Rubric 1. TECHNOLOGIES AND PROJECTS
Field – Design and construction of roads, subways, airfields, bridges and transport tunnels

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PAST, PRESENT AND FUTURE OF SUPERCONDUCTING MAGNETIC LEVITATION (SML)

A review of Superconducting Magnetic Levitation (SML) applied to MagLev trains will be presented. The paper is divided into low-speed and high-speed MagLev. The promising perspectives will close this review.

***Key words**:* Superconducting Magnetic Levitation, Ur ban Transportation, High-speed Transportation, MagLev Second Generation, Technological Innovation, MagLev history.

Рубрика 1. ТЕХНОЛОГИИ И ПРОЕКТЫ
Направление – Проектирование и строительство дорог, метрополитенов, аэродромов, мостов и транспортных тоннелей

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ПРОШЛОЕ, НАСТОЯЩЕЕ И БУДУЩЕЕ СВЕРХПРОВОДЯЩЕЙ МАГНИТНОЙ ЛЕВИТАЦИИ

Будет представлен обзор сверхпроводящей магнитной левитации, применяемой в поездах MagLev. Статья освещает действующие низкоскоростные и высокоскоростные линии MagLev. Многообещающие перспективы завершат этот обзор.

Ключевые слова: сверхпроводящая магнитная левитация, городской транспорт, высокоскоростной транспорт, второе поколение MagLev, технологические инновации, история MagLev.

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I. INTRODUCTION

The Superconducting Magnetic Levitation (SML) method applied to MagLev relies on high critical temperature superconductors (HTS) and rare earth permanent magnets, synthesized at the end of the last century [1, 2]. The availability of these materials for commercial applications, as expected, took some years. Therefore, the first prototypes of SML MagLev appeared at the turn of the century, practically 40 years after available prototypes of EML (Electromagnetic Levitation) and EDL (Electrodynamic Levitation) MagLev vehicles.

Disregarding small demonstrations, the first man-loaded example of SML has been presented in Chengdu, by Wang and his research group [3] in 2000. This example was followed by prototypes in Rio de Janeiro, Brazil [4], in Dresden Germany [5], and improvements in Chengdu, China [6]. These initial systems operated inside laboratories, in controlled environmental conditions and just for demonstration. A first outdoor prototype, presenting the conditions of a real urban transportation system, was disclosed at the last day of the 22*nd* MagLev Conference in 2014 [7]. A second outdoor prototype was launched on January 13*th*, 2021 at Sowthwest Jaotong University aiming high speed transportation.

The SML presents advantages, compared with EML and EDL solutions, regarding the stability of the levitation method, the slender elevated structures, and the simpler switch pieces of equipment. These characteristic leads to a lighter MagLev solution, suggesting a new category of MagLev vehicles that could be properly named MagLev^2. The exponent 2 reports to the Levitation and Light (Levis in Latin) properties, also bringing the message of a second generation of MagLev vehicles. In fact, besides applications for urban transportation, investigations are carried out to apply the SML technology for high-speed MagLev [8] as well.

Table 1. MagLev^2 SML as a second generation of MagLev Vehicles

English	Latin	Initial
Magnetic	Magneticus	Mag
Levitation	Levitatio	Lev
Light	Levis	Lev

In this paper, details of the past, present and future developments of the SML Technology will be disclosed for discussion. It is an updated version of a previous paper published in 2018 [9] and shows how much has been done in these 4 years even with the difficulties imposed by COVID-19.

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II. LOW SPEED SML MAGLEV

The first SML outdoor prototype was inaugurated on October 1st 2014, the last day of the 22nd International Conference on Magnetically Levitated Systems and Linear Drives (Fig. 1). The conference participants were able to ride in the vehicle, which, at that time, as a recently inaugurated project, still had some restrictions of operation.

