The Vital Contribution of MagLev Vehicles for the Mobility in Smart Cities

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Abstract: The role of transport in sustainable development was first recognized at the 1992 United Nations (UN) Earth Summit and reinforced in its outcome document—Agenda 21. It is also part of objective 11 of UN 2030 Agenda for Sustainable Development. The improvements in the traditional methods of transportation lag behind the necessities. This paper shows that Magnetic Levitation (MagLev) can fulfill the demand and fits with smart grid concepts. Moreover, the levitation method based on the diamagnetic property of high-temperature superconductors in the proximity of rare-earth permanent magnets presents advantages in comparison with other levitation methods. This technological solution was tested with the operation of a real scale prototype inside the campus of the Federal University of Rio de Janeiro (UFRJ), operating since 2014. The paper presents a historical and technological overview of the steps necessary to turn this prototype into a commercial product. The development is framed within NASA’s Technological Readiness Levels (TRL). A new transportation paradigm is on the verge of becoming a reality.

Keywords: MagLev; urban transportation; superconductivity; permanent magnets; smart cities; smart grids

1. Introduction

Nowadays, 50% of the world population lives in cities. In many countries, like Brazil, this percentage is greater than 80%. The mobility in these highly populated areas must be provided by non-polluting, energetically efficient and public transportation systems. Cities should belong to citizens and not to drivers, as we see today. In the near future, private vehicles, even electric ones, will be prohibitive. The trajectory of cars in the present century will be comparable to that of cigarettes during the XX century: from a fashionable consumer good to a villain of society.

This brings us to the concept of a smart city, which involves six axes: Government, Mobility, Environment, Economy, People and Living [1]. In the case of the axe “Mobility”, the focus of this paper concerns efficiency and flexibility.

The Magnetically Levitated (MagLev) Technology, applied to urban transportation, can fulfill the modern and future mobility requirements. Moreover, the MagLev technology based on the diamagnetic property of high critical temperature superconductors in the proximity of the field produced by rare earth permanent magnets, named in this paper as MagLev², offers advantages in terms of both construction and operation in comparison not only with wheel and rail solutions but also with other MagLev technologies. There is until today no commercially available MagLev² vehicle, but the perspectives are promising. The prototype developed in Brazil, named MagLev²-Cobra, reached level 7 in the NASA defined Technological Readiness Level (TRL) and is the most advanced one based
on this technological scale [2]. The experimentally available data confirm very low energy consumption due to the absence of wheel-rail friction and light weight. This fact makes the MagLev^2 an excellent vehicle for a world dominated by distributed energy resources, such as photo voltaic panels, small scale wind power and batteries, which allows the implementation of smart-grid concepts.

This paper begins with a review of Magnetic Levitation (MagLev) Methods applied to transportation. This is followed by a short description of the MagLev^2-Cobra prototype and the state of the art of MagLev technology in the world. A comparison between MagLev^2 with other MagLev methods completes the theoretical approach. Based on the experimental data of the MagLev^2-Cobra project, the perspectives of operation in an environment of intermittent energy are unveiled. The paper concludes with the steps to turn MagLev^2-Cobra into a Commercial Product.

Certainly, the wheel still represents an icon of human mobility. As the main contribution, this paper shows that a new paradigm, namely Magnetic Levitation, available with the technical achievements on superconductors, permanent magnets, and other new materials will impact urban mobility along this century.

2. Magnetic Levitation (MagLev) Methods Applied to Transportation

Magnetic Levitation techniques (MagLev), promising for applications in mass transport, are subdivided into three groups, described in the following [3].

2.1. Electromagnetic Levitation (EML)

This technique has its best showcase in the German levitation train proposal, Transrapid [4], which was commercially implanted in the year 2003, along a 30 km double line connection between the international airport in Pudong, Shanghai, and Lujiazui, a financial district in the city (http://www.smtdc.com). MagLev projects in commercial urban operation in Japan, China and South Korea also employ EML technology.

The basic physical foundation explores the attraction force that exists between an electromagnet and a ferromagnetic material. Vertical stabilization, in this case, is only possible with an active control system and regulator properly tuned (Figure 1a).

![Figure 1. Magnetic Levitation (MagLev) methods.](image-url)

2.2. Electrodynamic Levitation (EDL)

This type of levitation requires the movement of a magnetic field in the vicinity of a conductive material. The Japanese proposal for a levitation train, JR-MagLev (http://www.rtri.or.jp), applies this principle. There is a double line for demonstration and testing in Yamanashi, between Tokyo and Osaka, operating since 1997. In 2013, this line was expanded and currently covers 42.8 km. Japan
plans to extend it to complement the Shinkansen (HST wheel-rail), which links these two cities, but the technology has not yet been commercially deployed.

