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MAGLEV TRENDS IN PUBLIC TRANSPORT: THE PERSPECTIVES OF MAGLEV TRANSPORTATION SYSTEMS

Abstract. The idea of considering Maglev systems challenges established ways of thinking on how to deal with an increasing transport demand. Today, the railway industry seems focused on traditional business models that profit from friction, wear and tear of established conventional transport systems. Maglev Systems have begun to challenge those traditional business concepts. Maglev is a fundamentally different concept of transport – which might explain the reluctance, even ignorance, which Maglev systems continue to face.

Keywords: Maglev, High Speed Rail, Paradigm Shift

INTRODUCTION

Throughout history, events have often converged to create entirely new paradigms. Some of those paradigm shifts were entirely predictable; others came as a total surprise. Maglev is one of those ‘disruptive’ technologies that have the power to dramatically alter and improve the way we live and travel.

Magnetic levitation transport, or maglev, is still a modern form of transportation that suspends, guides and propels vehicles via electromagnetic force. This High-Tech method can be significantly faster than wheeled mass transit systems, potentially reaching velocities comparable to turboprop and jet aircraft (550 to 700 km/h) in regular service.

Maglev systems represent a revolutionary transport innovation. At the same time, they can also function as a technology development platform (e.g., superconductors, new materials, shielding methods). They can, in certain cases, bring positive economic benefits through the optimization of spatial networking, travel time reduction and resource efficiency.

Some aspects of the ongoing technology debate will be covered on the following pages.

I. IS MAGLEV A RELEVANT TECHNOLOGY TREND?

High speed ground transport requires a wide-ranging and interdisciplinary discussion in order to promote a sufficiently broad spectrum of opinion. Today, a

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realization of any kind of high-speed transport infrastructure cannot be justified anymore just through system technical advantages alone, if they are to find acceptance with the general public and politics.

A. Market Barriers

The less competition in the transport market, the more attractive it appears in the short-term for manufacturers to postpone a technological innovation and to secure current sources of income through long-term maintenance contracts (delivery, spare parts) that are linked to conventional wheel/rail contracts. Such a short term orientation on the commercially lucrative (rather than on the system-technologically superior) can strongly handicap, delay or under certain circumstances completely cancel transportation technological innovations.

Some of the maglev technology know-how leaders are also market-established producers of wheel/rail high-speed systems and even are sometimes also market leaders in traditional railway communication systems and conventional railway infrastructure components. Such companies are faced with a technological-commercial dilemma: managers must decide whether and when new technologies that have significant potential for rationalization should be introduced into the existing highly profitable wheel/rail high-speed transportation market (maintenance, replacement parts, and licensing business). If managerial success is defined on the basis of short-term balances, this feeds developments that disadvantage an innovation of maglev technology [12].

B. Interoperability

High-speed ground transport can only be safe and efficient when it is completely separated from slower systems. The autonomy of a maglev train running on its own infrastructure is hence an important system advantage that makes overall safety, efficiency and punctuality possible in high-speed maglev operations.

The demand for compatibility or interoperability of high-speed rail transport with the operation of slower rail transport is based on traditional steel-wheel/rail planning and is no longer meaningful in this form today.

Vehicles with extremely different speeds on the same traffic path create a mutual hindrance and introduce mutual safety concerns. Safety clearances and time needs must therefore increase. Mixing slow transport with high-speed transport is clearly not advantageous economically for either system. This is equally true for all transport systems: bicycles on a freeway would be just as senseless as auto racing on cycling paths.

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Combining rapid and slow transport systems creates a mutual hindrance and lowers the performance of the entire system. The operation of high-speed passenger trains should therefore be separated from freight trains and slower passenger transport. The Japanese Shinkansen train network has been completely separated from slower wheel/rail transport since 1964 and has operated fatality-free with incredible efficiency ever since.

The longer high speed running can be maintained, the better the performance will be, along with the cost effectiveness of the respective system. In this regard, maglev trains have the principle advantage through their independent routes and the automatic exclusion of mixed traffic [2].

C. Infrastructure trends

Through the technological developments of recent years, the infrastructure construction costs for high-speed maglev trains have converged to the same levels as those of traditional wheel/rail systems. Furthermore, there is a potential for further cost reduction. For topographically demanding routes, maglev trains already offer clear advantages in the cost of infrastructure construction.

Some Maglev systems can manage ascending grades of 10 % and more (Transrapid maglev), while traditional railroads are limited to grades on the order of 4 %. Maglevs adapt more easily to the landscape and therefore require fewer tunnels. This offers enormous cost savings in infrastructure construction, particularly in hilly landscapes.

New manufacturing processes in track construction, for example, the spun concrete construction technique and other modular production concepts, make it possible to reduce the costs of mass production considerably. In hilly landscapes, maglev guideways on pier foundations – spaced tens of meters apart – are considerably more economical than the massive, expensive embankments and causeways usually required for the entire length for most wheel/rail systems [2].

Maglev guideways can avoid obstacles without special additional bridge constructions. At-grade crossings with other traffic routes are eliminated and, therefore, collisions are rendered impossible. In the case of elevated track, alternative uses of the land under the track are still possible.

D. Environmental trends

Maglev trains do not create direct pollution emissions and are always quieter in comparison to traditional systems when operating at the same speeds.

In high-speed intercity transport, using maglev trains can offer an especially good cost-benefit ratio as regards land purchase, construction, operation, maintenance and environmental protection. Future technological advances can be expected to improve this ratio even more.

In the area of noise emissions, maglev trains are superior in every way to wheel/rail systems (when operating at the same speeds), not to mention airplanes.

Comparisons made at the same speed show that all rolling friction noises, every track screech, all shocks from wheel-on-rail contact are eliminated in maglev systems that use magnetic forces rather than physical contact to keep the vehicle upright. Noise generated by air turbulence is also greatly reduced with maglev high-speed trains, making them clearly superior to all wheel/rail vehicles. In particular, the noise from the conventional train's pantograph is replaced in maglev by a process of induction and the required energy is transferred without physical contact.

At speeds under 200 km/h (125 mph), maglev systems can hardly be heard, especially in an urban environment – an important advantage for populated areas. The Chinese Transrapid in Shanghai and the Japanese Linimo in Nagoya, as well as all urban transport maglev trains, offer impressive proof of this.

Maglev routes also do not divide the landscape as highways, train tracks and waterways typically do. Animals can cross under elevated maglev guideways, which they do without hesitation, and farmers can still use the land undisturbed, as this was shown by observation and experience at the test facilities in Japan's Yamanashi Prefecture and Germany's Emsland town of Lathen.

There is a strong demand to design future rail route architecture more aesthetically and open, in contrast to the massive constructions of the past. This public concern will affect maglev trains as well as wheel/rail systems [2].

E. Trends in Comfort and Safety

In the areas of travel comfort and safety, maglev trains clearly exceed other rapid transit rail systems. The design of the guideway – whether the German "T" shape for the wrap-around vehicle or the Japanese "U" shape with the vehicle enclosed – ensures that the trains are safe from derailment.

Today, maglev trains can generally be considered to be among the safest and most comfortable rapid transit systems in the world.

The amount of space available inside maglev cars is generous compared to the relatively narrow proportions of many established train cars. For example, a German Transrapid interior is nearly a meter wider than conventional rail cars, which makes for more spatial freedom, a wider range of seating options and contributes to a higher overall comfort level. The levitation of the vehicle using magnetic forces ensures a quiet and smooth ride, even at the highest speeds, whereas wheel-on-rail systems sometimes struggle with this even at the lowest speeds. The Japanese

Linimo as well as the South Korean Rotem Urban Maglev can substantiate this claim for quiet, comfortable travel in city transport applications [2].

F. Economics: Wear and Tear

While high-speed maglev infrastructure is relatively expensive to build, maglev trains are less expensive to operate and maintain than traditional high-speed trains, planes or intercity buses. Most of the power needed is used to overcome air drag, as with any other high speed train.

Maglev systems can operate at very high speeds almost without deterioration and are therefore more economical to operate than wheel/rail rapid transit systems that require regular intensive maintenance and experience exponentially increasing erosion with increasing speed. The fundamental freedom from mechanical erosion is one of the main advantages of maglev high-speed systems.

Maglev is the only trackbound transport system that has practically no mechanical friction during operation. In maglev, all the weight, propulsion and lateral guidance forces of the vehicle are transferred contact-free to the guideway, including the braking forces. As a result, maintenance costs of some maglev systems are only a fraction of the costs of traditional wheel/rail systems.

In traditional wheel/rail operations, the wheels eventually wear out. In addition, the resultant grit on the running surface of the tracks causes abrasion of the railheads.

Example: Each German InterCity Express (ICE) train wheel alone loses about 68 kg/150 lb of steel through friction from driving and braking before it is withdrawn from service, usually after two or three years (an entire ICE train loses about 8 metric tons / 17 600 pounds). TGV, KTX and conventional Shinkansen trains are equally subject to wear and tear [2].

G. Ethical requirements

For all transport infrastructure projects, it is of fundamental importance that long-term social orientation increases and the corresponding objective cost-benefit comparisons are made as the basis of future decisions rather than the short-term profit motives of the established wheel/rail manufacturing sector.

Transport infrastructures affect living spaces for many decades afterwards; future generations will carry the social and financial burden of the today's decisions made to build relatively inefficient and uneconomical structures.

Even when projects in transport infrastructure continue to be tested on a case-by-case basis to decide which technology should be put to use, maglev systems can often (not always) offer a qualitatively superior solution when subjected to an objective cost-benefit comparison [2].

From a national economic perspective, an important goal is to provide future generations with an efficient, high-capacity transport system whose long-term benefits are distinguished by its low operation and maintenance activities and hence its low life-cycle costs. Therefore, the decision as to the suitability of future intercity transport systems (air, wheel/rail or maglev) should be based on the cost-to-benefit ratio of the system as it develops over the decades.

In other words, we should think beyond the initial start-up costs of construction, infrastructure and vehicles and consider more clearly the future costs of upkeep and maintenance in order to create the most sustainable transport system [2].

H. Expectations

As magnetic levitation (maglev) systems might begin to come on line around the world, questions surrounding these new transportation technologies will naturally and inevitably arise; especially, as the price of oil continues to climb. This will increase awareness of transportation engineering options, traffic congestion mitigation, and improved land development and energy policies.

As a general requisite, Maglev Systems should be seen and evaluated in context with existing infrastructure, available resources and the future needs of society. Looking only at prospects and barriers of the maglev technologies without taking relevant context into account cannot provide realistic, helpful transport solution for the future.

Scarcely one hundred years ago when electricity began to be distributed into people's homes, it too was viewed with fear and amazement. However, it was not long before societies came to rely on reliable supplies of the now omnipresent electric power to light homes and factories after dark, to power labor saving machines, and to make instantaneous telecommunications possible worldwide. Indeed, it is our reliance on readily available supplies of reliable electricity that defines our world - without it, our modern world ceases to be modern.

Some experts consider Maglev as the logical progression of the electricity revolution that was begun by Edison and Tesla in the late 19th century, and were in fact conceived in the early 20th century. However, it was the rapid advancement in computer processing in the late 20th century that really propelled maglev development forward and transformed it into today’s premier transportation option.

Today, maglevs are essentially highly reliable computer-controlled electronic transportation systems, with most maglevs requiring no moving mechanical parts for suspension, acceleration or braking.

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All these innovations could result in potentially much lower operational and maintenance expenditures relatively lower energy consumptions while also enabling significantly higher speeds and faster rates of acceleration and deceleration.

Magnetic levitation is achieved in a variety of ways. What all these maglev systems share is the use of electro-magnetic power to suspend vehicles above and away from their guideways (tracks) rather than using wheels; although some systems use wheels for suspension at low speeds and while at rest.

By suspending vehicles away from their guideways, the friction resulting from wheel on track contact is eliminated as an impediment to higher speeds. This same electro-magnetic power is also used to propel vehicles, which also means they are not polluting their rights of way. The regular use of mechanical friction brakes is also eliminated, along with the need for expensive brake maintenance. High temperature superconducting materials are likely to play an increasingly important role and are already being tested in some Japanese systems.

Maglev systems are expected to be cost effective, quiet and energy efficient. If implemented according to their technological strengths, they might promise to fit seamlessly into the vision of developing sustainable and livable communities that enhance, rather than compromise, citizen mobility [2].

II. CONCLUSIONS

As the lifetime of high-speed rail/wheel infrastructures comes to an end, the technology question will arise again. Based on the operation experiences with high-speed-trains, the technology question is likely to arise significantly earlier than generally expected. The question then will be whether in restoring or maintaining high-speed routes the conventional wheel/rail technology continues to be used or whether such corridors should better be based on high-speed Maglev technology.

Worldwide, there are quite some corridors, for which interurban high-speed Maglev transport is potentially qualified or might appear meaningful, for example:

- Brazil: Rio de Janeiro - Sao Paulo corridor;
- Japan: Tokyo – Osaka Maglev line;
- Europe: Bruxelles / Hamburg – Berlin – Warsaw / Baltic States – St. Petersburg – Moscow [3] ;
- Asia: Moscow – Beijing (“Silk Road” / TransSib),
- Europe: St. Petersburg Harbor – Moscow Cargo Maglev corridor
- Europe: Pan-European corridor IV (Berlin – Prague – Vienna – Budapest);
- USA: Washington – Baltimore;
- Europe: London – Liverpool; Glasgow, Edinburgh;
- India: Delhi – Mumbai – Chennai.

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For such corridors and routes, a detailed, fair technology comparison and examination should be made with regard to high-speed Maglev [4].

Japan already leapfrogs to high speed Maglev systems. Russia strives for Cargo Maglev strategies. China and Korea boost the implementation of Urban Maglev technologies. Transrapid Maglev technology is being further developed by Chinese Universities. Germany has begun to build cable-free elevators based on Transrapid Maglev technology [5].

These are signs of upcoming, fundamental changes in transport policies and even might be considered trendsetters in deciding on updated renewal concepts for aged rail transport infrastructure.

A paradigm shift in transport in favor of Maglev seems likely.

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The results presented in the article also represent the official view of the International Maglev Board [2], [6].

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METHODOLOGICAL BASE FOR THE IMPLEMENTATION OF THE MAGNETIC LEVITATION TRANSPORT TECHNOLOGY PROJECT IN RUSSIA

Aim: determine the methodological basis for forecasting social economic effect from implementation of major infrastructure projects in world practice. To compile an individual list of evaluation criteria based on recent research about technical capabilities of magnetic levitational transport technology (MLTT) transport.

Methods: statistical methods of transport industry analysis and interbranch balance method are applied.

Results: the potential market for application of technology has been identified and a forecast for changing transport industry matrix has been made.

Conclusion: this article is the basis for conducting a comprehensive study of the social-economic response of the MLTT project implementation in Russia and determination of optimal parameters for public-private partnership during its realization.

Keywords: magnetic levitation, maglev, social economic effect, interbranch balance method, BIG DATA

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МЕТОДОЛОГИЧЕСКАЯ БАЗА ОБОСНОВАНИЯ РЕАЛИЗАЦИИ ПРОЕКТА МАГНИТОЛЕВИТАЦИОННОЙ ТРАНСПОРТНОЙ ТЕХНОЛОГИИ В РОССИИ

Цель: определить методологическую базу обоснования и прогнозирования социально-экономических эффектов от реализации крупных инфраструктурных проектов в мировой практике. На основании свежих исследований о технических возможностях транспорта на основе магнитолевитационной транспортной технологии (МЛТТ) составить индивидуальный ряд критериев оценки.

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Методы: в работе применены статистические методы анализа транспортной отрасли, метод межотраслевого баланса.

Результаты: определён потенциальный рынок применения технологии и сделан прогноз изменения матрицы транспортной отрасли.

Выводы: работа является базисом для проведения комплексного исследования социально-экономического отклика на реализацию проекта МЛТТ в России и определения оптимальных параметров государственно частного партнерства при реализации данного проекта.

Ключевые слова: магнитная левитация, маглев, социально-экономический эффект, межотраслевой баланс, BIG DATA

INTRODUCTION

Magnetic levitation transport technology (MLTT) has a huge potential for introduction into the transport complex of the largest world's countries (area above 3 million km^2), in which the improvement of transport mobility will significantly accelerate the processes of value creation. At the same time, high-speed magnetic-levitation transport systems, in contrast to the conventional "wheel-rail" technology, are suitable not only for passenger transportation, but also for freight. Such flexibility of the MLTT is due to this number of reasons:

1. Reduction of the dynamic component on high speeds. A detailed study of these aspects was carried out in [1, 2]. The resonance factor of MLTT train is determined to be 1.07; for high-speed trains this value is 3–4 [3, 4];
2. More controlled level of acceleration. The movement of MLTT trains is based on the high-frequency calculations of microcontrollers, thanks to which a more comfortable level of acceleration is achieved. This characteristic is important both for passengers and freight transportation;
3. Full automation of processes – it will lead to higher productivity of sort facilities.

ANALISYS OF METODOLOGICAL APPROACHES

The determination of social economic effects from the construction of a road network based on MLTT is a fundamentally new task that combines a combination of previously proposed solutions:

1. Construction of high-speed passenger railways [5, 6];
2. Correlation of the redistribution of passenger traffic between airports and high-speed railways [7–9];
3. Methodology for designing a multimodal transport network [10–11].

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4. The construction of road networks is an integral driver of region's development. But there is no universal method for estimating the effect from the construction of new routes. The exact answer to the questions about what feedback on the new transport network will come from different industries, private business, real estate market and integral growth of GDP is impossible. Any forecasting in this area has evaluation nature. And reports dedicated to estimating of social economic effects from new infrastructure objects use a combination of methods:

1. Interbranch balance method (inputs-outputs);
2. Evaluation of agglomeration effects;
3. Evaluation of reduced travel times between the concentration centers of consumers and the suppliers of products effects;
4. Effects on the budget: increase of the tax base; reduction of costs for the implementation of obsolete infrastructure.

Examples of the most relevant studies are the assessment of the social and economic effects of High Speed 2 in the UK, the modernization of the Chicago transport system until 2020, and the maritime logistics center in Portland, USA.

The construction of the Moscow-Kazan High speed railway (HSR) and analysis of project HSR «Eurasian» have demanded conducting similar researches in Russia. These developments were carried out by PwC and the Center of Strategic Development (CSD). The results of published reports are not equal and more detailed algorithm of calculating are not given [12, 13].

FORMULATION OF MODERN WAY OF INFRUSTRUCTURE DATA BASE ANALYSIS

At the same time, the reason for the high correlation of the results is absence of extensive statistical bases for the industrial branches and regional social economic indicators that researchers can operate on. The data published by Russian Federal State Statistics Service is very general and, in fact, obsolete by the time of release, so it can't be a basis of local infrastructure solutions which determinate of the overall development vector.

Nowadays when all spheres of life includes BIG DATA, implementation of large infrastructure projects requires a comprehensive automated analysis of current data bases. The demands of local directions should be correlated with each other. And on the basis of its conflicts, a set of optimal strategies should be allocated. The scheme of the methodological basis for making decision is shown in the Fig. 1.

Identifying of demands of individual enterprises and consumers, optimizing the transport connection between them is an actual task all over the world. Currently, there is a stable trend of introducing BIG DATA analysis in this direction. In the

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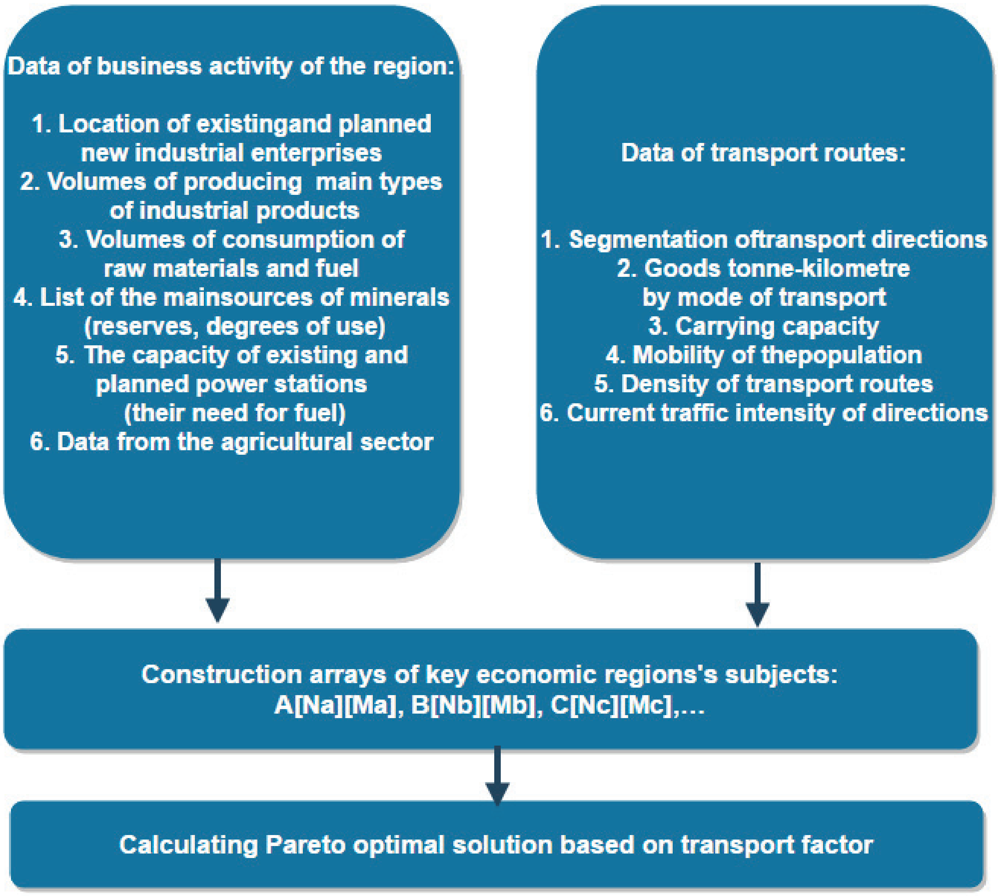

Fig. Modern methodological basis for making infrastructural decision

US, some of the solutions for optimizing the transport network are adopted using dynamic database analysis in the REMI, KTC, TREDIS software complexes [14].

FORECAST OF CHANGINGS IN RUSSIAN TRANSPORT INDUSTRY MATRIX AFTER MLTT INTRODUCTION

The economic justification for the construction of a route based on MLTT is a complex and responsible study. The major tasks of which are:

1. Determination of the optimal location of the network.
2. Determination of changings in transport industry matrix after MLTT implementation.

Taking into account the above-mentioned specificity MLTT, the decision about stages of network construction should be taken based on an expanded set of criteria mentioned in scheme above.

The second task is a consequence of the first. Analysis of data published by Russian Federal State Statistics Service [15] gives general summary of current Russian transport industry matrix – Table 1.

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Table 1. Matrix of Russian transport industry

	Group 1	***Group 2***	***Group 3***
Types of transport	Pipeline and railway	Automobile	Marine, river, air
Main characteristics	Long distances of transportation of goods and large volumes of goods tonne-kilometre	Small average distances and large tonnage	The volume of freight transportation is much lower

Based on these statistics and general transport characteristics of MLTT, it is possible to draw conclusions about a number of potential areas of it's implementation. Creation of high-speed freight/passenger ground transport with the possibility of full automation of shipment process will significantly increase the average route speeds of transportation, which for today on railway transport are only 15 km/h.

The implementation of MLTT will lead to a multiple increase in the carrying capacity of new lines.

Therefore, with the wide introduction of the MLTT in the continental part, the following changes will occur in the system of freight transportation – Table 2.

Table 2. Changes in the freight transportation matrix after implementation of MLTT

Types of transport	**Summary characteristics of changes**
Railway	Transportation for long distances will disappear; Local industrial application
Marine & River	Remain in demand transoceanic transport
Automobile	Remain relevant for transportation to medium and small distances
Pipeline	Never changers
Air	Remain relevant routes to hard-to-reach areas

CONCLUSION

The 21st century for the Russian Federation is a century of territorial potential reveal through the implementation of large scale infrastructure projects. In the area of construction of extended transport networks, the profit received by the carrier from the direct transport services is much less than the incomes received by the state (the increase of GDP). Therefore, the construction of these facilities - should be carried out according to the public-private partnership

This article listed the main methodologies for assessing social economic effects from the construction of new infrastructure projects. Based on the technical

characteristics of the magnetic levitation transport, the main vectors of integration existing methods were formulated. The main components of the integrated assessment method are given. There was identifying the demand of expanding industries monitoring to improve the accuracy of solving forecasting infrastructure tasks and improving the efficiency of management decisions in transport Industry.

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PROSPECTS OF ESTABLISHMENT OF EAST-WEST TRANSIT TRANSPORT CORRIDOR DEPLOYING MAGNETIC LEVITATION TECHNOLOGY

According to economist Klaus Schwab, the today's community is at the threshold of the Fourth Industrial Revolution which will influence transport branch especially. Today, we see a fundamental change of assessment of the place and role of transport in the world progress. At the governmental level the tasks of realisation of large-scale projects have been determined, which will be able to strengthen Russia's positions at the world freight transport market, namely container transport, increase Russia's transit potential, speed, quality of passenger service and freight transport.

The authors suggest options to solve the set tasks building on the idea of implementation of innovative magnetic levitation technology while establishing East-West Transport Transit Corridor.

Magnetic levitation technology is competitive with the existing modes of transport in key speed, sustainability, energy efficiency and safety parameters, namely ecological safety. The main purpose of establishment of a transit transport corridor is to introduce a new transport service with a unique number of properties. Accordingly, transport and technology tasks are solved which are associated with construction and modernisation of transport lines, terminals, information systems, etc. The project of transport transit corridor in question is suggested to undertake in three stages. The assessment of Russian container transport market and comparison study of maglev and conventional railway transport parameters confirm efficiency of the project. To deliver this project, the decision should be made at the governmental level.

Keywords: Transport Transit Corridor, Magnetic Levitation, Industrial Revolution, Innovations.

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ПЕРСПЕКТИВЫ СОЗДАНИЯ ТРАНЗИТНОГО ТРАНСПОРТНОГО КОРИДОРА «ВОСТОК – ЗАПАД» С ПРИМЕНЕНИЕМ МАГНИТОЛЕВИТАЦИОННОЙ ТЕХНОЛОГИИ

Современное общество, по мнению экономиста Клауса Шваба, стоит на пороге четвертой промышленной революции, которая, окажет особое влияние на развитие транспортной отрасли. Сегодня принципиально меняется оценка места и роли транспорта в мировом прогрессе. На государственном уровне определены задачи по реализации крупных проектов, способных укрепить позиции России на мировом рынке грузоперевозок, в частности контейнерных; наращиванию транзитного потенциала России, увеличению скорости, повышению качества обслуживания пассажиров и перевозки грузов. Авторы предлагают варианты решений поставленных задач, в основе которых лежит идея внедрения инновационной магнитолевитационной технологии при создании транзитного транспортного коридора «Восток – Запад».

Магнитолевитационная технология конкурентоспособна с существующими видами транспорта по ключевым показателям скорости, энергоэффективности и безопасности, в частности эколоигтической. Основная цель создания транзитного коридора – предоставление новой транспортной услуги с уникальным набором характеристик. При этом решаются главным образом транспортно-технологические задачи, связанные с сооружением и модернизацией путей сообщения, терминалов, информационных систем и т. п. Рассматриваемый проект создания транзитного транспортного коридора «Восток – Запад» на основе магнитолевитационной технологии предполагается выполнить в три этапа. Оценка российского рынка контейнерных перевозок и сравнительный анализ характеристик магнитолевитационного и железнодорожного транспорта подтверждают эффективность проекта. Для его реализации требуется принятие решения на государственном уровне.

Ключевые слова: транзитный транспортный коридор, магнитная левитация, промышленная революция, инновации

INTRODUCTION

Railway transport in Russia possesses a most significant strategic role to strengthen its economic sovereignty. Vast territory of the country having scarce population on most part of it justifies peculiarities of new technology revolution which is being encountered by the modern community.

The German economist, the founder and Executive Chair of the World Economic Forum in Davos, in his book "The Fourth Industrial Revolution"

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substantiated fundamental changes of the way humankind lives. Klaus Schwab does not provide operational definition of the Fourth Industrial Revolution but provides the basis for its assessment: coexistence of society and technology with the focus on technological innovations [1]. “The fundamental and global nature of this revolution means it will affect and be influenced by all countries, economies, sectors and people”, the authors says [2].

When it comes to studying transport sphere, it becomes clear that assessment of the place and role of transport in the world progress has changed fundamentally.

Russia’s transport network connecting densely populated eastern and western regions possesses a unique intellectual potential. In the 2030 Transport Strategy, which defines official policy in modernisation and is utilitarian centered, there is no emphasis laid on those revolutionary processes the today’s world is living on now. It is necessary to apply qualitatively new approaches to use those enormous opportunities granted by the technology revolution of the new era.

SETTING THE TASK

During the plenary session at the III Railway Congress (Moscow, November 29, 2017), the President of Russia Vladimir Putin put certain tasks the transport branch is facing, and which require prioritised and continuous attention, coordinated actions of the state, regions, and business [3]:

1) it is important to deliver large-scale projects which form an area for perspective development of industries and territories, will mitigate national producers expenditures, enable strengthening Russia’s positions at the world freight transport market, namely container transport market;

2) for a successful work at the internal market and improvement of transit potential of Russia, the national transport operators need constantly improve, increase speed and quality of freight and passenger transportation. It means that there is need in upgrade of transportation management systems, application of more efficient technical means, and logistics services.

The set tasks may be systematised in three blocks, each of which having their certain solutions.

Task 1. Delivering large-scale projects for the benefit of perspective development of industries and territories, strengthening of Russia’s positions at the world freight (container) transport market.

The Cluster “Russian Maglev” have addressed their developed offers on realisation of the project maglev transport mainlines from ports of Saint Petersburg and Leningrad Oblast extending to freight terminals in Moscow, which is seen as

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the main section of the East-West Transport Transit Corridor (TTC). According to the data available, the existing opinion that maglev technology is expensive is no more than a myth. Besides, on implementing this technology Russia will acquire an immense economic and image-building effect. Also, the task of debottlenecking of the entire country will be completed.

Task 2. Exploitation of transit potential of Russia at the expense of its railway transport.

The completion of this task is hindered by a number of limitations. In many extended parts of the mainlines during more than 100 years of their operation, a number of defects in the railway formation and civil structures, predominantly bridges, have accumulated. A crucial hindrance to augmentation of performance and capacity of mainlines, especially those in Siberia, is the curves limiting the permissive speed. For instance, Trans-Baikal Railway is 60 % equipped with curves which require smoothing.

Today, the solution to that problem centers around constant increase in investment in railway infrastructure “healing”.

The average speed of freight transportation (commercial) in Russia is approximately 17 km/h, the technical speed – ca 40 km/h, which is unacceptable for a vast territory.

Considering the actual state of railway transport, wheel-rail system specifics and railway transport infrastructure state, establishment of highly efficient TTC, which could be competitive to other modes of transport, does not seem to feasible.

The realisation of the project of establishment of a new railway mainline extending from the Far East ports to Russia’s western borders, as proposed by V.A. Trapeznikov Institute of Control Sciences of the Russian Academy of Sciences, will cost 18 trillion roubles, whereby the speed required by business will not be achieved [4].

The solution to that may become introduction of maglev technologies into transport industry.

Task 3. Transition to innovative freight transportation means.

In order to achieve transition to innovative freight transportation means, it is vital to introduce qualitatively new transport and associated technologies, which have proactively been developed for decades by Russian scientists and engineers. At JSC “Russian Railways” Joint Scientific Council meetings, this suggestion was considered. As a result, the following decisions were made, which provide answers to the key questions:

1) magnetic levitation transport technology is another stage of innovative development of the most widespread transport in the territory of Russia – the railway transport [5];

2) degree of readiness for application is determined by completion of the following stages:

– scientific surveys;
– mathematical and computer modelling;
– full-scale modelling.

Maglev transport technology meets demands of business and requirements of a new technology pattern in terms of:

– transportation speed;
– safety;
– minimal impact on environment, the opportunity to preserve natural area;
– power consumption;
– riding comfort;
– full automation during the entire course of operation;
– economic efficiency.

Using assessment of the actual state of railway transport in Russia and the tasks indicated by the Russian President, it is vital to develop a long-term development programme covering a span of 20–25 years. This time frame is determined by a long realisation period of such large-scale transport projects as East-West and North-South Transit Corridors, mastering new technologies while creating digital transport system, targeted development of transport engineering education, engineering science, and science.

ASSUMPTIONS

The world maglev transport technologies (MLTS) market is flourishing. The development of transport systems capable of commercial outdoing the speed limit of wheel-rail system has become the world trend. The best results in this competition of various ground transport in terms of speed, energy efficiency, safety are shown by MLTS having linear traction motors.

It needs to be pointed out that MTLS is used only for passenger transportation. Researches and development in freight maglev transportation are undertaken at Emperor Alexander I St. Petersburg State Transport University (Russia) and Hyperloop One (USA). However, the latter is at the marketing concept stage and has a number of problems which are thought to be insoluble at the present level of engineering and science.

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The development of freight maglev transportation using national technology is envisaged as part of East-West Transit Transport Corridor. Today, transportation at this direction is organised on several routes using maritime, railway, and air transport. More than 90 % of cargo is carried by maritime transport, according to Dee Sea (via ehe Suez Canal).

The popularity of maritime transport is explained by two factors, in general:

1) low shipment fees;

2) seamless shipment environment, ensuring minimal volume of customs procedures, repacking, reloading. All this fosters maximum safety of cargo;

Among the routes within TTC, there are [6]:

– Deep Sea – a 24 000 km maritime route via the Suez Canal. Transportation takes up to 45 days;

– The Northern Sea Route – a 15 000 km route through the southern part of the Arctic Ocean having. Transportation takes up to 35 days;

– The Trans-Siberian Railway – railway route spanning 11 500 km through Russia's territory. Transportation takes up to 14 days (works to increase the delivery speed are in progress);

– New Silk Road routes – both railway and combined (railway and maritime) routes via the territories of China, Kazakhstan, Russia, and Belorussia (as on option – bypassing Russia through Transcaucasia and Ukraine with two sea travels or through Marmaray tunnel) spanning approximately 9 000 km. Transportation takes 15 days (works to increase performance are in progress).

All mentioned routes have their disadvantages:

– Deep Sea is characterised by "bottleneck" in the Suez Canal. Besides, the route runs through politically volatile and unsafe Gulf of Aden;

– The Northern Sea Route – complicated navigation (ice-bound waters), infrastructure demands considerably high level of development;

– The Trans-Siberian Railway, acting as the main transport artery between Northwest (mainly Baltic ports), Volga, Siberian, and Far Eastern Federal Districts, has a very limited performance and significantly long "bottlenecks". When transporting goods to Western Europe, the conversion from 1520 mm to 1435 mm gauge is needed;

– The routes of the New Silk Road run through the territories of a number of states with the goods subject to customs procedures. At some directions, modes of transport are changed (reloading), and gauge conversion is needed as well.

China subsidises and actively develops ground alternatives to maritime routes at the expense of railway transport.

In this situation, implementation of innovative transport technologies within TTC East-West is a duly prepared solution of realisation of Russia's transit potential.

As it was said before, the project is expected to be delivered in three stages.

1. At the first stage, the line connecting the Bronka and Lomonosov ports with a dry port at the Vladimirskaya railway station will be constructed. According to technical and economic parameters of the multifunctional handling terminal Bronka, the maximum capacity of the port is expected to reach 21.6 million tonnes per year. According to the data of Lengiprotrans Company, the potential performance of the existing line after debottlenecking will not exceed 8 million tonnes per year. So, there will be 13.6 million tonnes left without access to railway lines. The Lomonosov freight port plans to handle up to 9 million tonnes per year. As a result, it will necessitate to transport additional 22.6 million tonnes of container freight through Saint Petersburg, which is not possible with the existing urban road network [7, 8].

2. At the second stage, it is planned to extend the line to terminals in Moscow. In the total volume of containers to be handled in Russian ports, over half of them will be processed in northwestern ports. Among them, the Big Port Saint Petersburg is the leading one, owing to its proximity to the regions having 57 % of population and 60 % of GDP of Russia. 20 % of containers arriving in Saint-Petersburg ports are intended for processing and consumption within the city, Leningrad Oblast and Northwest District. 80 % of containers are delivered to terminals in Moscow for further distribution within the Moscow agglomeration or transportation to other parts of Russia. The overall capacity of container terminals of Saint Petersburg and Leningrad Oblast makes 5.3 million TEU per year. After realisation of the planned projects of expansion of the terminals, their overall capacity will make 11 million TEU per year [9]. There are almost no reserves for enhancement of the capacity. By 2020, it is foreseen that there will be a dramatic lack of carrying capacity of railways and plenty of bottlenecks in road infrastructure.

3. At the third stage, the construction of the key transport artery, namely TTC East-West is planned.

EAST-WEST TRANSIT TRANSPORT CORRIDOR

The fundamental idea of any transport corridor is that transport, freight and passenger flows are brought together on mainlines characterised by maximum carrying capacity and developed infrastructure. Owing to this, acceleration of freight and passenger transportation is achieved as well as cost reduction as a result of economics of scale. Additional effect is seen in the case of multimodal transportation, when there are several communications of interacting modes of transport running through one corridor [10].

The main purpose of creation a transit transport corridor is to provide conditions for unhindered and economically efficient transport traffic. At this point, one generally solves transport and technology tasks, associated with construction and upgrade of ways of communication, terminals, hubs, informational systems, etc.

Apart from that, creation of TTC includes favourable customs, tax, administrative regimes and provision of a complex of additional logistics services for trade development between the regions connected by this TTC.

The transport and logistics system of TTC East-West encompasses the following operations:

– unloading ships arriving directly at ports; provision of those with electronic blocking device;

– customs clearance in rear terminals;

– transportation of goods to terminal and logistics centres.

TTCs are designed to play a systematic role in economic and social development of territories affected. Their establishment stirs development of industries and social sphere of adjacent regions.

GENERAL CHARACTERISTICS OF CONTAINER TRANSPORTATION MARKET

Container transportation is the most advanced and economical type of freight transportation used in international and national communication. Transportation of freight by containers is much sought after both by large production and trade companies, and small and medium business companies, which engage themselves in export and import of various products. Application of standard containers enables reloading-free delivery of goods from the sender to the customer, thus singificantly reducing the volume of interim handling operations.

The volume of the world sea container transportation is growing annually. The greatest volume of transported containers was recorded at short Asian internal distances. According to Container Trade Statistics Ltd (CTS) data, during 2017, approximately 40.9 million TEU (+4.3 % to 2016) were transported between Asian ports. At most important “long” trades CTS counted 18.5 million TEU transported from the Far East to North America (+7.3 % to 2016), and 15.8 million TEU on routes from the Far East to (+3.7 % to 2016).

The demand for trade connecting the Far East with African countries below the Sahara has also increased. In 2017, 2.8 TEU were transported using this route

(+5.9 % to 2016). The most considerable growth was achieved in trade on the route Far East – South and Central America – 3.6 million TEU, which is 10.7 % bigger than year before [11].

One of the key factors influencing development of international market of container transportation is adoption of transport strategies in a number of countries in order to increase containerisation, which is dictated by environmental, safety and other requirements.

Considering the Russian market, one should note that it has been rapidly developing over the last 10–15 years, significantly outrunning the world ones. This is connected with the following factors [12]:

– low initial freight containerisation degree;

– growth of containerisation of export (containerisation degree of internal transportation – 25 %, the export one – 7 %);

– stable economy growth rates;

– integration of transport complex of Russia and the world transport system;

– expansion of the list of the goods that can be transported in containers.

The Russian economy is characterised by high involvement of transport in products pricing. According to the data of the Ministry of Transport of Russia, the volume of transport expenditures in the cost of goods makes 15–20 %, with 7–8 % in developed western countries [13]. Apart from reasonable grounds (vast terrirory, unfavourable climate conditions) this is influenceb by poor development of transport and logistics complex of Russia. Therefore, development of container transportation (namely internal, export and import, and transit ones) is one of the strategic priorities of the government. The expansion of application container transportation technologies is included in one of the sections of Russia's Transport Strategy 2030. Within this section the construction of container terminals, acceleration of delivery speed, development of sea ports infrastructure, introduction of new approaches into transportation organisation (forming of container routes), and developmen of intermodal routes are planned.

Reduction of transport expenditures and optimisation of supply chains are highly relevant for subjects of economic relations. Increase of share of container transportation and ramp-up of quantity of fixed route shipments (provided that there is growth of external trade) can partially solve this problem.

Today, development of container transportation is hampered by the following factors:

– lack of modern logistics and storage terminals designed to provide container supplies;

– insufficient intake capacity of ports, especially container port terminals;

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– obsolete container ships;

– shortage of rolling stock (container flat wagons for carrying containers by railway) and container equipment;

– instability in organisation of transit container trasnportation by the Trans-Siberian Railway.

The Russian container transportation market is at its shaping and development stage. At the same time, the factors given and long-term tendency show that there is a potential for further growth of external and internal container transportation.

MAGLEV TECHNOLOGY – THE BASIS FOR EFFICIENCY OF EAST-WEST CORRIDOR

As a result of the study of economic and technological factors of freight maglev and railway transport, a number of conclusions has been made, which determine efficiency of establishment of TTC East-West (Table 1–4).

Table 1. Line design and structure components

Factor	Maglev transport	Railway transport
Track structure	Flyover; guideway (levitation, stabilisation assemblies, linear motor inductor)	formation; blanket; ballast layer; anti-creepers, guard rail, bumper bars, etc; underrail base (sleepers, bars, etc.); rails; fastenings
Land allocation (right-of-way width)	7.2 m	20 m
Construction period for 100 km track	18 months	39 months in case of double steam construction, parallel electrification, without considering additional facilities construction period [14]

Conclusion: maglev transport infrastructure is considerably simpler than that of railway transport in terms of construction and installation works; considering lesser degree of necessity in land allocation, this is justified by high construction tempos.

Table 2. Operational characteristics

Factor	Maglev transport	Railway transport
Commercial speed	500 km/h	43.75 km/h (programme “Transsib in 7 days” will allow 62.5 km/h)

Factor	Maglev transport	Railway transport
Power consumption	0.53 kWh per 1 wagon kilometre	0.61 kWh per 1 wagon kilometre
Carrying capacity for 720 km line	At least 10.3 million TEU per annum	352 052 TEU per annum
Demand in rolling stock for carrying 3 million TEU per annum via 11.3 thousand km TTC	16 295	81 474
Rolling stock life cycle	50 years	30 years
Minimal degree of curvature	50 m	160 m in specially complex conditions [15]
Maximum gradient degree	10 %	4 %
Overhaul intervals	Not required before 50 years of services	Every 1.4 billion of passed tonnage (on highly stressed lines – once in 5 years)
Physical wear	Justified only by environment as a result of contactless interaction of guideway and rolling stock	Formation; permanent way; bogies and frames of wagons; coupling (contact-based interaction of track structure and rolling stock)
Requirements to freight sizes	No limitations for oversize freight	Limited

Conclusion: technical characteristics of maglev transport allow larger volumes of transportation as compared to railway transport having higher commercial speed and energy efficiency. Due to a shorter turnover period, the demand in rolling stock is reduced. The infrastructure of a maglev transport is less demanding in terms of landscape and allows construction in complex conditions. The infrastructure and rolling stock of the maglev transport interact without physical contact, which significantly enhances their life cycle and also significantly reduces the need for diagnostics and all types of repairs.