Fig. 1. The last day of MagLev Conference in 2014

After one year of improvements, regular demonstrations, every Tuesday, started to visitors. The line is 200 meters long (Fig. 2), and the vehicle can carry 20 passengers at a speed of 12 km/h. Until COVID19 reached Brazil at the beginning of 2020, more than twenty thousand persons experienced the ride [10, 11].

Fig. 2. The 200 meters long elevated line of MagLev-Cobra

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The graphical abstracted depicted in Fig. 3 summarizes the technology.

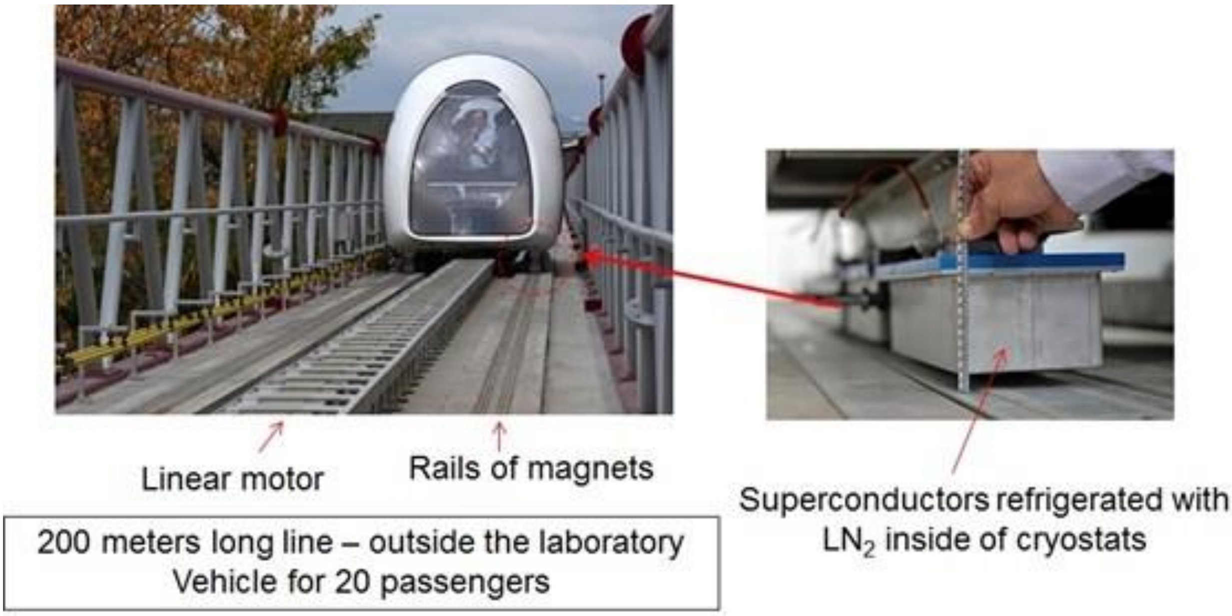

Fig. 3. Graphical abstract of the MagLev-Cobra project

The critical period of 2020-2021 was also a time for reflection and planning. The two main lessons can be summarized in the following points:

1. The weekly regular demonstrations of the MagLev-Cobra inside the university campus were interesting but not sufficient to go forward and turn the technology into a practical application. The virus was helpful to call our attention to this fact, that now sounds obvious, but was not in 2019.

2. A Public Privat Partnership (PPP) would be the best way to surpass the difficulties. For that, the public investment had to come first, but the private sector should also be prepared to assume responsibilities.

Based on these lessons, an aggressive search for funds and partners was launched. This was not restricted to national investors, but also international ones were contacted. Discussions with 6 potential partners and 4 projects to rise public funds were done during these two years. To make a long history short, finally, at the end of 2021, we signed MOUs with 3 Brazilian companies:

- Aerom Sea Horse
- Equacional

Moreover, we received the support of FAPERJ (research council of the State of Rio de Janeiro) to put an industrial prototype in daily operation. The start is foreseen to October 2023. The vehicle design is shown in Fig. 4.

