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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

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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 MagLev^2, 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 MagLev^2 vehicle, but the perspectives are promising. The prototype developed in Brazil, named MagLev^2-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 electro magnet and a ferromagnetic material. Vertical stabilization, in this case, is only possible with an active control system and regulator properly tuned (Figure 1a).

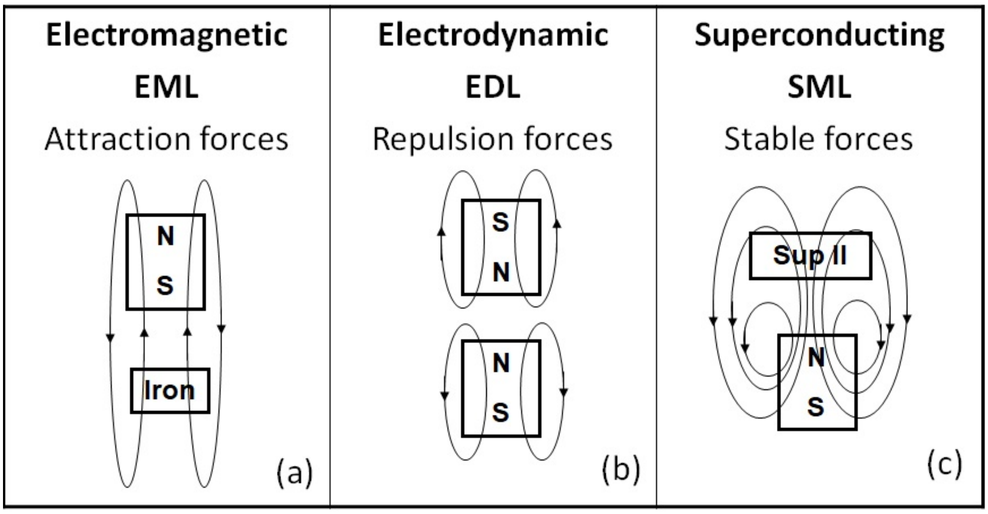

Figure 1. Magnetic Levitation (MagLev) methods.

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 imam. 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 $Nd_2Fe_{14}B$ (NdFeB), and high critical temperature superconducting (HTS) ceramics, such as $YBa_2Cu_3O_X$ (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.

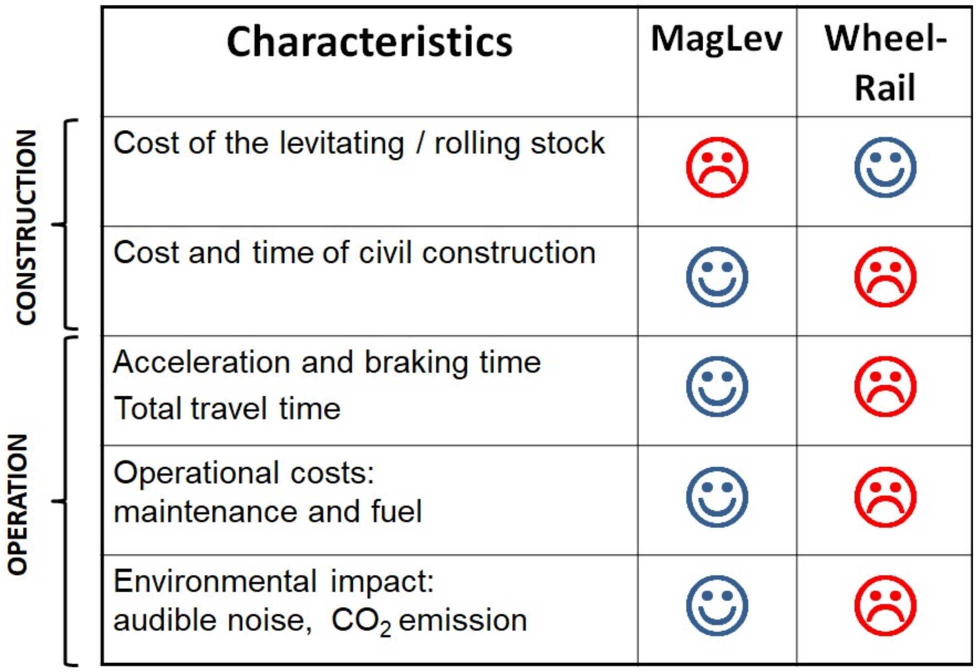

Figure 2. Comparison of MagLev x Wheel-Rail.