Table 3. Economic characteristics

Factor	Maglev transport	Railway transport
Cost of one year of life cycle for 11.3 thousand km, having 3 million TEU per annum	196 428 million roubles	304 091 million roubles (with new structure); 229 265 million roubles (with reconstructed line)

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Factor	Maglev transport	Railway transport
Cost of construction of one kilometre of track	582.4 million roubles	409.8 million roubles
Operational costs	448.73 kopeks per 10 tkm	590.44 kopeks per 10 tkm
Cost of rolling stock for carrying containers	15.25 million roubles	15.25 million roubles

Conclusion: despite higher cost of infrastructure construction, life cycle cost of maglev transport is considerably lower than that of railway transport, due to discrepancy in operational costs and number of repairs.

Table 4. Ecological characteristics and riding safety

Factor	Maglev transport	Railway transport
Level crossings	No	Yes
Derailment risks	Excluded due to magnetic forces and preventers	Yes
Collision risk	Excluded by operation system	Possible
Noise pollution	15 decibel	110 decibel
Emissions	No	From one train as follows: up to 1.5–20 mg/m^3 of dust; up to 1.0 mg/m^3 of sodium carbonate to; pollution with oil products 5–20 gr per 1 km of soil

Conclusion: maglev transport is more safe, namely in terms of ecology, than railway transport.

Summarising the above data confirms that in terms of the parameters considered maglev transport significantly excels railway transport, it is more efficient and is capable of meeting demand in large volume of transportation.

CONCLUSION

Considering the humankind's inevitable entering a new era of technological revolution, the priorities of the state policy in Russia's transport complex development using innovative transport and logistics technologies, necessity to strengthen Russia's positions at the world transit transportation market, the relevance of the East-West Transit Transport Corridor is obvious.

After the comparison study of transport technologies for freight transportation, the conclusion was made that application of maglev technologies for competitive TTC East-West is possible and necessary.

It needs to be pointed out that deliberate hampering of innovative development of transport, underestimation of significance of speed, breakthrough Russian engineering solutions decreases integral economic effect of the transport system as the most crucial element of the country's economy.

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RESULTS OF THE COMPLEX OPTIMIZATION OF MAGLEV

In this paper, the analysis of the *technology of complex optimization of transport* is performed on the example of various Maglev systems for the passenger and goods transport.

Keywords: Maglev technology, Maglev system, function model, optimization, system analysis.

1. INTRODUCTION

Maglev systems are in general regarding as more expensive and having a lower profitability in relation to its investment costs as wheel-rail systems or conventional bulk systems what substantially restricts the use of Maglev systems in the planning of transport infrastructure.

Therefore, in this paper the usefulness of the *technology of complex optimization of transport* [1] is shown how to reduce costs of Maglev systems. Using the results this can improve their chances in competition with traditional modes of transport on the existing transport market

2. METHODS OF SOLUTION

In accordance with the *technology of complex optimization of transport*, an *abstract model for a generalized transport system* was developed. This model determines mathematically the maximum balance between overall system components and provides adaptation of any guidedtransport system to its operation

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conditions. As a result, unnecessary costs are cut off to increase the efficiency of Maglev systems.

Two variants – internal and combined – for the optimization control of Maglev systems were implemented. For internal one, the optimal values of design parameters of Maglev systems are established automatically. For the combined one, the maximum train speed between the stops and the number of its sections are selected in a manual way while the values of other design parameters of the system are established automatically.

Also, for determination of the scopes of application of Maglev systems, a *dynamic model for the development of scopes for the effective application of transport systems* was developed to find the most effective transport system for every application case.

In this case the main evaluation criterion for determination of effective application of Maglev systems, as compared with the traditional types of transport, is the value of the specific travel tariff (Figure 1), which was received from the calculation of the payback of the total costs to the time of credit payment.

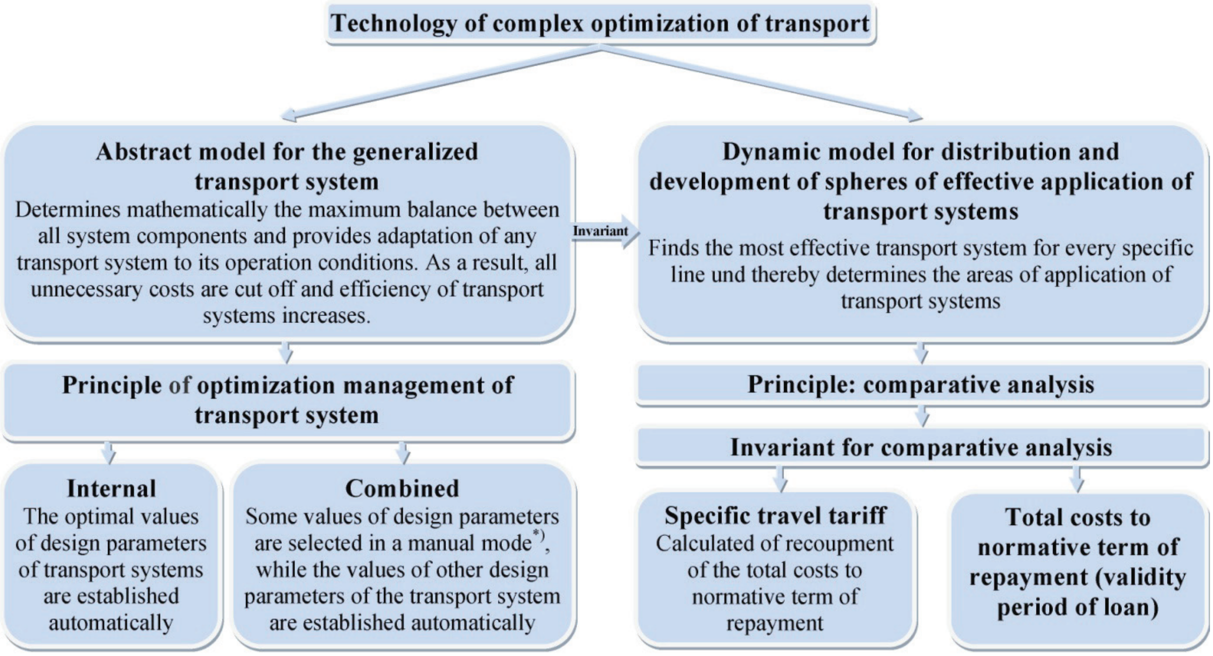

Fig. 1. Principles of the complex optimization process

3. INPUT DATA

The calculations were performed for four Maglevsystems:, TRANSMAG and TRANSPROGRESS as well as TRANSRAPID and MLX01.

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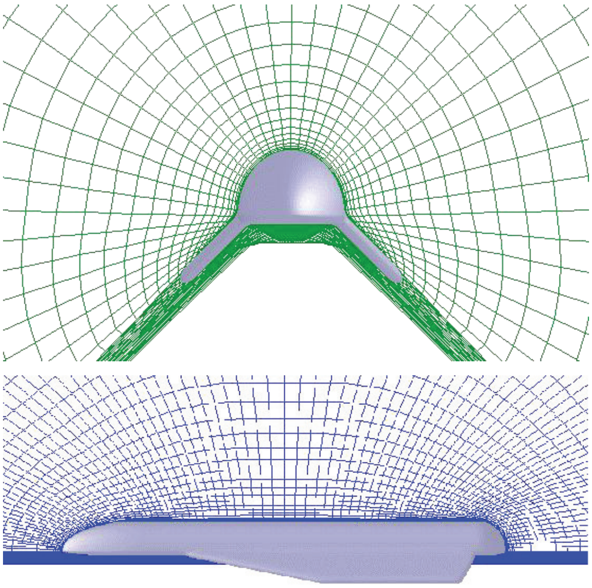
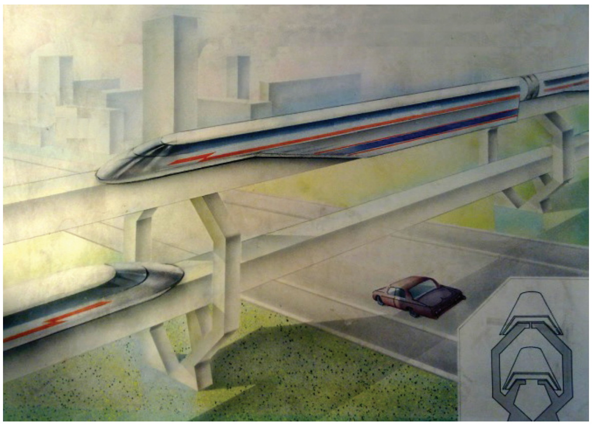
TRANSMAG is a Ukrainian Maglev system with aero-electrodynamic suspension, superconducting magnets and a long stator linear synchronous motor (Figure 2). It was developed at the Institute of Transport Systems and Technologies

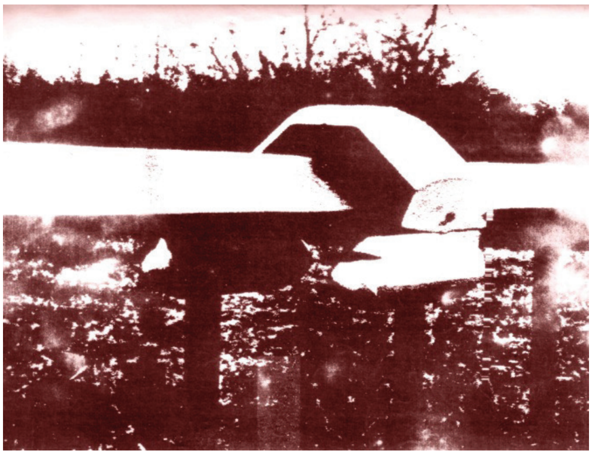


(a) Aerodynamic suspension



Specifications:
max. speed: 800 km/h;
section:
weight: 36 t, length: 40 m, height: 3 m,
wingspan: 6 m, width: 4 m;
passenger capacity: 120 person.

(b) Track-train structure



(c) test line of aerodynamic suspension of the vehicle (Dnepropetrovsk city, Ukraine)

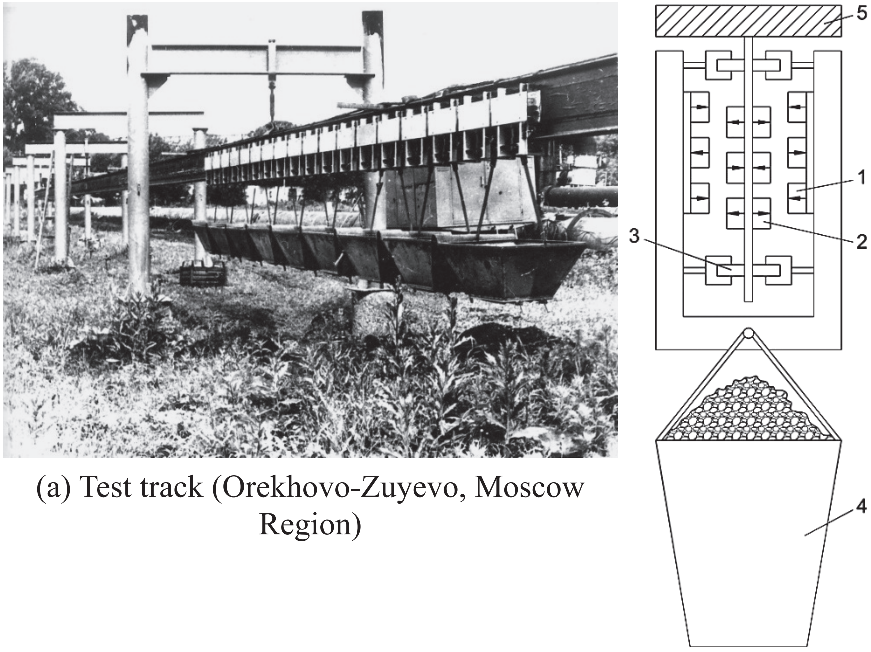
(d) Superconducting magnet

(e) Test track of aero-electrodynamic suspension of the vehicle (Dnepropetrovsk city, Ukraine)

Fig. 2. TRANSMAG Maglev system test vehicle and test trackline

of National Academy of Sciences of Ukraine [2]. The economic component of the calculations of TRANSMAG was obtained in accordance with the internal market prices.

TRANSPROGRESS is the Russian Maglev system on permanent magnetic suspension of vertical type with a short stator linear asynchronous motor (developed in the design office “Transprogress” (Moscow) from 1986 to 1990), intended for transportation of friable goods in ore mining and metallurgical enterprises Fig. 3 [3].



(a) Test track (Orekhovo-Zuyevo, Moscow Region)

(b) Structure of a vertical magnetic suspension

1 – magnets of the vehicle
2 – magnets of the track structure
3 – stabilization rollers
4 – bodywork of the vehicle
5 – track structure

Specifications:
– length of test line: 250 m;
– speed: 11 km/h;
– weight of train: 6 t;
– specific payload: 500 kg per linear m;
– train resistance is 20 times < than at a railway system;
– specific energy consumption is 5 times < than at a railway system.

Fig. 3. TRANSPROGRESS Maglevsystem on test track

On the basis of an *abstract model for a generalized transport system* for each of these Maglev systems an algorithm was written. For TRANSRAPID and MLX01, the principle of combined optimization control was applied, and for TRANSMAG and TRANSPROGRESS the internal one was used.

Calculations of TRANSRAPID and MLX01 performed for the selected model lines and for lines in operation as described in Table 1.

For TRANSMAG and TRANSPROGRESS, calculations were carried out for an array of input data that characterize a set of model lines. For TRANSMAG, the length of line was taken in the range from 250 to 4 500 km, and traffic volumes varied from 1 to 25 million passengers per year. For TRANSPROGRESS, the line

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Table 1. Initial design data of various lines TRANSRAPID

Parameter	Project						
	Unit	METRO-RAPID	MÜNCHEN	SHANGHAI	SHANGHAI-HANGZHOU Maglev Line	HAMBURG-BERLIN	SIC!
Line	end stopping	Düsseldorf Hbf – Dortmund Hbf	München Hbf – München Flughafen	Longyang Road Station – Flughafen Pudong	Longyang Road Station – Hangzhou East Station	Hamburg Hbf – Berlin Lehrter Bf	Berlin Papestraße – Budapest
Length	km	79	37	30	163	292	884
Number of stations	stations	7	2	2	6	5	10
Average distance between stops	km	13.15	36.80	30.00	32.60	73.00	98.22
Maximum longitudinal slope	‰	30	80	19	40	100	100
Design slopes	‰	4 [a]	7 [a]	5	4 [a]	5 [a]	6
Relative length of bridges [b]	%	3.00	5.80	1.24	3.00	1.70 [c]	1.20
Relative length of tunnels	%	5.06	20.00	0.00	14.72[d]	0.62	0.80 [e]
Relative length of at grade guideway	%	72.46	47.00	1.24	30.00	32.77	65.20
Reltive length of guideway elevated	%	22.48	33.00	98.76	55.28	66.61	34.00
Annual volume of passenger traffic in both directions	mil. pass. per year	34.37	7.86	10.00	33.00	10.50	6.10
Annual growth of the volume of passenger traffic per year	%	4.5	3.5	4.3	6.2	3.2	1.6
The normative repayment of costs incurred (the validity period of the loan) [f]	years	20	20	27	31	20	50[g]
Annual percent of the credit	%	5.00 [h]	5.00 [h]	2.81	5.34	5.00 [h]	4.37 [i]

---

[a] Approximate data.

[b] Track structure on bridges laid on pillars.

[c] Total length of 4.7 km [4].

[d] 24 km tunnel under the Huangpu River on a 32 km part between the Longyang Road Station and the airport Hongqiao [5].

[e] Five tunnels with total length: 6.3 km [6].

[f] From the moment of putting of the line into operation.

[g] For the overall design life of the project 50 years (of which 10 years account for design and construction work and 40 years on the phase of operation) on total costs was not the returned [6].

[h] Equals to the average discount rate: ~ 5% [7].

[i] 3 % – discount factor + 1.37 % – internal revenue [6].

lengths varied from 1 to 15 km with a slope from 0 to 40 ‰ and goods traffic from 0.1 to 0.9 mil. t/year were examined (Fig. 4).

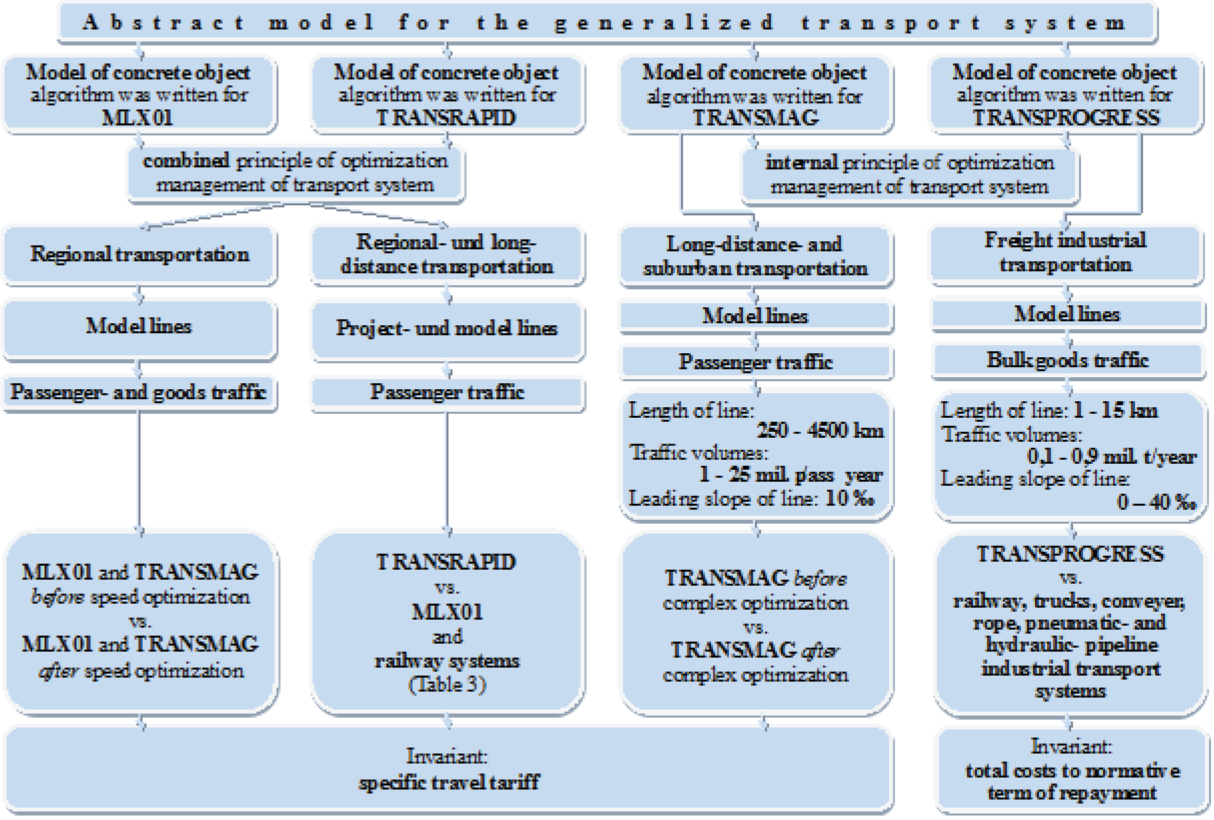

Fig. 4. Structure of the abstract model for the generalized transport system

For passenger transport, a comparison of Maglev system with conventional modes of transport the railway system was selected. These railway systems are operated or planned for the lines where in parallel concrete projects TRANSRAPID were investigated.

For goods traffic Maglev systems were compared with railway, trucks, conveyor, rope, pneumatic- and hydraulic- pipeline industrial transport systems.

In order to select the correct approaches for optimization of Maglev systems, the dependency of cost from the train maximum speed and the train configuration was studied

According to the results of the complex optimization, maglev-systems were evaluated by two criteria cost reduction and expansion of the application areas of Maglev systems compared to railway system (for passenger transport), as well as to other types of traditional transport (for freight industrial transport).

At the same time the limits of scopes of the application of TRANSRAPID and MLX01 were determined (Fig. 5).

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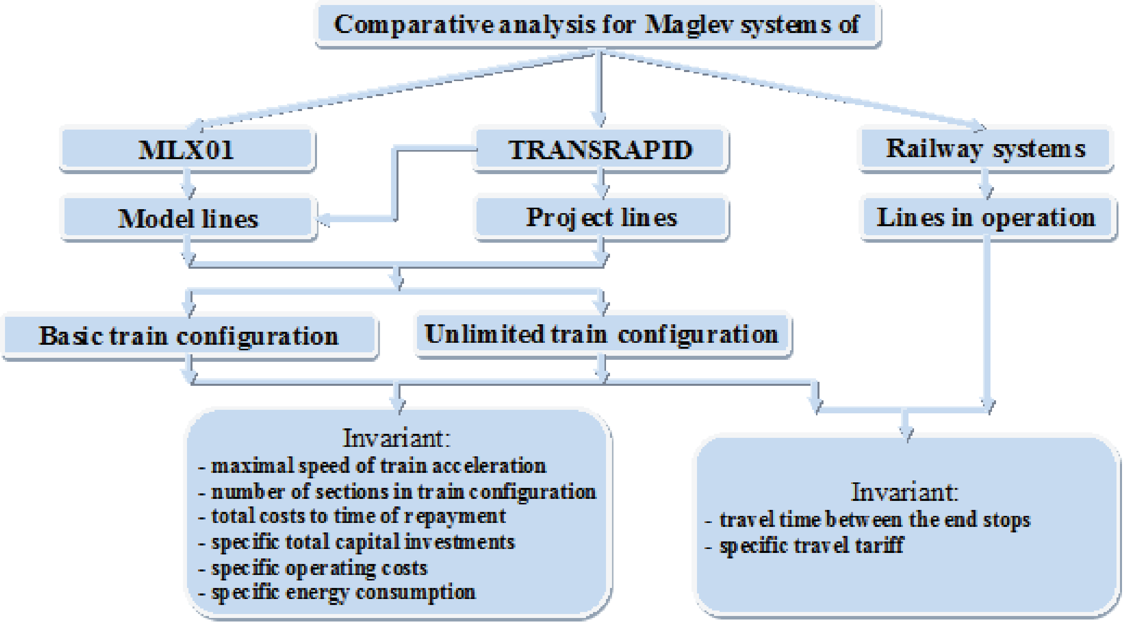

Fig. 5. Principles of the comparative analysis of Maglev systems

4. ANALYSIS AND ITS RESULTS

4.1 Analysis of complex optimization TRANSMAG

After conducting of the optimization of TRANSMAG [8] the value of the specific tariff was obtained for the transport of one passenger per one km, depending on traffic volume and line length (Fig. 6).

As a result of comparison of the tariffs of TRANSMAG before and after its complex optimization (Fig. 7) more than a double decline in the necessary traffic volume has been revealed at the fixed value of specific travel tariff 1,2 U.S. Cent per person*km (Table 2).

On this basis, it is necessary that at the fixed volume of annual traffic of 16 millions passengers per year, after complex optimization of TRANSMAG the size of travel tariff, after complex optimization of TRANSMAG, is approximately 2.11 times lower than the tariff before the system optimization (Table 3).

Thus, a 52.5 % decrease in the total expenses has been reached, decrease in capital investments and operational expenses defines economic efficiency of complex optimization of TRANSMAG.

More detailed structural analysis of expenses is presented in Table 4. It is showed, that the greatest part of their decrease constitutes of the operating costs.

The analysis shows a significant increase in efficiency of TRANSMAG as a result of its complex optimization [10].

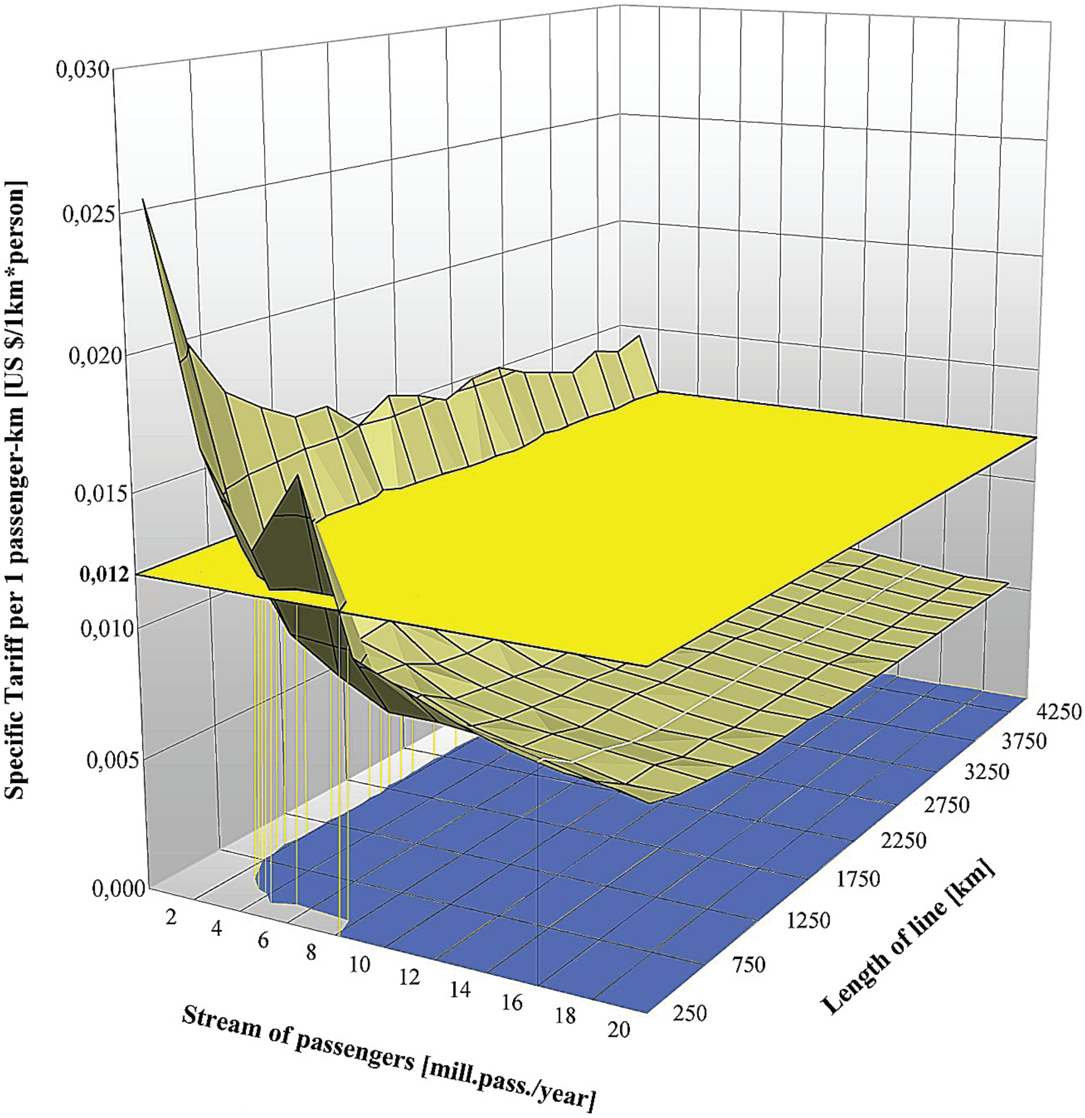

Fig. 6. Dependence of value of specific tariff of TRANSMAG on the traffic volume and line length, *after* the optimization

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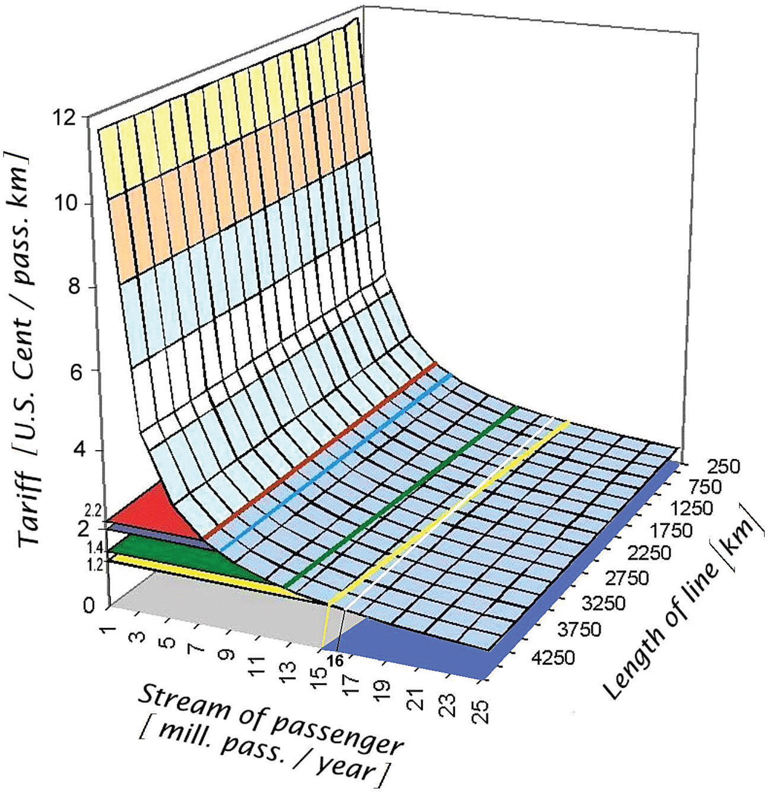

Fig. 7. Dependence of value of specific tariff of TRANSMAG on the traffic volume and line length, *before* the optimization [9]

Table 2. Determination of efficiency of complex optimization of TRANSMAG on the decline of traffic volume at the fixed value of travel tariff[a]

Parameter	**Unit**	**Before optimazation**	**After optimazation**
Specific travel tariff	U.S. Cent per person/km	1.2	
Normative term of exploitation of line, to repayment of the expenses	Years	10	
Low range of traffic volume, depending on length of line	mill. pass. per year	from 15–17	from 3–9.5
Arithmetical mean value of low range of traffic volume in both ends	mill. pass. per year	from 16	from 6.25
Coefficient of decline of necessary minimum volume of annual traffic for providing of self-repayment of the born charges to the normative term of exploitation of line	x times	0	2.56

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[a] Minimum necessary volume of annual traffic in both ends, for providing of self-repayment of the charges to the normative term of exploitation of line.

Table 3. Determination of efficiency of complex optimization of TRANSMAG on the decline of value of the spared travel tariff at the fixed value of volume of annual traffic

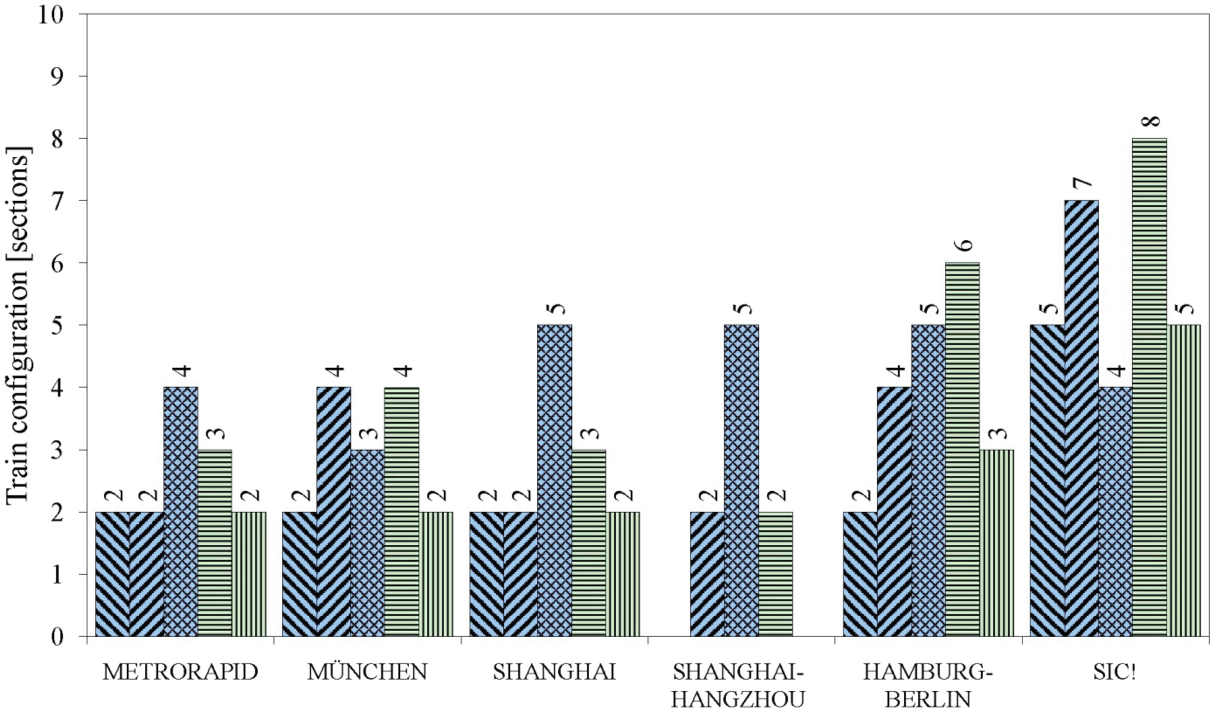
Parameter	**Unit**	**Before opti-mazation**	**After opti-mazation**
Volume of traffic	mill. pass. per year	16	
Range of tariffs at the set volume of annual traffic depending on length of line	U.S. Cent per person×km	1.1–1.3	0.8–0.53
Arithmetical mean value of tariff	U.S. Cent per person×km	1.2	0.57
Coefficient of decline of value of tariff at the set volume of annual traffic	x times	0	2.11
Stake of the total resulted cost cutting to the normative term of exploitation of line	%	0	52.5
Stake of capital investments from the total brought charges over to the normative term of exploitation of line	%	27.48	47.39
Stake of total operating expenses from the total brought charges over to the normative term of exploitation of line	%	72.52	52.61

Table 4. Structural determination of economic efficiency of complex optimization of TRANSMAG

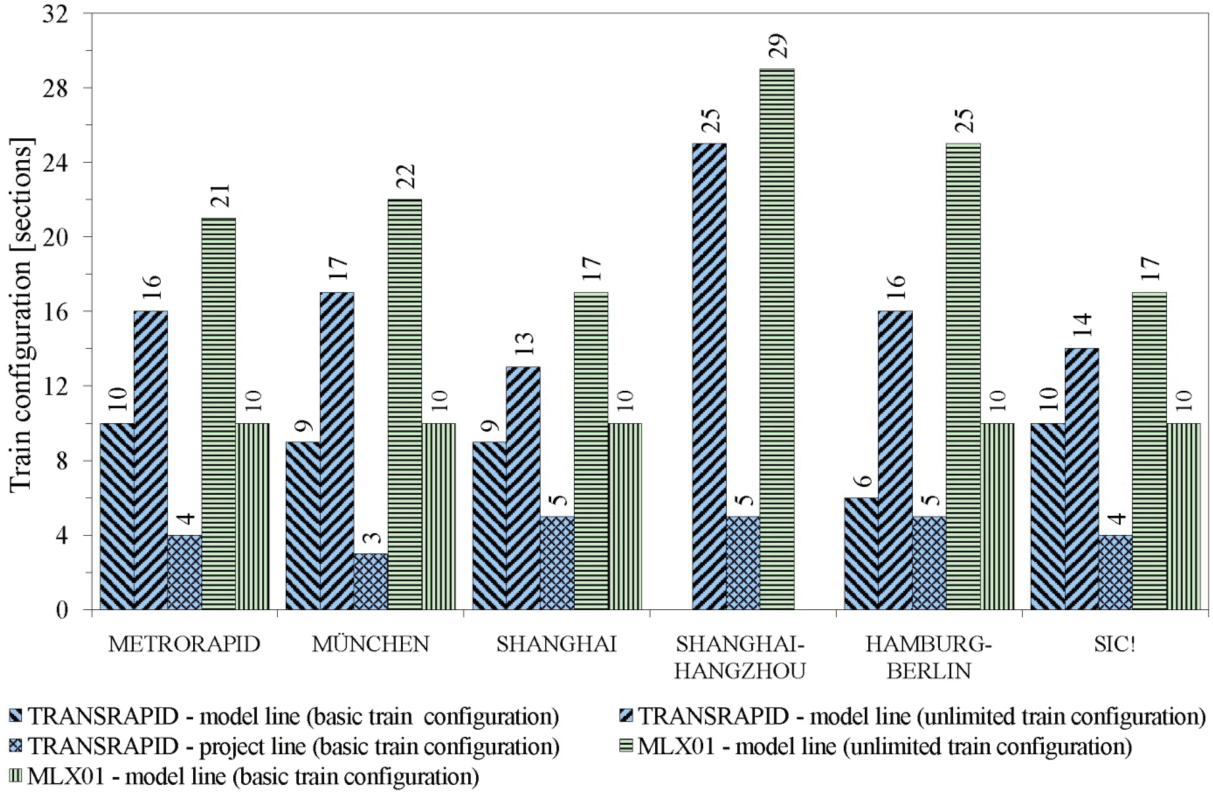
Parameter	**Unit**	**Capital investments**	**Operating Costs**
Reduction of costs at the expense of optimization	%	18	66
Reduction of the initial resulted costs	%	5	48
Reduction of the costs of the total economized sum	%	10	91
Reduction of the mean annual operating costs of the initial resulted expenses	%	missed	5
Reduction of the mean annual operating costs of the total economized sum	%	missed	9

4.2 Analysis of optimization MLX01 and TRANSRAPID

For the calculation of MLX01 and TRANSRAPID, the design data on the TRANSRAPID lines were used. Fig. 8–15 present the results of simulation of MLX01 and TRANSRAPID.



(a) In the first year of operation



(b) In 50th year of operation

Fig. 8. Number of sections in train configuration

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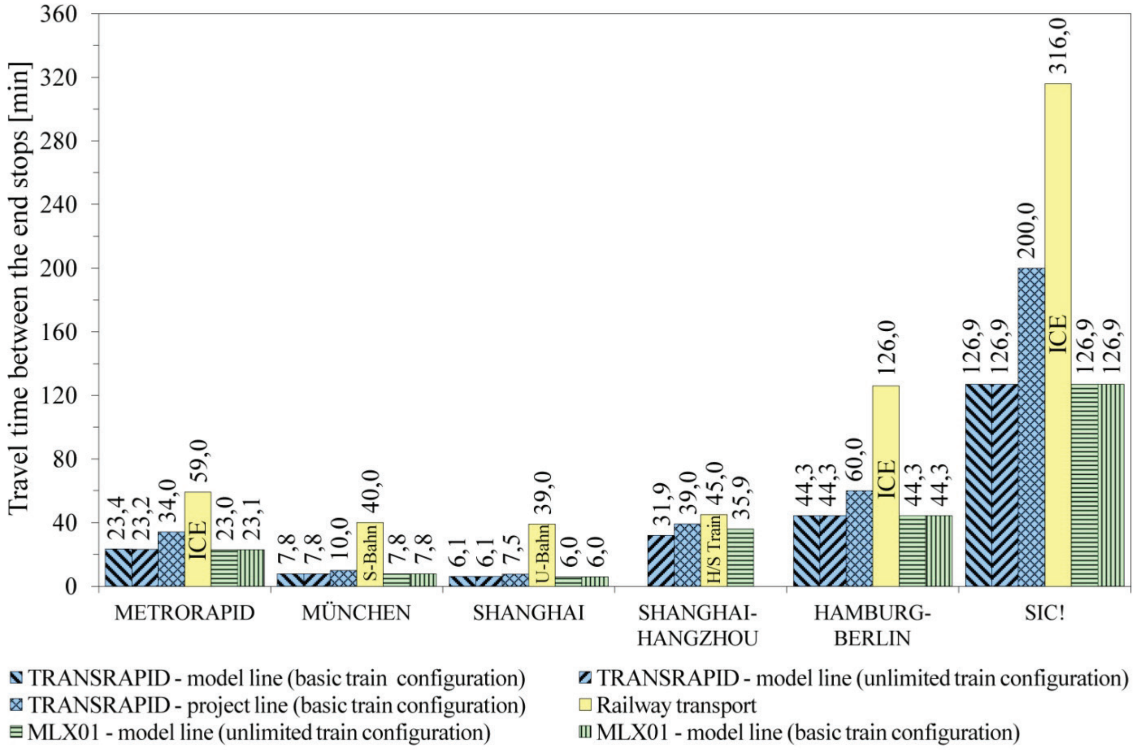

Fig. 9. Travel time between the end stops per line

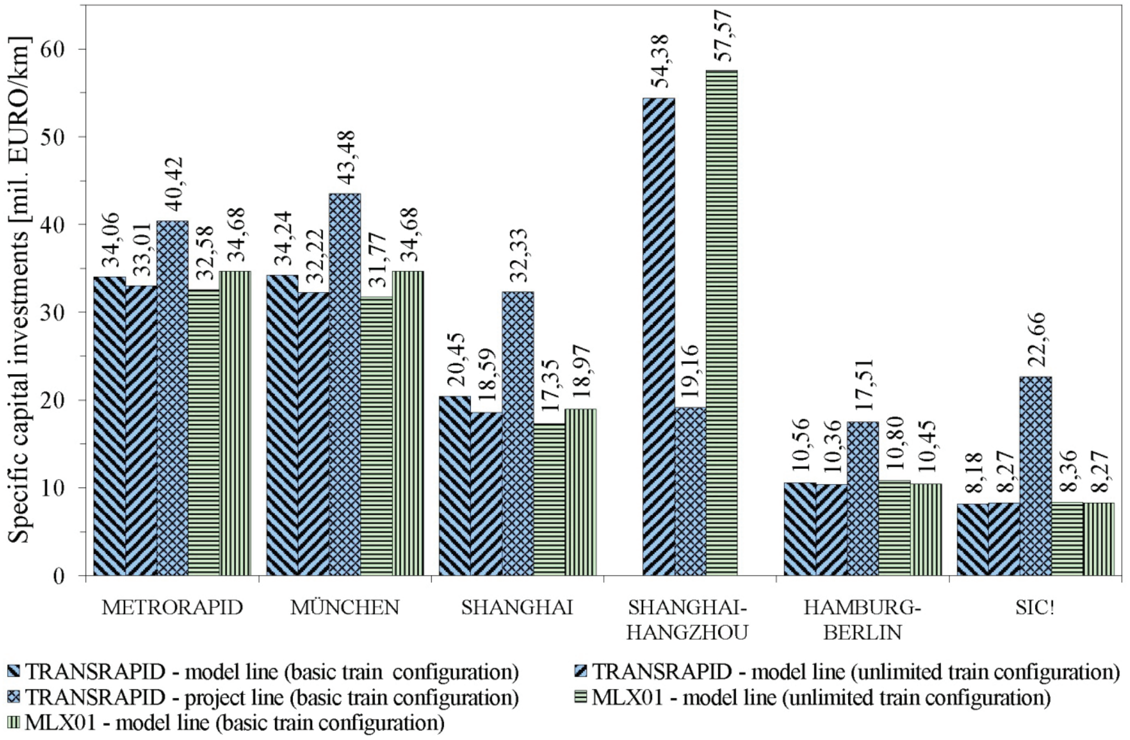

Fig. 10. Specific total capital investments per km length[1]

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[1] Without capital expenditures for the acquisition of additional rolling stock in connection with the increase in the volume of annual traffic.