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Fig. 4. Industrial prototype in development (Aerom)

The linear motor was also improved following Oliveira's Ph.D. research thesis [12, 13]. This can be seen in Fig. 5.

Fig. 5. Improved linear motor

Parallel to this work, the study of an 1km long line connecting the Centre of Technology to the Technological Park of the Federal University of Rio de Janeiro (UFRJ) has been the object of an internal competition of the Faculty of Architecture and Urbanism (Fig. 6).

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III. HIGH SPEED SML MAGLEV

This part mainly focuses on the development in the high- speed scenes, which is contributed by Southwest Jiaotong University, Chengdu, China.

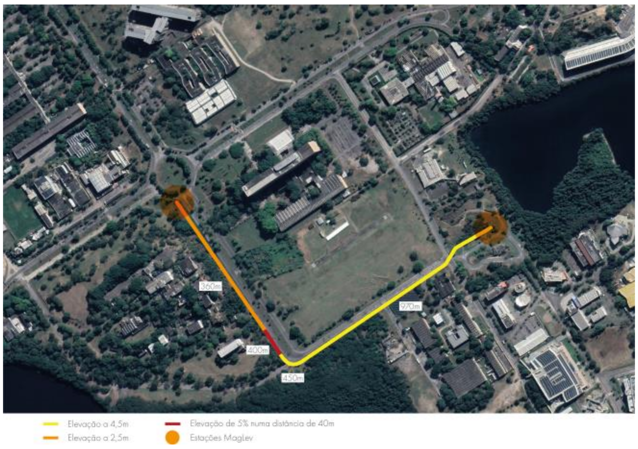

Fig. 6. The proposed 1 km MagLev-Cobra line

A. *Linear High-speed Test Platform*

For high-speed scenarios of SML in rail transit, a linear test platform [14] presented in Fig. 7 is developed for exploring the dynamic response during extreme and critical operations. Its tube can create a low-pressure environment for further research on train aerodynamics or hyperloop.

Fig. 7. The SML high-speed test platform

This platform is mainly composed of three components:

(1) the levitation system (i.e., a permanent magnet guideway (PMG) and a levitated model); (2) the linear propulsion system (involves a power supply, a control, and a linear motor); (3) the eddy-current braking which utilizes the permanent magnets. The main parameters are summarized in Table II.

As sketched in Fig. 8, the 142.6 m long PMG which arranged in a Halbach array for a stronger magnetic field is divided into an acceleration section, a sliding section, and a braking section. This dual guideway has a 173 mm gauge and is tightly assembled from several 1152 mm long segments.

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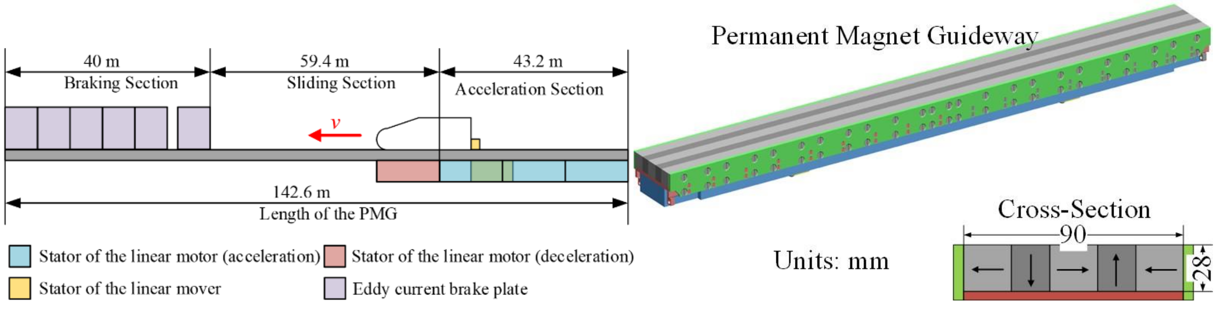