To understand the method, assume a magnet moving over a conductive sheet (e.g., aluminum). It is known that eddy currents will be induced in the conductor. These currents, in turn, generate another magnetic field which, by Lenz’s law, will oppose the action of the field from the iman. The interaction between these two fields produces a repulsion force, which increases with speed and allows for levitation. The system, if properly adjusted, can be passively stabilized laterally, but requires support wheels at low speeds (Figure 1b).

2.3. Superconducting Levitation (SML)

This method makes use of the diamagnetic property that excludes external magnetic fields from inside a superconductor. In the case of type II superconductors, this exclusion is partial, which reduces the levitation force but leads to the stability of the levitation due to the so-called “pinning” effect [5]. This property, which represents the great differential in relation to the EDL and EML methods, could only be properly explored from the end of the 20th century with the advent of new magnetic materials, such as Nd$_2$Fe$_{14}$B (NdFeB), and high critical temperature superconducting (HTS) ceramics, such as YBa$_2$Cu$_3$O$_x$ (YBCO). Brazil, with the MagLev$^2$-Cobra project, is the first country in the world to have a full-scale demonstration line of this technology (Figure 1c).

In a simplified way, Magnetic Levitation, regardless of the technique employed, is compared with the traditional wheel-rail technology for transportation, as shown in Figure 2, in which construction aspects (first two lines) and operational aspects (last three lines) are separated.

| Characteristics                  | MagLev | Wheel-Rail |
|----------------------------------|--------|------------|
| Cost of the levitating / rolling stock | ![Rating](Image) | ![Rating](Image) |
| Cost and time of civil construction | ![Rating](Image) | ![Rating](Image) |
| Acceleration and braking time     | ![Rating](Image) | ![Rating](Image) |
| Total travel time                 | ![Rating](Image) | ![Rating](Image) |
| Operational costs: maintenance and fuel | ![Rating](Image) | ![Rating](Image) |
| Environmental impact: audible noise, CO$_2$ emission | ![Rating](Image) | ![Rating](Image) |

Figure 2. Comparison of MagLev x Wheel-Rail.

3. Description of the MagLev$^2$-Cobra Prototype

Figure 3 depicts the MagLev$^2$-Cobra project as a graphic abstract. The vehicle is 6m long and is composed of four modules. The test line extends for 200 m. Two parallel lines of permanent magnetic rails interact with superconductors installed inside of 24 cryostats (12 at each side) filled with liquid nitrogen. The traction is given by a short primary linear induction motor.
The debut was on 1 October 2014, on the last day of the 22nd International Conference on Magnetically Levitated Systems and Linear Drives, held in Rio de Janeiro. After one year of improvements, the system was opened to the public. The visits take place every Tuesday, from 11 a.m. to 3 p.m. Until today, more than 20 thousand people, Brazilians and foreigners, including students, professors, staff, families, children, politicians, investors, took a ride and registered the presence in a memory book.

4. State of the Art of MagLev Trains

MagLev projects are usually divided into two main groups: high-speed (HST) and urban. Table 1 details some striking features of the HST projects.

Table 1. High speed MagLev projects.

| COUNTRY          | NAME    | LENGTH | OPENING          | LEVITATION |
|------------------|---------|--------|------------------|------------|
| Germany (Emsland)| Transrapid | 31.5 km | test line closed | EML        |
| China (Shanghai) | SMT     | 30.0 km | October 2003    | EML        |
| Japan (Yamanashi)| JR-MagLev | 42.8 km | test line       | EDL        |

Table 2 details the urban projects. It should be noted the greater interest in urban projects, the category in which MagLev²-Cobra is inserted [6].

All commercially available Urban-MagLev use EML technology for the levitation method [7]. The SML technology, adopted in the MagLev²-Cobra project, does not yet have a commercial prototype, but it is attracting the attention of several groups around the world, the most active of which are German, from IFW/Dresden [8], and Chinese, from Southwest Jiaotong University (SWJTU) [9], shown in Figure 4.