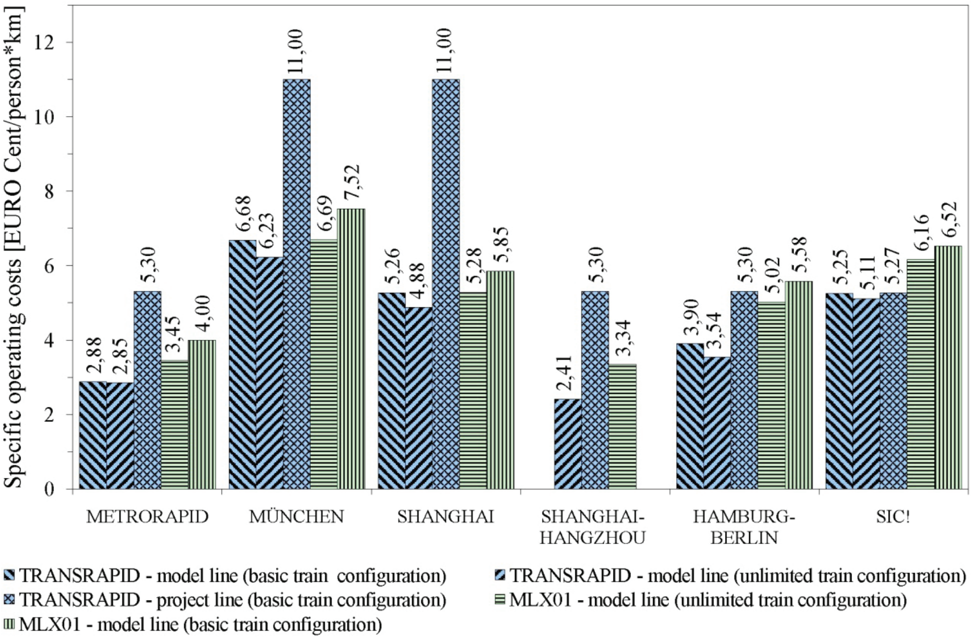

Fig. 11. Specific operating costs for one passenger and one 1 km length[1]

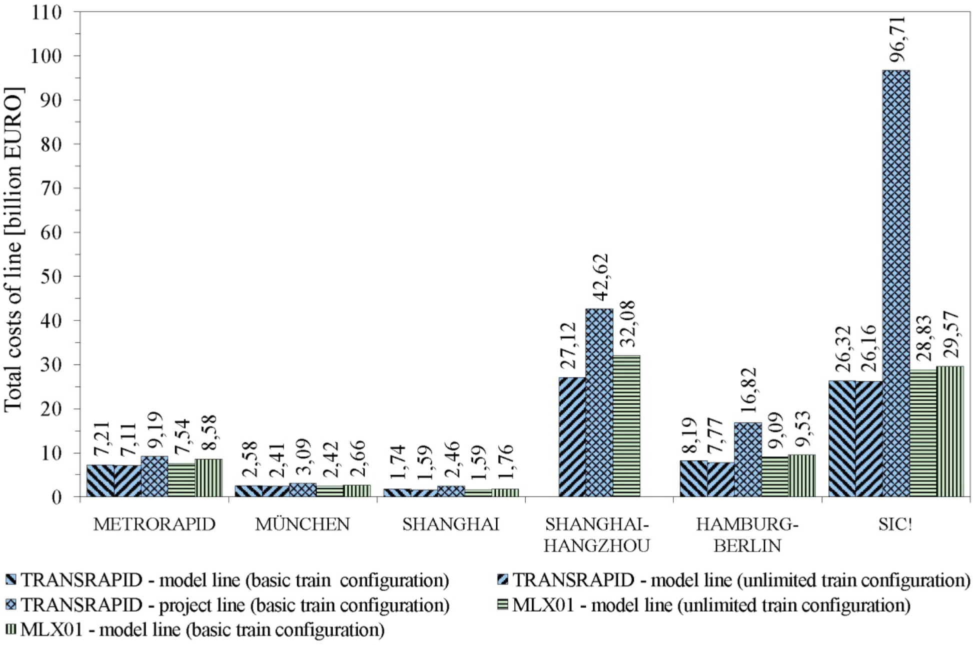

Fig. 12. Total costs to time of repayment (payment of the loan)[2]

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[1] The model-project operating costs are variating. Operating costs vary depending on traffic volume and train configuration, consumed energy costs, the number of staff etc. Therefore the average value of operating costs is taken.

Also the calculation was performed according to the German projects from the condition of 0.053 EUR/person×km for regional and 0.11 EUR/person×km for the city-airport communications [11].

[2] Taking into account capital expenditure for the purchase of additional rolling stock, in connection with the increase in the volume of annual traffic.

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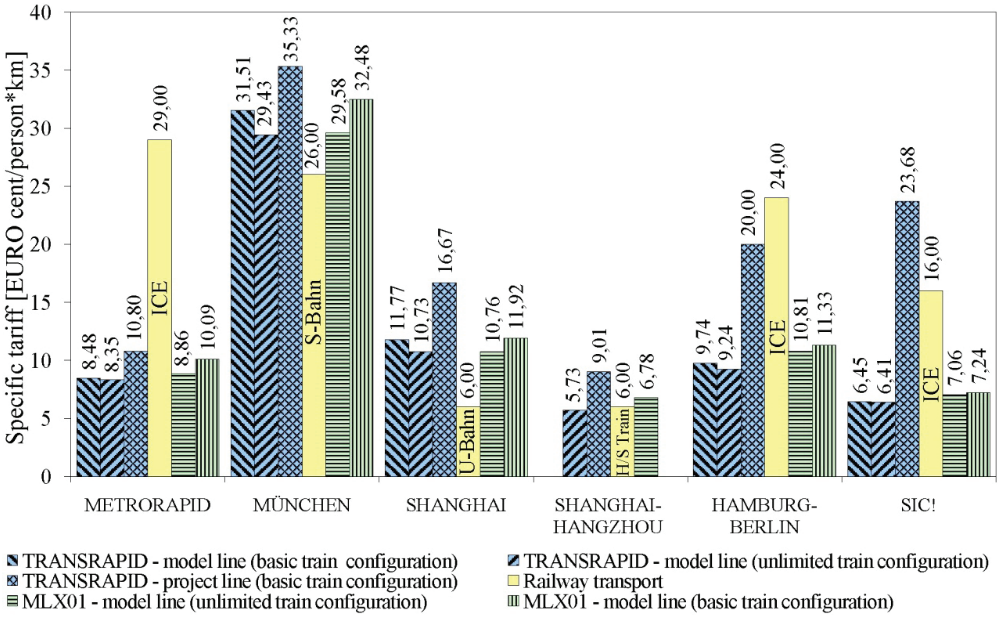

Fig. 13. Specific tariff for transportation of 1 passenger per 1 km (the car of 2nd class)[1]

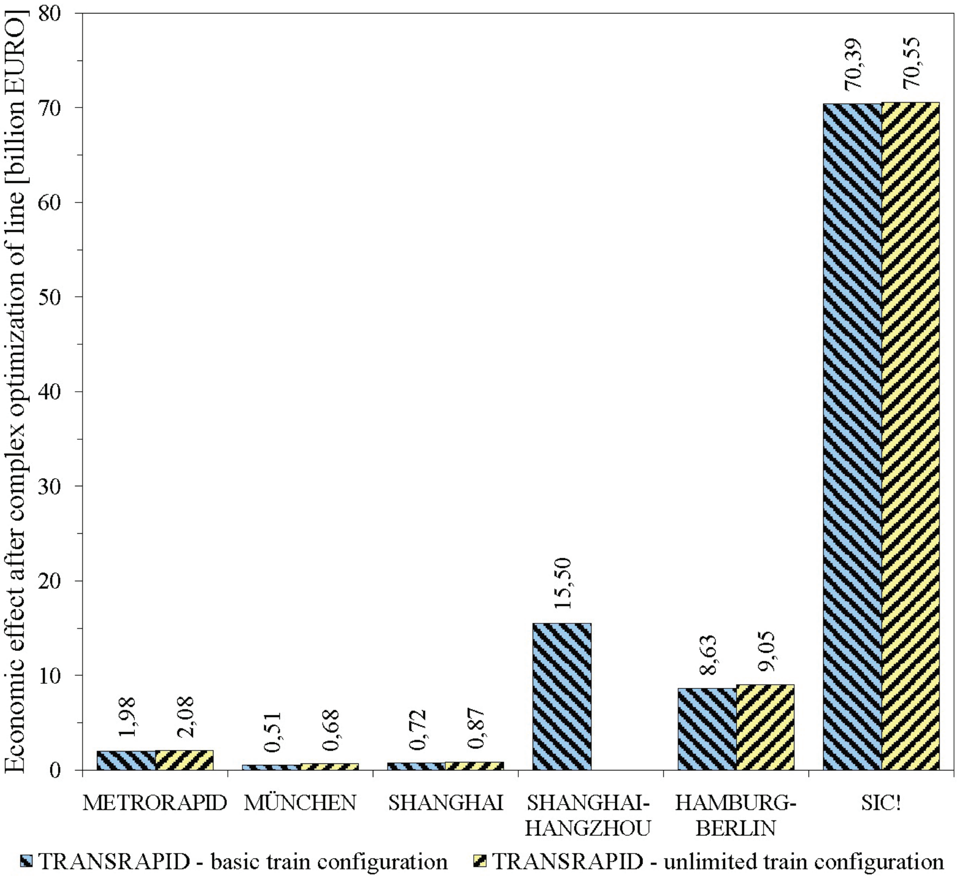

Fig. 14. Economic effect to time of repayment of the total costs (validity period of loan), of TRANSRAPID

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[1] Travel tariff are calculated taking into account factors of: the development experience of operating the new lines, discounting (reduction of costs at different times) and additional profit.

The optimization model showed that, in parallel with the increase in speed performance, economic efficiency of the TRANSRAPID has increased on one third compared to its design data (Fig. 14).

These results are quite analogous with the value of economic efficiency, obtained in the optimization of TRANSMAG (52.5 %). This testifies the reliability of the results.

It also demonstrates that the increase of maximal number of sections per train compared with the base configuration, results in an additional decline of expenses of Maglev-systems by 7 percent on average.

4.3 Determination of the Application scopes between TRANSMAG and railway System

The area, characterizes by the specific travel tariff of the Ukrainian high speed train (1/2 U.S. Cent per person×km), limits the scope of the effective application of TRANSMAG by the largest annual passenger traffic (Fig. 6, 7). By the optimization model of TRANSMAG, this low boundary moved up from 15–17 to 3–9.5 million passengers per year (Table 2) and thus *two and half* times enlarges the scope of its effective application.

4.4 Determination of the scope of TRANSPROGRESS in comparison with industrial bulk transport systems

For determination of the scope of effective application of the Maglev systems with traditional industrial transport systems for ore mining and metallurgical companies at transportation of friable loads, TRANSPROGRESS was chosen.

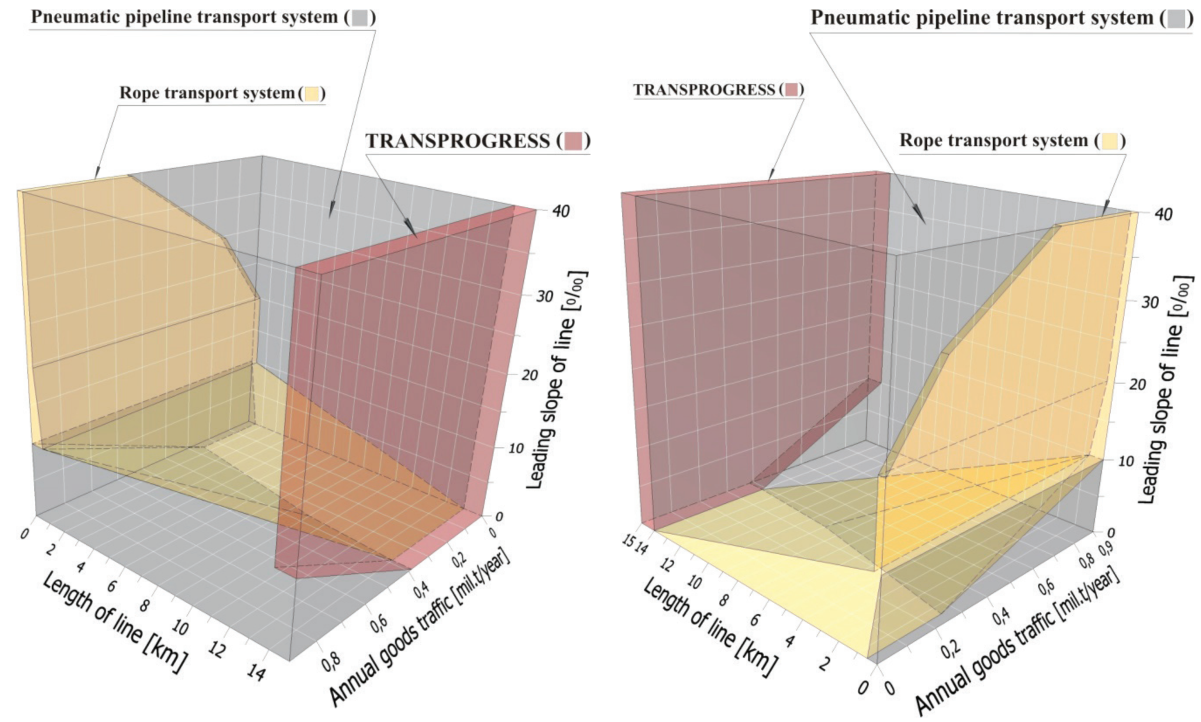
In this case the choice of the most effective transport system was carried out by minimum value of the total costs of line to the normative term of their repayment.

For TRANSPROGRESS, a *abstract model of a generalized transport system* was chosen. The method of calculation of the technical-economic indices [12] and preliminary optimization [13] were utilized. The technical-economic indices of other compared traditional industrial transport systems were executed via the methods of [14–15].

The scopes of effective application of the compared transport systems were determined in 3D co-ordinates, the axes of which correspond to the basic line parameters: length, size of leading slope and annual traffic of goods. Every point in the indicated co-ordinates system corresponds to most effective of compared transport systems.

The results of calculations for seven conventional goods transport systems showed that the hydraulic pipeline appeared to be the most effective. After excluding from comparison the hydraulic pipeline transport system, the next effective systems are the TRANSPROGRESS, the rope transport system and the pneumatic-pipeline transport system (Fig. 15). In this case other belt systems appeared not competitive.

Further for the exposure of scopes of effective application of TRANSPROGRESS, the rope (Fig. 16), pneumatic pipeline (Fig. 17) and conveyor transport systems were consistently excluded from comparison.

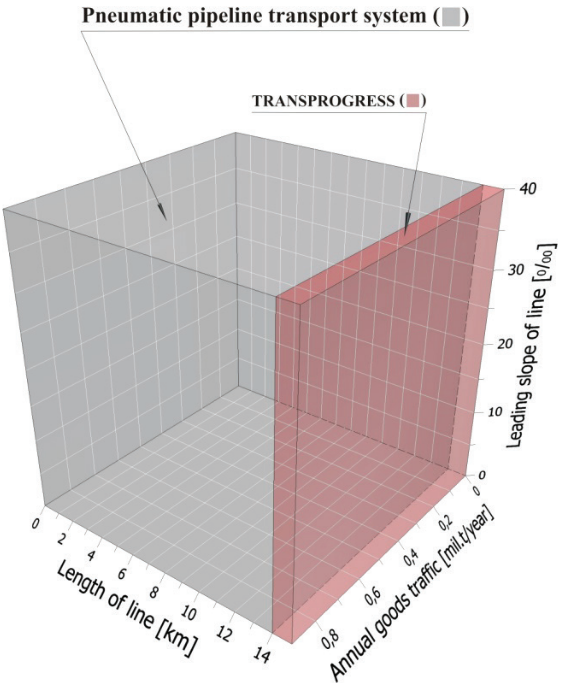


(a) Right-side view

(b) Left-side view

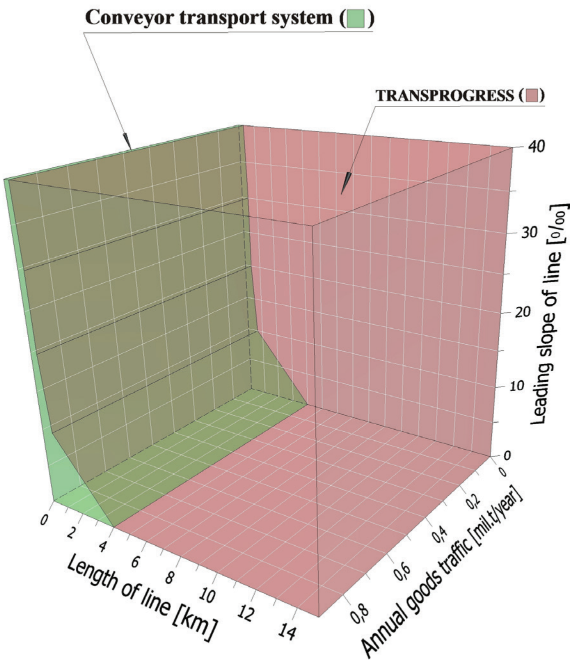
~~hydraulic pipeline transport system~~; pneumatic pipeline transport system; conveyor transport system;
rope transport system; TRANSPROGRESS; trucks;
railway transport system.

Fig. 15. Comparison of TRANSPROGRESS with rope and pneumatic pipeline transport systems for transportation of bulk good in the conditions of ore mining and metallurgical companies



~~hydraulic pipeline transport system~~;
~~rope transport system~~;
pneumatic pipeline transport system;
TRANSPROGRESS;
conveyor transport system;
trucks;
railway transport system.

Fig. 16. Comparison of TRANSPROGRESS with pneumatic pipeline transport system for the transport for of ore mining and metallurgical companies



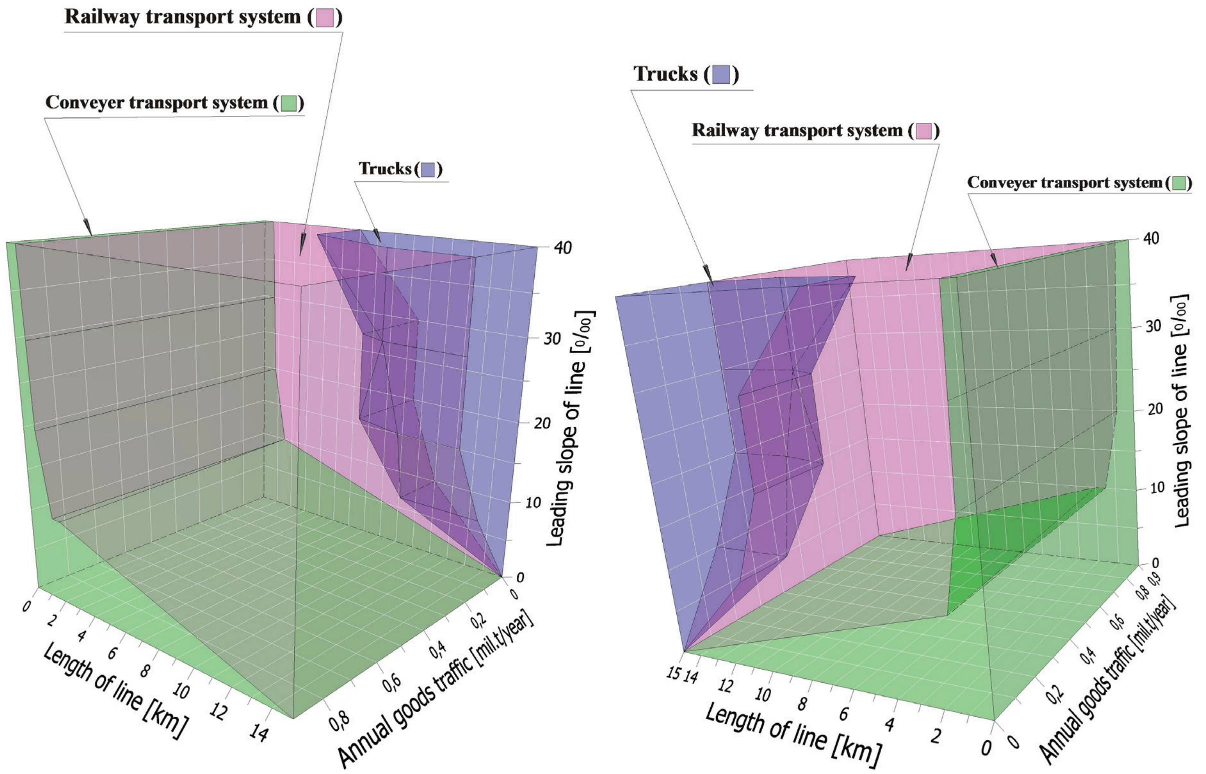
~~hydraulic pipeline transport system~~;
~~rope transport system~~;
~~pneumatic pipeline transport system~~;
TRANSPROGRESS;
conveyor transport system;
trucks;
railway transport system.

Fig. 17. Comparison of TRANSPROGRESS with conveyor transport system for the transport for of ore mining and metallurgical companies

As it is seen, after exclusion from comparison of the conveyor transport system, the TRANSPROGRESS stay the most effective transport as compared to remaining railway and motor-car.

Thus, in all cases of application of TRANSPROGRESS, the most optimum for composition of its trains appeared configuration of continuous (closed) type that technically fully corresponds to the conditions of transport in ore mining and metallurgical enterprises.

Thus, on the example of complex optimization of TRANSPROGRESS, the competitiveness of application of the Maglev system in ore mining and metallurgical companies was grounded. Also possibility of determination of scopes of effective application of the compared traditional industrial transport systems was evidently presented (Fig. 18).



(a) Right-side view (b) Left-side view

~~hydraulic pipeline transport system~~;
~~rope transport system~~;
~~pneumatic pipeline transport system~~;
~~TRANSPROGRESS~~;
conveyor transport system;
trucks;
railway transport system.

Fig. 18. Comparison of a conveyor belt system with trucks and a railway transport systems for the transport for of ore mining and metallurgical companies

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5. CONCLUSION

This study proved the validity of the *technology of complex optimization of transport* (for example Maglev systems). Its use will significantly reduce the cost of implementation of various transport systems and expand the scope of their effective application (Fig. 19).

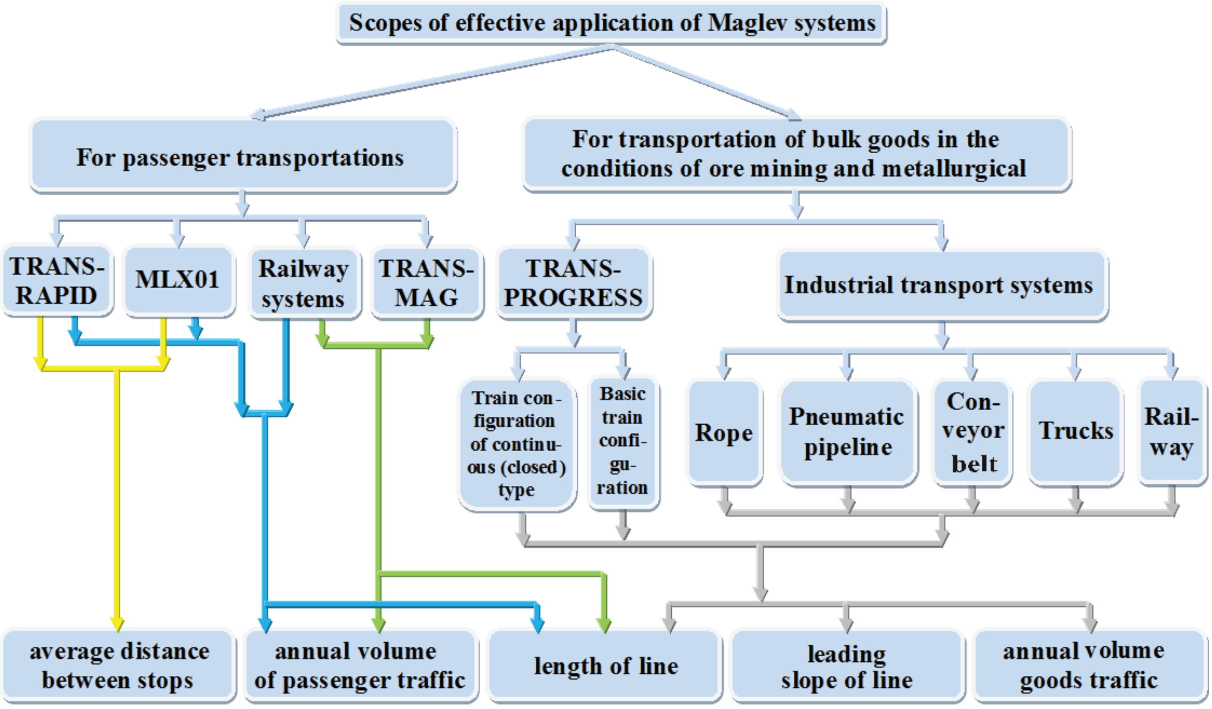

Fig. 19. Determination scheme of the scopes of effective application of Maglev systems

The results of theoretical researches presented in this work are intended above all for the exposure of basic directions of optimization of transport systems.

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RUSSIA INTEGRATED TRANSIT TRANSPORT SYSTEM (ITTS) BASID ON VACUUM MAGNETIC LEVITATION TRANSPORT (VMLT)

The Russian Federation is located at the crossroads of the trade routes of the Eurasian continent, where a significant volume of the transport flow of the world’s trade is formed. The transport potential of Russian territory, when implemented as an Integral Transit Transport System (ITTS), is comparable to the benefits from the traditional export of hydrocarbons and other raw materials. When analyzing the efficiency of transport systems, the key aspect is the energy approach. The concept of ITTS is considered to be based on all known transport lines and those, which are being developed now, including high-speed vacuum magnetic levitation transport (VMLT). The fundamental problems being discussed are about achieving the maximal speed, energy efficiency and throughput of VMLT. The preliminary findings presented were

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obtained from experiments on the test model of the VMLT route. The conclusion is that there is a need for a deeper study of the properties of magnetic and superconducting materials in extreme high fields, power and speed regimes to search for fundamentally new technical solutions for the creation of VMLT.

Keywords: transport transit corridor, vacuum magnetic levitation transport, integral transit transport system, superconductivity, magnetic materials, energy efficiency.

INTRODUCTION

In the 21st century, the need for a full-fledged realization of Russia large-scale transit transport potential through technologies of trans-Eurasian high-speed land corridors, composed of conventional and designed transport systems (TS), including ultra-high-speed systems based on vacuum magnetic levitation transport (VMLT) was recognized. All available and being developed transport technologies in complex will be able to compile the Integrated Transit Transport System (ITTS) [1–3]. The internal economic results obtained from a truly innovative project, such as ITTS, are comparable with the export of raw materials, traditional for the previous period of the country [4, 5].

The objectives of this work are the follows: firstly, to consider the physical, geographical and technological aspects of the ground, air, maritime, and underwater transportation processes, and try to formulate general physical principles for comparing different types of transport technologies, in particular, the principle of energy efficiency of transport; secondly, to consider the principal limitations for speed and energy efficiency of both designed and already-in-use means of transport; thirdly, to give a brief overview of the current state of development of the fundamentals of VMLT, which ccan probably be a record, both in speed and energy efficiency, and could therefore form the basis for ITTS; fourthly, to describe the preliminary findings of the experimental study of the magnetic levitation process on the test model of the route on the basis of permanent and superconducting magnets.

1. TRANSIT POTENTIAL OF RUSSIA REALIZED BY ITTS PROJECT ON THE BASIS OF VMLT

The uniqueness of Russia in geographical terms is not only in the record area of its territory. In modern geoeconomic and geopolitical conditions, Russia’s uniqueness is increasingly expressed in the fact that that through its territory China can be directly connected with Western Europe by high-speed land transport corridors. At this historical stage, the creation of ITTS with land corridors linking East Asia and Western Europe gives Russia and all the peoples of Eurasia as well

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a chance for a qualitative leap in development. For Russia it will also allow to take a new place in the structure of the world.

ITTS will allow to link the South Siberian and Far Eastern regions on the new economic, political and social levels with the European part of Russia. This will ensure the coherence of the country and the regions will receive a powerful impetus for development. The connectivity of the Russian territory on the basis of new high technologies will ensure Russia's position as one of the leading centers of the multipolar world, the country's deep integration into the system of international relations through development and attraction of international traffic flows. Vital interests of Russia correspond to the needs of the Eurasian continent in the creation of transcontinental mainlines, which allow to organize the states located in Eurasia in a qualitatively new civilizational construction.

The Russian Federation is located at the intersection of the shortest trade routes between the countries of Western and Northern Europe, the Middle East and Central Asia, the Asian part of the Pacific region, where a significant proportion of international commodity flows is formed. More than 20 % of the territory of Russia is located beyond the Arctic Circle. At present, 95 % of gas, 75 % of oil, the bulk of nickel, tin, platinum, gold and diamonds are produced over the Polar Circle. The oil and gas potential of the coastal zone and the shelf of the Arctic seas is estimated at more than 100 billion tons, or about 30 % of the world's oil and gas reserves. At the same time, the Arctic is also the most important transport corridor. There are sea routes between the markets of Northwestern Europe and the Pacific region . With further global trade and economic relations actively developing, the accelerated promotion of the Eurasian countries to the world's leading positions in economic, scientific, technical, technological, social relations is possible only by establishing transportation routes of a fundamentally new, innovative type [6]

According to statistics data, in 1992 the overall trade turnover between China and five Central Asian countries (Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, Tajikistan) was about $0.5 billion. In 2012, 20 years later, this figure, according to the Ministry of Commerce of China, rose to record $46 billion, so there wasan unprecedented 100 times increase. This incredible dynamics shows that in the future China will occupy more important place in the economic development of the Central Asian states. The Economic Silk Road Belt project or the Belt and Road Initiative (BRI), recently announced by China, are able to open new horizons for trade, economic and investment cooperation in various areas [7], inckuding Russia.

The urgency of BRI is also clear due to the fact that today’s Europe is actively looking for outlets for Asian markets and Asia is interested in the European market as well. To implement its BRI, China is creating such global financial development institutions as the Asian Bank for Infrastructure Investment ($100 billion) and the Silk Road Fund ($40 billion), whose capitals will be used to implement international infrastructure projects. In the coming decades such funds regarding national strategic projects will be beyond the means of any other country except China. Therefore, the unquestionable advantage of ITTS is its financial and economic security [7], which can be beneficial to Russia if it offers interesting and mutually beneficial options for the implementation of the BRI corridors through its territory.

The transition of society to a new technological paradigm determines the emergence of the corresponding system of economic relations, according to which time is one of the main efficiency criteria not only in the evaluation of information flows, but also in the traditional market of goods and services. Essentially, at present the economy of high speeds, which is extremely necessary for modern trade and transport communications, is being actively formed [8].

It is shown in works [2, 3, 9] that standard price of container (TEU) transportation on a route of SEA – Western Europe in the last 2 years fluctuates is within $ 600 – $ 1000. Cargo delivery time through one of the possible components of ITTS, - the route, which is proposed in [9] and constitutes an "under ice" transit transport corridor along the Northern Sea Route (NSR) across the Arctic Ocean, is supposed to be 15–20 days shorter than southern routes. At the same time, according to estimates, the delivery time via the ITTS land route on the basis of VMLT is almost 45 days shorter. Therefore, it can be assumed that even if the market price of such cargo delivery is higher, it will be profitable for the beneficiary of ITTS and the transit country. For the supplier this will also be very profitable as in addition to saving costs, faster delivery gives a number of competitive advantages in commodity markets. In particular, the profitability and competitiveness of the product increases due to the faster positioning of its innovative versions and updated positions of the model range in remote markets, so customer's satisfaction is also growing. The time of container turnover by NSR can be reduced (that makes possible for the supplier to confine with a smaller amount of TEUs), and there are some other reasons for preferring such transportations with faster cargo delivery.

The cargo in transit "freezes" together with the money spent for its production. At the hypothetical loan rate under consideration, even at 3.65 % per annum, 0.01 % of its amount is spent on its daily maintenance. Assuming an average cost of the goods in a container of $ 150 000, each day of the container's stay in transit costs the owner $ 15. For 15 days, it runs $ 225 for 1 TEU, for 46 days $ 690 for 1 TEU. It will be much more profitable for the cargo owner to pay the transit country, for example, an additional $ 200 – $ 500 for faster delivery than to spend an additional $ 225 – $ 690 for servicing the loan.

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Therefore, one can safely add at least \$ 200 – \$ 500 to a standard shipping price of about \$ 800. For example, the amount for the transportation of one TEU equivalent on the route Shanghai-Northern Europe through the Arctic ocean for 10–15 days can be \$ 1000 or \$ 1300 through the ground Russian corridor "ITTS" the based on VMLT and it will be quicker than in 1 day. Given the unprecedented growth in the volume of Internet commerce, Russian international transport corridors (including options for the future Moscow-Kazan-Yekaterinburg railway with the prospect of its extension to Beijing) may become competitive only if they provide very fast and high-efficient delivery of goods, for example, from Vladivostok to the European Union borders.

2. THE TRADITIONAL AND INNOVATIVE TRANSPORT TECHNOLOGIES, COMPONENTS OF ITTS

Accelerating the pace of scientific and technological progress and the globalization of the economy at the beginning of the 21st century is already at variance with the inadequate and limited development rates and possibilities for modernization existing traditional transport systems. There is need to find the effective solutions to this problem, in which the cardinal increase in speed and throughput of transport systems is combined with an acceptable cost and low energy costs for carrying passengers and cargo.

As it is stressed in the paper [5], it is important to take into account that "the size of a large state is determined by the so-called transport theorem linking the size of its territory with the speed of the transport used, and the time through which the system must respond to emergencies arising at its periphery". It also notes that "Russia's prospects are determined by technologies that allow it to sew and master its vast expanses beyond the Urals on the basis of new high technologies." "It would be ideal to provide an economically justified flow of people and goods, for example, from Vladivostok to the center with supersonic speed and a travel time of only about an hour. Neither aircrafts nor conventional high-speed trains solve this task" [5].

Therefore, new approaches to the solution of this problem are urgently needed. These approaches are proposed and published from time to time, but at the same time, the authors of new transport systems try to replace all the transport diversity with the sole one, offering mono-technology. Thus, to solve the problem of year-round operation and increase the throughput of NSR, the authors suggest several options of "mono-technology" transport systems, for example, atmospheric magnetic levitation transport (AMLT), icebreaking fleet, innovative airship systems, the creation of an innovative ice submarine fleet or a system of transport ekranoplans (ground-effect vehicles).

The problem of accelerating the social and economic development of the northern and eastern regions of Russia can be effectively solved by creating a whole form, which will determine its transition to the path of innovation, the widespread use of modern domestic technology and technique. This will make it possible to implement an industrial breakthrough in the Russian economy, the drive of the Eurasian integration [10].

We can also consider a broader problem of ensuring transport accessibility on the Eurasian scale. The unity of Eurasia will be assuredly ensured and the problem of distances will be solved if this territory is connected by a powerful transport system that should be adequate to the vast distances and diverse natural conditions of Eurasia: from the expanses of Siberia and the Arctic to the steppes of Kazakhstan. The transport system should have elements with extremely high speed, which will allow to "squeeze" distances, making distant economic centers close, as well as routes with high throughput.

To solve the strategic task of accelerated economic development of the Siberian, northern and Far Eastern regions of Russia, it will be possible to use the transport system within Russia itself, in territories east of the Urals. Thus, the new transportation system can begin functioning and give returns already at the first stages of its creation, immediately after putting into operation its main technical components – high-speed vehicles: vehicles not tied to roads, capable of acting autonomously both on land and on water. This technique was created in Russia: these are heavy ekranoplans and air-cushion vehicles that are not tied to roads. Their high speed and range of transportation, high carrying capacity, the ability to deliver goods without transshipment from one type of transport to another directly to the place where the consumer is located, make these machines indispensable both in Siberia and the Arctic and in Eurasia.

The creation of an innovative transport system based on ekranoplans is an alternative to the construction of airfields and roads in undeveloped areas, primarily for economic reasons. This shows a comparative assessment of the costs of implementing alternatives: traditional and innovative. Thus, the cost of construction of the 500 km Obskaya – Bovanenkovo (Polar Urals) railway constructed by Gazprom amounted to 130 billion rubles. 260 million rubles per kilometer. In the recount at the rate of 2007 – 9 million dollars per kilometer. Scheduled until 2017, the volume of traffic on this railway should be 250 thousand tons per year, i.e. 700 tons per day. This cargo flow can be provided by 6–7 Russian ekranoplans of the first generation "Lun", having a range of 2000 km and an aviation speed of 500 km/h. The cost of an ekranoplan of the "Lun" type does not differ from the price of a 500 ton Zubr air-cushion vehicle: $50 million. The construction of a group of ekranoplanes replacing the above-mentioned railway would cost 300–350 million

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dollars, which is much less than the cost of five billion. It is worth recalling that this road was built for 20 years, and the construction of the ekranoplan during mass production could take several months. It is not less expensive and long to construct highways and roads on permafrost [10].

So, there is reason to believe that for the development of the uninhabited territories of Russia, the transport support system should be created on the basis of new principles using innovative non-airfield bound means of transport: ekranoplans, air cushion vehicles, etc. In practice, the main mode of transport in these regions is aviation, namely, helicopters, because they also do not need airfields. However, helicopters cannot claim to be a full-fledged vehicle, since they are uneconomical, do not have sufficient cargo capacity and have a short flight distance. But there is an alternative: ekranoplans, since they allow one to solve the problem of economical delivery of goods weighing hundreds of tons with a sufficiently high speed for long distances. So, the effectiveness of the innovative scenario of the development of the transport system for the eastern regions of Russia is quite clear, as well as the promise of this system for solving the transport problem within the framework of the Eurasian Union [10].

But by our opinion, more effective will be the new strategic concept [1–4, 6]. The promising single ITTS must include as a consolidation of the optimal transport intermodality and original basic strategy of ultra-fast supersonic VMLT, all the necessary and adequate set of potentially related existing forms of transport and innovative TSs ("atmospheric" MLT, amphibious, "underwater\ice", ekranoplan, "flying container", aerostat, etc.), each of which is in its optimal functional place, from the standpoint of the general objective.

For the development of ITTS, it is necessary to analyze the transport systems of the future based on the criteria of speed, energy and their transport efficiency [1–4]. On this basis, data on existing and planned modes of operation should be analyzed, and each transport technology should be identified as its "most optimal economic niche" in the overall ITTS. At the same time, it is strictly necessary that the estimates of the transport efficiency of the newly proposed transport systems should be based on physically, technically and economically understandable and justified criteria for their mutual comparison.

3. LIMITATIONS OF VARIOUS TSS AND LIMITS OF THE QUALITY OF VMLT

For traditional ground vehicles, the main limiting factors are low speed, high energy consumption, insufficient transport efficiency, throughput and carrying capacity of transport highways. In particular, for the currentely used wheel-rail

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technology of railway transport, the problems with the successive achievement of two technological limits for the growth of the speed of rail vehicles [11–13] have arisen.

The first limit is associated with limiting the dynamics of acceleration and deceleration of the vehicle, depending on the adhesion of the wheel to the rail and the reliability of the current collectors of the constant and alternating current.

The second limit is connected with the limitation of the possibility of further raising the vehicle speed over 500 km/h due to the increase in aerodynamic resistance to its movement and energy costs proportional to the third degree of the speed achieved.

In the first case, the transition to contactless magnetic levitation transport traffic organization principles [11–14] is logical, in the second case – the transition to VMLT [1–4, 6, 15–18].

The disadvantages and unquestionable advantages of high-speed (about 500 km/h) magnetic levitation technologies realized in natural “atmospheric” environmental conditions, in comparison with traditional high-speed rail technology, are considered in detail in the works of Russian and foreign researchers [11–14]. In the technology of “atmospheric” magnetic levitation transport (AMLT), as the speed of motion increases, the aerodynamic resistance to the movement of the vehicle increases. With the already achieved record speeds of “atmospheric” vehicles over 1000 km/h, aerodynamic resistance plays a major role, and with the further increase in speed, it becomes possible to heat and destroy the structure of the vehicle.

On April 16, 2015, the magnetic cushion train of the Japanese company Central Japan Railway set a speed record, accelerating to 590 km per hour. In March 2016, a speed record of AMLT using airjet thrust was set - more than 1000 km per hour, and the most of the drive power of the vehicle was forced to spend on overcoming the aerodynamic friction.

Let us dwell on the problem of the maximum achievable parameters of VMLT, which was proposed in Russia more than 100 years ago [15]. Since the article emergence [19], many authors have noted that VMLT has very high limiting velocities, possibly limited from above by the first cosmic velocity (orbital velocity) at 7.9 km/s. At the same time, VMLT, in case of successful application of energy recovery, probably needs a record low necessary energy consumption for transporting of a unit of payload mass. Unfortunately, traditional vehicles, including AMLT, are forced to expend a lot of energy, both during acceleration and cruising speed, and during braking. It should be noted that at present it is considered that the maximal quality characteristics of VMLT are not established, and probably depend on a lot of physical, technological, geophysical, biological and system factors that have not yet been taken into account. Consequently, the study of these limitations represents an interdisciplinary fundamental scientific research and technological problem.

Obviously, a broad search for the most effective solutions to the problem of cardinal increase of the speed and throughput of the vehicle at low energy costs is necessary [1–4, 6]. To achieve this goal, it is proposed to consider a large-scale infrastructural project for the creation of such ITTS based on VMLT, combining energy efficiency, sustainability, speed (including supersonic) of travel of passenger and cargo vehicles that are unattainable in other approaches, as well as high throughput and safety with an acceptable cost of freight and passenger transport [1–4, 6, 16–18].

4. STRATEGIC CONCEPT OF ITTS BASED ON VMLT

The strategic concept of the promising unified ITTS must include ultra-fast supersonic VMLT as consolidation of the optimal transport intermodality and original basic strategy, all necessary and adequate set of potentially related existing forms of transport and innovative TSs (AMLT, amphibious, non-airfield, "underwater\ice", ekranoplan, "flying container", aerostat, etc.), each of which is in its optimal functional place, from the standpoint of the general objective.

Considering the large-scale project of ITTS, the technology of VMLT is an example of convergence of magnetic, superconducting and vacuum technologies for surface land transport, which allows in the future to reach hypersonic speeds at high throughput of the main overpass and record low energy costs due to emerging opportunities, maximize the degree of energy recovery of the vehicle.

The basic principles of the symbiosis of two key ideas − the concept of transport on magnetic suspension in an artificially created vacuum medium inside a sealed pipeline – were first formulated, developed, tested and published by B.Weinberg [15], and later developed in [1–4, 6, 16–18, 35, 36]. Magnetic levitation "atmospheric" transport AMLT is the first stage of development of ultra-high-speed land transport.

In the strategic perspective, wide application for freight and passenger transportation by AMLT and VMLT will open up new opportunities for the creation of intercontinental transport routes, the development of a number of new technological solutions in the field of energy, fiber optic, superconductivity, cryogenic technology, which can significantly change the environmental situation.

For example, a new transport concept of powerful and cost-effective so-called "energy pipelines" on the basis of VMLT was proposed [6]. According to preliminary calculations, they will be able to supply various classes of energy carriers (oil, gasoline, diesel fuel, oil products, etc.) with the speeds of about 6500 km/h (1800 m/s), at distances of thousands and tens of thousands of kilometers with almost no significant transport losses and with energy costs less than 0.004 kWh/t-km [6, 16–18].