(a) (b)

Fig. 8. (a) Schematic diagram of the test line and (b) structure of the PMG

Table II. Main parameters of the linear high-speed test-platform

Item	Parameter
Scale	1:10
Length of the test line	142.6 m
Diameter of the tube	4.2 m
Levitation height	10-20 mm
Load capability	200 kg
Propulsion mode	Linear motor
Maximum propulsion force	70 kN
Maximum test speed	120 m/s

Due to the limitation of the length, the model withstands an approximately 15 g acceleration and 70 kN traction force to reach a speed of 120 m/s (432 km/h) within 50 m. This platform therefore requires large energy output in a very short time (the total power of the motor reaches 16 MW), which is provided by a flywheel energy storage (the storage energy reaches 28.5 MJ). The traction force is transmitted by contact between the motor mover and the vehicle body. Once the motor decelerates, the vehicle will separate from the mover and keep moving by inertia. When the model vehicle reaches the braking section, the permanent magnets on the vertical brake plate on both sides of PMG interact with the aluminum alloy shell of the model vehicle to produce braking force.

The dynamic model test platform adopts the reduced scale model, which can simulate the actual dynamic response of the SML vehicle at high speed accurately. In addition, the high-speed test platform can also serve the research of vehicle aerodynamics.

Fig. 9 shows the structure and appearance of the levitated model with 2.1 m long and 120 kg weight. It has four levitation units to provide the stable levitation and guidance force, and eight wheels to support its weight at non-levitation state. The material of the shell is aluminum alloy, which is a good conductor for eddy current braking, moreover, it is not only lightweight but also

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non-ferromagnetic (little interact with a PMG. Four three-axis accelerometers are installed above the four levitation units (only one is powered currently at the red spot in Fig. 9b), and four laser displacement sensors will be installed beside the levitation units as well. The levitation unit is introduced in [14].

(a) (b)

Fig. 9. The (a) photo and (b) schematic diagram of the model vehicle in High-speed Test-Platform

B. *Rotating High-speed Test-Platform*

The cost efficiency is quite low to measure the dynamic characteristics of the SML vehicle running on an actual line at ultra-high speed; therefore, the ultra-high-speed maglev test rig is established based on the principle of equivalence. A rotating circular guideway is applied to replace the translational motion of the levitation vehicle. Moreover, a vibration exciter is introduced to directly excite the test samples, and it is equivalent to replacing the vibration caused by track irregularities. The test rig is shown in Fig. 10 [15]. The experimental conditions are set through the control system and can automatically collect the experimental data and complete the storage during the experiment.

In this test rig, an inverter-fed AC motor with a rated power of 550 kW drives the stainless-steel rotor with a diameter of 2500 mm to rotate. The key component of the rotational plate is a T shape. To overcome the centrifugal force, the Halbach- array PMG and aluminum guideway fixed on the two inner sides of the stainless-steel rotor will rotate together, and the structure is shown in [15]. The inner surface diameters of the two guideways are both 2210 mm. Its maximum linear speed of the guideway reaches 600 km/h when the stainless-steel rotor rotates around the central axis at 1440 rpm, and the rotor speed error is less than 1 % under the adjustment of the control system. The total mass of the guideway rotor is 8.2 t. The technical specifications are introduced in Table III.

To ensure its stable operation under the experimental speed of 600 km/h, its development top-speed standard has been increased to 700 km/h. The measurement system of the test rig is equipped with an electromagnetic

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vibrator, triaxial force sensor, vibration sensor, laser displacement sensor, servo linear displacement drive device, etc., making sure a more comprehensive experimental study on dynamic levitation characteristics of SML can be carried out. The development of ultra-high- speed maglev test rigs can provide necessary experimental conditions for the research on the high-speed operation of SML, which will play an important role in promoting the research and engineering application of maglev technology.