Linear Induction Motors (LIM), short primary, promote the traction in all Urban MagLev Projects.
Table 2. Urban MagLev Projects in commercial use.

| COUNTRY          | NAME            | LENGTH | OPENING  | LEVITATION |
|------------------|-----------------|--------|----------|------------|
| Japan (Nagoya)   | HSST-Linimo     | 9 km   | March 2005| EML        |
| South Korea (Seoul) | EcoBee         | 6.1 km | February 2016 | EML       |
| China (Changsha) | Airport line    | 18.5 km| May 2016  | EML        |
| China (Beijing)  | Mentougou line  | 10.2 km| December 2017 | EML      |

Figure 4. Superconducting Levitation (SML) projects developed in China (left) and Germany (right).

5. Comparison of MagLev\(^2\) Technology with Other MagLev Methods

The technology applied in the MagLev\(^2\)-Cobra urban transportation system proves to be simpler and lighter than the EML technology used in commercially available urban MagLev trains. This is because the levitation mechanism does not depend on heavy electromagnets installed in the vehicle, also making the elevated track more slender. Moreover, the MagLev EML Track Switch requires movement of the track. In the MagLev\(^2\)-Cobra, the switch will result from the mere energizing of the track in the changing places, where the magnets on the track will be replaced by electromagnets.

Figures 5–7 below say more than a thousand words.

These characteristics suggest the adoption of the name MagLev\(^2\)-Cobra. The exponent “2” refers to “Lev” raised to the square, highlighting the differentiation between the MagLev\(^2\)-Cobra project for urban transport from the other MagLev projects, based on the EML technology of attractive forces. That is because, the Cobra project, besides levitating, is light. Table 3 explains the name, having as root Latin.

Cobra is the Portuguese name for Snake, referring to a smooth and silent movement, along sharped curves and slopes, which are the main characteristics of the system. Cobra is also in English the “Naja Snake”, reinforcing the name.
Figure 5. Comparison of MagLev Electromagnetic Levitation (EML) in urban commercial operation in Japan, China, South Korea with the MagLev$^2$-Cobra experimental line, which uses SML levitation: lighter and slender.

Figure 6. Comparison of the system required to obtain EML levitation (left side) with the cryostats required for MagLev$^2$-Cobra, which employs SML technology (right side): simpler and more robust.
Figure 7. Track Switch. EML on the left, SML on the right.

Table 3. The name MagLev$^2$-Cobra.

| English       | Latin     | Initials |
|---------------|-----------|----------|
| Magnetic      | Magneticus| Mag      |
| Levitation    | Levitatio | Lev      |
| Light         | Levis     | Lev      |

6. Experimental Data of the MagLev$^2$-Cobra Project

Tables 4 and 5 present experimental data obtained over five years of operation of this experimental system. Table 6 presents a comparison of normalized energy consumption with other urban transportation systems [10].

Table 4. MagLev$^2$-Cobra experimental prototype system.

| Characteristic                        | Data                                      |
|---------------------------------------|-------------------------------------------|
| Capacity                              | 20 passengers = 6 pass./m$^2$              |
| Cruising speed                        | 10 km/h                                   |
| Line length                           | 200 m                                     |
| Declivity                             | 1 m/100 m = 1%                            |
| Traction                              | Linear Induction Motor                    |
| Modules (wagons) dimensions           | H = 2.8 m; W = 2.3 m; L = 1.5 m           |
| Supporting force per cryostat         | 250 kgf                                   |
| LN2 consumption per cryostat          | 20 L / day                                |

Table 5. MagLev$^2$-Cobra: Energy Balance.

| Equipment                          | Energy                                  |
|------------------------------------|-----------------------------------------|
| Linear Motor (traction)            | 0.1 kWh/trip (400 m)                    |
| Linear Motor (traction)            | 10 kWh each hour                        |
| Air conditioner (refrigeration)    | 12 kWh each hour                        |
| Photo-voltaic panel (each one)     | 1 kWh/day                               |
| Photo-voltaic panels (12)          | 12 kWh/day                              |
Table 6. Normalized energy consumption of urban transportation systems.

| Transportation System                        | Energy Consumption (kWh/pass.km) |
|----------------------------------------------|----------------------------------|
| Cars (1.3 passengers)                        | 0.768                            |
| Padron Bus (80 passengers)                   | 0.074                            |
| Metropolitan train (300 passengers)         | 0.054                            |
| Subway train (225 passengers)               | 0.051                            |
| MagLev^2-Cobra (20 passengers)              | 0.025                            |

Twelve solar panels, shown in Figure 8, supply the energy necessary for operation.