In comparison with the trains of high-speed rail system (HSR), the material capacity of VMLT in terms of one passenger will be less than 1/20 of the material capacity of HSR and the specific energy consumption of VMLT is record low. The cost of creating and maintaining a vacuum is also not too high. According to [16-18], the transportation of 1 800 passengers over a distance of 1km will require energy costs within only about 1 kWh, and in the cargo version, about 0.004 kWh/t-km of cargo.

Recently, Russian developers have proposed innovative, cost-effective and energy-saving design principles of engineering structural elements, various types of power superconducting cables for power supply of equipment systems of VMLT networks as well as experimentally confirmed effective methods of noise-resistant control and monitoring network equipment based on various principles of long-range fiber optic diagnostics and cryogenic fiber sensors [20, 21]. These technologies work steadily and reliably in difficult conditions of combined action of vacuum, low (cryogenic) temperatures, strong influence of constant and variable electric and magnetic fields along the entire length of the route. As noted above, the concept of VMLT represents a synergy of magnetic levitation, superconducting and vacuum technologies for land transport, which allows to reach the vehicle speed of 6 500 km/h and above [18].

Thus, one can conclude, that today the only economically and technically acceptable solution to the problem of energy-efficient speed increase of both high-speed (up to 500 km/h) and ultra-high-speed (from 500 km/h to 6 500 km/h, and mpre) sustainable land transport is the replacement of the wheel-rail system with a magnetic suspension system and the replacement of the natural environment with an artificially created one, in which the aerodynamic resistance of transport will be relatively small. Due to the practical straightness of the route, the time of delivery of passengers and cargo will be minimal. In our opinion, the best solution here can be the creation of ITTS based on VMLT.

5. ENERGY CRITERION OF THE EFFICIENCY OF THE TRANSPORTATION VEHICLE

“We live in the era of upheavals and drastic changes in energy and material economic fundamentals. The era of cheap energy is coming to an end”, ”Some people hope that new technologies such as artificial intelligence, the Internet of things and blockchain will extempt workers and minimize production costs.... These optimists do not take into account the colossal infrastructure that will be needed to deploy these innovation technology. Meanwhile, its creation requires even more energy. We should admit that we will not be able to maintain the current level of economic growth. Reaching the current or higher level of energy supply of the economy via using renewable energy in the coming decade will be extremely difficult or even impossible.We will have to take measures to reduce the energy costs of transport" [23]. The realization of any transport project is closely linked and complementary worthy with the development of related energy project: together they make up an inseparable technical and economic unit. Due to the usage of additional generating capacities of 165 GW, by 2020 the transport of Russia will have consumed 54 GW, which is more than current capacities of all hydroelectric power stations of the country [24].

This is why energy economy issues are becoming key factors in choosing the most effective basic systems in any transport system. The optimal composition of the additional transport subsystems included in the ITTS can be determined, among other things, from the analysis of their energy efficiency. Some results of the TSs comparison are given in Tables 1 and 2 (see [1–4, 6] for more details on energy efficiency). The main energy criterion for transportation here is the criterion of specific energy costs for the transportation of a unit of cargo weight per unit of distance. This criterion can be denoted as specific energy consumption (SEC). The value of SEC is determined by the formula:

$$w(\mathrm{SEC}) = N / M \text{ x } V, \tag{1}$$

where N is the useful power of the traction machine (traction motor) of the transport system, in kilowatts (kWs), M-weight of cargo in tons, V is the speed at which the load is carried by the transport system in meters per second (kilometers per second).

With the help of the SEC figure it is possible to solve the problem of determining the perspective directions of development of various modes of transport, including VMLT. Table 1 presents the results of a comparison of the main conventional and advanced modes of transport, including land, sea (water) and air/ Below theis is an estimation of VMLT based on the data [22, 25].

As can be seen from table 1, without taking into account "VMLT", the best parameters of energy efficiency (if not always with comparable speed of transportation) has, according to the selected criterion, the classical type of sea (water) and railway transport. However, the efficiency of VMLT is almost an order of magnitude better than railway transport and better than sea (water).

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Table 1. SEC (specific energy consumption) performance of transport systems

№	Transport system	Type of transport	Power. MW	Velocity, m/s	Cargo weight, T	w (SEC), kJ/T*km
1	Boeing -747	Avia	71	253	64	4 380
2	Ekranoplan «Lun»	EP	137	138	120	8 333
3.	Ekranoplan «Orlenok»	EP	11	111	20	4 966
4.	Hovercraft «Bora-Samum»	Hovercraft	30.87	28	200	5 512.5
5.	Hovercraft «Jeyran»	Hovercraft	23.25	26	76	11 902.8
6.	Hydrofoil «Vikhr»	Marine	3.5	19.4	26	7 009
7.	Freight train	Railway	4.4	20.0	2000	110
8.	Heavy-weight train with 2 3-section electric locomotives «Ermak»	Railway	19.68	13.56	6 000	235.25
9.	Heavy-weight train with locomotive «Vityaz»	Railway	5.0	16.7	4 000	74.85
10.	HSR mainline (TGV)	Railway	8.8	83.3	50	2 173
11.	Transrapid	MLT	3.53	111	15	2120
12.	Trailer truck	Auto	0.338	22.2	20	761
13.	STY	String	0.040	3.3	4	120
14.	Baltic motor car ferry	Marine	17.6	10.8	3345	487
15.	Tanker Batillus	Marine	190.7	8.3	65500	36.2
16.	Tankers Admiralty Shipyards	Marine	3.36-25.0	6.7-8.2	7 000-70 000	43.4-71.8
17.	Tanker «Oleg Koshevoy»	Marine	1.18	5.4	4 696	46.53
18.	Tanker «Kazbek»	Marine	2.9	6.27	11 800	39.19
19.	Tankers («Prague», «Lisichansk», «Series»)	Marine	13.35-13.98	8.9-9.62	34 640-48 370	32.82-47.3
20.	VMLT (evaluation)	VMLT	0.5 (Impuls 18 sec.)	180	0.4	14.05

Legend of table 1: EP – ekranoplan, HSR – high-speed rail, TGV – Train à Grande Vitesse, STY – string transport of Yunitsky.

The applied energy indicator can be used in the evaluation of the implementation of the transit transport resource of Russia, for example, for some of the transport corridors listed in Table 2.

As a criterion, it is advisable to use the total energy costs for the movement of a ton of cargo from the point of departure to the point of arrival (in kilojoules per ton), i.e. P =w x L (dimension kJ/ton), where L is the distance. The results of comparison of two modes of delivery (sea and rail) for Europe-Asia transit are given in Table 2 on the basis of data [22]. Here is an assessment of a similar Russian transit China-

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Western Europe with the help of the transport system VMLT. From the tables, the advantage of VMLT in all compared parameters is obvious, and target parameter

- P – total energy consumption,
- VMLT is almost 10 times better.

Table 2. Overall figures of specific energy consumption and delivery time for different transport cargo systems and routes [22]

№	**Transit Type**	**SEC kJ/T*km**	**L , (km)**	**P, (kJ /T)**	**Goods delivery time (days)**
1	Railway (Russian transit) (China – Finland)	110	10 000	1.1×10^6	12 (7)
2	Sea (China – Finland)	54.3	21 000	1.14×10^6	28
3	Railway (Russian transit) (South Korea – Western Europe)	110	11 000	1.2×10^6	14
4	Sea (South Korea – Western Europe)	54.3	22 000	1.2×10^6	30
5	Railway (Russian transit) (China – Western Europe)	110	11 000	1.21×10^6	15
6	Sea (China – Western Europe) (Shanghai – Amsterdam)	54.3	23 000	1.25×10^6	27-46
7	VMLT (Russian transit) (China – Western Europe) (Shanghai – Amsterdam)	14.05	11 000	1.54×10^5	0.1

The legend in Table 2: L is the approximate length of the path, P is the energy consumption per unit of mass.

6. TRANSPORT CORRIDORS OF ITTS

Let us focus on some of the main geographical routes that can become the main transport corridors of ITTS.

DZUNGARIAN CORRIDOR [2, 3]. It currently serves as a railway corridor between China and the West. Among the possible transport corridors, the primary purpose of which is the implementation of high-speed communication between Beijing and Moscow, for many reasons, the Dzungarian corridor, located along the route that had a historical prologue eight centuries ago, is immediately distinguished. This route is the most direct and the most geographically natural from the point of the fastest transportation of passengers and cargo from China to the European part of Russia and back.

THE NORTHERN SEA ROUTE (NSR). In the message of the President of the Russian Federation to the Federal Assembly, the prospects of the NSR are noted

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as follows: – " The Northern sea route is going to be the key to the development of the Russian Arctic and the regions of the Far East. By 2025, its freight traffic will increase tenfold and reach 80 million tons. Our task is to make it a truly global, competitive transport artery" [27]. In 2018, the SMP started deliveries of Russian liquefied natural gas by ice-free sea transport.

In addition to the existing traditional competitive transport capabilities of ITTS, in our opinion, as options for extra innovative transport subsystems, there can be used other systems of ground-lift planes, innovative airships, magnetic freight transport in the port infrastructure and, especially, the recently proposed very interesting option of the submarine/subice fleet, (with vessels, the hull of which are made of heavy-duty "nanoconcrete"), allowing to make year-round navigation on the NSR faster and cheaper [9].

TRAIN ROUTES: THE BAIKAL AMOUR MAINLINE (BAM) AND TRANS-SIBERIEAN RAILWAY (TRANSSIB). In the same speech with regards to BAM and Transsib it is said: "For six years, the capacity of BAM and Transsib will increase by one and a half times, up to 180 million tons. Containers will be delivered from Vladivostok to the western border of Russia in seven days. This is one of the infrastructure projects that will give a quick economic return. The need for cargo transportation in this direction is very high, so all investments will contribute to the development of these territories and will be paid off very quickly. The volume of transit container traffic on our railways should increase by almost four times. Our country will become one of the world leaders in the transit of containers between Europe and Asia" [27].

This can be achieved for a period of T=180 000 000 tons/170 000 tons/h =1 059 h, i.e. in about 45 days, or not more than 1.5 months, with appropriate time of freight haulage of 1 TEU of 3 hours or less than a day from Vladivostok to the western border of Russia. With a full load of the route, the VMLT can transport to 365/45 = 8.111 times more cargo in a year (which is approximately 8 times more). Having accepted the cost of transit of goods received from the carriage of a freight equivalent of 1 TEU of $ 1000, we will receive annual revenues from the VMLT analogue of the BAM and TRS routes in the amount of 8x180 000 000 t / (15t / eq.1TEU) x 1 000 dollars. It equaled 96 billion dollars a year.

To sum up, it can be said that ITTS based on VMLT would not probably have competitors because ,despite the large capital costs, it has excellent energy efficiency and speed. However, its creation raises a large number of fundamental issues that will need to be solved by bringing together experts, both fundamental science and engineers of various industries from material science and physics of magnetic phenomena to geology and geophysics.

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7. INVESTIGATION OF VMLT PRINCIPLES

In a number of countries, including Russia, experimental work is under way to study the principles and fundamental capabilities of VMLT [2, 3, 16, 32, 33, 35]. The Moscow Aviation Institute (National Research University) has carried out theoretical calculations and experimental work and has created models of "atmospheric" AMLT vehicles (Fig. 1) [30, 31].

At the Khristianovich Institute of theoretical and applied mechanics SB RAS the computational and experimental modelling of the processes of VMLT were carried out [32, 33]. In particular, the following preliminary results were obtained:

1. The lower boundary of the optimal values of operating pressures in the tunnel of the vacuum transport system, using the existing traditional technical solutions, are estimated in the range of 25÷80 Pa.

2. The main contribution to the aerodynamic resistance is the wave resistance of the VMLT pod. The bottom pressure and friction resistance to the pod walls give a significantly smaller contribution. In case of the pod movement in the channel, two fundamentally different variants of the gas-dynamic flow can be realized.

Here the ratio of the squares of the pod and the channel is an important parameter: $\theta = SD/Sd$, where SD is the area of the channel, Sd – the area of the pod. In some critical areas (when $\theta = \theta c$) the nature of the flow is changing.

The case is favorable ($\theta > \theta c$), when the thickness of the gap between the inner wall of the channel and the wall of the pod is sufficient to "swallow" the whole air captured by the pod. In this case, the total resistance of the pod may be even slightly lower than in free flight due to the greater pressure in the aft of the pod (the result of the interference of the pod and channel).

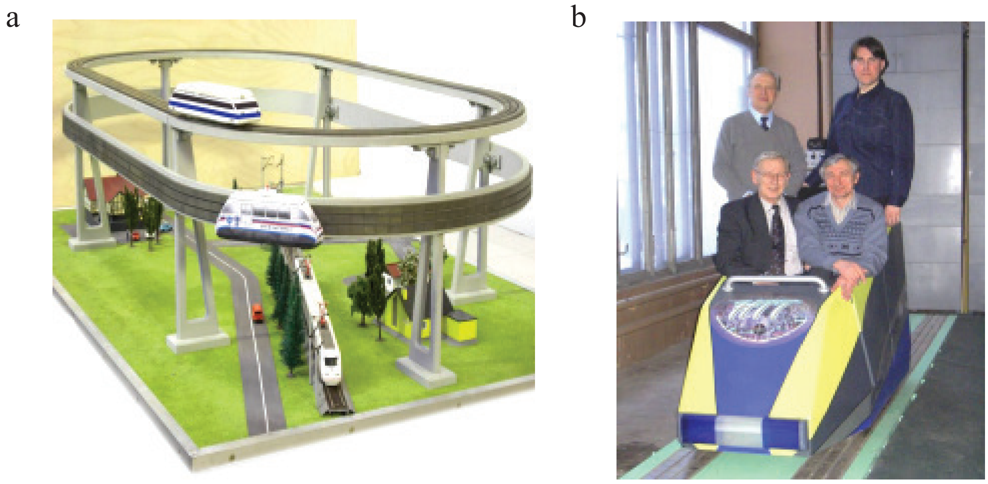

Fig. 1 . The current model of “atmospheric” magnetic levitation transport (a) and magnetic HTSC levitating car with a load capacity of 500 kg (b) [31]

The second variant of implementation of VMLT IS unfavorable from the point of view of aero-thermodynamic characteristics. The gap between the channel and the pod is so narrow ($\theta < \theta c$) that all captured gas is not "swallowed". A flow formed is somewhat similar to the movement of a semipermeable piston in the pipe. The pod pushes most of the gas in front of it. A shock wave in front of the pod forms. Resistance of the body increases sharply.

The number of conservative pods of VMLT, simultaneously located in the vacuum channel, is the determining parameter that affects the optimal pressure of operation of the vacuum transport. The greater the density of the pod is, the lower the pressure limit follows. Conversely, the fewer transport pods on the way there are, the greater the pressure energetically and economically justified is.

3. To improve the overall transport efficiency of vacuum transport it is necessary to conduct a comprehensive optimization of its parameters on the basis of new and innovative technical solutions for each case .

At present, the appropriate experimental installations have been developed and created, where several cycles of computational and experimental studies are planned to be held. A preliminary experimental study of the aerodynamics of the simplest model of a vehicle vacuum levitation transport system in the overpass under conditions of rarefied air flow with Mach numbers from M=0.1 to M=5 on the aerodynamic installation "MAU" in Khristianovich ITPM SB RAS was carried out. Flight simulation is supposed to be performed according to the reversed scheme, when the stationary model is blown by the air flow with the specified parameters.

In the initial, simplified version, the tests will be carried out in the mode of the attached pipeline, with the entrance of the channel-overpass docked to the nozzle of the aerodynamic installation. The output of the channel, the nozzle (200 mm), is connected to a vacuum tank with a volume of 220 m3. The schematic diagram of the experiment and the experimental stand are shown in Fig. 2. To perform the tests, a model of the vehicle with built-in two-component load cells will be made. Currently existing ballistic installation with preliminary calibration experiments is done at a flow rate of up to 400 m/s. In the future it is planned to carry out experiments directly with the same layout using the magnetix track pods, levitating above, with drain-free cryostat and superconducting units inside.

8. THE MODEL OF A MAGNETIC LEVITATION TRANSPORT ON THE BASIS OF HIGH-TEMPERATURE SUPERCONDUCTORS AND RARE EARTH PERMANENT MAGNETS

Researcher’s attention in many countries is attracted to magnetic levitation technologies based on high-temperature superconductors (HTSCs) of the second order, which have the advantages of stable passive levitation, low energy

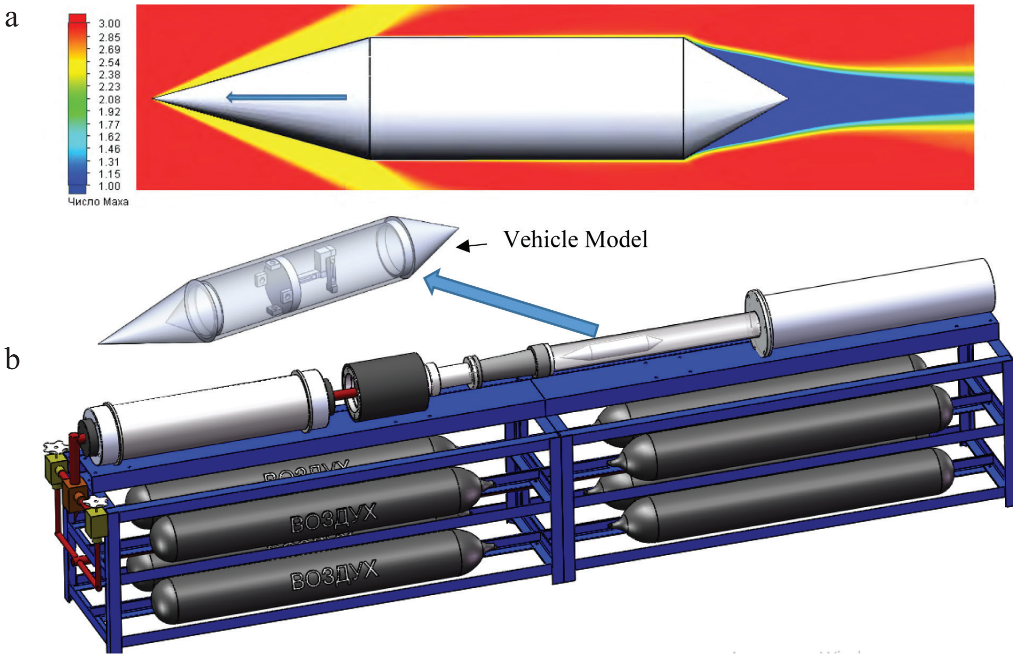

Fig. 2. Thermo-aerodynamic theoretical and experimental modeling of the movement of the layout of pods of VMLT in the rarefied atmosphere. a – calculation of the velocity and pressure of the gas flowing around the model of the pod of VMLT, b – schematic view of the experimental setup for the study of hypersonic air flow around the model of the pod of VMLT [33]

consumption, low noise, potentially high speed and pollution-free operation [28–31, 34–51]. The superconducting ceramics Y-Ba-Cu-O (YBCO), which allows one to create high magnetic fields and demonstrates the superconducting properties at liquid nitrogen temperatures (77 K), is relatively technological and not expensive, is used as a basis in many works. These materials have been used in almost all experimental models of vehicles (manned and unmanned), developed to date. In particular, they were used in the first manned model of a magnetic levitation vehicle tested at Southwest Jiaotong University, China in 2000 [38], as well as in the first AMLT prototype of vacuum magnetic levitation transport in 1914 & 2014 [15, 35] and in a full-scale, 200 m long and in HTSC-based model, built at the Federal University of Rio de Janeiro, Brazil, in 2014 & in Italy [39,40]. A number of important effects have been revealed in numerous fundamental studies of the magnetic levitation process using permanent magnets and bulk YBCO HTSC [34, 41–44].

In recent years, new bulk high-temperature superconductors based on GD-Ba-Cu-O ceramics (GdBCO) with excellent superconducting and mechanical properties have been developed [42-44]. In 2014, it was reported that the permanent superconducting magnet with a trapped magnetic field of magnitude 17.6 T was created, which was assembled from two cylindrical bulk superconductors GdBCO, 24 mm in diameter and 15 mm in height [43]. This result exceeds the achievements of the captured field in YBCO bulk superconductors [44].

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However, many fundamental questions in the field of HTSC materials for magnetic levitation remain insufficiently studied. For example, among them there are the effects of dynamic force interaction between bulk superconductors and permanent magnet guideways (PMGs) [45]. It is very important to determine the maximum possible speed of the future VMLT based on HTSC, to identify the impact of mechanical force and the variable component of a strong magnetic field, manifested in rapid motion and fluctuations on the VMLT route. In particular, the effect of weakening of the levitation force in the systems with bulk superconductors and permanent magnets, moving at a speed of 400 km/h or more was studied in [45–50]. However, at present, such issues as possible instability of superconducting properties and energy loss in systems based on superconductors of the 2nd order with strong fluctuations of power mechanical effects, rapid relative movement of magnets and superconductors and rapid changes in the magnetic field remain untreated.

In Kotelnikov Institute of Radio Engineering and Electronics of RAS with the participation of specialists from Moscow Aviation Institute [30, 31] the experimental small-scale (1.2 m long) model of the AMLT route was made, based on rare earth magnets (REM) PMGs of NdFeB alloy and HTSC ceramics of Y-Ba-Cu-O (Fig. 3, 4).

A distinctive feature of the experimental model of the AMLT track was the implementation of continuous movement of the cryostat with a levitating HTSC element over the three PMG lines (Fig. 3, 4). The original technical solution implemented in the development of the present model is called "magnetic force mirrors" - the elements, for example, of the massive REMs installed on the ends of PMGs. The effect of the “magnetic force mirrors” was to reflect the mobile superconducting HTSC objects - VMLT pods - at the ends and to "multiply" the effective length of the route in above 100 times. The “magnetic force mirrors” present the idea of "energy magneto-kinetic storage and recuperator batteries".

The field measured at the ends of the magnets is approximately 0.3 T. The weight of the cryostat is about 0.27 kg. The resistance to motion is small, allowing the cryostat, once set in motion at a speed of several m/s, to make more than 100 non-stop passes of the track, elastically reflected from the "magnetic force mirrors”.

Cross-sectional view of the model of the AMLT on the base of HTSC is schematically shown in Fig. 3b. Three lines of permanent magnets (NdFeB), oriented as shown in the figure, are fixed on a strip with a length of 1.2 m. At the ends of the strip, as shown in Fig. 3c, there are two massive magnets of the same alloy, creat “magnetic force mirrors”.

During the experiment, the cryostat with HTSCs at room temperature was pre-installed on a non-magnetic stand, of height h above the track.Then

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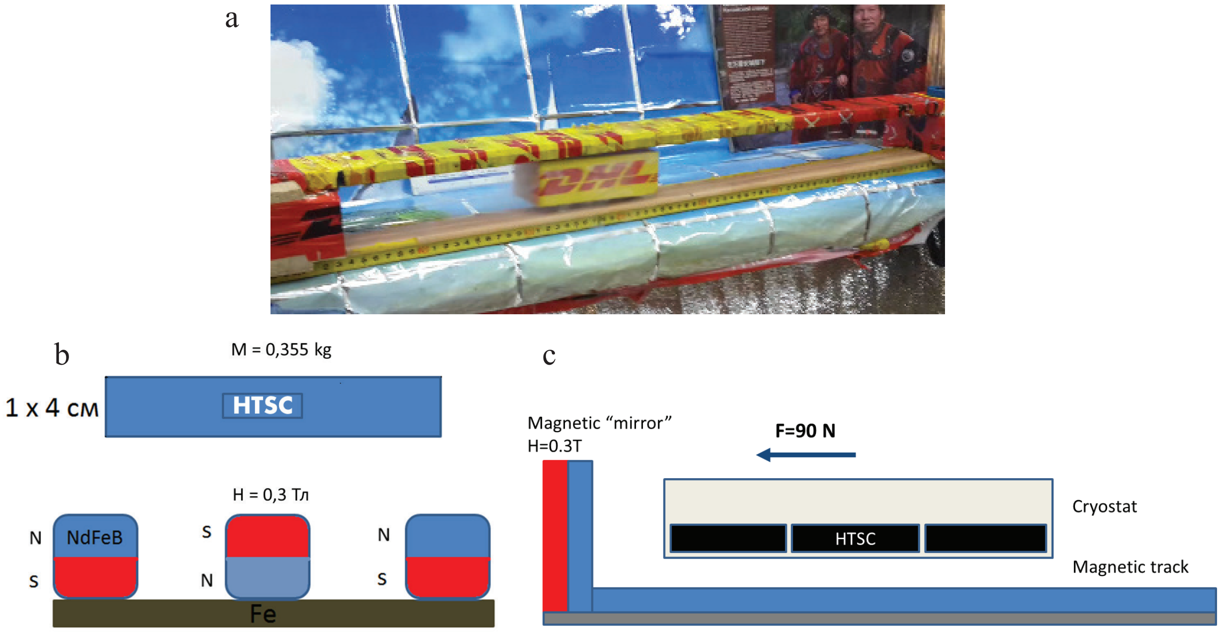

Fig. 3. Experimental miniature model of Maglev track based on PMG and HTSC ceramic. On the left and right ends of the route, there are «magnetic mirrors» strong permanent magnets. Reflecting from the «mirrors», the prototype can fly on the track more than 100 passes continuous movement before to stop. a – the general view of the model, b – cross section scheme of the experimental model of the HTSC Maglev route with a track of three lines PMG, levitating cryostat with HTSC ceramic, c – scheme of «magnetic mirror» at the ends of the track

HTSCs were cooled by pouring liquid nitrogen into cryostat. After pouring, the nonmagnetic stand was removed, and the cryostat with a HTSC of the 2nd order was in a state of levitation. At the same time, it is affected by magnetic forces, both vertical, holding from falling on the track, and horizontal, holding on the line of the track. Fig. 4 shows the levitation of the cryostat under external load and without it.

Qualitatively, the very preliminary results of the evaluation of the power characteristics of the model in dimentionless units N, are shown on the graphs in Fig. 5 a–d. These graphs reveal the dependence of the forces: F1 – the force required to break the cryostat from the track in the vertical direction – up, F2 – the lateral force required to break the cryostat from the track to the left or right, F3 – the vertical force directed downwards, necessary for the touch of the route from the height of the stand h, which was located on the cryostat over the track. Also presented is the graph of the dependence of a on h, where a is the height of levitation of the cryostat after being freed from the stand (a < h). The thickness of the bottom of the cryostat was about 3 mm. As can be seen from the graphs in Fig. 5, the height of levitation a increases with increasing h to 12 mm, and then decreases. F1, F2 decrease, and F3, on the contrary, increases with the growth of h. The dependences are in good qualitative agreement with the literature data.

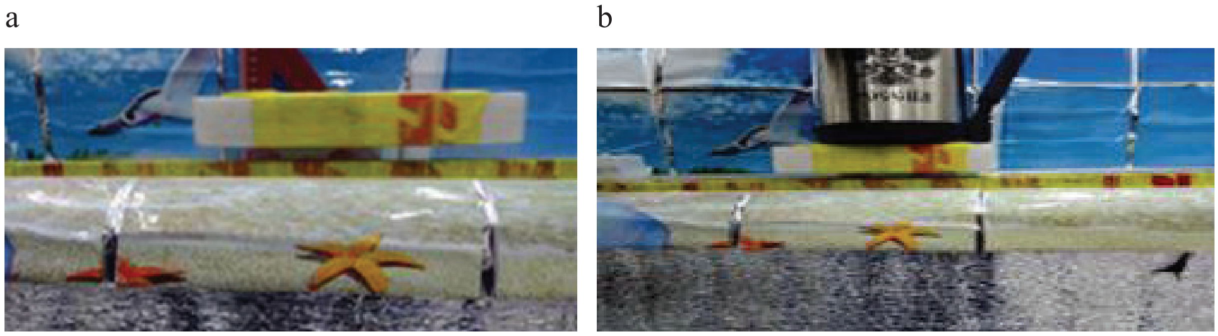

Fig. 4. Demonstration of vehicle model levitation, in which cryostat with HTSC blocks is used, maintained at a temperature of liquid nitrogen. a – free levitation of the model, b – levitation of the model under external load

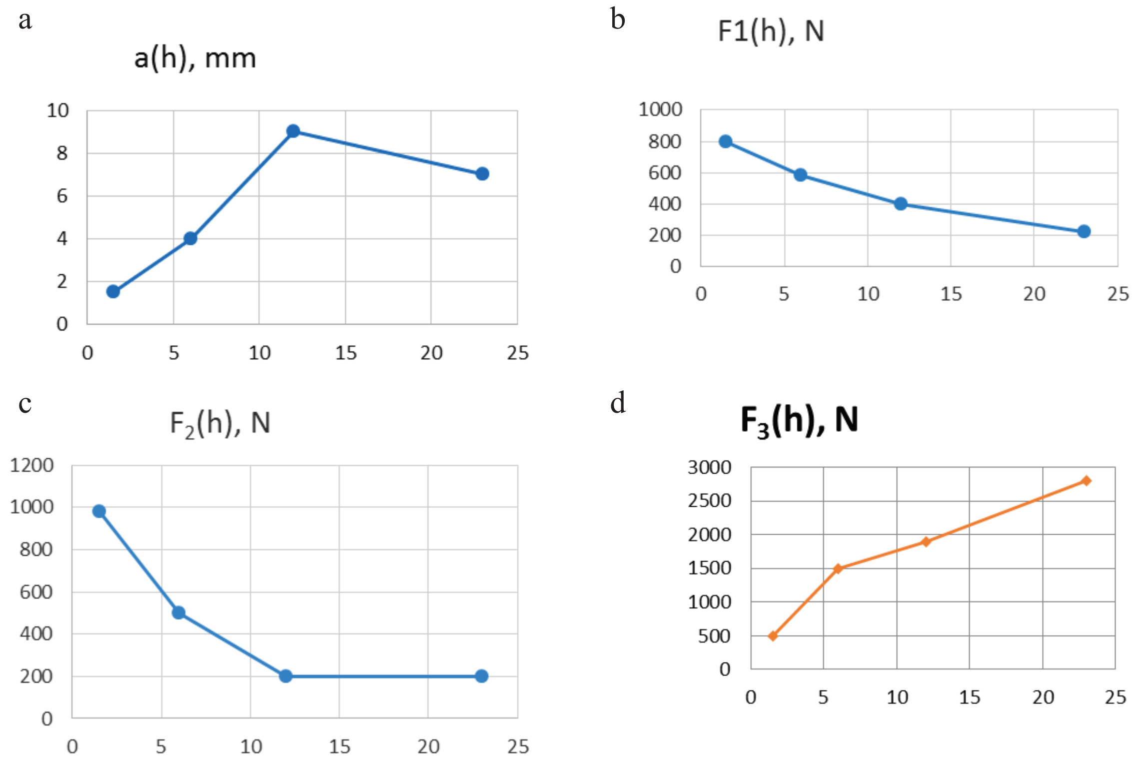

Fig. 5. Results of measurement of force characteristics of the experimental model of the HTSD AMLT vehicle and PMG, depending on *h*, mm
a – dependence of the height of levitation *a*(*h*); b – dependence of the separation force F1(*h*); c – dependence of the lateral stabilizing force F2(*h*); d – dependence of the maximum load force F3 (*h*)

Experiments on the study of force characteristics in the interaction of a levitating cryostat with "magnetic force mirrors" are of interest. It turned out that the force required to overcome the repulsion and touch the "magnetic force mirror" is about 900 N. As a result of the application of such significant forces, an effect of "magnetic plasticity" was observed. That is, after the mechanical force have acted near the "magnetic force mirrors", HTSC elements in the cryostat probably changed their magnetic state and acquired a new, weakly expressed position of the equilibrium along the alignment line near the "mirror". The effects of energy losses and magnetic state change of HTSC at extremal forces, depending on the speed of mutual movement of the superconductor of the 2nd order and the magnetic track, should be studied in details to justify the quality and reliability of the design of the VMLT vehicle.

At present, on this experimental basis a series of calibration experiments, production and verification of various versions of AMLT protypes, based on HTSC, are carried out. The variants of routes of PMG NdFeB, different types of cryostats, assemblies of bulk elements of HTSC, maintained at the boiling point of liquid nitrogen, are studied. Different variants of configurations of the arrangement of PMG, relations of power characteristics with the magnetic field intensity near the track are experimentally investigated on the model.

As a result of the preliminary experiments one can conclude that the main tasks to be solved are: theoretical and experimental study of interaction forces between the permanent magnets of the stationary tracks and movable vehicle in different versions of their spatial orientation and with different combinations of permanent magnets and superconducting elements, at different temperatures of their superconducting properties stability, obtained with the help of cryocoolers in the range from 3 K up to 70 K, and with respective drain-free cryostats and cryogenic "cold accumulators". The stability of motion and dynamic modes such as acceleration, stationary motion and braking at a given point, the amount of energy, which is necessary for acceleration, motion and braking, energy recovery processes (the process of returning braking energy to the electric source, consumed for first accelerating of the vehicle in the atmosphere and then in vacuum) are supposed to be studied.

9. CONCLUSION

The main results and conclusions of this work are as follows:

1. When analyzing the efficiency of transport systems, the key aspect is the energy approach. The technologies and further development of high – and ultra-high-speed vehicles, combined into ITTS are, undoubtedly, relevant and cost-effective for Russia. The problem of creating an effective ITTS on the basis of traditional TSs is unsolvable. The analysis of existing and being developed transport systems from the points of view of maximum speed, productivity and energy efficiency indicates the need to search for new, breakthrough and innovative scientific and technical solutions.

2. The implementation of high-speed transport routes of VMLT based on HTSC, which have, in principle, a record speed, energy and economical efficiency is particularly attractive.

3. The analysis of international and national experience, as well as preliminary experiments on small-scale models, shows that to justify pilot projects of VMLT based on HTSC, it is necessary to perform a large amount of fundamental and applied theoretical and experimental work. First of all, it is necessary to study the properties of promising superconducting and magnetic materials to prove the stability of their electromagnetic and electromechanical properties at high speeds and significant dynamic mechanical and magnetic loads.

4. The results of fundamental theoretical and experimental studies, as well as technological experiments carried out on miniature models, will allow to create a "medium scale" model of VMLT track based on HTSC , on which it would be possible to simulate the processes of acceleration, braking and energy recovery. Successfully tested, it will be possible to turn to the creation and testing a larger scale of VMLT based on HTSC, first to demonstrate the capabilities and then for practical use.

5. It is necessary to recognize at the State level – by the Russian Federation Government decision - to include the magnetic levitation transport (AMLT and VMLT) in the "Russian Federation Transport Development Strategy up to 2030".

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PRACTICAL INVESTIGATION OF FUTURE PERSPECTIVES AND LIMITATIONS OF MAGLEV TECHNOLOGIES

Results of an International Survey among Transport Experts and Specialists Maglev

With the aim of tracking current trends in the market perspectives of magnetic levitation, or maglev technologies, the non-profit International Maglev Board conducted a primary study in the spring of 2018 among maglev specialists and transportation professionals. More than 1 000 professionals took part in the survey. Main topics of the study are questions comparing the suitability of conventional wheel-on-rail and maglev technologies according to application areas. Predicted opportunities and developments in maglev technology, acceptance issues and research needs are analyzed. The results are broken down by expertise and nationality of the participants. This short version presents selected findings of the survey in compressed form.

Background: There is an obvious need for information on international trends in the application of Maglev transport technologies. The study attempts to grasp the global dimension of magnetic levitation developments in a structured way.

Aim: To track current trends in magnetic levitation transport system innovation. Identify perspectives, research tasks and implementation barriers. Comparison of magnetic levitation systems with steel wheel systems. Analysis of the key topics of the debate.

Methods: Primary study in spring 2018 among 1 058 maglev specialists and transport experts. Internet-based online survey.

Results: The ratings vary greatly according to the expertise and origin of the respondents. In certain fields of application, wheel-rail systems remain the preferred transport technology. But in certain other fields of application, maglev technologies have become preferred over conventional steel-wheel-rail by a majority of transport professionals. This is particularly the case for high-speed maglev transport and for the new application of maglev elevators in buildings. At the same time, many respondents see a continuing need for research.

Conclusion: Overall, there is a differentiated picture. Respondents from North and South America, Russia and Asia are on average particularly open to an implementation of certain maglev technologies.

Keywords: Maglev, wheel-rail systems, urban maglev, high-speed transportation systems, Transrapid, Linear, Chuo maglev, Hyperloop, evaluation, perception, suitability

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1. METHODOLOGY & THEORETICAL APPROACH

The study examines the acceptance and prospects of maglev systems in the transport sector. Basically, the suitability of maglev systems in comparison with conventional wheel-rail systems is considered and differentiated according to different fields of application. Barriers are analyzed and research needs are determined. Overall, a picture of the future suitability of maglev systems is developed from a technical point of view.

The study was funded exclusively from internal funds of a non-profit organization, The International Maglev Board (www.maglevboard.net). There was never any influence of third parties, neither on the research aims nor the evaluation process. It was carried out anonymously and the analysis and evaluation strictly followed well-established scientific standards.

The relevant topic areas for the survey were defined in an expert workshop in the spring of 2018. The primary theoretical foundations were the current standard works on maglev technologies [1, 2] and analyzes of historical development [3]. The survey's 22 questions from 10 question groups were then developed in several further workshops with more experts from the transport sector and maglev technology specialists. Based on the original English version, the study was subsequently translated into German, Chinese and Russian.

The announcement of the survey took place from May of 2018 primarily via the newsletter of the International Maglev Board and via social networks (twitter, Facebook groups, Xing, Linked-in, transport forums on the web). Between May and June 2018, more than a thousand participants (1058) from the transport sector took part in the survey, see Fig. 1.

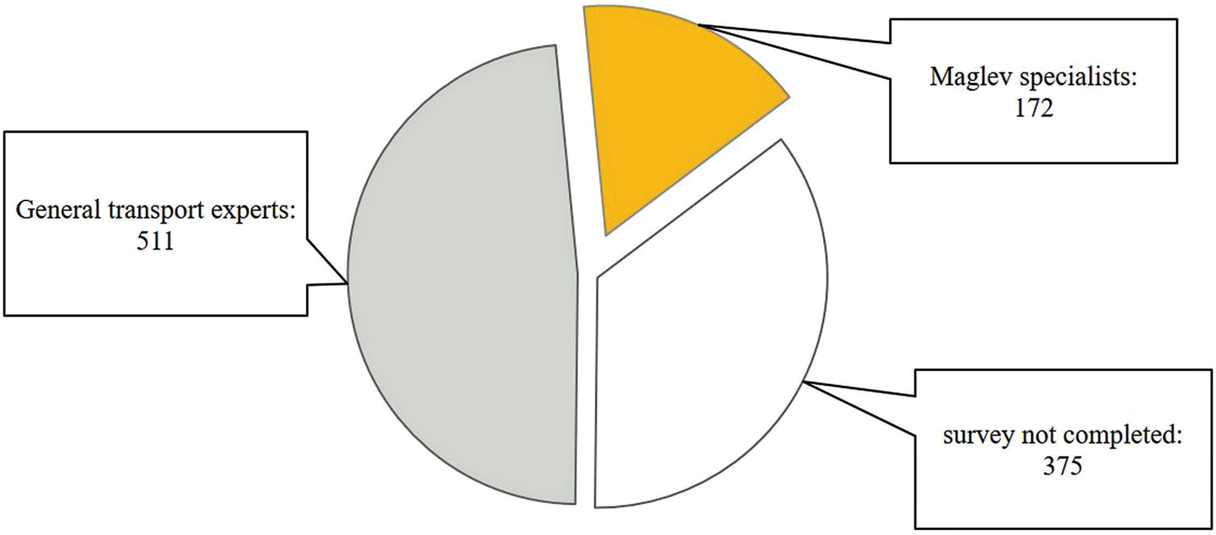

Fig. 1. Participants of the study (Total participants = 1 058; maglev specialists = 172)

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Participants' responses were analyzed on the basis of demographic criteria (country of origin, age) as well as on the basis of their respective knowledge about maglev technology (maglev specialist / general transport experts).

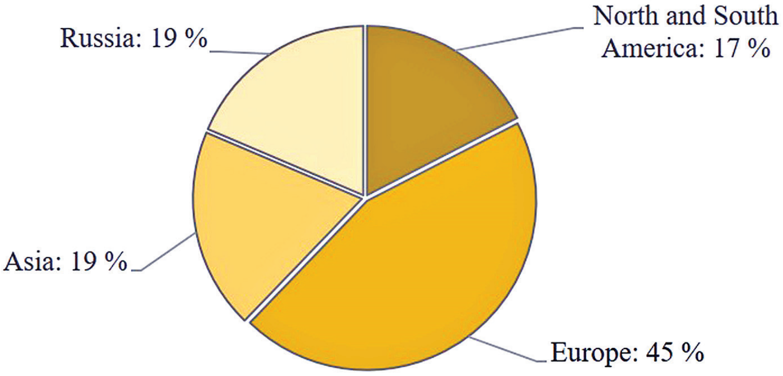

Fig. 2. Geographical origin of maglev specialists in this survey.
(Total participants = 1 058; maglev specialists = 172)

Participants were defined as Maglev experts if it was possible to demonstrate in-depth Maglev know-how according to several defined criteria. The self-assessment of the participants was just one criterion among several others, here. Without demonstrable Maglev qualification, participants were grouped into the category of general transport experts. There were no participants from the African or Australian continent that could meet the defined criteria for maglev specialists. The selection procedure is described and explained in detail in the German long version of the study.

About 16 % of the study participants appeared so well versed in maglev subjects that they could be narrowed down as maglev specialists.

In the field of high speed ground transport, the maglev systems Chuo Linear Shinkansen and the Shanghai Transrapid were considered (and compared with conventional steel-wheel-rail systems). In the field of urban transport, the Japanese Linimo, the South-Korean Ecobee and Chinese urban maglev systems were compared with conventional urban transport systems. Maglev cargo systems are still under development; they were discussed from a more theoretical perspective.

Limitations of the project: The study is not representative of the total population of the respective countries, but it is an indicator of the view that transport experts and citizens with a professional connection to transport have on the subject of maglev. In countries where there is only a limited freedom of the press or little freedom of expression, there may be "politically desirable" answers (despite individual anonymity), especially when maglev technologies are a central government research

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program and / or the Internet is a censored medium. The study cannot prevent such influence or control for possible impacts.

The situation on the African continent could only be studied to a limited extent, only a few transportation experts from Africa could be found for the survey. The same applied to Australia and New Zealand, where public transport experts with some expertise in maglev technologies seem to be rare.

2. COMPARISON AND SELECTION OF MAGLEV TRANSPORT SYSTEMS

Research question: Which track-guided system should prevail in the future (depending on the area of application)?

Results:

Transport experts and maglev specialists from all countries currently see the central suitability of maglev technologies in high-speed passenger transport over long distances. In general, the ratings are relatively close to each other for general transport experts and maglev specialists. The statistical deviations are less than 10 % even in the maximum case, see Fig. 3.