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.

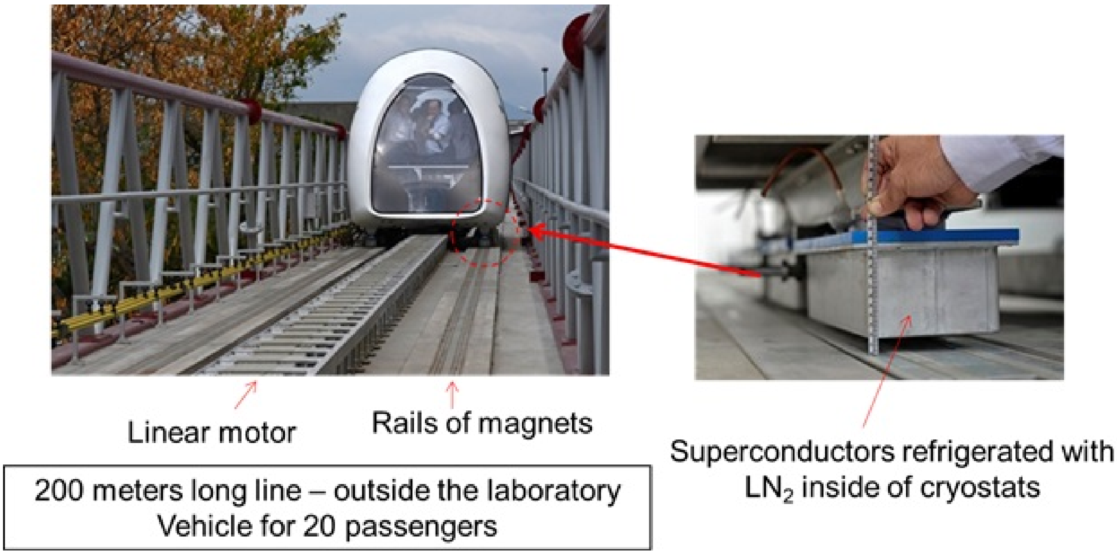

Figure 3. Graphic abstract of the MagLev^2-Cobra project.

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.

China has operated the Germany Transrapid technology commercially in Pudong Airport, Shanghai, since October 2003. The velocity record of 501 km/h was tested in November 2003. Nowadays, the maximal cruise speed is 450 km/h. d Japan plans to extend the Yamanashi test line and to start the operation connecting Tokyo-Nagoya in 2027 and Tokyo-Osaka in 2045. The velocity record 603 km/h was reached in April 2015, but the foreseen cruise speed will be 500 km/h.

These two icon projects use different levitation methods, but the traction, in both, is given by Linear Synchronous Motors (LSM) of long primary.

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 MagLev^2-Cobra is inserted [6].

All commercially available Urban-MagLev use EML technology for the levitation method [7].

The SML technology, adopted in the MagLev^2-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

