 8 Conclusions

The U.S. Urban Maglev program provides a new approach for low speed transportation suitable for very challenging urban environments. Analyses and testing to date give confidence that there are no major technical obstacles to initial demonstration of the system at a test track leading to full-scale deployment at a selected urban site.

## 9 Acknowledgements

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