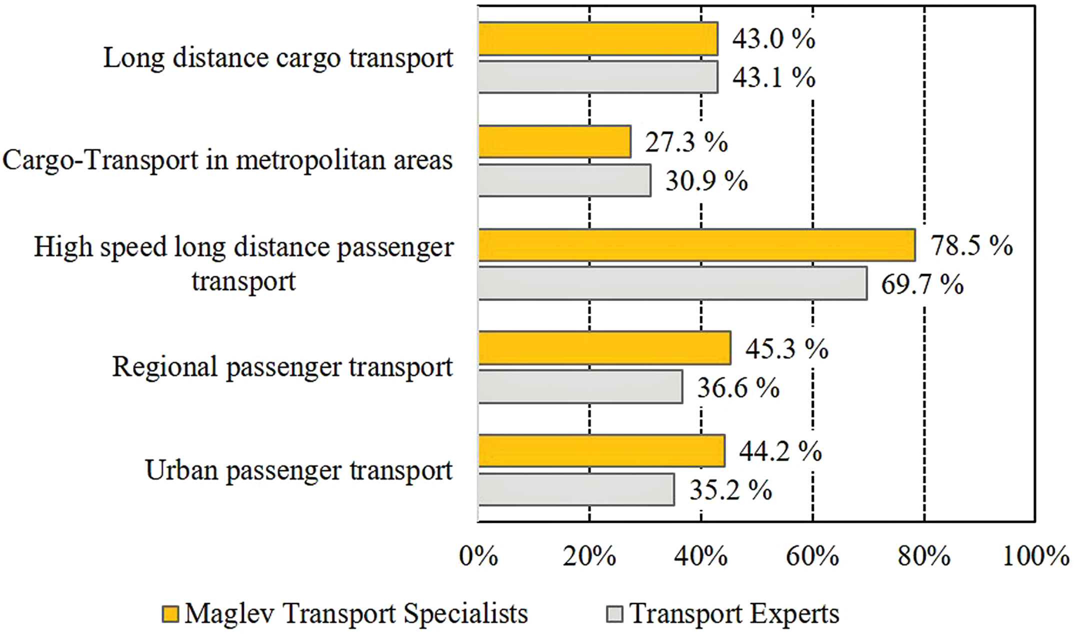

Fig. 3. Maglev system preference over wheel-rail, by field of application. Percentage of respondents that have chosen maglev technologies as their preferred system for the respective field of application.
Question: "If you should decide today which track-guided system should prevail in the future: How would you decide on the following fields of application?"
(number of respondents = 683)

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For maglev specialists the average approval rate (for high-speed maglev over long distances) is especially high, approaching 80 %. Russian and American maglev specialists vote particularly strongly, with approval rates up to 90 %, see Fig. 4.

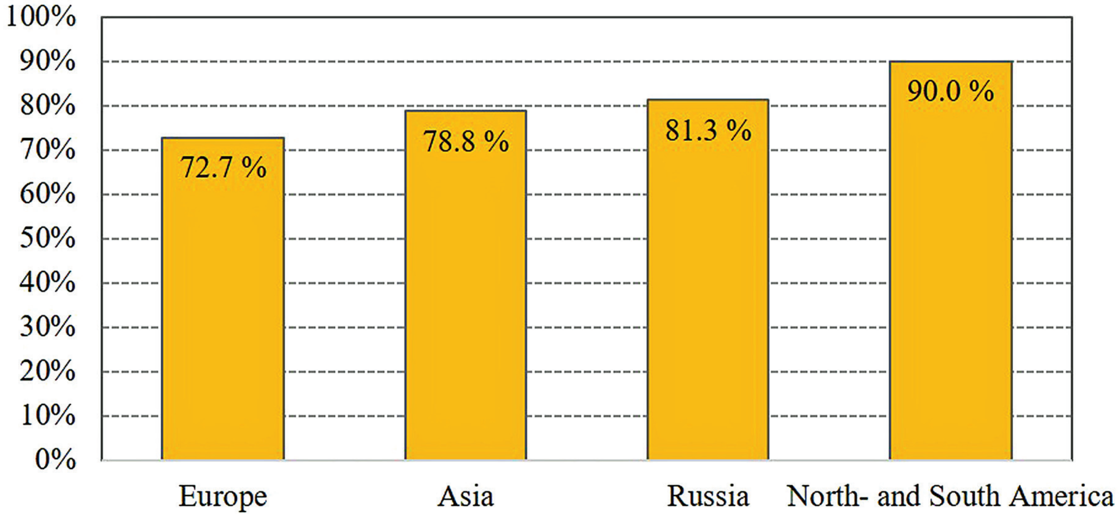

Fig. 4. Maglev specialists' degree of support for high speed maglev systems for long-distance transport applications.
Question: "If you should decide today which track-guided system should prevail in the future: How would you decide on the field of high-speed long distance passenger transport?" Opinion of maglev specialists (number of respondents = 172)

The analysis also shows a correlation between the age of respondents and their assessment of high-speed maglev, with younger maglev specialists particularly in favor of maglev systems for long-distance passenger traffic.

Maglev specialists tend to rate the suitability of technologies quite differently. They see strengths of wheel-rail systems in several application fields. In urban and regional public transport, for example, the majority of maglev specialists see an overall high suitability for wheel-rail systems.

Overall, all participants are relatively critical of urban maglev and regional maglev technologies. The reasons for this are difficult to pin down, but in general it has been shown in recent debates that maglev specialists and other transport experts are reluctant to supplement existing wheel-rail mass transit systems with maglevs too quickly, in order to avoid additional economic costs arising from the simultaneous operation of different technical systems. Another factor in favor of this interpretation is that countries in which public transport operating at grade level (not in tunnels) tends to underperform are much more radical in terms of launching the new maglev systems. For example, maglev specialists from North and South America and Russia strongly support the use of maglev systems in urban and regional transport. Many of these nations have excellent subway systems in their cities, but their urban surface transport (bus, tram, suburban train) is often considered to be in great need of development.

In the field of long-haul cargo transport, wheel-rail systems should continue to be used from the point of view of a narrow majority of the maglev specialists surveyed, who most clearly advocated the field of cargo transport in urban areas and voted in favor of wheel-rail systems (55.2 %). A particularly clear advocacy of wheel-rail systems was also provided by Asian maglev specialists — with a share of 72.7 %, they voted in favor of wheel-rail in the field of cargo transport in urban areas.

In the application field of long-distance cargo transport, Russian maglev specialists hold a national special position: In contrast to about 43 % of all surveyed specialists who advocate the use of maglev systems for long-haul cargo transport, 75 % of Russian specialists would prefer maglev systems in this field of application.

An explanatory interpretation for this unique Russian position is that the transport problems in Russia, due to its enormous geographic extent, have a significantly different dimension than, for example, in the rather small, multi-state confines of Western Europe. Therefore, in the Russian Federation, the factors of time requirement and transport speed are likely to have a much more urgent dimension which requires a special readiness for innovative transport solutions.

3. FUTURE RELEVANCE OF MAGLEV TECHNOLOGIES

Research question: How will the relevance of maglev technologies develop worldwide in the next 20 years?

Results:

The results of the study show that maglev specialists and transportation experts around the world generally expect a significant increase in the importance of maglev technologies. From the point of view of maglev specialists, the increase in importance in the coming 20 years will mainly concern the following areas:

- High speed passenger transport;
- Urban maglev;
- Regional maglev;
- Applications of maglev technologies in buildings and public spaces (elevators and escalators);
- Military applications (e.g., maglev launch pads for missiles and aircraft carrier catapults).

The assessment seems highly dependent on the geographical or cultural context. Most skeptical and cautious are the specialists from European countries who regard maglev's prospects as relatively low in almost all aspects. One exception concerns maglev elevator technologies, which are seen by European experts as a growth industry, see Fig. 5.

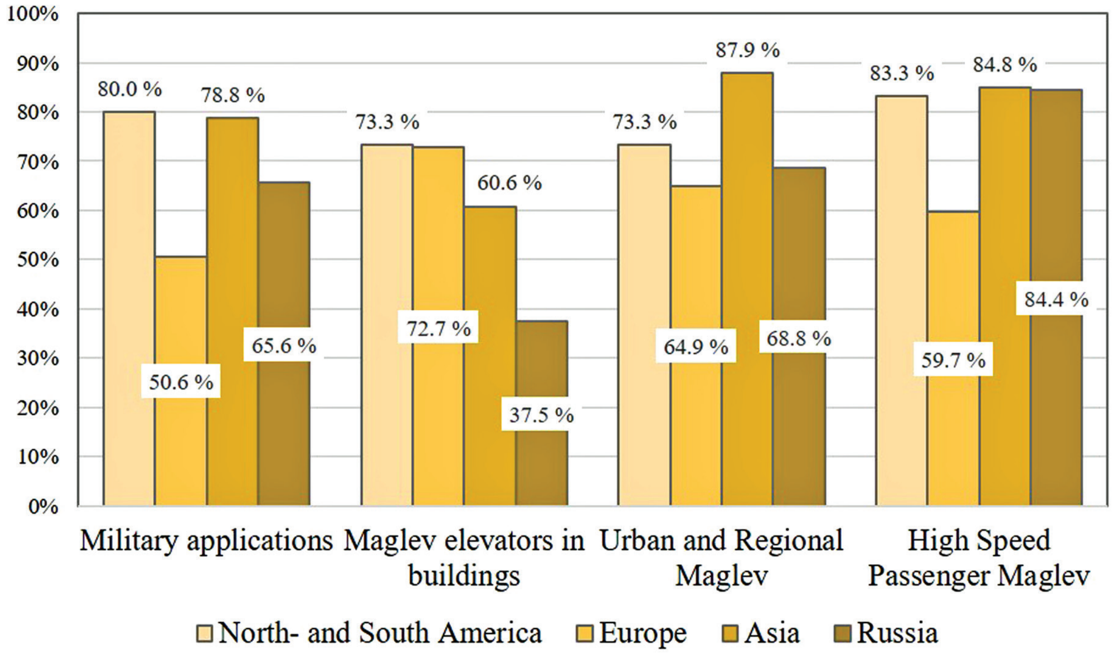

Fig. 5. Maglev Technologies with growth potential. Percentage of maglev specialists that see maglev grow in the respective application field.
Question: "During the next 20 years, how will the situation of maglev technologies develop worldwide?" Opinion of maglev specialists (number of respondents = 172)

At the same time, the majority of maglev specialists as well as the majority of general experts assume that urban cargo transport by maglev technologies will remain irrelevant over the next 20 years (maglev specialists: 55.8 %; general experts: 59.9 %).

Overall, an average of 73.3 % of all maglev specialists see an increase in the importance of maglev high-speed passenger transport systems over the next 20 years. More than 80 % of maglev specialists from North and South America, Asia and Russia even expect that the relevance of maglev systems in the field of high-speed traffic will grow. Again, European maglev specialists remain skeptical, with only about 60 % seeing a growth potential here, see Fig. 5.

4. PROBABILITY OF MAGLEV IMPLEMENTATION

Research question: In which countries / continents will a realization of a new maglev project (passenger or freight) begin in the next 20 years?

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The question investigates whether maglev specialists assume that a relevant project will be realized within their respective home country within the next two decades.

Results:

Looking at the four selected continents, it becomes clear how strong the Asian expectation is that maglev projects will be implemented. Nearly 91 % of the Asian maglev specialists expect the construction of a new maglev project in passenger or freight traffic in their respective home countries within the next 20 years. Russian and American specialists share equally strong expectations regarding the realization of a maglev project in their respective countries, see Fig. 6.

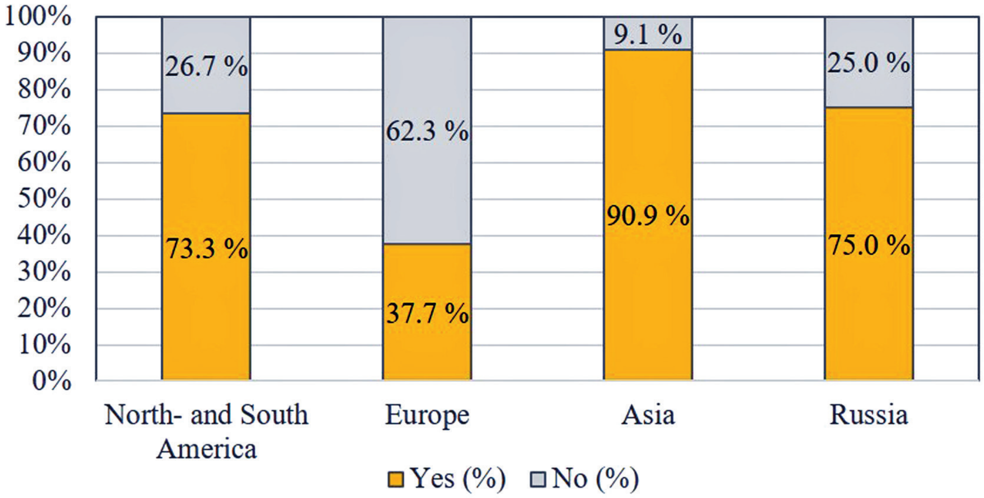

Fig. 6. Realization of a maglev project in the country of respondent in the next 20 years. Question: "Do you think a new maglev transport construction project – either for passenger transportation or cargo transportation – will begin in your country in the next 20 years?" Opinion of maglev specialists (number of respondents = 172)

In contrast to this high expectation stands the skepticism of European specialists, of whom only a good third expect a maglev project in a European country to become reality in the future.

If the global opinion of all maglev specialists is compared with the average opinion of general transport experts, the following Fig. 7 emerges:

While maglev specialists consider a realization to be quite likely, general transport experts see this almost exactly the opposite way and expect to only about 40 % such a realization of maglev projects in their countries. This global assessment is significantly influenced by strong European skepticism and the high proportion of European transport experts in the study.

In general, it seems to be true: maglev transport specialists are, as a group, much more optimistic about the chances of realizing maglev technologies than

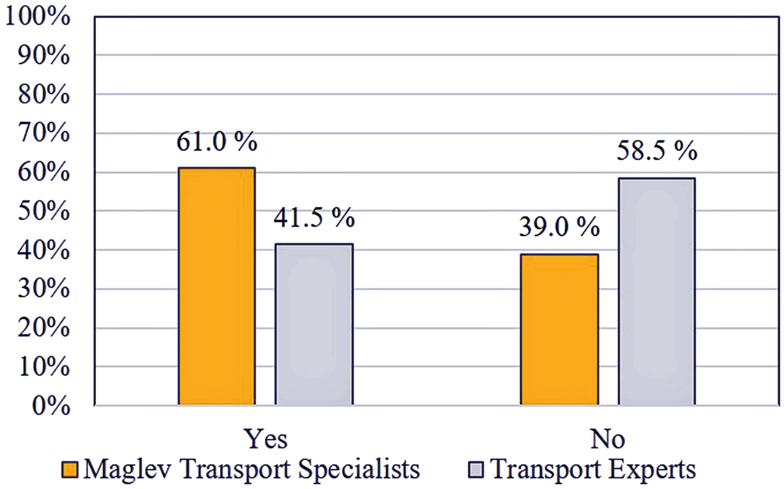

Fig. 7. Realization of a maglev project in the country of respondent in the next 20 years. Worldwide perspective, comparison of maglev Transport Specialists and Transport experts. Question: “Do you think a new maglev transport construction project – either for passenger transportation or cargo transportation – will begin in your country in the next 20 years?” (number of respondents = 683)

the majority of classic transport experts who do not possess in-depth maglev knowledge.

5. KEY FACTORS AND POSSIBLE WEAK POINTS

Research question: Which topics can play a crucial role in *preventing* a maglev project?

The question seeks to narrow down those aspects that can be regarded as weak points in the realization of maglev projects for the contemplated continents [1, 2]. In order to increase the sensitivity of the participants for the topic, the questions refer to the respondent’s home country.

Results:

Aspects are addressed that are usually intensively debated in the public debate (regardless of whether they are factually correct or not) in order to prevent the realization of a planned maglev project in the respective country. The analysis of these aspects is at the same time an indication of which topics should be discussed particularly intensively and seriously when communicating with transportation experts, politicians, researchers and citizens, in order to increase the chances of success of meaningful maglev projects — or to either optimize or prevent projects which appear to be unsuitable.

The results show that from the point of view of maglev specialists, the question of infrastructure investment costs is by far the most critical aspect, see

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Fig. 8. However, more than half of the specialists also consider the question of whether or not the existing wheel-rail systems could be cannibalized or threatened with their business results. Russian specialists have a special role to play here: only 21.9 % consider the risk of economic damage to already existing systems as a critical issue (average of all specialists: 51.7 %).

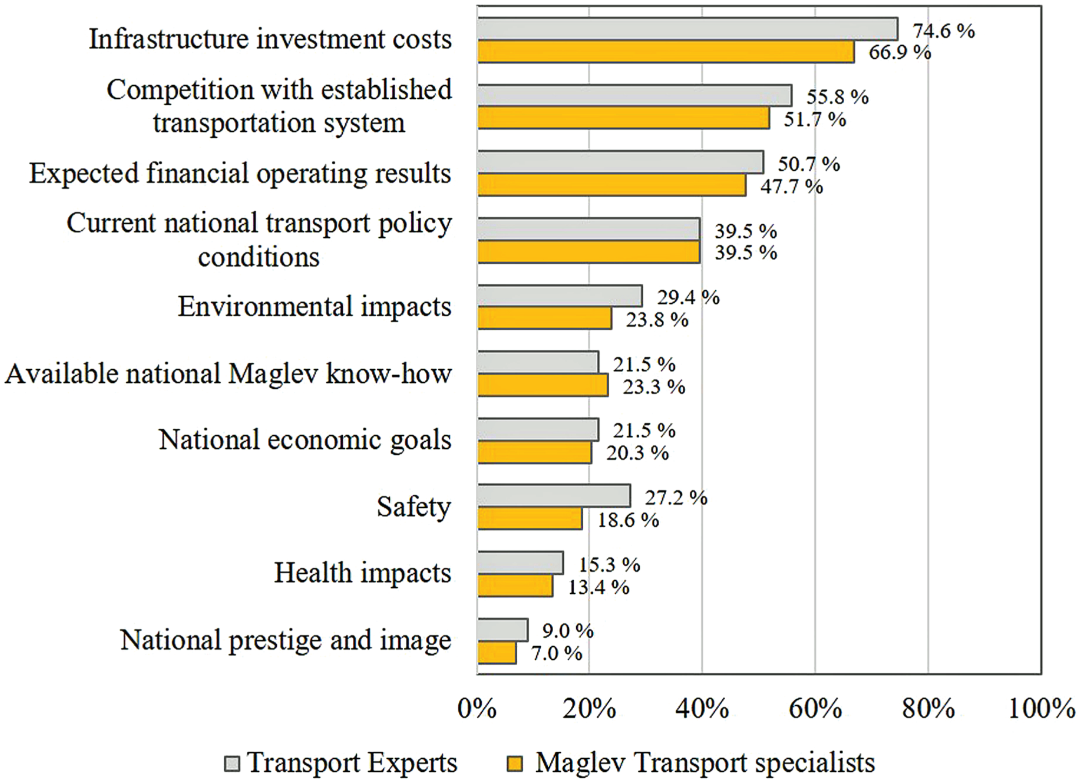

Fig. 8. Topics that are critical to success in project communication. Comparison of maglev specialists and general transport experts.
Question: “Please imagine the following situation: There is a plan to build a maglev transport project in your country. You are opposing its realization. Which aspects would you address to successfully prevent its realization?” (number of respondents = 683)

Overall, the ranking of topics reveals striking differences between the continents: the aspect of ‘national economic objectives’ is ranked by the North and South American experts (30 %) among the top five most frequently cited aspects. This aspect ranks much lower on other continents.

The aspect of ‘technical system safety’ can be found among Asian and Russian maglev specialists among the five most chosen aspects. By contrast, this technical safety aspect is much less relevant for North and South American experts.

The aspect, ‘forecasted financial results,’ was selected by 47.7 % of all maglev specialists as decision-relevant and is placed by all expert groups in the five most frequently mentioned aspects.

A comparison of maglev specialists and general transport experts on this topic shows a high level of agreement between the opinions for the global perspective. Although differences appear again concerning continents and age groups, the overall strong agreement appears quite striking.

At the same time, it has become clear that general transport experts are more frequently and more strongly selecting the different topics than maglev transport specialists. In the interpretation, this may be considered a heightened caution, or perhaps a sensitivity of general transport experts to these issues and possible shortcomings of maglev technologies.

6. MAGLEV RESEARCH NEEDS AND RESEARCH TASKS

Research question: In which areas are the most important research needs for maglev systems?

When considering and selecting possible research needs for maglev systems, a distinction is made between the following four areas of application:

- High-speed passenger transport;
- Urban and regional transport;
- Cargo transport / container transport;
- Transport in Buildings.

Result 1 (High-speed passenger transport):

For the evaluation of the results, the assessments of the general transport experts and the assessments of the maglev specialists are compared.

Most of the maglev specialists surveyed (73.8 %) see infrastructure investment costs as the most important area for research needs for further development of high-speed maglev systems. Just over half of the experts (52.3 %) also selected the area of energy efficiency, see Fig. 9.

Third in nomination, maglev specialists from North and South America and Russia chose the Infrastructure Maintenance Costs section. European experts chose the area ‘investment costs of maglev vehicles.’

In contrast to the average opinion of all maglev experts, of whom only 17.4 % see research needs in the environmental impact of high-speed maglev systems, the environmental aspect is far more relevant to Asian experts, who see the value as almost twice as high, at 30.3 %.

Of note is the high percentage at which Asian maglev specialists have selected 'vehicle aerodynamics' (27.3 %) as a task to improve. An interpretation of this result may suggest that the selection of this aspect recognizes the minimization of noise emissions and the reduction of energy consumption at high speed [1].

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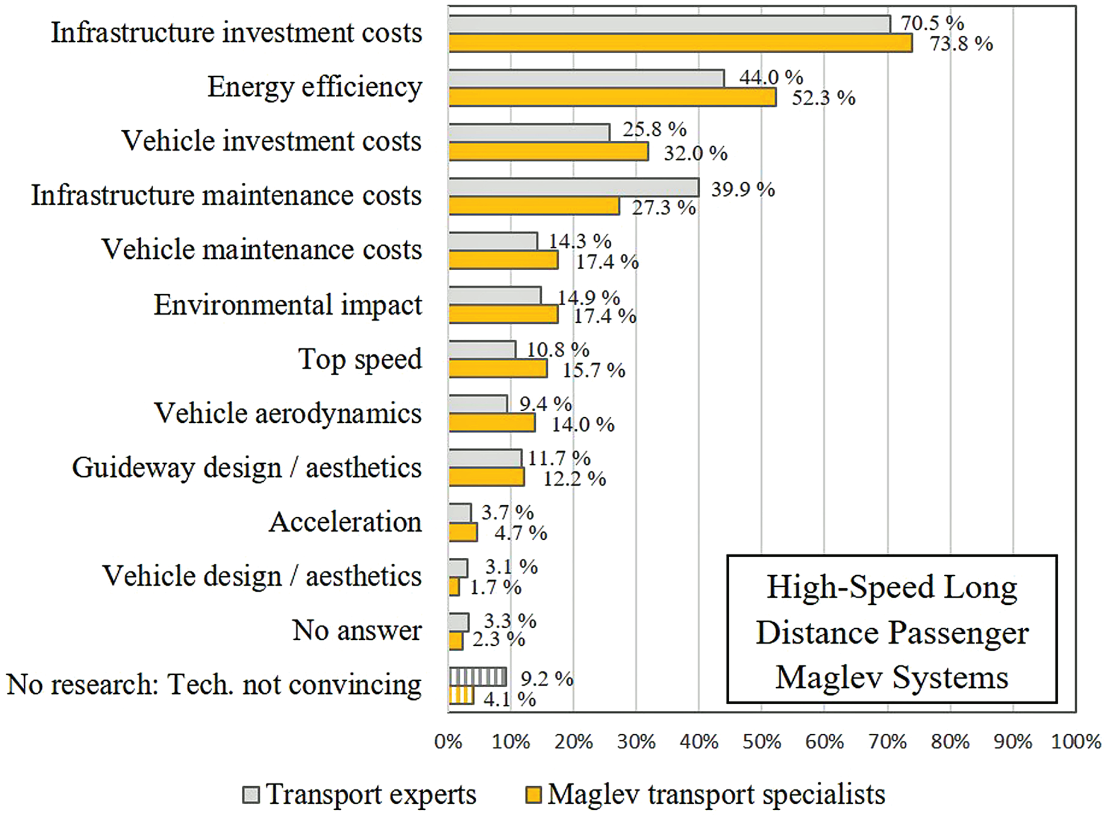

Fig. 9. Important research tasks for further development of high-speed maglev systems, comparison of maglev specialists and general transport experts.
Question: “What do you consider the most important tasks for further improvement of high-speed maglev systems?” (number of respondents = 683)

To note is, that 9.1 % of the European maglev specialists determined the considered technologies (high-speed maglev systems) are not convincing and therefore no further research is required.

In total, the opt-out answer, “No further research needs: The technologies are not convincing,” was chosen by 4.1 % of all maglev specialists and by 9.2 % of all general transport experts.

Result 2 (Urban / regional transport):

More than two thirds (68.6 %) of the maglev specialists see particularly important research needs for the further development of urban / medium-speed maglev systems in the area of ‘Infrastructure investment costs.’, see Fig. 10.

When analyzing by continents, there are differences: the field of energy efficiency was the second most frequently chosen aspect by maglev specialists from Europe, Asia and Russia. Energy efficiency appears less important to the maglev specialists from North and South America as a whole (30 %).

For 40 % of the maglev specialists from North and South America, the area, 'design / aesthetics of the track,' is particularly important.

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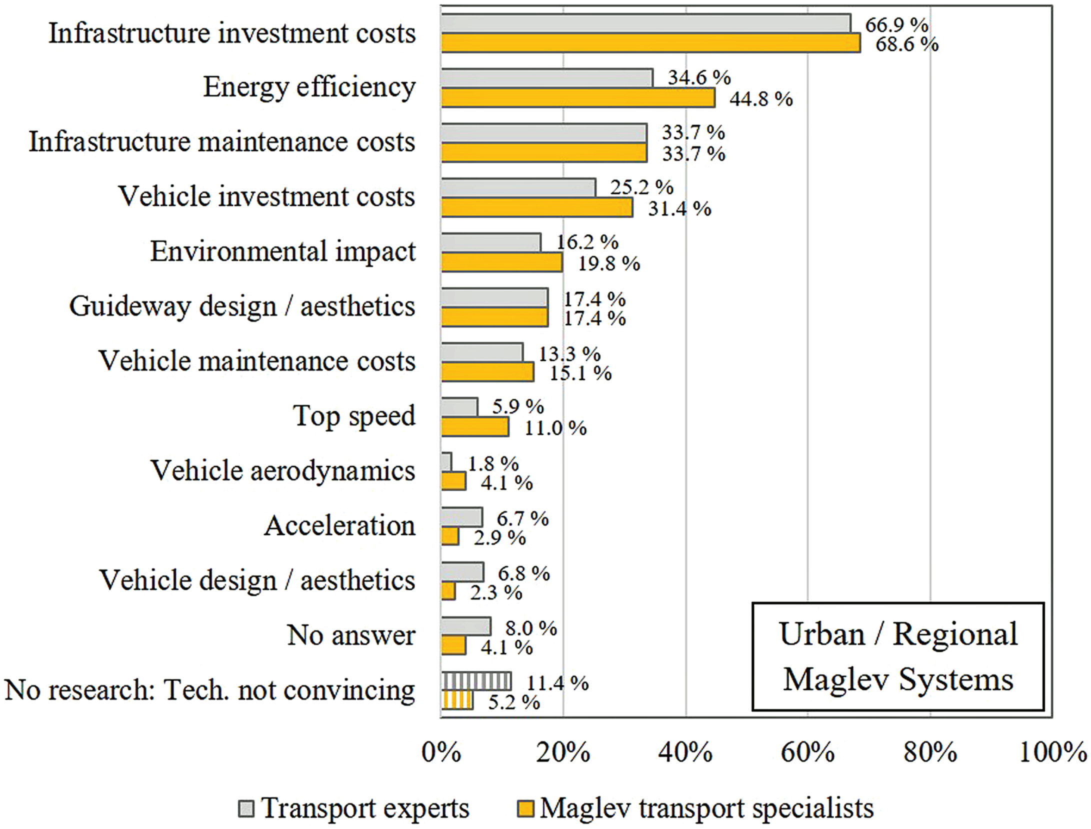

Fig. 10. Important research tasks for further development of urban and regional maglev systems, comparison of maglev specialists and general transport experts.
Question: “What do you consider the most important tasks for further improvements of urban / medium-speed maglev Systems?” (number of respondents = 683)

The opt-out answer, “No further research needs: The technologies are not convincing,” was chosen by 5.2 % of the maglev specialists and by 11.4 % of general transport experts.

<u>Result 3 (Cargo / container transport)</u>:

For a further development of cargo maglev systems, a majority of maglev specialists (64.5 %) sees research needs in the area of ‘infrastructure investment costs.’ An improvement in the area of energy efficiency is also considered very relevant for the further development of cargo maglev systems, according to 43 % of maglev specialists worldwide, see Fig. 11.

The opt-out answer, “No further research needs: The technologies are not convincing,” was chosen by 12.2 % of the maglev specialists and by 14.3 % of general transport experts. This number appears to be relatively high, at least for the maglev specialists, who obviously doubt that the technology is convincing for cargo transport.

There are valuation differences between the continents that are not visible in the categories shown above: For maglev specialists from North and South

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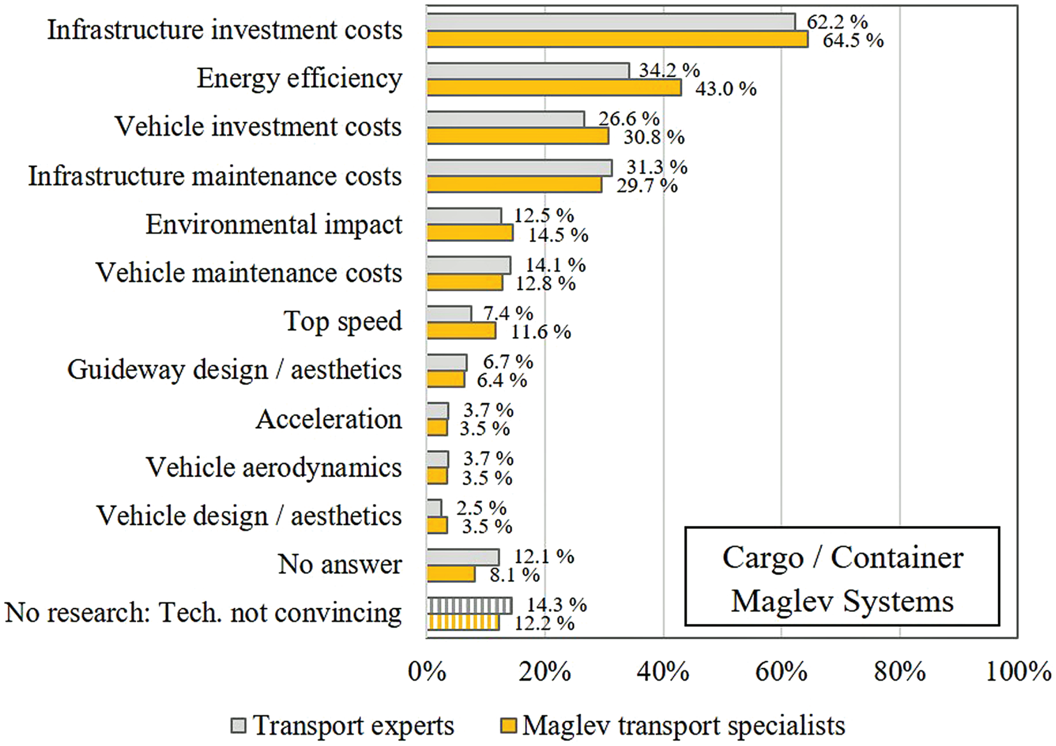

Fig. 11. Important research tasks for further development of cargo maglev systems, comparison of maglev specialists and general transport experts.
Question: “What do you consider the most important tasks for further improvements of cargo maglev Systems?” (number of respondents = 683)

America, Asia and Russia, 'Infrastructure maintenance costs' appeared very important. For European experts, 'vehicle investment costs' were especially relevant (33.8 %).

A relatively high proportion of Russian experts (31.3 %) sees (higher) 'top speed' as an important research necessity for further development of the cargo maglev systems.

European maglev specialists are particularly critical of the cargo maglev systems. About one fifth does not consider the maglev technology to be convincing here and does not see any further research needs for it.

7. HYPERLOOP – MORE THAN A SHORT-LIVED FAD?

Research question: Are Hyperloop evacuated-tube technologies suitable for passenger or cargo transport?

The current discussion of Hyperloop technology, which relies on maglev systems components, are controversial in both public and transportation expert communities. Analyzing this topic requires a differentiated point of view.

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A clear majority of maglev specialists and transportation experts consider Hyperloop evacuated-tube technologies unsuitable for passenger transportation, see Fig. 12.

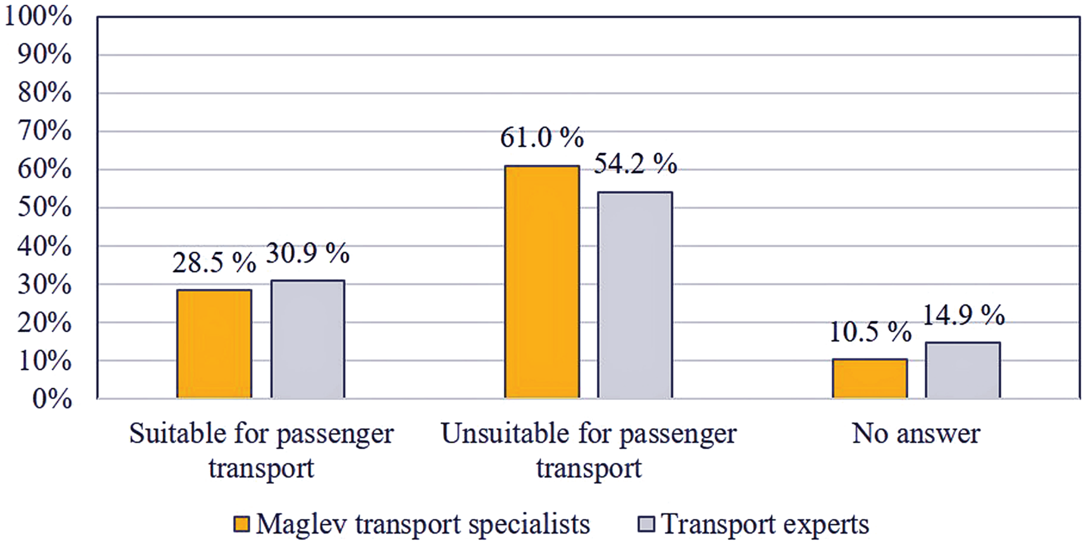

Fig. 12. General evaluation of the suitability of Hyperloop vacuum tube technologies in passenger transport, assessment of maglev specialists and general transport experts. Question: “Are Hyperloop evacuated-tube technologies in practice suitable or unsuitable for passenger transport?” (number of respondents = 683)

The majority of maglev specialists on all continents do not see suitability for Hyperloop operation in passenger transport. Nevertheless, the degree of rejection varies widely.

Roughly 40 % of Asian transport specialists are convinced of the suitability of this technology for passenger transport, which is the highest in the international ratings. This group of 40 % of maglev specialists, then, who see a transport suitability, can be considered a particularly strong minority.

The clearest rejection of Hyperloop systems is shown by maglev specialists in Europe, where almost 70 % of the European specialists surveyed do not assume that Hyperloop systems are suitable for transporting people. The rating by American specialists is quite similar, since the rejection level is almost two-thirds of the respondents (63.3 %), see Fig. 13.

Also striking is the high proportion of Russian experts who do not give a rating here (28 %).

Result 2 (cargo transport):

Hyperloop evacuated-tube technologies should be generally suitable for the transport of small and special designed containers, like air cargo boxes according

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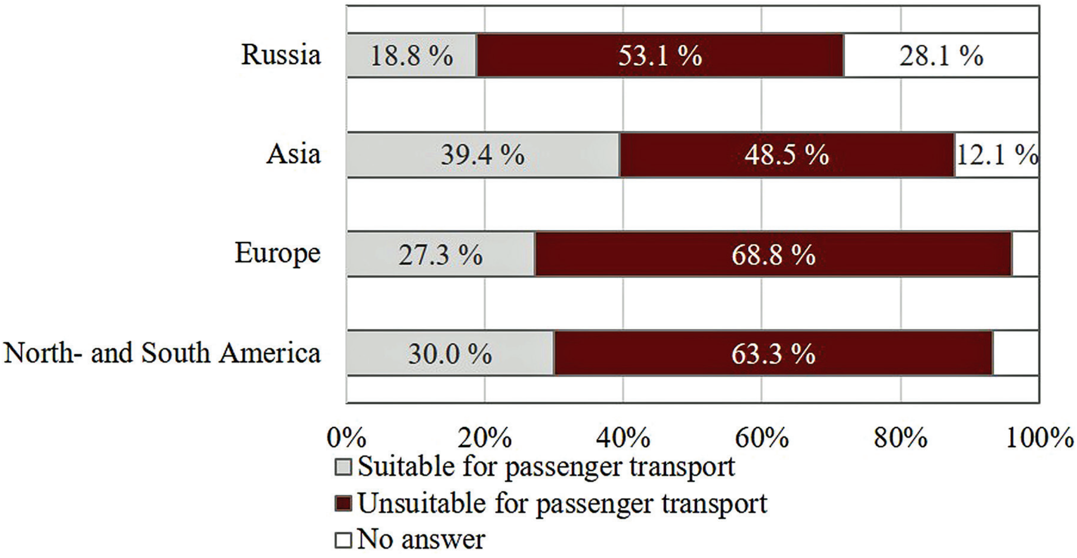

Fig. 13. Evaluation of the suitability of Hyperloop vacuum tube technologies in passenger transport, assessment of maglev specialists by continent.
Question: "Are Hyperloop evacuated-tube technologies in practice suitable or unsuitable for passenger transport?" (number of respondents = 172)

to a majority assessment of maglev transport specialists and general transport experts, see Fig. 14.

The analysis of the assessments by continents shows clear deviations, see Fig. 15.

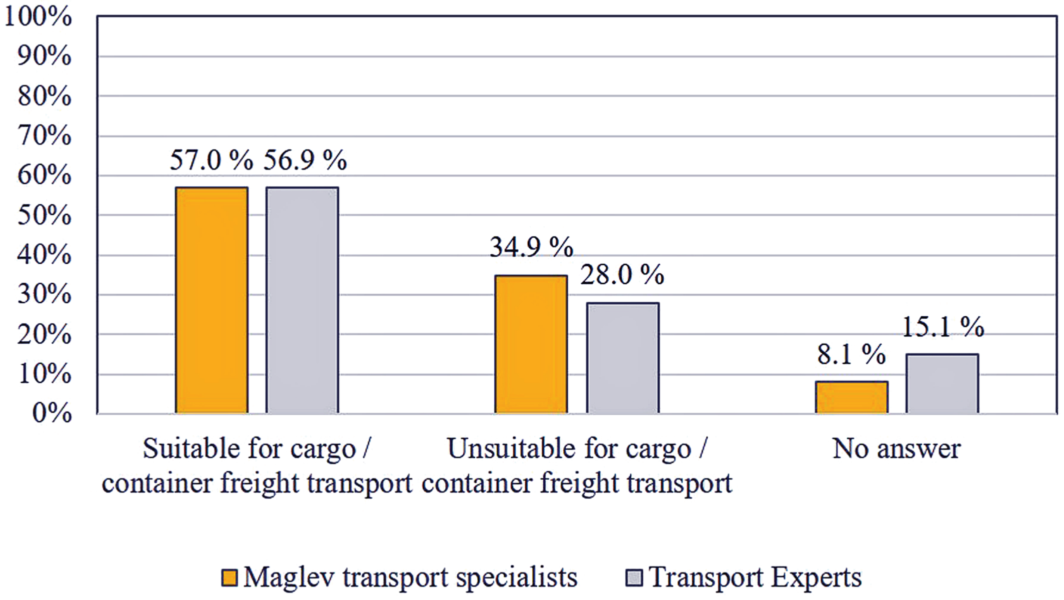

Fig. 14. Evaluation of the suitability of Hyperloop vacuum tube technologies in cargo transport, assessment of maglev specialists and general transport experts. Question: "Are Hyperloop evacuated-tube technologies in practice suitable or unsuitable for passenger transport?" (number of respondents = 683)

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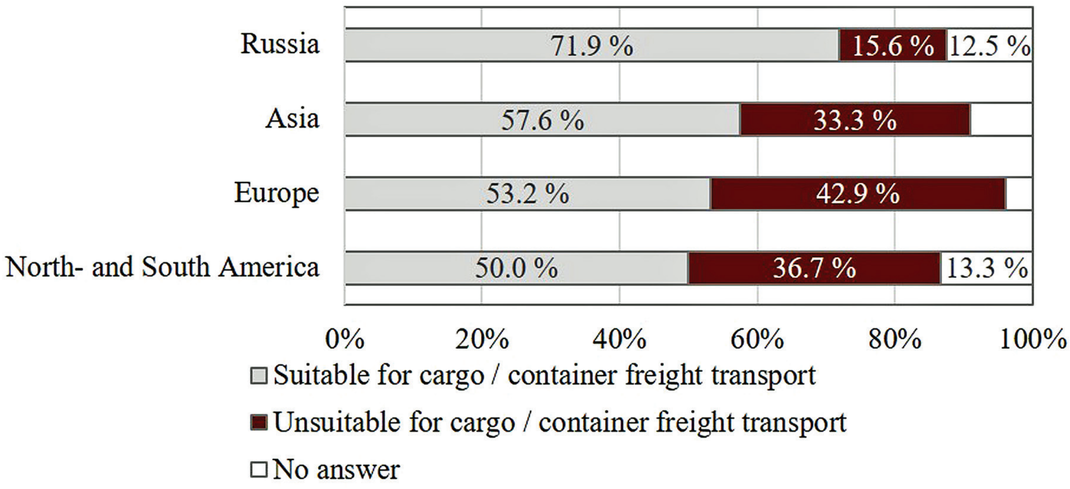

Fig. 15. Evaluation of the suitability of Hyperloop vacuum tube technologies in cargo transport, assessment of maglev specialists by continent. Question: "Are Hyperloop vacuum-tube technologies in practice suitable or unsuitable for passenger transport?" (number of respondents = 172)

As is the case with several other topics, the maglev specialists from Europe seem particularly skeptical about the cargo transport suitability of Hyperloop systems (42.9 %). Nevertheless, the majoritarian opinion of maglev specialists in Europe still is that Hyperloop can be suitable for the cargo application.

Russian maglev specialists appear particularly convinced of the applicability of Hyperloop systems in the cargo area. With a share of 71.9 % approval, they are at the top of the ratings, well ahead of their Asian, European and American counterparts.

8. CONCLUSION

The following summarizes the results of the study according to the main fields of maglev applications.

1) High-Speed Passenger Transport

Transport experts and maglev specialists from all countries currently see the central suitability of maglev technologies in high-speed passenger transport over long distances (Fig. 3). Russian and American maglev specialists vote particularly strongly, with approval rates up to 90 %. Maglev specialists from Europe are significantly more skeptical here (Fig. 4).

Most of the maglev specialists surveyed see infrastructure investment costs as the most important area for research needs for further development of high-speed maglev systems. Just over half of the experts also selected the area of energy efficiency (Fig. 9). 27 % of Asian maglev specialists have selected 'vehicle aerodynamics' as a task to improve.