Figure 8. Twelve solar panels of 250 Wp each (total of 12 kWh/day).

7. MagLev^2-Cobra Operation with a Smart-Grid

The world is experiencing an energy transition process in which centralized generation, represented by large power plants, has given rise to small production, which is usually closer to consumers’ centers and, therefore, is called distributed generation. Among these technologies, photovoltaic (PV) panels and small scale wind power stand out, which are characterized by the intermittency resulting from the availability of sun and wind, respectively, which imply the need to adopt advanced forms of energy storage, monitoring, control, and protection [11].

Therefore, energy systems have evolved from the concept of distributed generation to that of distributed energy resources (DER), which are made up of energy generation or storage devices located at consumers’ facilities (behind-the-meter) or in the distribution systems, capable of supplying partially or totally the local demand. Among the DER, we can highlight the distributed generation, batteries, demand response and electric vehicles.

For the monitoring, control, and protection of power systems, automation, computing, and digital communication technologies, that is, smart grids have been used intensively. This requires the installation of smart meters and bidirectional communication networks between meters and data centers control, in addition to the availability of other types of sensors and control devices that allow the automation of the operation of the distribution grid. They also include Data Analysis and Big Data technologies to process the large volume of information from advanced measurement systems,
identify patterns and assist decision processes based on that information, through the application of mathematical or mechanical methods.

It is noted, therefore, that the expansion of the use of the MagLev\textsuperscript{2}-Cobra is fully inserted in the context of smart cities, in which low-cost mass transportation is used, which does not require fossil fuel burning or electricity from large power plants. It is a smart-grid, where the electricity for propelling the vehicle comes from a PV panel, which can be associated with a set of batteries and a smart meter that allows controlling both the supply and the use of energy.

8. Conclusions: The Steps to Turn MagLev\textsuperscript{2}-Cobra into a Commercial Product

Figure 9 outlines the development stages of the MagLev\textsuperscript{2}-Cobra project, framing them on the TRL ("Technology Readiness Level") scale proposed by NASA \cite{2}, as shown in Figure 10. In fact, the scale TRL only goes up to nine. We introduced the TRL10 level, which does not belong to the Standard. This is understandable, since NASA is satisfied with a few copies of the equipment it develops. However, we are not, and industrialization on a large scale means a new level of difficulty.
Each step of the TRL scale requires more mental, physical and financial effort, as expected from a climber who wants to reach the top of Everest. The MagLev\textsuperscript{2}-Cobra development has been reported in papers regularly presented at the International Conference on Magnetically Levitated Systems and Linear Drives, the most important conference on MagLev technology, as organized in Table 7.

**Table 7.** The MagLev\textsuperscript{2}-Cobra evolution framed in the TRL scale.

| TRL    | Publications |
|--------|--------------|
| TRL 1  | [12]         |
| TRL 2  | [13]         |
| TRL 3  | [14]         |
| TRL 4  | [15]         |
| TRL 5  | [16–18]      |
| TRL 6  | [19]         |
| TRL 7  | [20–22]      |
| TRL 8  | [23,24]      |
| TRL 9,10 | not yet disclosed |

The industrialization, the last step, imposes cooperation with companies. This effort is underway and should be achieved in a period of three years of hard work and some luck.

This 20 year long journey does not differ from similar experiences of other MagLev vehicles. For instance, the Germany efforts to turn the Transrapid technology into a commercial product took more than 30 years. The Japanese JR-MagLev is planned to start commercial operation at the end of this decade, after more than 50 years since the first research efforts. The HSST-Linimo, EcoBee, and Chinese urban MagLev Systems also lasted for more than 30 years to overcome all TRLs levels. These facts serve as an example and an incentive to the MagLev\textsuperscript{2}-Cobra team to endure and work hard to turn the system into a commercial product.

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**Abbreviations**
The following abbreviations are used in this manuscript:

| Abbreviation | Description |
|--------------|-------------|
| DER          | Distributed Energy Resources |
| EDL          | Electrodynamic Levitation |
| EML          | Electromagnetic Levitation |
| HSR          | High Speed Rail |
| LSM          | Linear Synchronous Motor |
| LIM          | Linear Induction Motor |
| MagLev       | Magnetically Levitated |
| PV           | Photo Voltaic |
| SML          | Superconducting Magnetic levitation |
| TRL          | Technology Readiness Level |
| UN           | United Nations |
| UFRJ         | Federal University Rio de Janeiro |
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