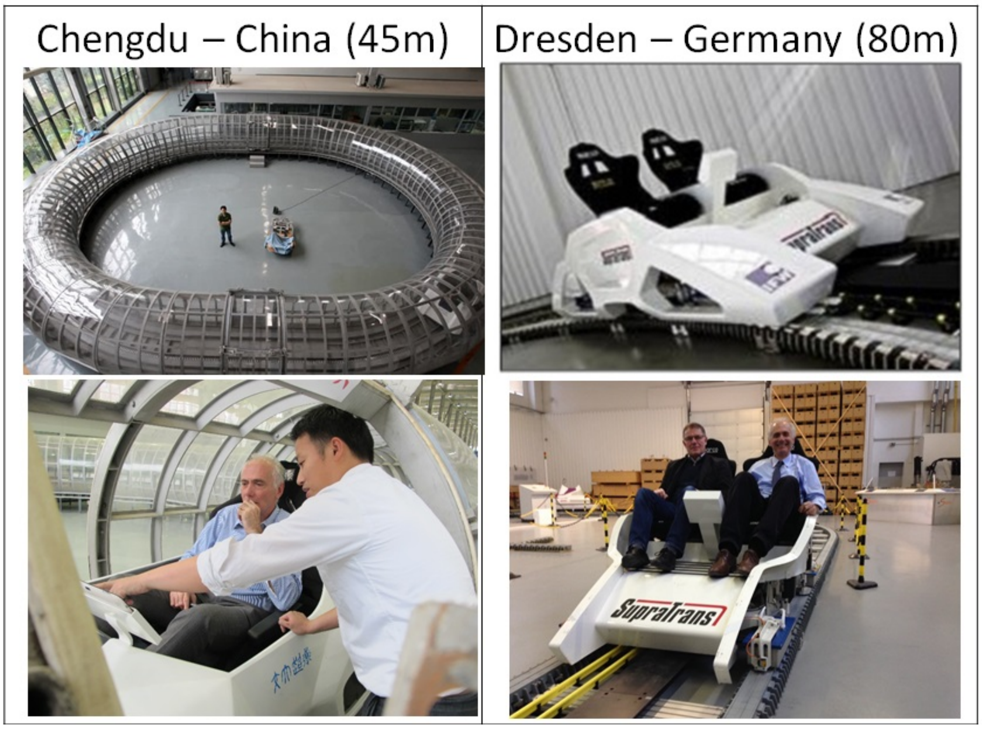

Figure 4. Superconducting Levitation (SML) projects developed in China (**left**) and Germany (**right**).

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.

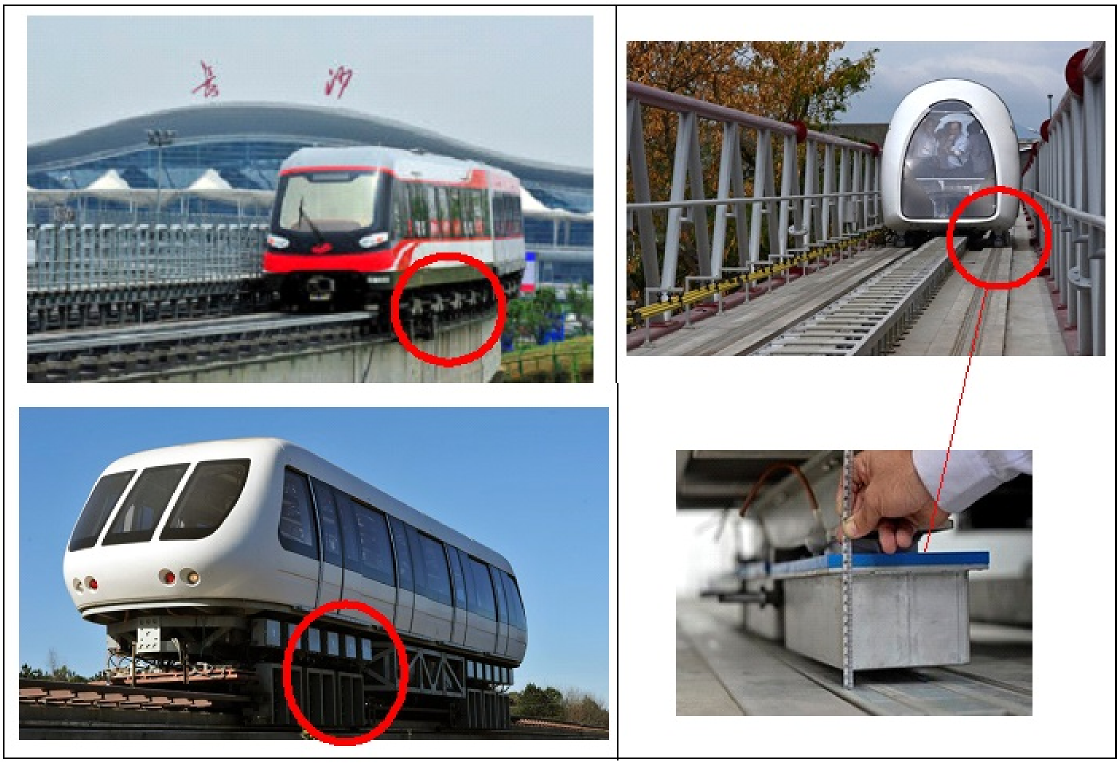

Figure 6. Comparison of the system required to obtain EML levitation (left side) with the cryostats required for MagLev^2-Cobra, which employs SML technology (right side): simpler and more robust.