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2) Urban and regional transport

In urban and regional public transport, the majority of maglev specialists see an overall high suitability both for wheel-rail systems and maglev systems (Fig. 3).

More than two thirds of the maglev specialists worldwide see particularly important research needs for the further development in the area of ‘Infrastructure investment costs’ (Fig 10). The field of energy efficiency was the second most frequently chosen aspect. For maglev specialists from North and South America, the area, ‘design / aesthetics of the track,’ is particularly important.

3) Cargo transport

In the field of long-haul cargo transport, wheel-rail systems are expected to continue to be used from the point of view of European, Asian and American maglev specialists. Meanwhile 75 % of Russian specialists would prefer maglev systems for cargo transport.

In general, no positive perspectives are seen for urban cargo maglev systems in metropolitan areas. European maglev specialists are particularly skeptical of all variants of cargo maglev systems.

For a further development of cargo maglev systems, a majority of maglev specialists sees research needs in the area of ‘infrastructure investment costs’ (Fig. 11). An improvement in the area of energy efficiency is also considered very relevant for the further development of cargo maglev systems.

4) Future application of maglev technologies

From the point of view of maglev specialists, an increase in maglev importance in the coming 20 years (approximately to the year 2040) will mainly concern the following areas:

a) High-speed passenger transport;

b) Urban and regional (medium-speed) maglev transport;

c) Maglev elevators and escalators in buildings and public spaces;

d) Military applications (e.g., maglev launch pads for missiles and aircraft carrier catapults).

The majority of both maglev specialists and general experts assume that urban cargo transport by maglev technologies will remain irrelevant over the next 20 years.

The assessments of the experts seem highly dependent on the geographical or cultural context. Most skeptical and cautious about future developments are the specialists from European countries, who regard maglev’s prospects as relatively low in almost all aspects (Fig. 5). But there is one exception: maglev elevator technologies are seen by European experts as a growing industry.

5) Probability of maglev project realizations

In general, maglev transport specialists are, as a group, more optimistic about the chances of realizing maglev technologies than the majority of classic transport experts. Maglev specialists consider a realization to be quite likely, while general transport experts see this almost exactly the opposite way and expect (up to about 40 %) such a realization of maglev projects in their countries (Fig. 7). Again, this global assessment by general transport experts is heavily influenced by strong skepticism from Europe.

Nearly 91 % of the Asian maglev specialists expect the construction of a new maglev project for passenger or freight transport in their respective home countries within the next 20 years. Russian and American specialists share equally strong expectations. In sharp contrast to this high expectation stands the skepticism of European specialists, where a vast majority doubts that a maglev project in a Western European country will become reality in the future (Fig. 6).

6) Key factors and weak points of maglev systems

From the point of view of maglev specialists, the question of infrastructure investment costs is by far the most critical aspect. More than half of the specialists also consider the question of whether or not the existing, conventional transport systems could be cannibalized or threatened with their business results sensitive. The aspect, ‘forecasted financial results,’ was selected by about 50 % of all experts (Fig. 8).

Overall, there are striking differences between the continents: the aspect of ‘national economic objectives’ is ranked high by the North and South American experts, but this aspect ranks much lower on other continents. The aspect of ‘technical system safety’ is rather irrelevant, except for Asian and Russian maglev specialists.

7) Hyperloop technologies

On average, a clear majority of maglev specialists and transportation experts considers Hyperloop evacuated-tube technologies unsuitable for passenger transportation. The main reason for this consideration could be unsolved safety issues. The clearest rejection of Hyperloop systems is shown by maglev specialists in North and South America and Europe.

For cargo transport, the valuation is different: Hyperloop evacuated-tube technologies are seen as generally suitable for transporting cargo containers, according to a majority assessment of maglev transport specialists and general transport experts worldwide. Russian maglev specialists appear particularly convinced of the applicability of Hyperloop systems in the cargo area.

Basic statistics:

In total, 1 058 experts participated in this study. Of this, 172 persons were maglev specialists and 683 participants were general transport experts. The study was conducted between May and June 2018 as an internet survey.

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CURRENT MODE PERFORMANCE OF A TRACTION LINEAR INDUCTION MOTOR DRIVEN FROM THE VOLTAGE CONVERTER

Background: The paper deals with the modelling of a traction Linear Induction Motor (LIM) for public transportation. Typical problems arising from the electromagnetic finite element model development are described. The end effect causes asymmetry of phase impedances of the LIM. Because of that, if the LIM is supplied from the voltage inverter, which is usually the case, the phase currents become asymmetric. This causes performance calculation discrepancies in models that assume phase current symmetry.

Aim: The aim of the paper is to develop a method for calculating the imbalanced three-phase LIM currents to precisely predict the LIM performance.

Methods: Here, a method is developed to calculate the LIM phase current asymmetry by means of a self-developed electromagnetic finite element program – ELMAG, capable of adapting mesh generation based on Reynolds, Péclet and skin-depth numbers.

Results: The calculated asymmetric currents are used in a real size traction LIM calculation in COMSOL, to derive the performance characteristics for comparison with the results achieved when supplying the LLIM with the symmetric three phase current.

Conclusion: These results show that the natural asymmetry of the currents is an important factor that must be considered in appropriately calculating the LIM performance.

Keywords: Linear Induction Motor, Finite Element Analysis, eddy-currents, Péclet number, voltage supply.

INTRODUCTION

Traction Linear Induction Motor (LIM) has been deployed worldwide in driver-less transit systems requiring very short headways for all weather conditions. The systems based on LIMs have proven to be, by far, the least expensive in operations and maintenance (including energy consumption). Electromagnetic FEA (Finite Element Analysis) calculations are crucial to optimizing the LIM system performance as they can provide results necessary to construct the mechanical characteristic – force versus speed, shaped by the so-called end effect, which further

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contributes to designing the most efficient controls [1, 2], [13]. To simplify the FEA model and to minimize the time to numerical solution, the symmetrical three-phase current can be used; however, this does not reflect the reality when the LIM is driven from the voltage inverter. This paper shows differences in slip versus thrust characteristics between the simplified FEA approach and the one where asymmetry of phase currents arises naturally from the real supply conditions.

PROBLEM FORMULATION

Linear induction motors can be found in numerous applications from the industrial low power material handling systems to high output military aircraft launch equipment and electric transit vehicles. The advanced LIM design must always take into account the so called end-effect. This effect, resulting in demagnetization of the front-end of the machine, is speed and frequency dependent. Some aspects of the end effect evaluation have already been described in literature.

Typically, the established analytical models of the LIM express the excitation currents in the primary coils as infinitely thin current sheets or discrete coils. Fig. 1 (left) shows both parts of the typical LIM and Fig. 1 (right) presents its 3-dimensional model.

The speed and convenience of the analytical computations make the analytical model of the LIM an efficient and practical tool capable of rapidly predicting the qualitative changes in LIM performance and serves to qualify the selected FEA solution method. The discrete coils approach leads to a more realistic model of the LIM and allows for representation of spatial harmonics due to discrete current

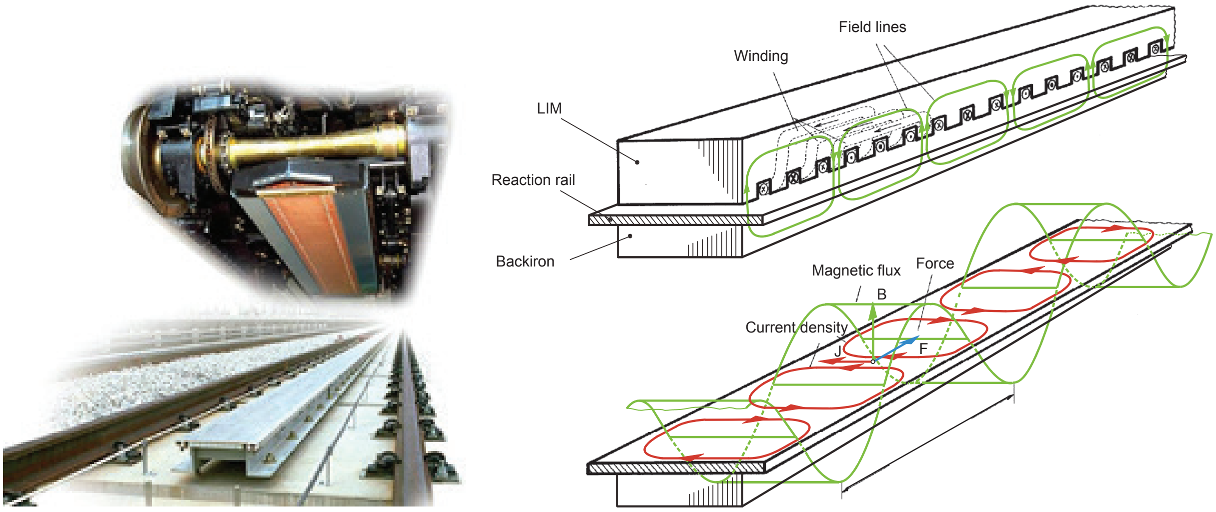

Fig. 1. LIM primary (supplied part) and secondary (reaction rail) [1] – left.
The 3-dimensional model of the LIM [2] – right

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distribution. However, in recent decades, LIM modeling and analysis started relying more on Finite Element Analysis instead of analytical solutions. Due to its finite nature, resulting in end-effect, the FEA electromagnetic transient solver is mostly applied to carry out computational tasks. However, it has been shown [3] that if applied properly, the frequency domain solver FEA simulation can not only validate and cross-check the analytical model of the LIM but also establish the validity and applicability of the FEA frequency domain solver solution as a preferred replacement for the time consuming electromagnetic transient FEA calculations.

Fig. 2 shows some simplified calculation models of the subject LIM which can be used for the analytical evaluation of its parameters. The following assumptions have been made to the LIM structure in order to simplify the calculation process:

1. Two-dimensional analysis can be used,
2. The iron magnetization curve is linear,
3. The conductivity of the reaction rail is constant,
4. The motion in only *x*-direction is allowed.

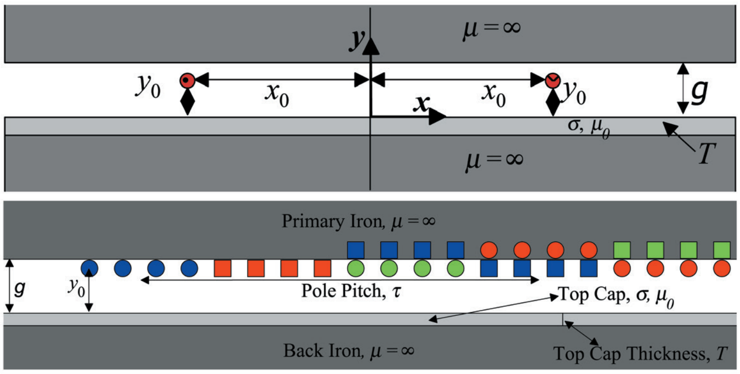

Fig. 2. 2-dimensional models ot the LIM used for the analytical evaluation [3] and [4]

Introducing the vector potential ***A***:

$$B = rot\, A \tag{1}$$

and using the usual simplifications one can obtain the following differential equation for one component of the complex vector potential (in *z*-direction) describing the magnetic field distribution in the whole region (2-dimensional case):

$$\frac{\partial^2 A}{\partial x^2}+\frac{\partial^2 A}{\partial y^2}=\mu(-J+j\omega\sigma A+\sigma v\frac{\partial A}{\partial x}), \tag{2}$$

where *A* is the *z*-component of the magnetic vector potential, *J* is the impressed current source density (*z*-component), ω is the angular frequency of the harmonic field, μ and σ are the permeability and conductivity of the medium respectively, and v is the relative horizontal (x-direction) velocity of the medium. Given the source's excitation field in the air-gap, an analytic solution for equation (2) can be obtained, following the formalism given in [3, 4].

In some formulations for thin conducting plates, the magnetic field due to eddy-currents can be neglected, what leads to the simplification of the problem. It is possible for low magnetic Reynolds number, i.e.

$$Re_m = \mu_0 \sigma \omega_m d b \ll 1, \tag{3}$$

where ω_m denotes the angular frequency of the movement, d denotes the plate thickness and b is a characteristic dimension of the plate [5].

The quantity which defines the penetration of electromagnetic field into the conducting region is the skin-depth δ:

$$\delta = \sqrt{\frac{2}{\omega\mu\sigma}}. \tag{4}$$

The magnetic Reynolds number together with the skin-depth give appropriate information about the magnetic field penetration into a conducting region and allow for the proper choice of the calculation algorithm, either the analytical or purely numerical.

LIM FINITE ELEMENT ANALYSIS

The Finite Element Analysis should be applied to determine all important parameters of the real LIM. The biggest challenge which must be solved is the proper FEA of the penetration of electromagnetic field into the moving and conducting region of the reaction rail (in fact the active part of the LIM moves). Such modelling and analysis can be extremely difficult and time-consuming. It requires the proper choice of the FE mesh what usually leads to very large systems of algebraic equations describing the problem and can cause numerical instability.

In the FEA a characteristic (average) size h of finite elements in the conducting region of rotating machine can be estimated by the Péclet number [6, 7]:

$$P_e = \frac{\sigma\mu h |v|}{2}. \tag{5}$$

If $P_e > 1$, numerical instabilities may occur when applying the standard Galerkin discretization technique [7]. Reynolds number, skin-depth and Péclet number give some indications regarding the FE-mesh size for evaluation of sinusoidal fields in moving conducting media. The conditions (4), (5) usually lead

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to the large number of finite elements in the conducting region, what results in long calculation times and can also lead to instability the of numerical calculations. These are the reasons necessitating a very careful approach to choosing an FE-mesh. Additionally, this mesh should be changed according to the actual skin-depth value, i.e. for each value of speed and frequency.

In order to check the stability and the accuracy of the computation some simplified FE LIM-models have been developed.

Fig. 3, 4 show the exemplary magnetic field distributions within the 3-phase LIM supplied from the current source (identical currents in all phases) obtained by the self-developed calculation program ELMAG. The values of the main parameters for the calculation were: $\mu_{Al} = 1.05\mu_0$, $\mu_{Fe} = 1000\mu_0$, $\sigma_{Al} = 36.59 \cdot 10^6$ S/m, $\sigma_{Fe} = 10.02\ 10^6$ S/m, $f = 50$ Hz, $v = 25$ m/s.

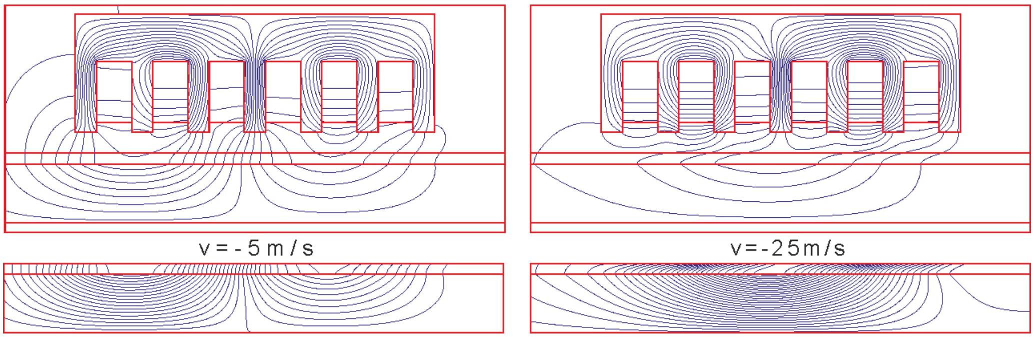

Fig. 3. Magnetic field distribution within the simplified model of the LIM and within the reaction rail (for nonconducting iron part) for different speed values

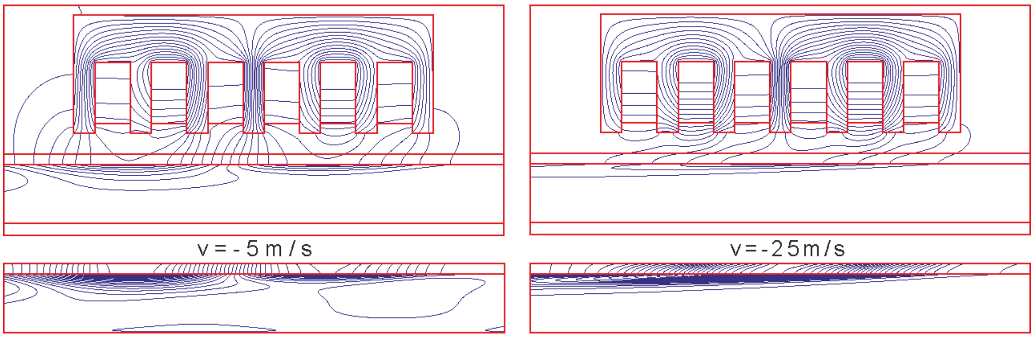

Fig. 4. Magnetic field distribution within the simplified model of the LIM and within the reaction rail (for conducting iron part) for different speed values

The skin-depth for above data $\delta_{Fe} = 0.71\ 10^{-3}$ m leads to the characteristic value of finite elements in conducting iron $h \leq 0.24\ 10^{-3}$ m, but (5) requirement says that $h \leq 0{,}006\ 10^{-3}$ m. This is a very rigorous condition which is very hard to fulfil (*Al*-thickness 4.5 mm, *Fe*-thickness 25 mm). The coarse finite element mesh can cause instabilities and large calculation errors.

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From Fig. 3, 4 it can be seen that the magnetic field distribution on both ends of the machine shows typical asymmetry. These end-effects have already been analyzed in many papers, both analytically and numerically [8–11], [14]. If the machine is supplied from the voltage inverter, this end-effect asymmetry leads to the asymmetry of phase currents.

An advanced LIM simulation tool was developed based on finite element software, which made it possible to determine all important characteristics of the machine, such as forces, power losses, inductances, etc. Fig. 5 shows the results obtained by applying the new tool for the above simplified model of the LIM (obtained by COMSOL [12]).

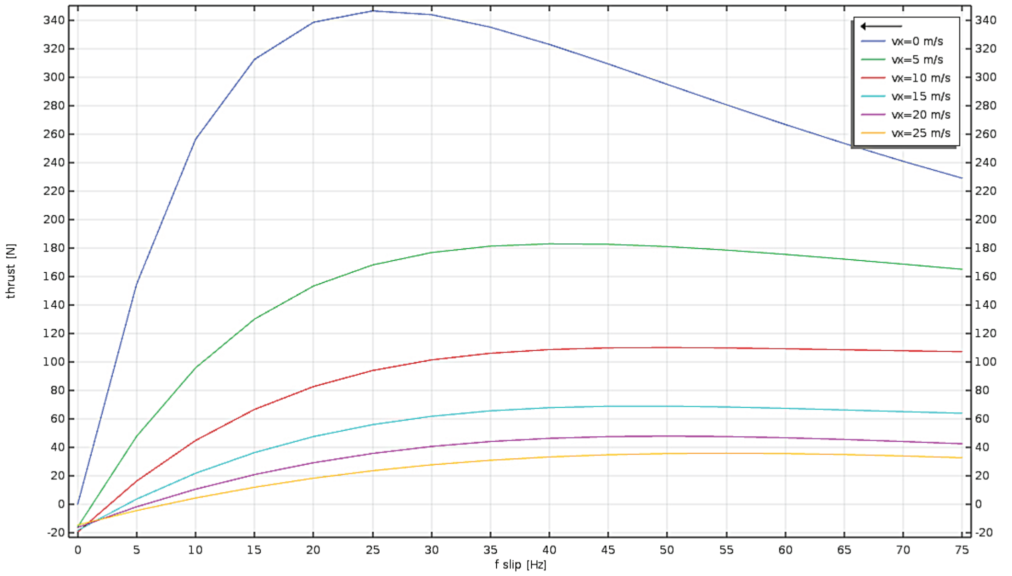

Fig. 5a. Thrust of the LIM as a function of slip for different speed values

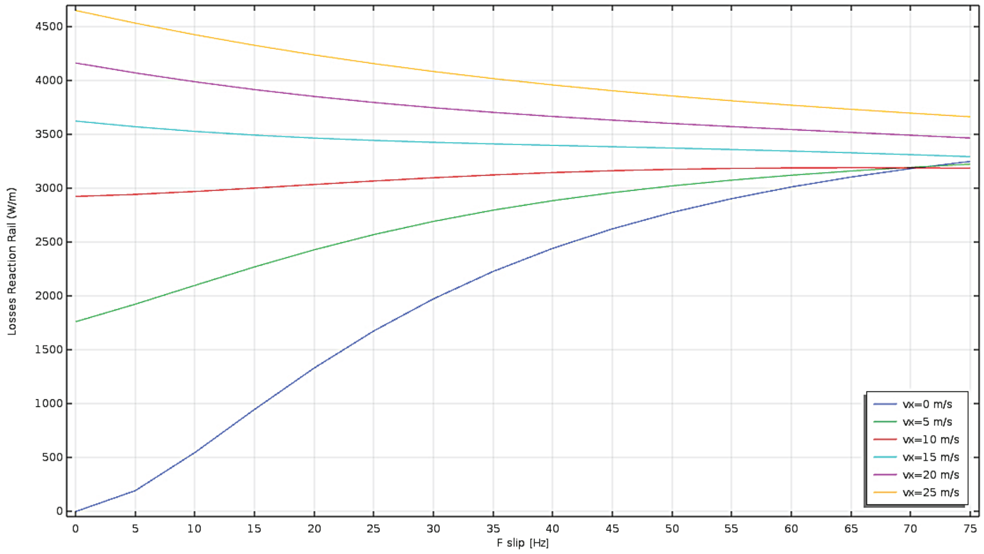

Fig. 5b. Power losses in the reaction rail as a function of slip for different speed values

LIM SUPPLY AND CONTROL

Fig. 6 shows a typical supply system of a traction LIM.

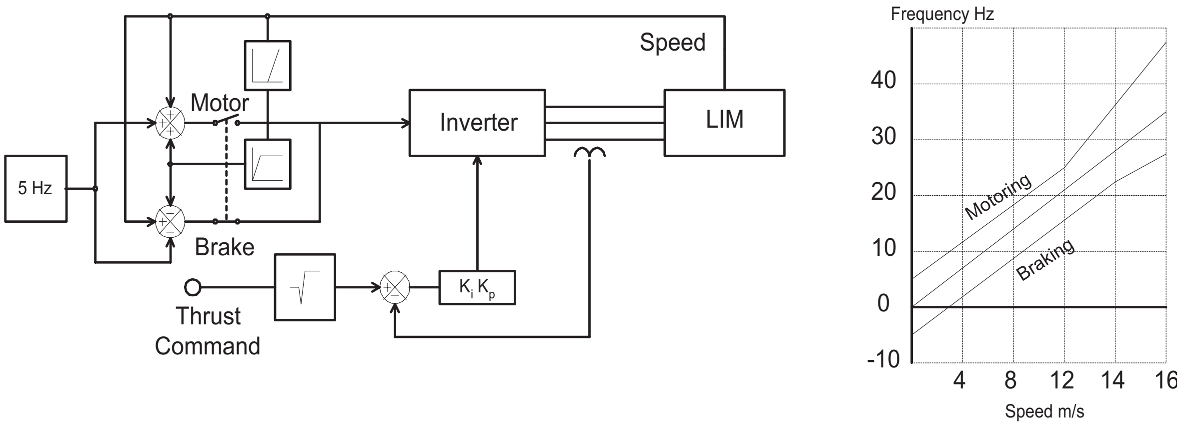

Fig. 6. Typical LIM supply system [2], [13]

The LIM is typically supplied from the voltage inverter converting thrust command into current by PWM control. However, as the impedances of the LIM are unequal, due to the end-effect, the three phase currents differ in their phase and magnitude, producing negative sequence of phase currents, which leads to decreased performance. The three phase currents can be equalized by proper voltage control if only the LIM impedances were known. The magnetic field calculations shown above enable the determination of the self- and mutual-inductances of the LIM windings. Because the winding currents are magnetically coupled with one other and additionally coupled with induced currents in the reaction rail, these impedances are frequency and speed dependent, thus their determination can be very involving. The global impedance L_a (by supplying of all LIM phases) of one winding carrying the effective current I can be obtained by calculating the system energy W_m:

$$L_a = \frac{2W_m}{I^2}\,. \tag{6}$$

Calculation of the above inductance for each phase for different speeds and frequency values gives the required information about differences of theses inductances under different operating conditions. This calculation was performed by means of ELMAG and after that the average values of the impedances were used in COMSOL field modelling by supplying the LIM with unequal currents (voltage mode, approximated method).

It should be stated here that this algorithm can also be realized directly via COMSOL by solving the appropriate voltage equations – results obtained by both methods are very similar.

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RESULTS

All above considerations can be used for the proper evaluation of the real LIM. Next Fig. 7, 8 show the magnetic field distribution within the subject LIM.

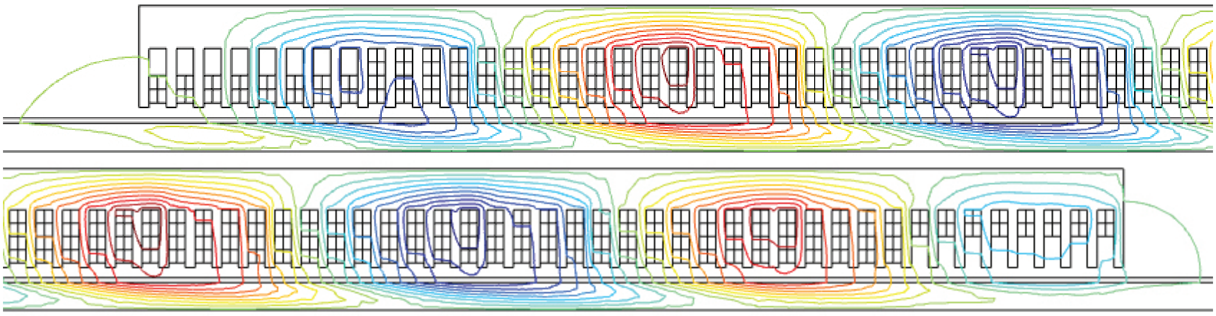

Fig. 7. Magnetic field distribution for $v = 0$ m/s within the LIM (COMSOL)

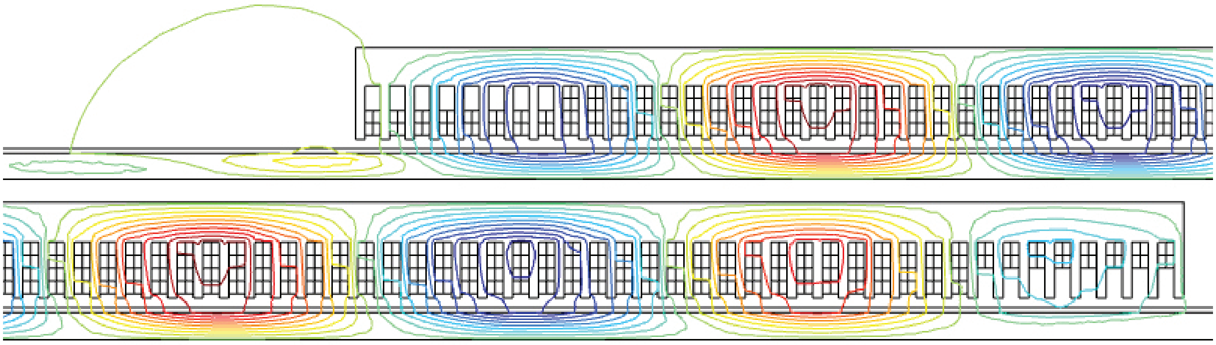

Fig. 8. Magnetic field distribution for $v = 5$ m/s within the LIM (COMSOL)

Comparison of LIM characteristics obtained by COMSOL for the current- and voltage supply have been shown in Figs. 9, 10.

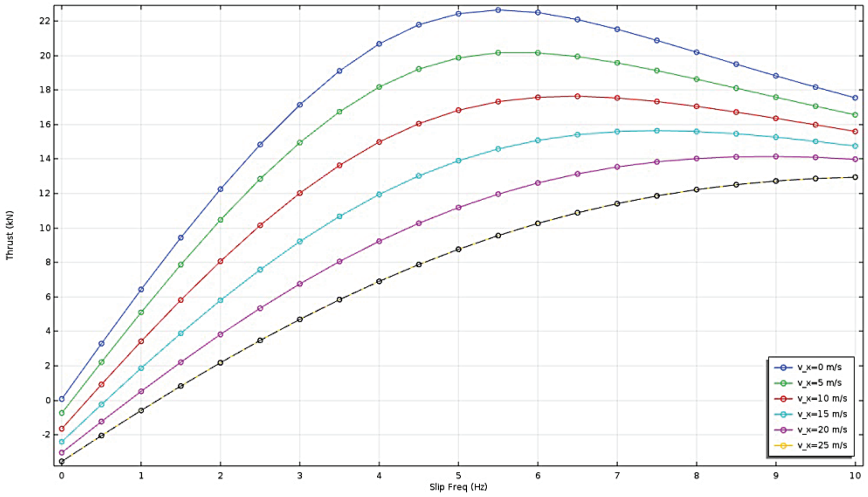

Fig. 9a. Comparison of LIM characteristics obtained for the current-supply

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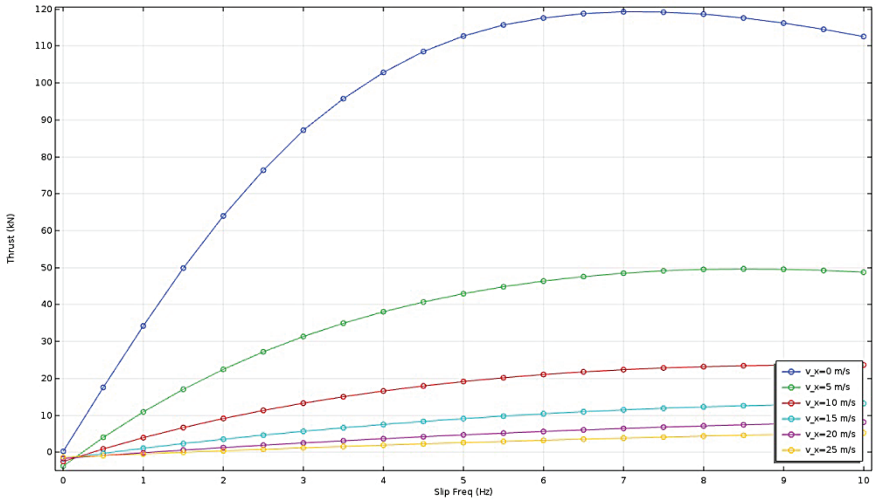

Fig. 9b. Comparison of LIM characteristics obtained for the voltage-supply

CONCLUSION

The method of calculating phase current asymmetry in LIMs has been proposed. The self-developed electromagnetic FEA software, ELMAG, was used to calculate phase inductances and in consequence the prospective LIM currents when fed from the voltage inverter. The resulting asymmetric currents were then applied in COMSOL to simulate the real size LIM performance and compare it with the results obtained by feeding the symmetric currents. The same results have also been obtained directly by COMSOL These results prove that the natural asymmetry of the currents is an important factor that must be considered in appropriately calculating the LIM performance.

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DISRUPTIVE TECHNOLOGIES TRANSFORMING URBAN MOBILITY? THE ROLE OF THE ECOBEE URBAN MAGLEV SYSTEM IN THE SEOUL TRAFFIC VISION 2030, SOUTH KOREA

The dynamics and extent of disruptive technologies have been very well developed in Asian cities by the beginning of the 21st century, and are becoming particularly future-oriented. It also appears that urban mobility strategies in Asia are hardly slowed by resistance such as seen in the European context, where holding on to existing systems is the norm. The effects of accelerated mobility strategies in Asia are already apparent compared to what may be expected in Europe. So one could ask, which innovation processes will allow mobility to further develop? How will urban transport systems likely change in the future to minimize adverse impacts of current forms of mobility? In looking forward, any implementation of innovative mobility strategies heavily depends on spatial structures, transport networks and technologies as well as a political planning and decision-making. In Asia, concepts of transport and innovative transportation concepts (such as Rotem's Ecobee Urban Maglev) are developing with considerable promise, which, if successful, can turn into trendsetters with considerable future relevance on a global scale.

Aim: The aim is to identify relevant effects of new mobility strategies on cities and to analyze to what extent so called disruptive transport technologies are considered. The city of Seoul with its transport strategy 2030 and the disruptive maglev system Ecobee serves as an example.

Methods: Analysis of official documents of city and transport planning departments of Seoul city. Evaluation of interviews with Maglev experts.

Results: Seoul's transport strategy may seem ambitious. However, it does not take into account the Ecobee Maglev technology in the official plans – even though it is a South Korean proprietary development that is considered to be particularly environmentally friendly. Instead, planning for Seoul's future has so far taken place solely on the basis of established transport systems, which become more efficient through better IT-based management. Disruptive technologies, such as the Ecobee Urban Maglev, do not play any relevant role in the strategy.

Conclusion: It might be advantageous to discuss a leapfrog approach like the Ecobee Urban Maglev on a rational basis rather than ignoring it.

Keywords: mobility strategy, urban transport, maglev, Ecobee, Asia, Seoul, Incheon.

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INTRODUCTION

Asian cities pursue ambitious, sometimes contradictory, urban mobility strategies. Even disruptive technologies – also fundamental technologically new developments – can be part of efforts to provide future-oriented answers to the various challenges of designing urban and regional mobility. On the one hand, highly technology-based transport management approaches are used. However also, procedures are being tested with a view to a fundamental reduction of selected modes of transport.

While Asian cities, for example, cannot usefully decouple from globalized trends in airport developments, there are at least concrete opportunities for their own development in a regional context, such as public transport, slow transport (pedestrians, bicyclists) or the management of the car transport. In addition, some scientists are also proposing new – and potentially disruptive – linear motor-based rail systems such as maglevs or urban cableways for public transport in Asian cities.

For a possible objective analysis and evaluation of possible trends, the foresight method seems to be a meaningful (scientific) approach for strategic transport infrastructure planning. The approach, for example, asks several questions of urban developers: How will urban transport systems likely change in the future in order to minimize adverse impacts of current forms of mobility? How can the efficiency of transport infrastructure be increased? Overall, how is the future of mobility and transport meaningful to create and which trends should be trendsetting? The extent to which such strategic transport infrastructure planning can actually have future-oriented solutions (and where there may also be limitations and *blind spots*) can be demonstrated by using the strategic plan *Seoul Traffic Vision 2030* as an example.

SEOUL TRAFFIC VISION 2030: BUILDING AN ECO-FRIENDLY TRANSPORTATION SYSTEM

Beyond Seoul: The South Korean capital, Seoul, has about 10.3 million inhabitants and a relatively high density (compared to Europe) with 17,018 inhabitants per square kilometer. The city occupies a land area of 605 square kilometers. Fourteen percent of this area will be used for roads and transport infrastructure. Seoul has invested heavily in its transport infrastructure and is using vehicle infrastructure in the form of city motorway – Information and Communication Technologies (ICT) for managing transport volumes. The urban modal share of public transport is about 66 percent. The public transport network consists of nine subway lines and over 350 inner-city bus lines [1] (pp. 95–96), [10].

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Seoul has attempted to shift urban transport planning priorities from vehicle-based prioritization to more people-centered mobility based on public transport and slow transport through planning and decision-making processes, although the focus continues to be on the requirements of motor vehicle transport. However, another factor relates to significant strengthening of public transport. The problems of air pollution, traffic jams and land usage (parking lots), which are usually the consequences of a car-centered urban development, seem too massive.

The bus reform in 2004 was already a first step towards a strategic reorientation of public transport policy. Since then, a semi-public bus operating system has been introduced, allowing the city government to intervene to control the design and operation of the bus networks. A Bus Information System (BIS) was also implemented, which determines real-time information (such as arrival times, current location of the buses) and informs the customer [1].

Since 2004, Information Technology (IT)-based transport control systems have been in everyday use in Seoul as well. Electronic ticket systems, road sensors and cameras monitor, among other things, using GPS (Global Positioning System) transport flows in the city. The real-time data flows into a central system for updating and evaluating digital street posters and transport reporting systems. The transport- and information service (Transport Operation and Service Information Service, TOPIS) of the city government controls transport flows through a control center [1]. Urban maglev systems are not currently included in urban areas. Instead, they will be realized in metropolitan peripheral locations in the surroundings of the Incheon International Airport and tested for suitability.

Seoul is pursuing a relatively broad-based strategy to shape its urban transport infrastructure with the strategic plan *Seoul Traffic Vision 2030*, which was presented by the city government in 2013. The strategic plan includes all relevant forms of urban mobility: public transport, motor vehicle transport, slow transport (pedestrians, bicyclists). One focus of the *Seoul Traffic Vision 2030* is the networking of technologies, infrastructures, mobility services and mobility to offer an optimal as possible transport efficiency. In addition to ICT-based transport management, so-called *green* mobility solutions are to be expanded. For example, over the next 20 years (from 2013), there will be reach a 30 % reduction of car traffic volume, a 30 % reduction of commuting time by public transport and a 30 % increase in the use of environmentally-friendly modes of transport (walking, cycling, public transport). These concepts and goals require a structural reduction of motor vehicle transport. At the same time, they are also related with massive investment in better-networked public transport. “By 2030, the city of Seoul will have evolved into a city with a highly convenient transport system, where people will not need to rely on their cars” [2]. The strategic plan *Seoul Traffic Vision*

2030 requires a paradigm shift that calls for a rethinking of different actors – e.g., politics, society, economy and planning.

Relevant aspects of the paradigm shift for Seoul include:

- prioritizing transport by considering pedestrians instead of cars;
- taking a bottom-up approach for decision-making processes instead of top-down approach;
- integration transport solutions instead of divided modalities.

The strategic plan *Seoul Traffic Vision 2030* identifies a variety of long-term goals and visions for transport design. The strategic plan is intended to demonstrate a basic orientation of transport policy in Seoul. Also, specific concepts are discussed. A key issue here is so-called eco-friendly, efficient mobility solutions. It is noticeable, however, that disruptive new technologies are not mentioned in the concepts and strategies. Disruptive transport technologies, such as the Ecobee Urban Maglev (an urban transport maglev train), which is considered to be low in emissions and resource-efficient, have no discernible value in the concepts. Is a new urban mobility-system like the Korean Ecobee Maglev therefore not desirable? If so, will this technology not be needed in cities of the future?

ASPECTS OF REASONS AND OBJECTIVES OF THE URBAN MAGLEV PROJECT: ECOBEE MAGLEV

The South Korean Ecobee (Fig. 1), South Korea's domestically developed urban maglev system, has in commercial operation since 2016 at Incheon International Airport. The pilot project is the result of a collaboration between the Korea Institute of Machinery and Materials (KIMM), a government-funded research institute, and the rail vehicle manufacturer Hyundai Rotem.

The system is based on traditional magnetic-levitation technologies, in which the vehicles levitate over a track, or guideway, without touching it. This allows a large reduction in friction and wear during operation of the system, which can reduce operating costs [3].

The objective of the Korean project developers is to set new standards for urban transportation concepts worldwide with this disruptive technology. However, can the Ecobee system credibly fulfill the claim to be a trendsetter for city and transport infrastructure projects if it is not considered in its own country (South Korea) in the strategic plans that are typically considered forward-looking efforts?

Selected for the maglev project was the far from city center location of Incheon International Airport and its surroundings [6]. Incheon International

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Fig. 1. Ecobee Urban Maglev on its guideway at Incheon Airport [4].
So far, this innovative transport system, which is considered to be very environmentally friendly, plays no role in the strategic plan 2030 of the city of Seoul

Airport, launched in 2001, was built on a new ground-polder area in the sea and is a major hub of air transport in East Asia. Around 58 million passengers use the airport every year (as of 2016) [5]. This high number of passengers – and thus potential users of the Ecobee system – is cited as a major reason for choosing the Incheon location, which succeeded in a competition against the cities of Daegu, Daejeon and Gwangju [6]. In the master plan of the new ground area, the center of Incheon International Airport can be found as well as the International Business Center, theme parks, shopping centers, hotels, residential areas and other facilities. These projects should ensure adequate passenger numbers in the future.

A complete structural implementation of the Incheon master plan was not attained for various reasons, which is why the passenger numbers of the system probably do not have the desired values. In contrast, the international airport will be expanded, with another passenger terminal being opened in 2018. Whether this contributes to an increase in use of Ecobee, however, remains to be seen. A senior official on the project team expresses his critical view of Ecobee maglev's location choice: “If the line had been built in Daejeon, Gwangju, or Daegu – which competes with Incheon for the bid – the technology would probably become commercially viable and successful more quickly. It's a bit unfortunate” [6].

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Since the maglev project is located in a new ground area in the sea, the Ecobee Maglev is exposed to crosswinds, which are rather unlikely in urban transport. Crosswinds can have a high impact on lateral displacements of the electromagnetic guidance systems on the vehicles. An adaptation of vehicles and guideways to withstand these crosswind effects was therefore inevitable before commercial use. Also, the inspection intervals should be adapted to the salty winds [3].

Why a maglev project in Incheon? The Incheon International Airport connects the South Korean capital of Seoul, which is about 60 kilometers southwest, and relevant parts of the country, among others, with rail infrastructures in place since 2007. These include the Airport Railroad Express (AREX) train with express (non-stop) and commuter (all-stop) options for connecting to the city center of Seoul. The conventional high-speed train Korea Train Express (KTX) has been in operation since 2014 and links Incheon with Seoul, Daegu, Busan and other Korean cities. The Ecobee Maglev, as an additional system, seems primarily intended for use by people living and working around Incheon Airport.

Three phases are planned to be realized for the Ecobee Maglev over a distance of about 57 kilometers along the coastline of Yeongjongdo Island, on which, among others, is the Incheon International Airport. The pilot line (Fig. 2) – the first implementation stage – with a length of about 6 kilometers has been completed and connects the airport and Yongyu with each other.

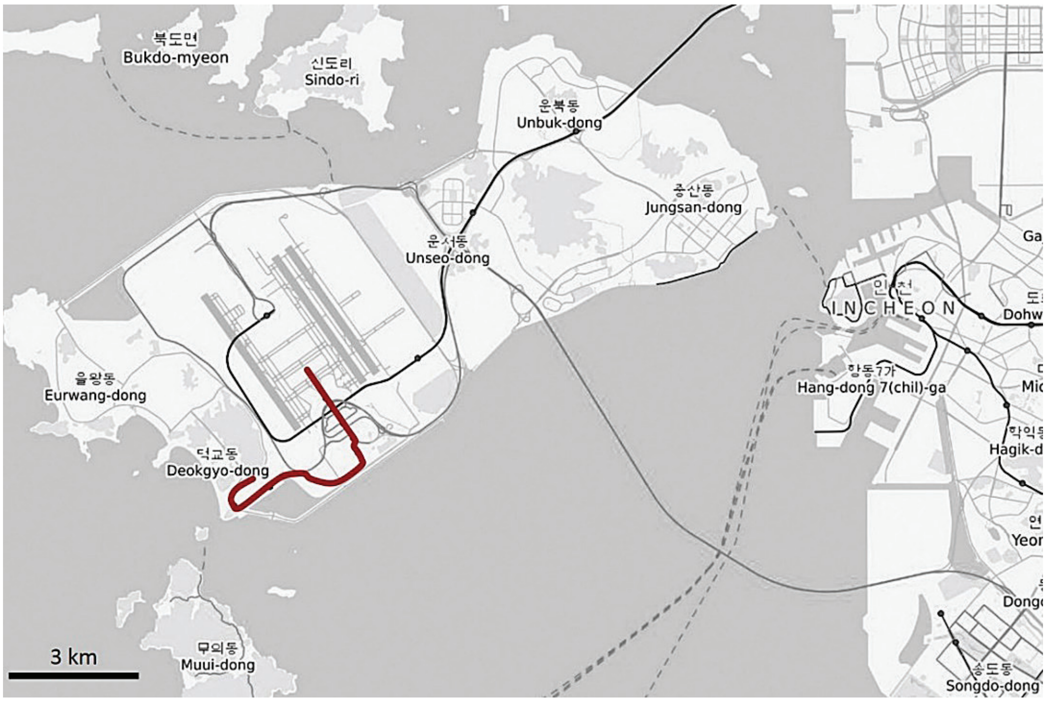

Fig. 2. The Incheon International Airport with the current Ecobee pilot line
[Visualization based on OpenStreetMap, Aug 2018]

For this line, the Ecobee takes about 15 minutes driving time, stopping at five stations [3]. The track is elevated. The Ecobee Maglev is a fully automated, driverless system based on the electromagnetic suspension (EMS) system. Propulsion and braking take place via a linear induction motor (LIM) [3].