(a) (b)

Fig. 10. The (a) photo and (b) schematic diagram of the rotating High- speed Test-Platform

C. *Engineering prototype*

On January 13, 2021, a full-scale engineering SML vehicle and test line rolled off at Southwest Jiaotong University, China [16], as shown in Fig. 11. Since the official opening of the high-speed SML engineering prototype and test line, the project has received more than 70 visits from various fields.

The full-scale engineering SML vehicle operates stably, and the cumulative running time of the vehicle exceeds 900 hours, nearly 10,000 visitors have been transported in total.

Table III. Main parameters of the rotating platform

Item	Parameter
Diameter of the stainless-steel rotor	2500 mm
Width of the stainless-steel rotor	520 mm
Dynamic balance accuracy grade	G2.5
Maximum speed	600 km/h (1440 rpm)
Speed error of the guideway	$\leq 1\%$
Maximum excitation force of vibrator	350 N
Maximum amplitude of vibrator	10 mm
Variable frequency AC motor power	550 kW

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(a) (b)

Fig. 11. Engineering prototype of SML in Chengdu, China. (a) Photo; (b) display inside the carriage

This engineering prototype of SML is a comprehensive large-scale system including suspension, propulsion, braking, operation control, and other aspects as shown in Fig. 12. The track adopts a U-shaped track beam. Mechanical brake plates are installed on two sides of the track beam. The permanent magnet dual track is introduced in [16]. The linear synchronous motor for vehicle propulsion lies in the middle of the tracks and the ground positioning system is used for speed measurement and positioning. In addition, the engineering prototype is also equipped with a safety support track for the field cooling procedure of SML and supporting the vehicle after the bulk superconductors enter the normal state.

The main parameters of the engineering prototype are shown in Table IV. Southwest Jiaotong University completed the transformation of the existing engineering test platform in January 2022 to further promote the engineering process of SML. The engineering traction and speed measurement and positioning system, condition monitoring system, vehicle ground communication, and integrated operation control system were optimized, and an 8-m long test platform was built. An upgraded model vehicle for testing was also developed. The new 8-m dynamic model test platform is shown in Fig. 13a, and the upgraded model vehicle is shown in Fig. 13b.

At present, the performance verification of the long-stator single-sided three-phase coreless permanent-magnet linear synchronous traction system was completed. The traction system realizes various functions, e.g., speed tracking, position control, fast and uniform start, uniform acceleration and deceleration, fixed-point parking with a <150 mm parking error.