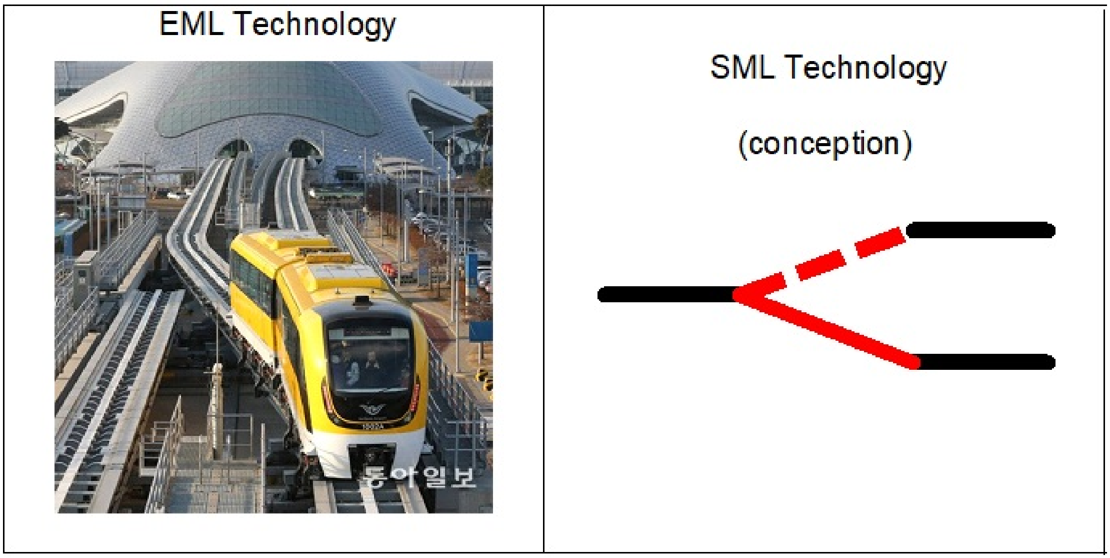

Figure 7. Track Switch. EML on the left, SML on the right.

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, photo voltaic (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^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^2-Cobra into a Commercial Product

Figure 9 outlines the development stages of the MagLev^2-Cobra project, framing them on the TRL ("Technology Readiness Level") scale proposed by NASA [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.

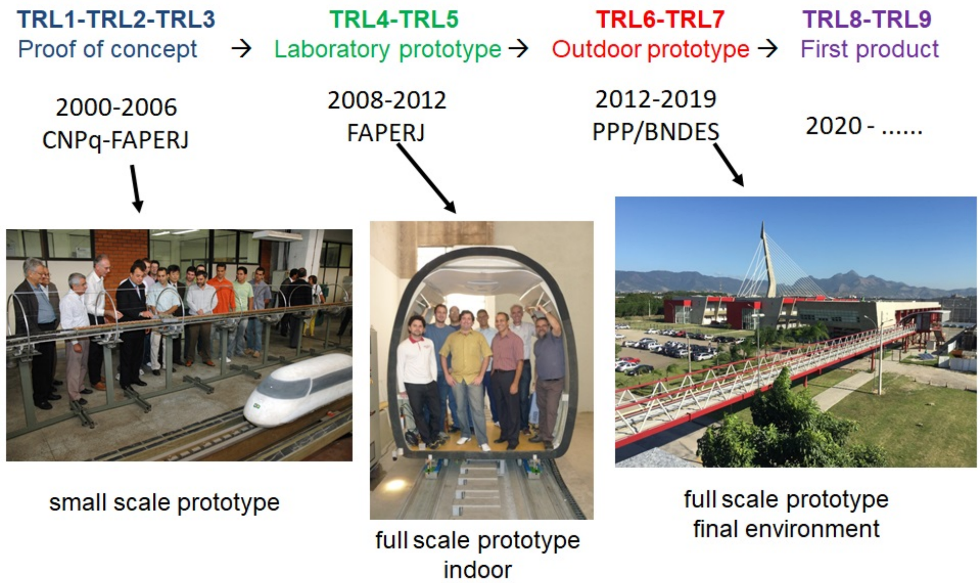

Figure 9. The stages of the MagLev^2-Cobra project within the TRL scale.