Hyung-Suk Han, a scientist from the Korea Institute of Machinery and Materials (KIMM), characterizes Ecobee Maglev as a «very environmentally friendly train. It produces less than 65 A-weighted decibels (dBA) noise, which practically means that we don't have to build noise walls. Also, vibrations are very limited. That is crucial in an urban environment, because it means that the impact on buildings is low" [7]. The Ecobee, as a low-speed maglev train, reaches a maximum speed of 110 km/h and a maximum operating speed of 80 km/h. Johannes Klühspies also states: "At speeds under 200 km/h (125 mph), maglev systems can hardly be heard, especially in an urban environment – an important advantage for populated areas" [8]. The Japanese Linimo in Nagoya, which has been in commercial use since 2005, as well as the Chinese Changsha (commercial operation since 2016) prove this impressively.

In maglev technology, there is usually no wear from rolling friction – in contrast to conventional wheel-rail systems. The wheel-less levitation minimizes, among others, rolling noise and vibrations. Maintenance is considered simple and relatively inexpensive. These features appear to make maglev trains such as the Ecobee Maglev fundamentally interesting for operation in urban transport.

South Korea claims to take the maglev project into a new era of urban transport and now also sees its maglev system as ready for mass transportation. The development should not only serve the state-owned infrastructure, but also lay the foundations for exporting the South Korean maglev technologies to other countries, such as China, Malaysia, Russia and the USA over time.

Scientific publications have been discussing this disruptive, new urban transport system, Ecobee Maglev, since the Ecobee came into operation relatively extensively. An application as a metro line in the South Korean city of Daejeon has also been discussed, but the urban maglev project was not realized. Only Hyung-Suk Han and Dong-Sung Kim state that in 2014, the transport infrastructure plans seemingly changed to avoid implementing the maglev project in Daejeon [3]. Reasons are not named. Concrete information on the reasons for these changes to the plan cannot be found, either in academic or in grey literature.

CONCLUSION: NEW WAYS OF TRANSPORTATION

Asian cities are characterized by their openness to technology. Asian cities combine a high degree of flexibility in their mobility design with highly adaptable

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and highly efficient strategies. Nevertheless, it is undisputed that disruptive technologies, such as the urban maglev system, could have a high relevance for future transport infrastructure development. “Maglev is a competitor to automobiles, trains and airplanes, as well as buses and metro-systems,” [9] emphasizes Laurence Blow, an American consultant in the transportation. Cities need more efficient transport infrastructure systems for which meaningful ways of implementation should be found.

In the case of Seoul, the development of public transport systems shows a relatively long planning horizon in international comparisons, technology-oriented strategies and a consistent focus on transport services for a growing urban area. As early as 1971, when Seoul began planning the first subway line, its integration into the regional rail network was an important criterion.

Future-oriented mobility strategies are also characterized by their positive connections to existing transport infrastructure systems. This seems to have been achieved with the Ecobee Maglev at Incheon International Airport, even though it is only a pilot route so far. If the Ecobee Maglev is meaningful and attractive in the long term; if it can become a trendsetter on a global scale, all this also seems to be dependent on the vision and the technology openness of the relevant actors from politics, society, economy, media. The rather limited marketing as well as the lack of consideration in urban strategic plans currently seem to be of little advantage for the future prospects of the South Korean system. It seems necessary to overcome this structural disadvantage of a disruptive but interesting technology and to discuss it on a rational basis as another innovation.

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CHARACTERIZATION OF LEVITATION FORCE FOR A SUPERCONDUCTING MAGNETIC LEVITATION VEHICLE

Background: In Superconducting Magnetic Levitation (SML) transportation systems, such as the MagLev-Cobra prototype, the levitation force plays an important role, both for efficiency and safety reasons.

Aim: Determination of the maximum load on the magnetic suspension.

Methods: To determine how much load the magnetic suspension system supports, numerical simulations, based on computational models, and laboratory experimental tests are normally used.

The most commonly way for characterization of a SML bearing is the measurement of the levitation force as a function of distance between a Superconductor (YBCO) [1, 2] and a Permanent Magnet Guideway (PMG). The measurement of levitation as a function of distance, the banana curve, has a hysteretic behavior with the results depending of the history of measurement: whether the distance between the superconductor and the PMG is decreasing the force is higher than when the distance is increasing, the force is higher with faster movements and so on. A different approach of levitation force test will be proposed as an alternative to the hysteresis curve. This method, applied to characterize the levitation dynamics of the Maglev-Cobra vehicle, provided more reliable and consistent data with the levitation dynamics observed during the operation of the real scale prototype in the transportation of passengers.

The bench-top levitation test emulates the behavior of the vehicle along its operation, regardless of the position history between the magnets and the superconductor materials. The test consists in placing the superconductor, refrigerated inside cryostats, in a predetermined Field Cooling (FC) position, and slowly move the cryostat above the PMG to a lower high, for example 15 mm, and wait 10 minutes. After that, the high is decreased 1 mm and again hold there for 10 minutes. The procedure is repeated until a high of 10 mm is reached. The hole process is repeated at least 5 times. This routine replicates the load condition during the vehicle operation when passengers board the train and the load stay constant until the end of the journey. After that, another group of passengers takes place inside the vehicle and is carried to the next station.

This kind of test shows the creep of the levitation force over time with slow dynamics and gives the average load over height of levitation along the given time of operation, helping engineers to predict the load capacity of the vehicle and design a more reliable layout.

Results: Three FC positions were investigated. The position currently used by the MagLev-Cobra (35 mm) and other 2 positions (45 mm and 55 mm) of initial height between the superconductor and the permanent magnet guideway.

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Conclusion: All these results contribute to an improvement in the criticality index and a safe application of this system on transportation of persons.

Keywords: Superconducting Magnetic Levitation, Urban Transportation, Superconductors, Rare Earth Permanent Magnets, Force Measurements.

INTRODUCTION

In handling systems that use superconducting levitation [3], it is extremely important to make the most of the levitation force for both efficiency and safety reasons. To determine how much load the magnetic suspension system supports, it is possible to use models and numerical simulations or physical tests in the laboratory. Just as important as using a suitable mathematical model is to perform tests in a manner consistent with levitation and operation.

To determine the ideal levitation height of the Maglev, some bench tests were performed in the laboratory, in which the actual operating conditions were reproduced. It was decided to perform tests because the modeling of the phenomenon of levitation still be a subject not totally dominated by researchers around the world. Several theories attempt to reproduce the experimental results mathematically without success. The superconductors used in the Maglev Cobra are type II.

THE HYSTERESIS CURVE

The most used curve to characterize a superconducting bearing is the banana curve that represents a force versus displacement graph between a superconductor and a magnet (Fig. 1).

The repulsive force between a magnet and a superconductor is a complicated mechanism to be analyzed. What can be said is that the force increases as the superconductor approaches the magnet and decreases as it moves away. However, it is different when the two are moving away or approaching. When the magnet moves away, the repulsive force between the magnet and its image diminishes. In addition, flux pinning lines cause an attractive force that reduces liquid repulsive force. This results in a curve force vs distance with hysteresis.

Moreover, the equilibrium position depends on the amplitude of the excursion that the superconductor performed on the magnetic field of the magnet. As can be seen in figure1 there are 4 Hysteresis curves measured for the same magnet and superconductor assembly. The first curve with the largest displacement is the displacement curve of 25 to 10 mm where it is possible to observe the largest Hysteresis. The three following curves (2, 3 and 4) are displacements (20 to 15 mm),

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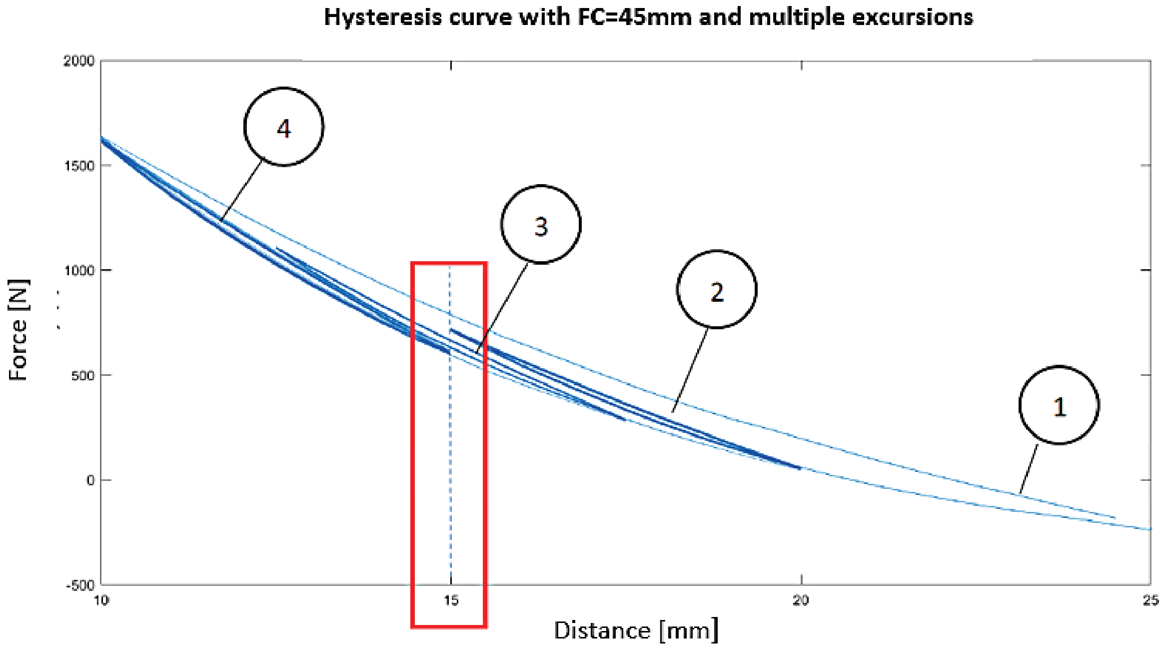

Fig. 1 . The classical Banana curve for different amplitude excursions

(17.5 to 12.5 mm) and (15 to 10 mm), so it is impossible to determine the ordered pair (position, force) without knowing the displacement history of the assembly.

One can take as an example the position of 15 mm in the different curves. To know the force associated with this position it is necessary to know what displacement was done around this position.

EXPERIMENTAL SETUP

The levitation force testing system is illustrated in Fig. 2 and allows movements in the vertical direction. The equipment is connected to a computer that uses the Labview software both for control of the movement and for the acquisition of the data of the load cell. Other researchers also perform levitation tests in their laboratories [4, 5, 6].

The test configurations are listed in Table 1.

Table 1.Test Configuration

Step	0.5 mm
Speed	3 mm/s
Sample rate	10 kHz
Resolution	¾ N
Waiting time after movement	10 min

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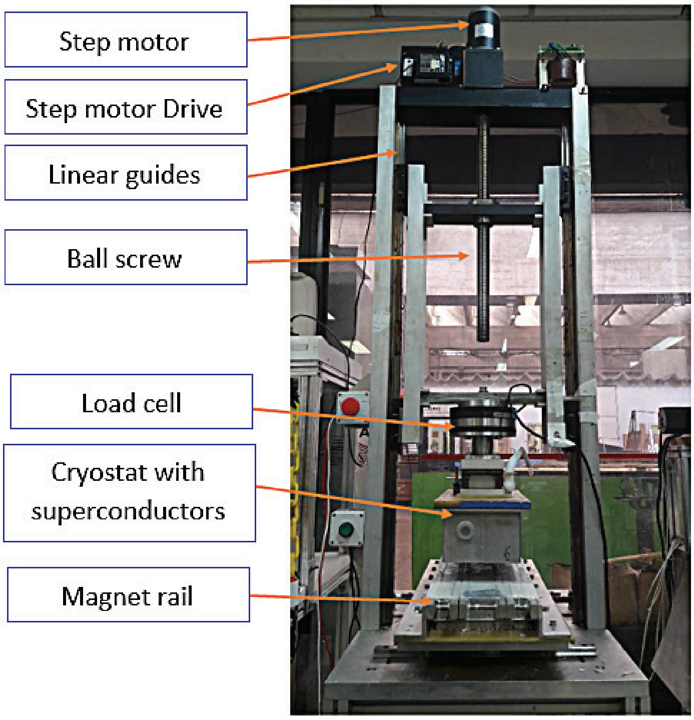

Fig. 2. Experimental Setup

RESULTS AND DISCUTION

In order to perform bench-top levitation tests, we tried to get closer to the behavior of the vehicle over the operating time [7].

Three Field Cooling positions were investigated (YBCO cooling in the presence of magnetic field). Position currently used by the Maglev (35 mm) and other 2 positions (45 mm and 55 mm) of initial height between the superconductor and the rail. To evaluate the force as a function of the levitation gap throughout the day the procedure used was placing the superconductor, refrigerated inside cryostats, in a predetermined Field Cooling (FC) position, and slowly move the cryostat above the PMG to a lower high, for example 15 mm, and wait 10 minutes. After that, the high is decreased 1 mm and again hold there for 10 minutes. The procedure is repeated until a high of 10 mm is reached. The hole process is repeated at least 5 times.

With this procedure, gradual loading of the cryostat is simulated throughout the day in the same way as the vehicle with the entry and exit of passengers at each trip. It is impossible, however, to repeat the exact loading that the vehicle suffers with the transport of passengers during its working period, as the load distribution of the vehicle is not homogeneous, and passengers will not always position themselves in the same place inside the vehicle.

With the proposed test methodology, it is possible to evaluate the force curve by displacement over time in a discrete way by averaging each 10-minute period evaluated and plotting the curve of these points for each position (10, 11, 12, 13, 14 and 15 mm).

The first test cycle represents the so-called field pumping when the superconductor is pressed for the first time against the magnetic field of the magnet, this action causes a stress in the pinning network and has the consequence called the Flux Creep and, therefore, decay of levitation force. This Creep of the first cycle is more pronounced than in the other cycles of tests and can be observed in the following three graphs that represent the first test cycle for each height of FC. Another observation is that the levitation force is always greater during field pumping than during the other stages of testing.

This phenomenon can be observed in Fig. 3, 4 and 5.

To observe the levitation force over the hours, the mean force measured over the 10 minutes was used as a representation of the cryostat's capacity in this time window. By performing several test cycles with at least 1-hour interval between them it was possible to use each midpoint along the hours.

With these results it is possible to observe the decay of the levitation force for different FC heights and to know how much load the vehicle can carry along the operating time depending on the height of Field Cooling used. The first hour of testing is not part of the tables because it is when the creep flux shown in the

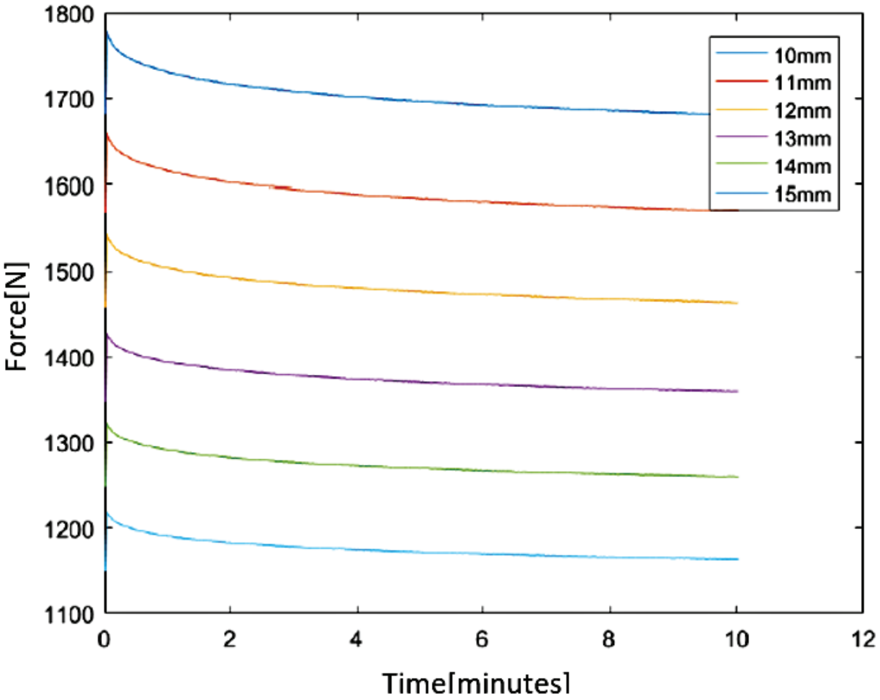

Fig. 3. First test (flux Creep) FC 35 mm

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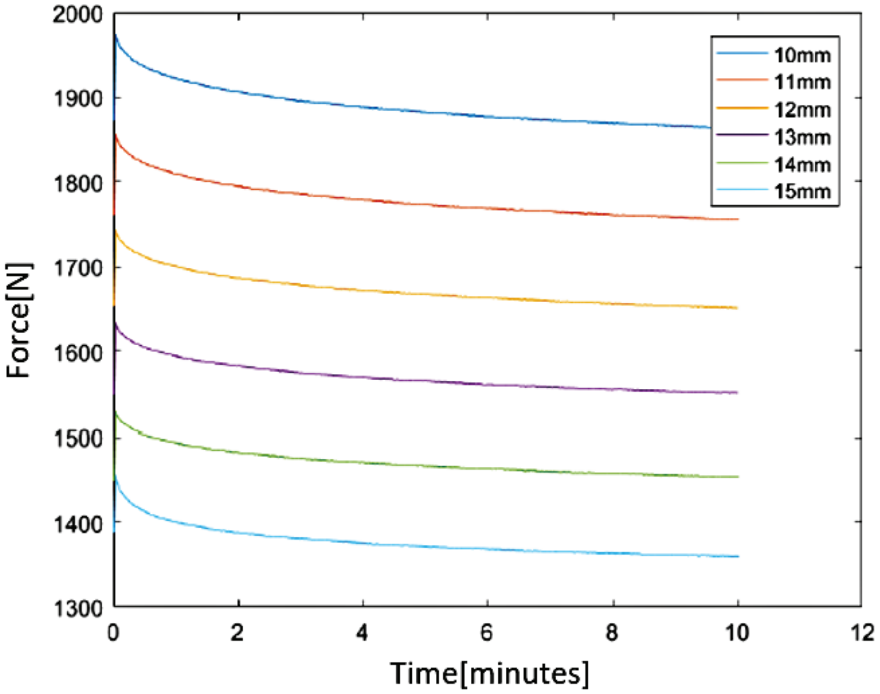

Fig. 4. First test (flux Creep) FC 45 mm

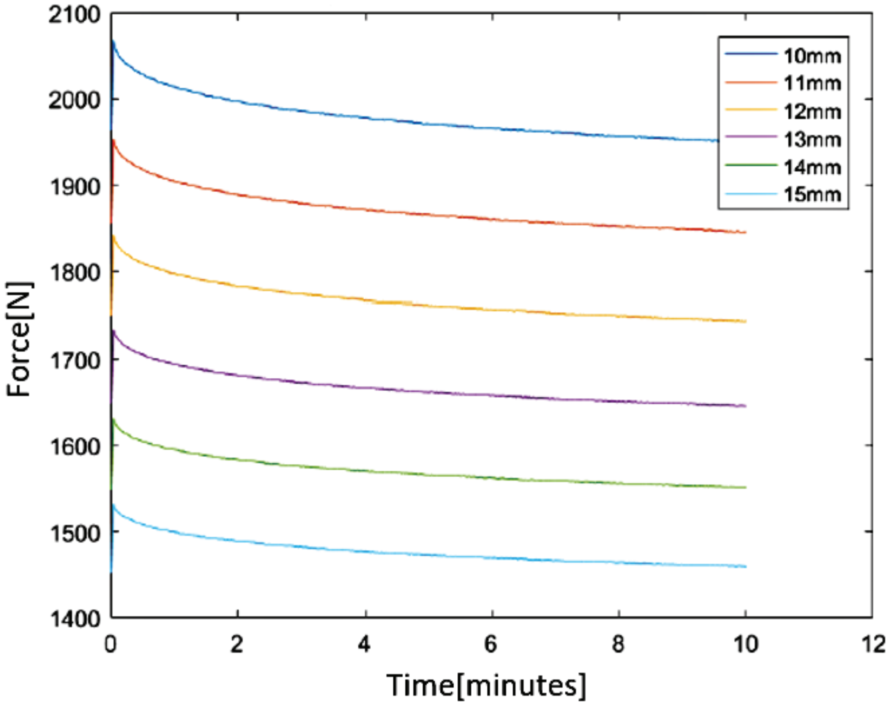

Fig. 5. First test (flux Creep) FC 55 mm

previous Fig. 3, 4 and 5 happens and where the levitation force is larger but does not represent the true load that levitation is able to withstand.

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Table 2. Force Average by levitation Gap and accumulated losses (FC 35 mm)

	FC (35 mm) Force Average [N]					Accumulated Losses
mm	**Hour 2**	**Hour 3**	**Hour 4**	**Hour 5**	**Hour 6**	
10	1667.90	1651.20	1641.52	1634.04	1628.09	2.4 %
11	1484.18	1463.59	1450.55	1442.21	1435.34	3.3 %
12	1297.11	1275.76	1262.84	1254.15	1247.79	3.8 %
13	1117.60	1096.08	1083.46	1074.47	1068.38	4.4 %
14	947.76	926.61	914.19	905.55	899.77	5.1 %
15	787.78	767.73	755.41	745.88	740.21	6.0 %

Table 3. Force Average by levitation Gap and accumulated losses (FC 45 mm)

	FC (45 mm) Force Average [N]					Accumulated Losses
mm	**Hour 2**	**Hour 3**	**Hour 4**	**Hour 5**	**Hour 6**	
10	1851.23	1832.55	1821.05	1812.18	1805.15	2.5%
11	1665.48	1639.21	1624.55	1614.68	1607.53	3.5%
12	1470.76	1443.73	1429.11	1419.64	1413.06	3.9%
13	1284.01	1257.16	1242.73	1234.04	1227.79	4.4%
14	1105.37	1078.80	1064.85	1056.28	1050.79	4.9%
15	935.65	909.64	895.77	888.04	883.03	5.6%

Table 4. Force Average by levitation Gap and accumulated losses (FC 55 mm)

	FC (55 mm) Force Average [N]					Accumulated Losses
mm	**Hour 2**	**Hour 3**	**Hour 4**	**Hour 5**	**Hour 6**	
10	1936.73	1915.56	1903.08	1893.23	1885.89	2,6 %
11	1750.90	1721.99	1705.69	1693.83	1685.33	3,7 %
12	1554.74	1524.63	1508.27	1496.01	1487.93	4,3 %
13	1366.34	1336.08	1319.88	1307.74	1299.97	4,9 %
14	1185.78	1155.57	1139.47	1127.74	1120.33	5,5 %
15	1013.49	983.47	967.83	956.21	949.05	6,4 %

As the vehicle weights 2 300 kgf (2 2540 N), the number of passengers should be limited safely, since the number of cryostats is fixed at 24 units in this project.

Thus, the following scenarios are possible at the end of 6 hours of operation with 10 mm of levitation gap:

According to table 5, considering that each passenger weighs average of 80 kgf, it is possible to estimate the capacity of transport of the vehicle for each height of FC.

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Table 5. Overall Capacity by FC height

FC height	Capacity by cryostat	Total capacity	Total capacity minus vehicle weight	Number of passengers (80 kg f/person)	Safety index with 15 passengers
35 mm	1628 N	39072 N	16532 N	21	1,40
45 mm	1805 N	43320 N	20780 N	26	1,76
55 mm	1885 N	45240 N	22700 N	28	1,93

The tests show that the force decay is small (2.4 % to 6.4 %) for a period of eight hours after the Field cooling and that when the cryostat works more heavily and closer to the rail the loss of force levitation is lower.

Another result is that the quasi-static progressive loading used does not show a logarithmic decay as observed in dynamic Hysteresis type tests. Perhaps because in conducting the dynamic tests there is the movement of a superconductor in the magnetic field of the magnet, causing in addition to the creep, induction of currents inside the superconductor during the movement which in turn generates repulsive forces in the system increasing the levitation force.

With this kind of tests presented, it is possible to predict the behavior of the cryostat over the time of operation, it being enough to know which was the FC used and in which position the cryostats are of the rail. The latter information can easily be obtained by using distance sensors in the vehicle.

The graphs in Fig. 3, 4 and 5 represent the magnetic field pumping curves in the first test cycle explain why the Maglev Cobra levitates higher in the first trips causing the collision of the linear motor safety bearings, causing slight discomfort to the passengers.

CONCLUSIONS

These preliminary data suggest that it would be interesting to change the height of Field Cooling currently used in the Maglev Cobra from FC 35 to FC 45, thereby increasing the carrying capacity. For this change it would be necessary to also investigate the lateral force behavior that holds the vehicle in the path of the rail.

During the tests of levitation force, it was possible to observe that a curve of approximation of amplitude in the range of 5 mm no longer represented the actual load supported by the levitator, and to know the payload for each levitation height a static test should be used. With this, a new test methodology was adopted to approximate the maximum as possible the behavior of the vehicle during its

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operation. Also, was possible to observe that the levitation force for the cryostat is lower than expected for 10mm distance, but the decay measured over time was lower than estimated according to the tables 2, 3 and 4. These data should be confirmed when height sensors are fitted to the vehicle.

Through the tests the number of passengers inside the vehicle can be assessed with greater confidence and a safety coefficient can now be applied according to table 5. Thus, the failure mode – levitation loss due to overload can be mitigated. All these results contribute to an improvement in the criticality index and a safe application of this system on transportation of persons like proposed in [8, 9, 10].

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ENERGY CONSUMPTION OF TRACK-BASED HIGH-SPEED TRAINS: MAGLEV SYSTEMS IN COMPARISON WITH WHEEL-RAIL SYSTEMS

Background: The energy consumption of a high-speed system is an important part of its total operational costs. This paper compares the secondary energy demand of different wheel-rail systems, such as ICE, TGV and Shinkansen, and maglev systems, such as Transrapid and Chuo Shinkansen.

In the past, energy values of systems with different conditions (train configuration, dimension, capacity, maximum speed) were frequently compared. The comparative values were often represented by the specific energy consumption based on passenger capacity and line-kilometer values.

Aim: The goal is to find a way to compare the specific energy consumption of different high-speed systems without any distortion of results.

Methods: A comparison of energy values based on normative usable areas inside the high-speed systems will be described and evaluated in this paper, transforming the results to a more distortion-free comparison of energy consumption of different systems.

Results: The results show the energy consumption as an important characteristic parameter of high-speed transportation systems based on an objective comparison and give ranges of expected energy demand of different systems dependent on maximum speed level.

Conclusion: Up to the design speed of wheel-rail systems there are slight advantages in terms of energy consumption for the Transrapid maglev. From the perspective of energy consumption under consideration to reduce travel time, high-speed maglev systems represent a promising option for new railway projects. However, a project-specific system decision must be based on a complete life-cycle cost analysis, including investment cost.

Keywords: Energy consumption, maglev system, high-speed trains, wheel-rail systems, specific energy consumption, Transrapid, Chuo Shinkansen, ICE, TGV

1. INTRODUCTION

Energy consumption is an important criterion of the operating costs when comparing the operational features of modern High-Speed railway (HSR) systems for

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long-distance services. This article presents and compares the energy consumption of selected HSR systems based either on magnetic levitation and long stator motor technology (Maglev systems) or on wheel-on-rail technology (R/S systems).

1.1. Objective and focus of the research

The purpose of the study is to achieve an objective and comparative representation of the energy consumptions for the High-Speed railway systems available in the market. Various railway systems have been compared in the past mostly based on different fundamentals (so-called distorted comparisons), that is, the energy consumption values for vehicles of different lengths, widths and speeds were compared without retroactive calculation on a standardised basis. This study aims to achieve a view that can enable a better result in terms of objectivity.

The focus of the research can be stated as follows:

How much energy, differentiated by speed, is required for a train with a normalised effective area, when it is driven by a certain High-Speed railway system, R/S system (TGV, ICE, Shinkansen) or Maglev (Transrapid, Chuo-Maglev)?

The statements relate to the requirement of secondary energy. This includes the actual traction energy consumption as well as the energy consumption for auxiliary systems (such as for support and guidance, lighting and air-conditioning) on board the vehicles. The generation of primary energy, i.e., the underlying primary energy sources, as well as their specific efficiency chains, are not considered in this comparison because these factors depend on country and operator-specific conditions and it is not possible to generalise.

In addition to operating costs (such as maintenance, operating personnel, insurance, operating and marketing), operational performance aspects also have to be compared. Such factors include designed speed, travel time (between stations), transport capacity and train frequency, and, for system decision in the case of a specific project, a comprehensive life cycle-cost analysis, including the investment costs associated with the power supply infrastructure. These additional system aspects are not included in this study, which is confined to the operational aspects of energy consumption.

1.2. Relevance

The topic becomes relevant again especially due to developments in Japan and in the United States of America, where the construction and operation of the Japanese Maglev system L0 has become a concrete topic. A High-Speed Maglev

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line is already being constructed between Tokyo and Nagoya in Japan, with an estimated investment of approximately 50 billion € (US $ 62 billion) for the infrastructure. The construction of the same Japanese Maglev system to connect Baltimore and Washington is already in an advanced stage of planning.

2. DATA SOURCES AND COMPARISON CRITERIA

Systems which have been in trial and operational for many years and for which the most possible reliable data is available were selected for the comparative study of energy consumption. This is true for the selected Wheel-Rail systems of Shinkansen, ICE and TGV, as well as the Maglev system Transrapid.

2.1. Selection of the railway systems to evaluate and the information basis

The German ICE 3 was chosen due to the solid data availability, even though other developed versions, such as the Spanish Velaro E or the Chinese CRH380A, are in operation. The latest ICE 4 system of DB AG, although it is more modern than the ICE 3 on the whole, was not included in the comparison because the ICE 4 is not completely suitable due to its top speed limit of just 250 km/h.

For the Japanese Maglev system Chuo Shinkansen (Maglev L0), the information from a scientific point of view appears to be remarkably slight, although the first stage of the project, a 290-km-line between Tokyo and Nagoya, is already being constructed. A comprehensive technical data fact sheet for the Maglev L0 is so far not available despite the advanced stage of implementation. Hardly any technical specifications are officially available due to the restrictive information-sharing policy of the project leader, Central Japan Railway (JR Central). Partial information can be obtained about the project from other Japanese sources, which, although technically sound, can be mainly attributed to the critics of the Maglev L0 based on the respective arguments. Some information is also available in official letters from the Japanese government or ministries. Other indications can be found occasionally (but not verifiably) in Japanese newspapers and railway magazines.

Because the Maglev L0 is an ongoing project with high market impact, a study which did not try to include the Chuo Shinkansen would make little sense. The following information and calculations pertaining to the Chuo Shinkansen were compiled from several, mainly Japanese, sources [1, 2, 3], and by associating the data referred in them with the few available official statements. By making a comparison with at least the rough data of the previous MLX vehicle, verification can be made in principle as to whether the representation for the Maglev L0, which is based on the same technical system principles, can be regarded as realistic.

2.2. Basis of energy consumption calculation

In principle, the specific energy consumption values for a railway system depend on the technical system design, the maximum speed, and the train configuration for the different application cases. The main reasons for the energy consumption values which are to some extent quite different include:

- the different line characteristics, topography,
- the considered clearance,
- the different train configurations of the railway systems being considered,
- specific operator requirements in terms of fittings (number of seats and comfort), aisle width, luggage storage space and restaurant service, and therefore the maximum total seating capacity,
- the design of the traction system and power supply, particularly in the Maglev systems,
- the different vehicle lengths (which impact driving resistance, vehicle weight),
- the respective operational design speed, and
- number of stations and distance between stations.

The data of the Wheel-Rail systems considered here are shown for 300 km/h (N 700) and 330 km/h (ICE 3). Therefore, the energy can be directly compared among the Wheel-Rail systems and Maglev systems only for this speed range. By including the Velaro E (RENFE series 103) or Velaro CN based on the ICE 3, as well as the Chinese CRH 380A, a comparison at higher speeds up to a maximum of 380 km/h would be possible. Higher speeds of up to 550 km/h in normal operation appear feasible only with Maglev systems based on the long stator drive system.

In the following study, the specific energy consumption for the systems are compared based on the two parameters Wh/Pl/km (conventional representation, according to number of seats) and Wh/m²/km (new, according to surface area, as discussed in section 5).

2.3. Overview of key figures of the selected railway systems

The following railway systems for High-Speed long-distance services were selected for comparison:

- Wheel-Rail systems:
  - ICE 3 (Germany)

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  - TGV Duplex Dasye (France)
  - Shinkansen N 700 (Japan)
- MAGLEV systems
  - Transrapid 08 (Germany/China; electromagnetic system - supporting and guiding systems based on attraction – coupled with longstator linear motor)
  - Chuo Shinkansen Maglev L0 (Japan; differential flow system for support, guidance and propulsion with 8-shaped coils in the track side walls and superconducting magnets in the vehicle)

Table 1. Data relevant for comparing High-Speed railway systems

	ICE3 (Velaro D) [4]	**Shinkansen N700** (7000–8000) [5, 6, 7]	**TGV Duplex Dasye** [8]	**Transrapid TR 08** [9]	**Chuo Shinkansen** [1, 2, 3]
Number of cars/ sections	8	8	10	4/5	3 to 12
Number of motors	16	32	8	Linear motor	Linear motor
Drive power (kW)	16×500	32×305	8×1160	Depends on the project	Depends on the project
Unloaded weight (t)	455	356	380	226/282	300
Seats (total)	460	522+24	510	360/446	106 to 704
Length l (m)	200.7	204.7	200.2	100.5 / 125.3	80 to 299
Width w (m)	2.92	3.36	2.90	3.70	2,90
Basic area in m ² (for computation l * w)	586	688	581	372/464	233 to 867
Effective area in m² (basic area minus areas used by system)	538 see chap. 5	627 see chap. 5	533 see chap. 5	331/423 see chap. 5	156 to 660 see chap. 5
Maximum speed (km/h)	330	300	320	500 Depending on project	550 Depending on project

For future applications, it must be recognised that both wheel-on-rail technology and Maglev systems have further potential for development. This applies to Wheel-Rail systems with regard to the efficiency of their drive system, and to Maglev systems with regard to the efficiency of the drives and to power transmission, energy supply and control. Such development potentials are not taken into account in this study so as not to allow for speculative assumptions.

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2.4. Selection of potential application routes

This comparison of energy consumption values is based on the following potential application routes:

- Berlin – Hamburg, approx. 290 km, 3 stops, railway systems considered: Transrapid, ICE 3 [10];
- Berlin – Budapest, approx. 900 km, 8 stops, railway systems considered: Transrapid, ICE 3 [11];
- Leipzig – Dresden, approx. 110 km without stops, railway systems considered: MLX (predecessor of Chuo Shinkansen L0), Transrapid, ICE 3, [9]. Here, the Japanese Maglev system MLX is operated on an open-air, above-ground section, in contrast to the current Chuo Shinkansen system, for which operation is planned almost exclusively in tunnels during its first commercial application. Data are available only for tunnel sections for the current Chuo Shinkansen system. These values may be updated with current vehicle and route data from a JR Central source, but so far no recent publications are available;
- Rio de Janeiro – Campinas, approx. 510 km, 6 stops, railway systems considered: Transrapid, ICE 3 [12];
- Zuiderzeelijn (Netherlands), about 180 km, 8 stops, railway system considered: Transrapid [13];
- Rhine – Rhone, 140 km, 2 stops, railway system considered: TGV [8].

Only energy consumption values for so-called cruising in the tunnel are available for the current Japanese Maglev system Chuo Shinkansen [1]. An average energy consumption value on the Tokaido HSR line [14], as well as some energy consumption values during cruising [1], are available for the Japanese wheel-on-rail system N 700.

3. PRESENTATION AND CLASSIFICATION OF THE RESULTS

Energy parameters for different railway systems can be determined with high accuracy using simulation calculations. Simulation methods allow train operation profiles, including the electric drive and power calculations by specifying the operation, route, vehicle and drive system configurations. These simulations also allow appropriate plausibility checks for railway systems. The specific energy consumption values mentioned in this article are based mainly on simulation results. Typical application-specific speed profiles, which essentially consist of the driving states of acceleration, cruising and retardation/braking, are taken into account. In particular, the acceleration and braking processes that have significant impact on the energy parameters of the systems are taken into account. Owing to poor information availability for some systems, it is also necessary to use static calculations for constant speed (so-called cruising) and adapt it computationally if other reliable data are not available. Based on the graphical representation of these data, bandwidths can be determined for the specific energy consumption of High-Speed systems depending on the approach.

The conventional approach based on ‘energy consumption per seat and kilometre’ will be amended in chapter 5 to include a new, more practical representation based on the actual system-typical effective area of High-Speed railway systems. The criterion of effective area can enable better retroactive computation and a more realistic mathematical comparison of different technologies and systems.

3.1. Basis of the comparison

Since absolute energy consumption representations may apply only for specific trips with a specific train configuration, and the transport capacity of the railway systems in question may significantly differ from one another, the question is how to compare without much distortion. Firstly, a representation commonly used in the industry is shown.

One usual, conventional form of representation is to compare the energy consumption values per seat and for one-kilometre distance depending on the speed.

Such a conventional comparison commonly used in industry is, however, not considered sufficient from the perspective of the authors, as it is strongly dependent on individual operating requirements such as comfort and mixing ratio — the number of seats can be compared in almost any configuration, which influences almost any statement on energy consumption per seat. For example, the decision alone regarding the sizes of the 1st class and 2nd class sections calculated for the systems being considered has a considerable effect on the subsequent result of the comparison [15].

Therefore, the authors have chosen a new form of representation: comparing the specific energy consumption with respect to the system-typical effective area of the railway systems and a 1-km distance based on speed. They feel this approach provides a significantly better method of representation without much distortion.

The comparison of the energy consumption is made at the medium voltage level in the substation, for example, 15 kV in the ICE 3/20 kV in the Transrapid system. Different measuring points/interfaces are marked accordingly.

The basic setup of the power supply and drive structure of the Wheel-Rail systems and Maglev systems based on the long stator motor technology (Transrapid, Chuo Shinkansen) is shown in Fig. 1. Whereas all the drive components are inside the vehicle in the Wheel-Rail system, the main drive components such as the route cable system, switching points and long stator winding are arranged along the track or directly on the track in the case of the Maglev system.

The project-specific design of track-side infrastructure has a significant influence on operational performance and flexibility, the equipment costs, the energy parameters of the system, and therefore the energy costs in the case of the long stator system. In a Wheel-Rail system, the performance data and efficiency curves of the drive system are defined largely by the train configuration regardless of the route.

The specific energy consumption values were calculated under various boundary conditions (vehicle configurations, route characteristics, average distance between stations, and technical system design for the Maglev system). With this information, the specific energy consumption values from various project plans were used especially for the Maglev system, which are based on different technical system designs of the drive and power supply components. Specifying boundary conditions allows a range of energy consumption values to be determined (see section 6).

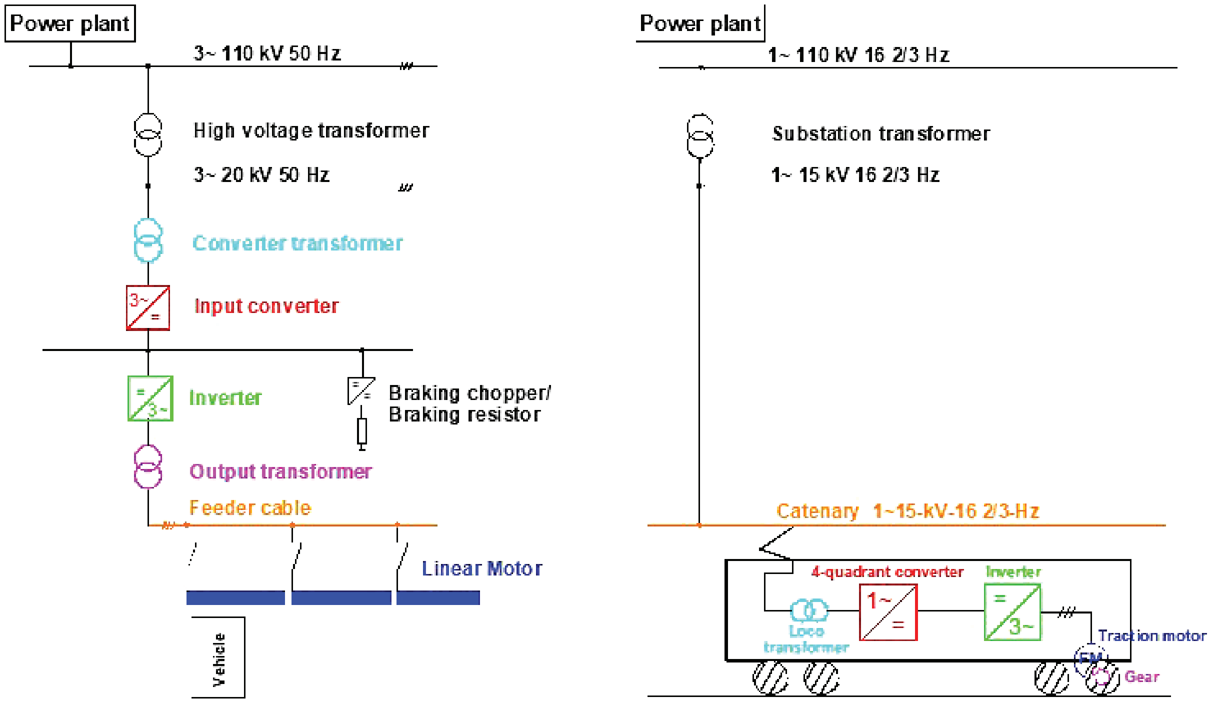

Fig. 1. Basic setup of the energy supply structure for the Maglev system (long stator) and for the wheel-on-rail system with the respective interfaces

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3.2. Comparison of driving resistances

An important factor for the energy consumptions of High-Speed railway systems is the driving resistance, or the resistance that has to be overcome by the system for vehicle movement.

Driving resistance consists of the vehicle resistance, the track resistance and acceleration resistance.