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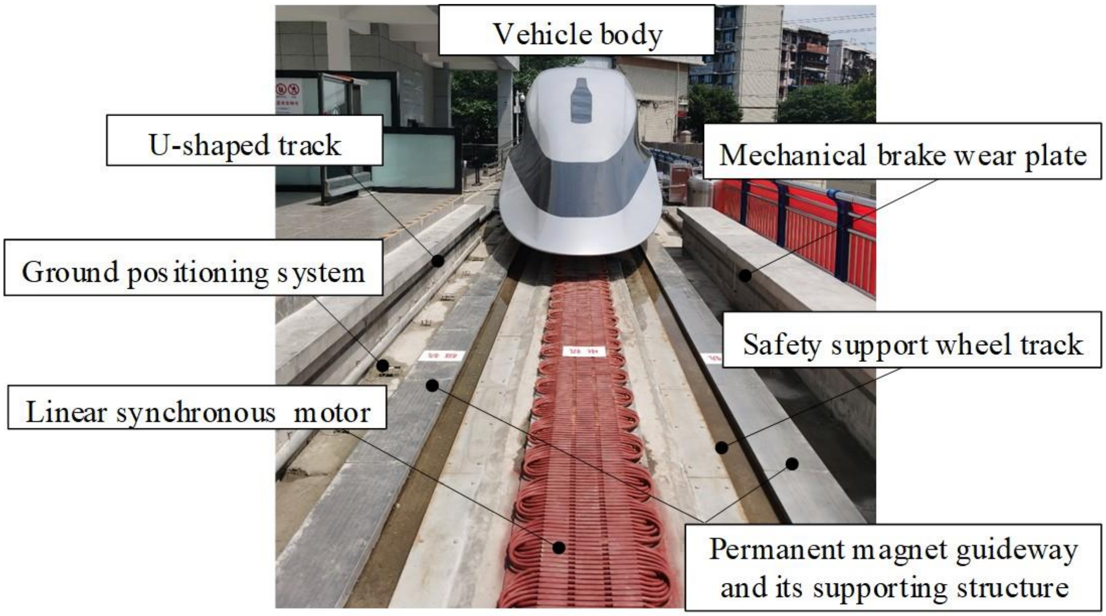
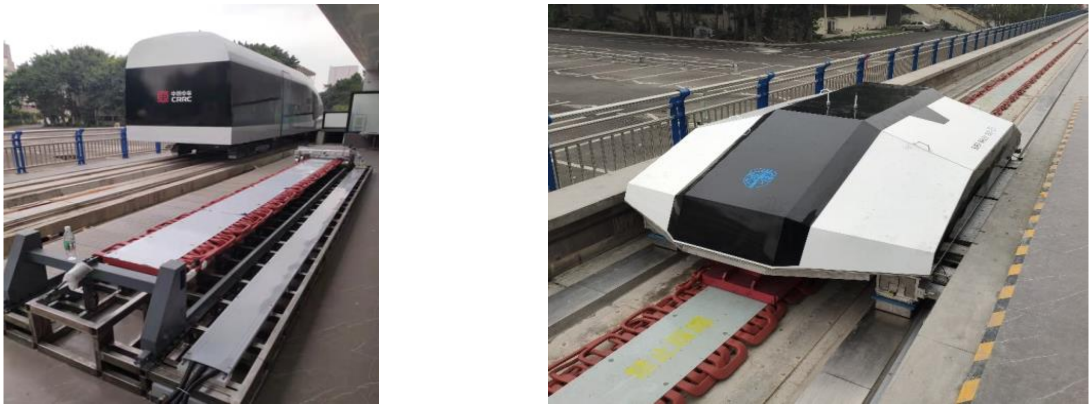


Fig. 12. Main structure of the engineering prototype of SML

Table IV. Main design parameters of the engineering prototype

Item	Parameter
Length of the test line	165 m
PMG gauge	2 m
Rated Levitation height	10 mm Levitation height
Load capability	15 t
Maximum load	30 people
Propulsion mode	Linear synchronous motor max. propulsion force
Design speed	620 km/h



(a) (b)

Fig. 13. Transformation of the SML engineering test-platform:
(a) Thetest-platform; (b) the upgraded model vehicle

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IV. COMPARISON: SML AND TRADITIONAL MAGLEV

A. *Levitation System*

The SML technology is intrinsically stable, just the PM rail and the cryostats (the wheels of this technology) are necessary to achieve levitation, as already shown in Fig. 3. On the other hand, the stability of the EML can be obtained only with a closed loop control system, which requires sensors, signal processing, A/D and D/A converters, EMI (Electromagnetic Interference) reduction, back-up energy supply and heavy and bulk electromagnetic actuators made of iron core and copper windings. Fig. 14 turns this advantage of the SML technology evident.

B. *Civil Engineering Construction*

As a direct consequence of the simplicity of the SML method and its lower weight, the civil engineering construction of the SML technology presents advantages in comparison with EML systems, as shown in Fig. 15. As proof of this, the Brazilian prototype for 20 people weighs only 2.3 tons empty.