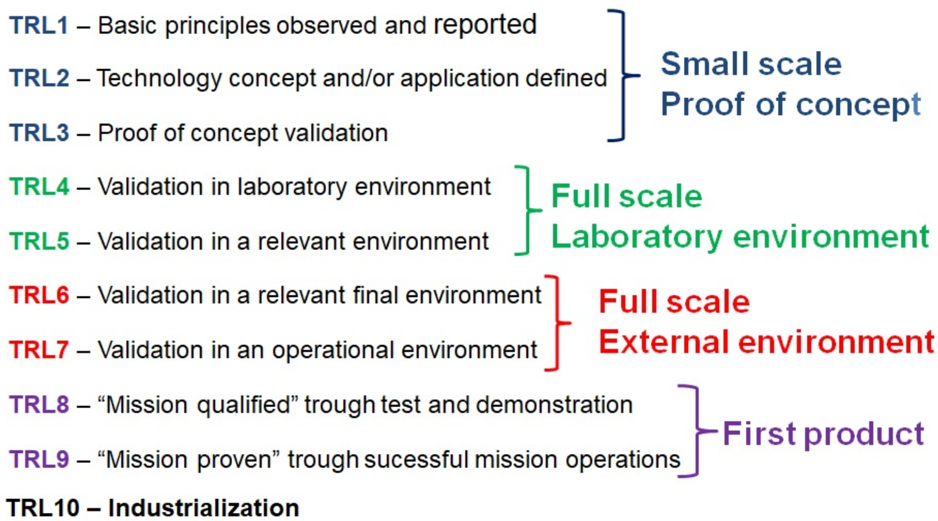

Figure 10. The TRL scale, proposed by NASA with the inclusion of a 10th level.

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^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^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^2-Cobra team to endure and work hard to turn the system into a commercial product.

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Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

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

References

1. Alonzo, C.M.; Aletà, N.B.; Ruiz, R.M.A. Smart Mobility in Smart Cities. In *XII Congreso de Ingeniería del Transporte*; Springer: Valencia, Spain, 2016; pp. 1209–1219.
2. European Association of Research and Technology Organisations. *The TRL Scale as a Research and Innovation Policy Tool*; EARTO: Brussels, Belgium, 2014.
3. Sinha, P.K. *Magnetic Levitation*; IEE Press: London, UK, 1987.
4. Schach, R.; Jehle, P.; Naumann, R. *Transrapid und Rad Shine System*; Springer: Berlin, Germany, 2006.
5. Sheahen, T. *Introduction to High-Temperature Superconductivity*; Springer: Berlin, Germany, 2002.
6. Liu, Z.; Long, Z.; Li, X. *MagLev Trains: Key Underlying Technologies*; Springer: Berlin, Germany, 2015.
7. Han, H.-S.; Kim, D.-S. *Magnetic Levitation: MagLev Technology and Applications*; Springer: New York, NY, USA, 2016.
8. Schultz, L.; de Haas, O.; Verges, P.; Beyer, C.; Rohlig, S.; Olsen, H.; Kuhn, L.; Berger, D.; Noteboom, U.; Funk, U. Superconductively Levitated Transport System—The SupraTrans project. *IEEE Trans. Appl. Supercond.* **2005**, *15*, 2301–2305. [CrossRef]
9. Wang, S.; Wang, J.; Wang, X.; Ren, Z.; Zeng, Y.; Deng, C.; Jiang, H.; Zhu, M.; Lin, G.; Xu, Z. The Man-Loading High-Temperature Superconducting MagLev Test Vehicle. *IEEE Trans. Appl. Supercond.* **2003**, *13*, 2134–2137. [CrossRef]
10. D'Agosto, M.D.A. *Transportation, Energy Use and Environmental Impacts*; Elsevier: Amsterdam, The Netherlands, 2019.
11. Pérez-Arriaga, I.; Knittel, C. *Utility of the Future, an MIT Energy Initiative Response to an Industry in Transition*; MIT Energy Initiative: Boston, MA, USA, 2016.
12. Nicolsky, R.; Stephan, R.M.; de Andrade, R.; Ferreira, A.C. The Brazilian Project for a Superconducting Magnetic Levitation Train. In Proceedings of the 16th Int. Conf. on Magnetically Levitated Systems and Linear Drives, Rio de Janeiro, Brazil, 7–10 June 2000.
13. Nicolsky, R.; Stephan, R.M.; Ferreira, A.C.; de Andrade, R.; Moreira, M.A.; Rolim, L.G.; Neves, M.A.; Rosário, M.A. The Current State of the Brazilian Project for a Superconducting Magnetic Levitation Train. In Proceedings of the 17th Int. Conf. on Magnetically Levitated Systems and Linear Drives, Lausanne, Switzerland, 3–5 September 2002.
14. Stephan, R.M.; Ferreira, A.C.; de Andrade, R.; Moreira, M.A.; Rolim, L.G.; Neves, M.A.; Rosário, M.A.; Machado, O.J.; Nicolsky, R. A Superconducting Magnetic Levitation Train Prototype in Closed Loop Track. In Proceedings of the 18th Int. Conf. on Magnetically Levitated Systems and Linear Drives, Shanghai, China, 26–28 October 2004.
15. David, E.; Stephan, R.M.; Costa, G.C.; de Andrade, R.; Nicolsky, R. Feasibility Study of an HTS-Maglev Line at the Federal University of Rio de Janeiro. In Proceedings of the 19th Int. Conf. on Magnetically Levitated Systems and Linear Drives, Dresden, Germany, 3–15 September 2006.
16. Stephan, R.M.; David, E.G.; de Andrade, R.; Sotelo, G.G.; Machado, O.; Haas, O.; Werfel, F. A Full-Scale Module of the MagLev-Cobra HTS-Superconducting Vehicle. In Proceedings of the 20th Int. Conf. on Magnetically Levitated Systems and Linear Drives, San Diego, CA, USA, 15–18 December 2008.
17. Stephan, R.M.; David, E.G.; Haas, O. Maglev-Cobra: An Urban Transportation Solution Using HTS-Superconductors and Permanent Magnets. In Proceedings of the 20th Int. Conf. on Magnetically Levitated Systems and Linear Drives, San Diego, CA, USA, 15–18 December 2008.
18. Motta, E.S.; Stephan, R.M.; de Andrade, R.; Norman, J.H.; Kuhn, L. Optimization of a Magnetic Rail for the HTS-Superconducting Vehicle Maglev-Cobra. In Proceedings of the 20th Int. Conf. on Magnetically Levitated Systems and Linear Drives, San Diego, CA, USA, 15–18 December 2008.
19. Stephan, R.M.; de Andrade, R.; Ferreira, A.C.; Machado, O.; Santos, M.D.; Sotelo, G.G.; Dias, D.H. The First Full Scale Functional Prototype of the Superconducting Magnetically Levitated Vehicle MagLev-Cobra. In Proceedings of the 21st Int. Conf. on Magnetically Levitated Systems and Linear Drives, Daejon, Korea, 10–13 October 2011.
20. Stephan, R.M. MagLev-Cobra: Tecnologia de levitação magnética no Brasil. *Ciência Hoje* **2015**, *55*, 20–25.
21. Stephan, R.M.; Costa, F.; de Andrade, R.; Ferreira, A.C.; Rodriguez, E.F. The experimental line of the MagLev-Cobra project for urban transportation. In Proceedings of the 23th Int. Conf. on Magnetically Levitated Systems and Linear Drives, Berlin, Germany, 23–26 September 2016.

22. Stephan, R.M.; de Andrade, R.; Ferreira, A.C.; Sotelo, G.G. Superconducting Levitation Applied to Urban Transportation. In *Wiley Encyclopedia of Electrical and Electonics Engineering*; Wiley: London, UK, 2017.
23. Stephan, R.M.; Costa, F.; Rodriguez, E.; Deng, Z. Retrospective and perspectives of the superconducting magnetic levitation (SML) technology applied to urban transportation. *Transp. Syst. Technol.* **2018**, *4*, 195–202. [CrossRef]
24. Stephan, R.M.; Levi, C.; Benetti, P. UFRJ Campus: A City of Innovative Mobility. In *World Sustainability Series*; Springer International Publishing: Berlin, Germany, 2018; Volume 24, pp. 371–384.