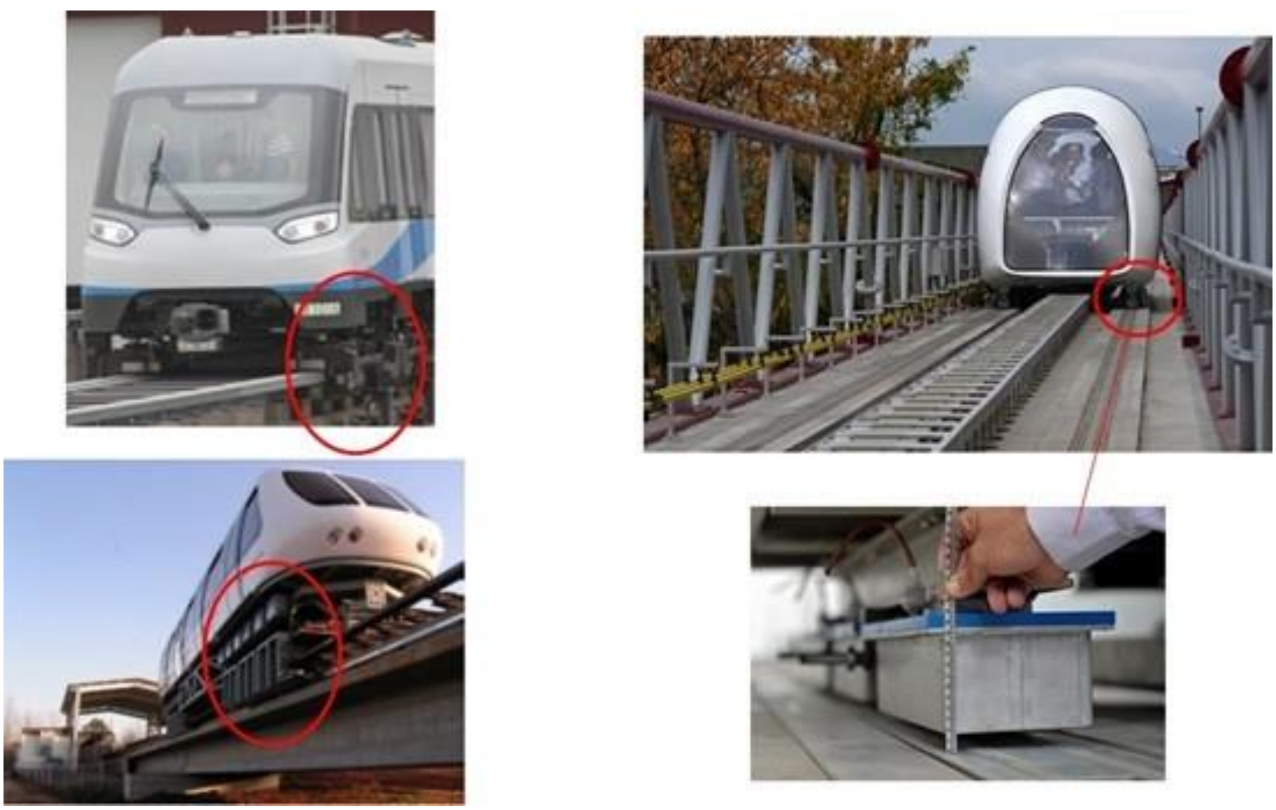

Fig. 14. The EML levitation method (two examples on the left side) in comparison with the SML levitation equipment (on the right)

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Fig. 15. The EML civil engineering construction (three commercial lines) in comparison with the real scale prototype of the SML technology

V. CONCLUSION

This paper presented the state of the art of the disruptive MagLev Technology based on flux-pinning property of superconductors in the proximity of permanent magnets, the SML method. The technology is promising. Efforts are in course to construct a test line with all characteristics of a commercial system. The sentence coined by the colleagues of KIMM (Korean Institute of Machinery and Materials) on the occasion of the 2011 MagLev conference, held in Daejon, lends itself very well to conclude this article: MagLev trains are not just ordinary trains but wings that will help mankind take another leap forward in the future.

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