- The vehicle resistance is crucial for the energy consumption, especially in the upper speed range. This includes rolling resistance (linear function of the weight), the air resistance (linear function of the speed) and the aerodynamic driving resistance (quadratic function of speed) in the case of the Wheel-Rail system. In the case of Maglev system, the vehicle resistance consists of the linear generator resistance (depending on the decoupled power and speed), the Eddy current resistance (so-called 'magnetic roller friction') and the aerodynamic driving resistance (quadratic function of speed);
- The track resistance depends on the gradients and bending (sag and crest) of the track;
- The acceleration resistance is proportional to the vehicle weight and acceleration.

The following Fig. 2 shows the vehicle resistances of the HSR systems being studied for specific train configurations having similar seating capacities.

What is notable here is the very high resistance of the Chuo Shinkansen [1] at 100 km/h, which is due to the large magnetic resistance of an EDS system (electro-dynamic system) at the beginning of levitation (the system is still supported on wheels up to about 100 km/h).

4. SPECIFIC ENERGY CONSUMPTION ON A CONVENTIONAL BASIS (SEAT-KM)

The Japanese Shinkansen N 700 records the maximum value for Wheel-Rail systems at speeds up to 300 km/h. At a constant speed of 300 km/h, it has a specific energy consumption of 28 Wh/Pl/km (Watt hours per seat and per kilometre) [1]. With this driving condition of constant inertia (speed), the energy-intensive acceleration processes of a typical speed profile are missing. For real N 700 speed profiles with a maximum speed of 285 km/h [14], the mean specific energy consumption is about 70 Wh/Pl/km in spite of a comparatively high number of seats (1,123 seats in 16 cars and 546 seats in 8 cars [6, 7]), which is therefore higher than the comparable values of other systems at 300 km/h, and which would again be higher at 300 km/h for the N 700.

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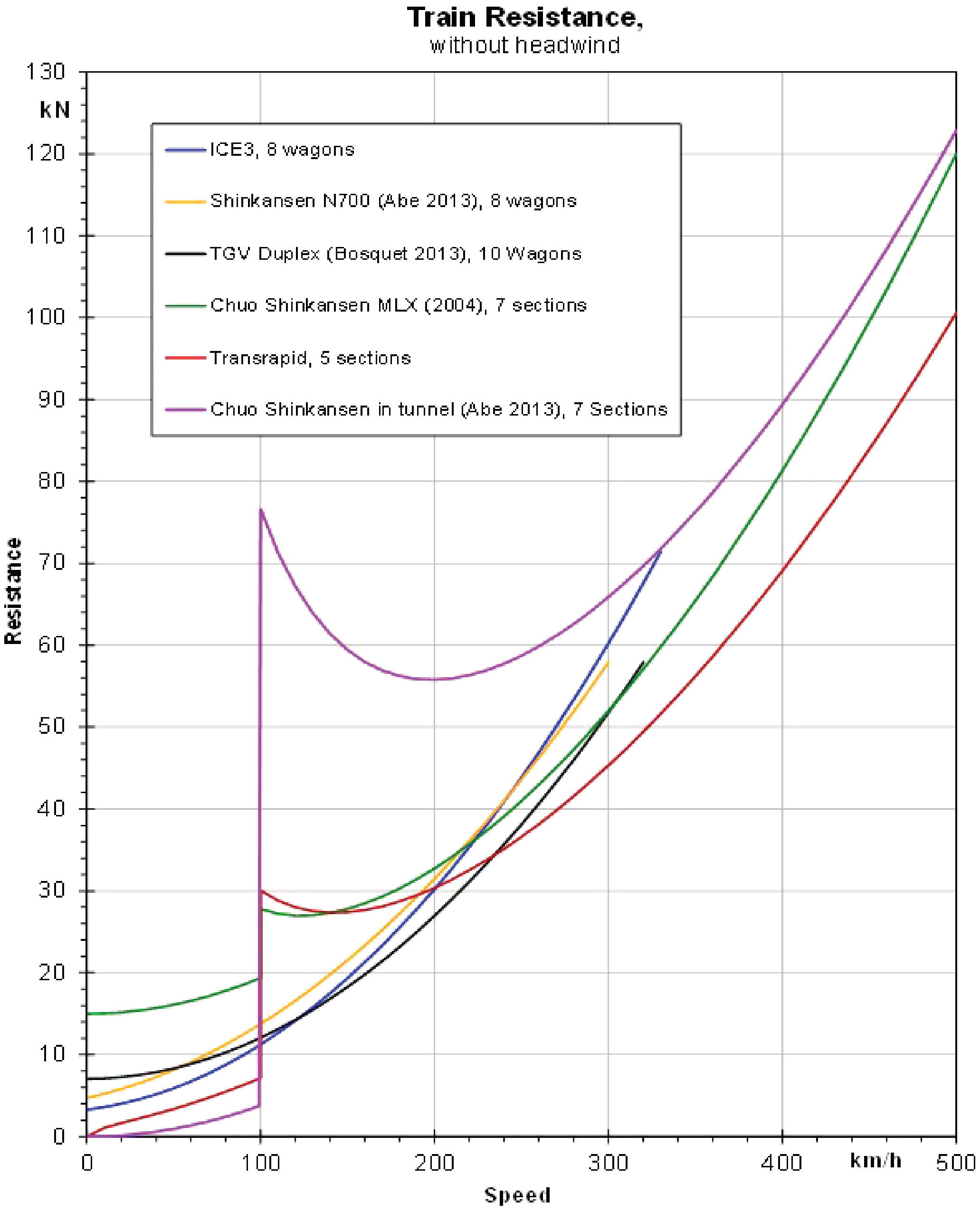

Fig. 2. Driving resistance curves of the considered Wheel-Rail and Maglev systems on an open-air section

Fig. 3 shows the specific secondary energy consumption of the considered systems with reference to 1 seat and a 1-km distance (Wh/Pl/km) depending on the respective maximum speed.

If Maglev systems are operated with short vehicles (e.g., TR with 3 sections), then the drive efficiency is reduced compared to trains with 5 or more sections, depending on the system. In the case of simultaneous use on routes with short distances between stations, and consequently many acceleration and braking sections in the total speed profile, relatively high specific energy consumption values are

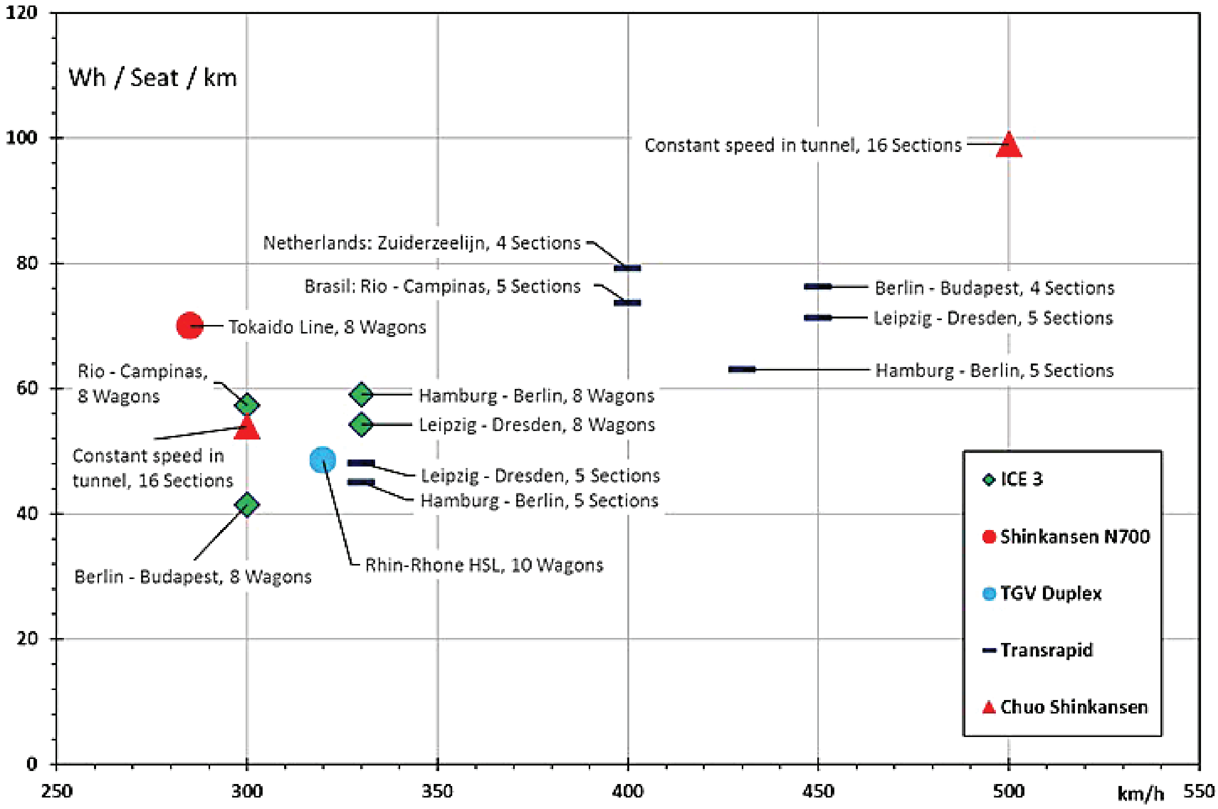

Fig. 3. Conventional representation:
Specific energy consumption of the HRS systems being considered per seat-km (Wh/Pl/km) based on the projects under study. Note on distortion: Different vehicle sizes and seat numbers are being compared. The speed range below 250 km/h is not shown

expected, as shown in the Zuiderzeelijn project (average distance between stations about 20 km [13]). High specific energy consumption values are also expected for routes that are topographically challenging, as in the Rio de Janeiro (sea level) – Campinas route (685 m above sea level [12]).

The comparison of the energy consumption values at 330 km/h is shown in the following Fig. 4 separately for different Wheel-Rail and Maglev systems. At this maximum speed, the Transrapid (5 section vehicle Hamburg - Berlin route) has the lowest energy consumption with 45 Wh/Pl/km, and the ICE 3 has the highest energy consumption on the same route with 59 Wh/Pl/km (+ 31 % compared to Transrapid). It is worth noting here that the Transrapid has just a 7 % higher energy consumption at 430 km/h (+ 30 % higher max. speed) with 63 Wh/Pl/km than the ICE at 330 km/h on the same route.

For long stator systems, it is also necessary to take into account that the synchronous internal voltage (reverse voltage), which varies with the weight, and therefore with the typical system effective area, is not proportional to the power and the energy consumption. The aspect of internal voltage therefore has to be

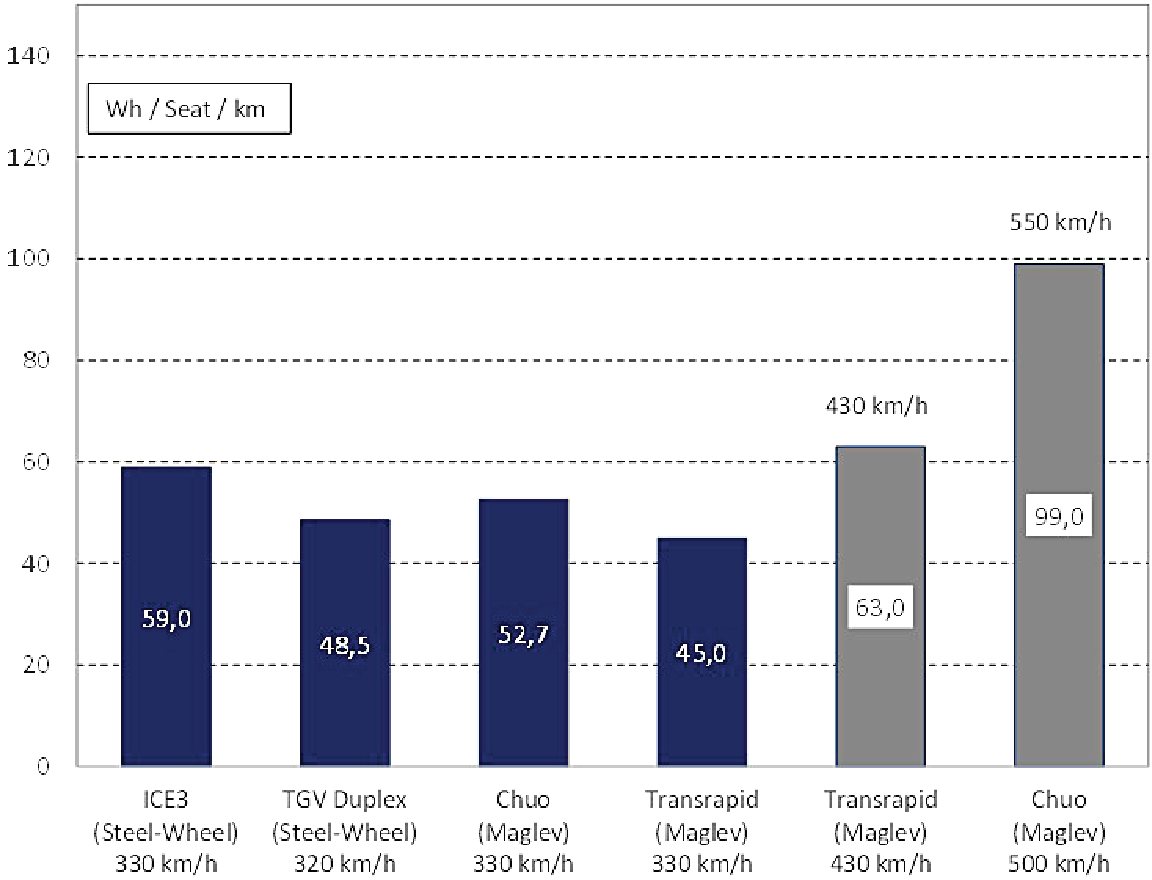

Fig. 4. Specific energy consumption in Wh per seat-km (Wh/Pl/km) at 330, 430 and 500 km/h (conventional representation)

properly determined when calculating the specific energy consumption based on a standardised area, assuming a certain train/vehicle configuration.

For the Japanese Maglev system Chuo Shinkansen, the specific energy consumption at a cruising speed of 300 km/h in the tunnel is 54 Wh/Pl/km [1]. This value is in the same range as values for the ICE 3, based on speed profile simulations. It must be pointed out that the aerodynamic resistance coefficients increase, especially when going through tunnels, as compared to open-air routes, which inevitably leads to higher energy consumption values *for all railway systems.*

The energy consumption values of the two Maglev systems, Transrapid and Chuo Shinkansen, on an open-air route are comparable at a maximum speed of 450 km/h – Transrapid with 76 Wh/Pl/km (Berlin – Budapest route [11]) and 71 Wh/Pl/km (Leipzig – Dresden route [4]) and Chuo Shinkansen with 78 Wh/Pl/km. The specific energy consumption of 99 Wh/Pl/km mentioned by S. Abe [1] is significantly higher for the Chuo Shinkansen at a cruising speed of 500 km/h in the tunnel, based on the Tokyo-Osaka route. This high value is essentially due to the increase in driving resistance, which increases by 15 to 20 % from 450 km/h to 500 km/h on an open-air route (Fig. 2). Moreover, the additional aerodynamic driving resistance component due to the tunnel route assumes considerably higher values that need to be overcome by the drive system. Based on the information available for the Japanese Maglev system, it is assumed that most of the route (approx. 80 %) is through the tunnel, and the higher values are therefore realistic.

5. SPECIFIC ENERGY CONSUMPTION ACCORDING TO TYPICAL SYSTEM EFFECTIVE AREA (NEW APPROACH)

To answer the question of how energy consumption depends on operating speed for a system with standardised effective area for a specific High-Speed railway system (TGV, ICE, Shinkansen, Transrapid or Chuo Maglev), the seat-based approach is not adequate, as the available effective area also depends on the technology used. The previous approach based on 'Wh per seat and kilometre' will therefore be amended and extended to include a new, more practical representation based on the actual *system-typical effective area* of High-Speed railway systems.

APPROACH

- The first step is to define and calculate the system-typical effective areas of the different systems under consideration (section 5.1);
- The second step is to standardise the results mathematically to a common reference: an effective area of 500 m² (section 5.2).

5.1. Definition of 'system typical effective area'

Railway systems can be distinguished based on the ratio of basic technical area (length x width, in m²) to the effective area. To determine the effective area, all the technical areas required by the system – and essential for the system operation – have to be deducted from the basic technical area.

In the case of Wheel-Rail trains, the essential system areas at present are the driver's cabs; in the case of automated Maglev systems, e.g., the unusable areas of the crash zones, the (empty) driver cabs or the technical installations in the interior. In contrast to these technical system installations (and their respective space requirement), air conditioning systems, restaurant kitchens, sanitary equipment,

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etc., form part of optional installations, are omitted, because they can be configured based on the choice of the operator.

The calculation of system-typical effective areas of the High-Speed railway systems being considered is shown in Table 1 as defined below:

Table 2. Definition of system-typical effective area of High-Speed railway systems

Effective area calculation		
ICE, TGV, Shinkansen N 700	***TR 08 (Maglev)***	***Chuo Shinkansen Maglev L0***
Calculated basic area minus driver cab areas and crash zones. Restaurant cars are considered as passenger cars	Calculated basic area minus driver cab areas and crash zones in the two bow sections	Calculated basic area minus areas for 16 m bow section projections, and minus areas of interior fittings for magnetic coils & shielding
• ICE = 538 m² • TGV = 533 m²; calculated like ICE 3 • N 700 = 627 m²	• TR 08 = 331/423 m² (depends on configuration, see table 1)	• 156 to 660 m² (depends on configuration, see table 1)
Sources: • TGV Duplex Dasye [8] • Shinkansen N 700 [5, 16] • ICE 3: Manufacturer details	Sources: [4] and manufacturer details	Sources: [1, 2, 3]

An alternative criterion of comparison, which may specifically appear to be useful for freight transport applications, is the energy consumption per tonne and kilometer depending on the speed. However, this criterion is not used in this study because we are considering passenger traffic and not the transport of heavy loads, as in container transport. None of the established High-Speed railway systems is designed for transporting heavy goods. However, transport of light goods or mail transport is possible.

5.1.1. Effective area and seating density of the chuo shinkansen maglev L0

To clarify the available data (based on Japanese sources [1, 2, 3] an overview of the values determined for the Maglev L0 is first shown in Table 3, because this system appears to be the least scientifically documented.

The actual available effective area of the Maglev L0 is reduced by about one quarter, based on the assumptions measured at technical basic area of the Maglev L0.

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Table 3. Effective area and seating density of the Chuo Shinkansen Maglev L0

	Length in m	**Width in m**	**= Basic area in m²**	**Effective area in m² calculated**	**Seats**	**Minimum seats calculated**	**Maximum seats calculated**
Bow section (BS)	28	2.9	81.2	about 50	24	24	24
Middle car (MW)	24.3	2.9	70.47	about 56	58 to 68	58	68
10 MW + 2 BS	299	2.9	867.1	about 660	604 to 704	628	728

5.2. Comparison of railway systems by system typical effective area

5.2.1. Energy consumption of the wheel-rail systems based on system typical effective area

For realistic clearances of N 700 with a maximum speed of 285 km/h [14], the specific energy consumption is 60 Wh/m²/km with respect to the typical system effective area. This is partly much higher than the values of comparable Wheel-Rail systems at 300 km/h: ICE 3 routes Berlin – Budapest (35 Wh/m²/km, [11]) and Rio – Campinas (51 Wh/m²/km [12]).

5.2.2. Energy consumption of the maglev systems based on system-typical effective area

When comparing the Maglev systems at a maximum speed of 330 km/h, as well as at 450 km/h, the values are almost the same for the Japanese and the German system (see Table 4). The very high and constant value of the Japanese system at 500 km/h is mainly due to the high aerodynamic resistance in tunnels, in addition to the high driving resistance of the vehicle.

Table 4. Energy consumption of the Maglev systems, calculated based on system-typical effective area for different applications

	Leipzig – Dresden 330 km/h	**Leipzig – Dresden 450 km/h**	**Berlin – Budapest 450 km/h**	**constant 500 km/h**
Chuo Shinkansen	51 Wh/m²/km	75 Wh/m²/km	–	112 Wh/m²/km
TR 08	51 Wh/m²/km	75 Wh/m²/km	83 Wh/m²/km	–

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In general, it can be seen that the energy consumption values across systems (based on the typical system effective area) become similar when compared to the specific energy consumption values based on the number of seats. Fig. 5 illustrates this situation.

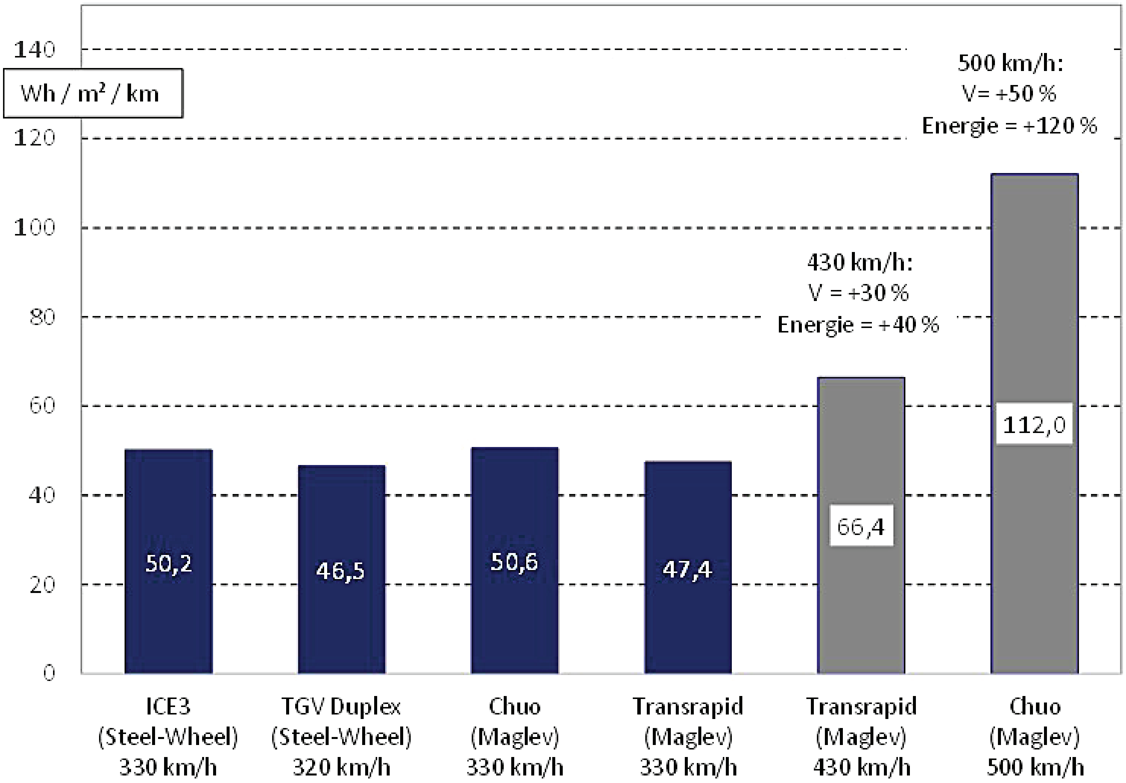

Fig. 5. Specific energy consumption per m²-km of system-typical effective area at 330 km/h and 500 km/h

The differences in the energy consumption values between the discussed systems are less than 10 % up to 330 km/h.

5.2.3. Interpretation of the results

None of the considered systems has any significant advantages in terms of energy consumption based on the criteria of effective area. Thus, same-speed energy consumption is therefore not a relevant criterion for any decision for or against a certain high speed railway system.

Project- and operator-related specifications, such as seating densities and the mix of 1st and 2nd class, are not considered when determining the specific energy consumption based on the effective area. Fig. 6 shows the calculated results of the specific energy consumption based on the respective effective area *for several*

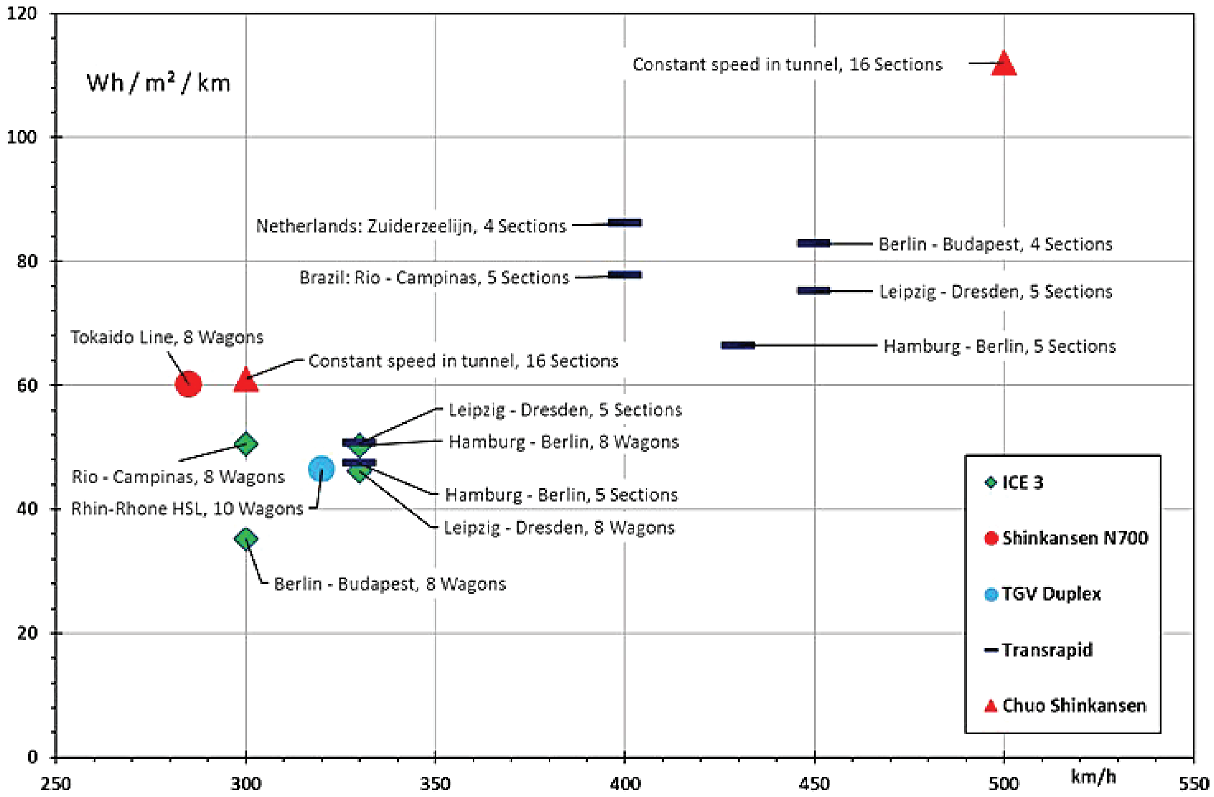

Fig. 6. Specific energy consumption of the HSR systems being considered in Wh per m²-km (system typical effective area) for various applications (projects). Comment: The speed range under 250 km/h is not shown here for purposes of better readability

applications. From the authors' point of view, this is a more realistic and therefore preferable approach compared to the conventional method.

5.3. System comparison based on a calculated standardised effective area

To compare the HSR systems being considered on the same system-typical effective area, the energy consumption values are based on 500 m² of the system-typical effective area per vehicle for all systems. This value was chosen by taking into account the system-typical effective area of the systems in this study (see the summary in Table 1).

Fig. 7 shows the specific energy consumption of various HSR systems based on a typical system effective area of 500 m² per system at a maximum speed of 330 km/h, taking into account the above-mentioned inherent property of the long stator drive system. This representation now allows statements about the specific energy consumption for different railway systems with a system-typical effective area of 500 m². For the applications shown in Fig. 7, the specific energy consumption

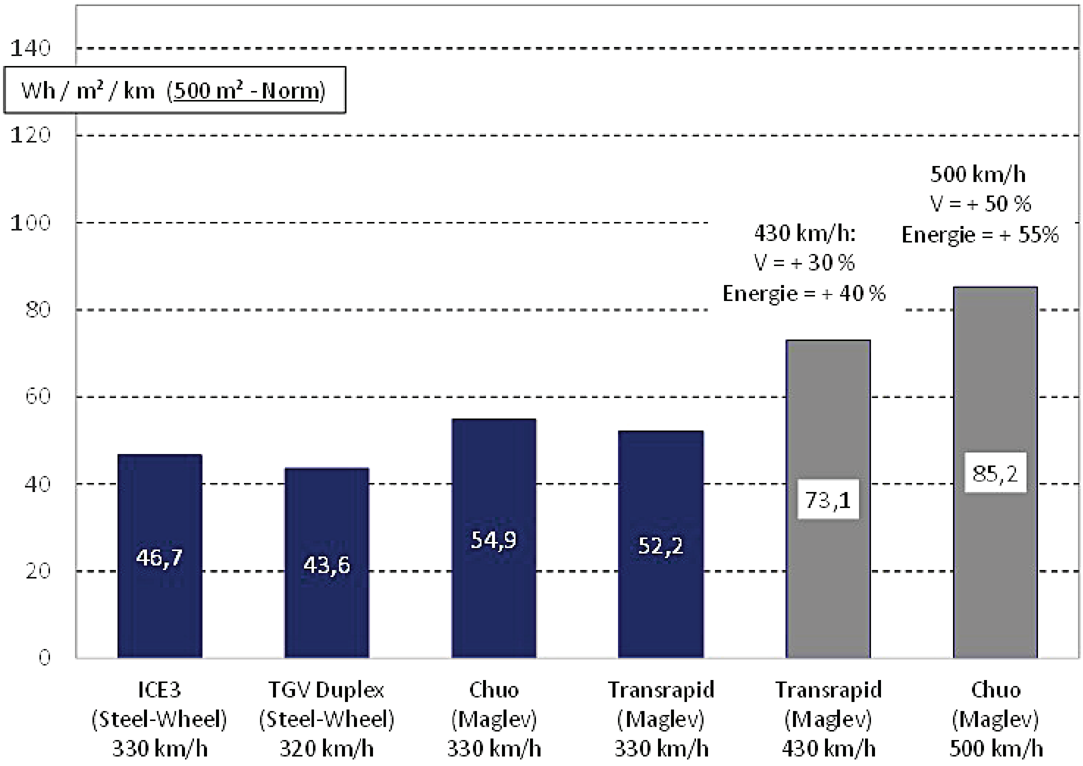

Fig. 7. Specific energy consumption per m²-km at 330 km/h to 500 km/h, calculated for a typical system effective area of 500 m² per system

of the HSR systems are comparable between 45 Wh/m²/km and 55 Wh/m²/km. The long stator systems have an approximately 10–15 % higher specific energy consumption than the comparable Wheel-Rail systems (330 km/h).

The specific energy consumption for different applications can also be calculated in kWh/km based on a standardised system-typical effective area of railway systems (500 m²):

Table 5. Specific energy consumption in kWh/km for standardised effective area of 500 m² per system, mathematical comparison for different applications

	Application being considered	**Average specific energy consumption**
Transrapid	Hamburg – Berlin, 330 km/h	26 kWh/km
Transrapid	Hamburg – Berlin, 430 km/h	36 kWh/km
Transrapid	Leipzig – Dresden, 450 km/h	41 kWh/km
Chuo Shinkansen	Leipzig – Dresden, 330 km/h	27 kWh/km
Chuo Shinkansen	Tokyo – Nagoya – Osaka, 500 km/h	85 kWh/km (cruising)
ICE 3	Hamburg – Berlin, 330 km/h	23 kWh/km
TGV Duplex	Rhine – Rhone, 320 km/h	22 kWh/km

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Due to the strong project-specific and design-specific influences on the energy consumption, particularly in case of the Maglev systems, the results shown in Fig. 7 and Table 5 cannot be generalized for other applications. Nevertheless, the specific data derived can be used as a reference for estimating the energy consumption values for comparable projects with the same levels of speed.

5.3.1. Results

By referring to the already mentioned incomplete information and uncertainties, the considered High-Speed railway systems can be mathematically compared based on a standardised effective area (here: 500 m²). The results are the best possible approximation to reality with the mentioned restrictions.

Further detailed representations may be possible only if the respective manufacturers and operators of High-Speed railway systems provide additional, verifiable technical parameters of the railway systems or energy consumption data from implemented applications for scientific analyses.

6. SUMMARY

In the past, High-Speed railway systems were often compared based on Wh/Pl/km with regard to their energy consumption. The previously published comparisons could be interpreted in many different ways because the systems being considered have very different characteristics when compared directly (basic area, effective area, or weights). In order to objectively compare railway systems, the comparison should be carried out on a uniform basis. In this study, the comparison was carried out based on the same system-typical effective area. The electrical energy required for operating a high-speed system has been investigated with a standardised effective area depending on the speed, based on a certain High-Speed railway system (TGV, ICE, Shinkansen, Transrapid and Chuo Maglev).

Comparative statements about the specific energy consumption always depend on the route and the application, owing to various system-related properties of the railway systems under consideration. An accurate evaluation of the energy consumption of the systems is only possible when based on the same boundary conditions (route, clearance, maximum speed, vehicle configuration, etc.). However, based on the data available at present, and considering existing information and missing data, the energy consumption of various railway systems can be approximately compared.

For a comparative assessment of the specific energy consumption values of the railway systems being studied, it also makes sense to specify ranges for these

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values. In general, the range of the specific energy consumption increases due to the increase in driving resistance and the associated power consumption, which characteristically increases with the maximum speed. Various other operational and technical design parameters also influence the specific energy consumption.

Based on the existing data, the following ranges are, in principle, available for the specific energy consumption of High-Speed railway systems:

- The specific energy consumption of High-Speed Wheel-Rail systems is in the typical system speed range between 300 to 330 km/h – 40 Wh/Pl/km (ICE 3) and 70 Wh/Pl/km (N 700) or between 35 Wh/m²/km (ICE 3) and 60 Wh/m²/km (N 700);
- The specific energy consumption of the Maglev systems Transrapid and MLX/Chuo Shinkansen is in the speed range from 330 km/h to 500 km/h – between 45 Wh/Pl/km (TR) and 100 Wh/Pl/km (Chuo) or between 50 Wh/m²/km (TR) and 110 Wh/m²/km (Chuo);
- Based on a calculated standardised system-typical effective area of 500 m² per railway system, specific energy consumption values between 22 kWh/km (TGV) and 27 kWh/km (Chuo) are obtained for the railway systems being studied at a maximum speed of 330 km/h;
- Based on a calculated standardised system-typical effective area of 500 m² per Maglev system, specific energy consumption values between 36 kWh/km (TR) and 85 kWh/km (Chuo) are obtained for the Maglev systems in the speed range between 430 to 500 km/h.

CONCLUSION

This comparison of High-Speed railway systems shows that if the same speed range up to 330 km/h is considered, none of the systems being studied shows significant advantages in terms of energy consumption. At this designed speed, which is currently the limit of a reasonable operational application of Wheel-Rail systems, there are slight advantages in terms of energy consumption, at least for the Transrapid. In addition, only High-Speed Maglev systems can be operated economically at significantly higher speeds.

Since the Japanese Maglev system between Tokyo and Nagoya is almost entirely operated along a tunnel route, the energy consumption for the Chuo-Shinkansen system is considerably higher due to the very high tunnel resistance in the High-Speed range when compared to the previous Transrapid projects, which were mostly elevated or ground-level routes without long tunnel sections.

On the whole, this study shows that High-Speed Maglev systems can be objectively considered to be operationally advantageous and useful transport systems from the perspective of energy consumption, especially in the area of High-Speed transport exceeding 300 km/h. If the objective is to reduce travel time and thereby achieve a high speed of a transport system, then High-Speed Maglev systems represent a promising option from an energy consumption point of view, which should always be included in the planning stage of railway projects.

From the perspective of the authors, the planning of High-Speed routes is therefore complete, future-oriented and non-discriminatory *only if all the possible railway system options are considered*. A system decision, which is also based on the power or energy related aspects, should be open to different technologies and should therefore include High-Speed Maglev systems right from the beginning.

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STUDY ON THE OPTIMIZATION OF LINEAR INDUCTION MOTOR TRACTION SYSTEM FOR FAST-SPEED MAGLEV TRAIN

Background: The short stator linear induction motor (LIM) is normally used in medium-low speed maglev train.

The restriction by mounting space on bogie and motor input voltage from the third power supply rail lead that the maximum speed of medium-low speed maglev train can reach no more than 120 km/h.

Aim: In this paper, by means of the LIM design optimization, improvement of the LIM force characteristic in high speed range, the maximum speed of medium-low speed maglev train can reach 160 km/h.

Methods: After comparing the LIM theoretical calculation and actual test data, it shows that the new designed LIM is effective.

Conclusion: Afterwards, by installing the new designed LIMs, the traditional medium-low speed maglev train becomes a fast-speed maglev train, and it has a bright future in transportation applications.

Keywords: linear induction motor, maglev train, medium-low speed, fast-speed, suspension bogie, traction system, F-shaped track, Changsha maglev express.

INTRODUCTION

Till now, three maglev research and development groups in China have respectively built three 1.5~1.7 km long medium-low speed maglev engineering test line in Zhuzhou, ShanghaiandTangshan. All these three test trains on the three test lines use linear induction motors (LIM) with VVVF converter and control system. Due to the restriction of mounting space on the suspension bogie and motor input voltage (DC 1500V converted for 5 series connection motors), the maglev train can reach the highest limit speed about 100 km/h.

As China's first, the world's longest commercial short stator medium-low speed maglev line – Changsha maglev express was put into application in 2016, the medium-low speed maglev train with advantages of green, quiet and comfortable, strong climbing ability, small turning radius and low construction cost, reflects the strong adaptability to the environment and higher economy in city rail transportation

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applications [1]. The Changsha maglev express as showed in Fig. 1 uses short stator linear induction motor (LIM, the structure is indicated in Fig. 2) to drive, since LIM with simple structure and no intermediate transmission device that can directly generate linear movement thrust, has been widely used in the fields of industry applications such as transportation, maglev train, subway / light rail train, piling machine, pumping device, electric vehicle door [2, 3]. Maglev train with no traditional wheel and rail, and the state of train operation, such as traction and braking, positive and reverse operation, is completely realized by linear motor frequency converter system. The main circuit of the traction system of maglev train consists of traction inverter, linear motor and corresponding control and detection circuit [4]. Due to the special structure of the maglev vehicle, the linear motor in the medium-low speed maglev train with the short length of air gap, terrible electromagnetic load, weight index of strict restrictions, leads to some difficulties for the design and manufacture. Generally, in order to achieve matched traction / braking characteristics, the speed of the maglev train resistance characteristics is calculated firstly, then, the related technical parameters and the design of single motor and traction inverter for obtaining the required traction power and traction characteristics are specified.

Many researches of the design and performance analysis of LIM have been done around the word, and in those researches also a lot of simulations and measurements are carried out [5, 6]. With some of those studies, the formation of improvement design of LIM have provided experience for faster speed applications.

For some application situations of urban or suburban, higher maximum speed maglev trains are expected, for example airport or satellite city connection

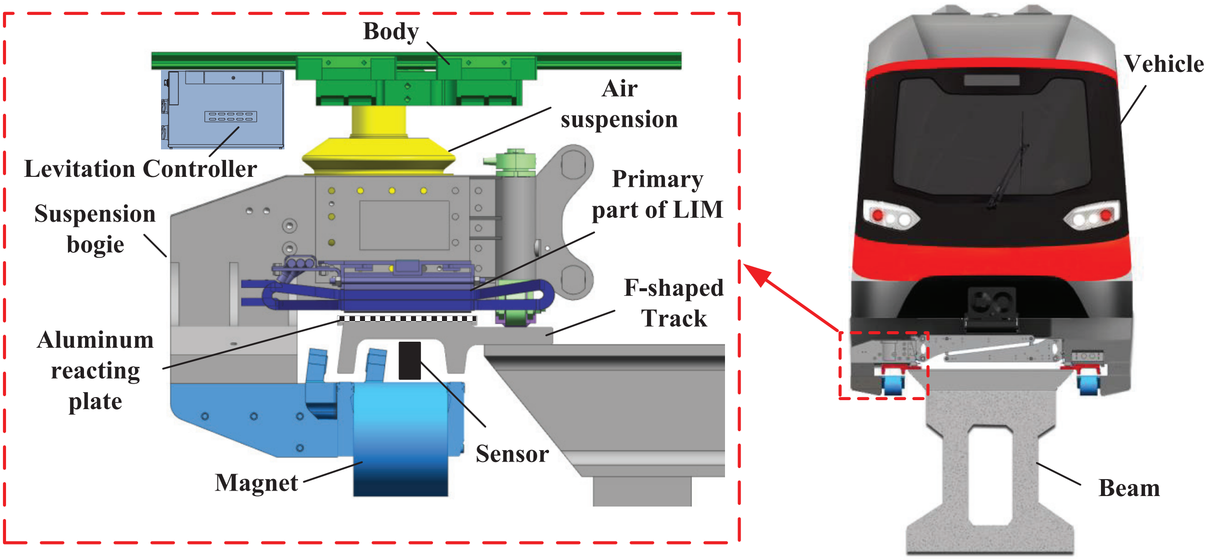

Fig. 1. The levitation and traction structure of medium-lowspeed maglev train

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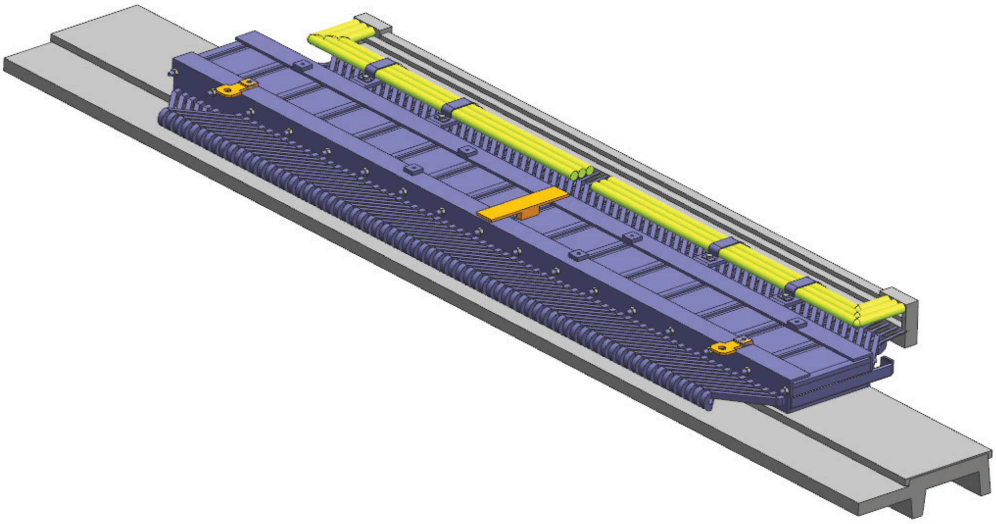

Fig. 2. The primary and secondary parts of a LIM

to downtown. Therefore, a new LIM is specially proposed and realized to meet the higher speed requirement. Through optimization of the traction system including VVVF converter, the highest speed could reachup to 160 km/h according to theoretical calculation and actual comparison.

DESIGN OF THE NEW LIM FAST-SPEED MAGLEV TRAIN IN COMPARISON WITH THE ORIGINAL LIM FOR CHANGSHA MAGLEV EXPRESS

Tab.1 shows the main parameter and dimension of the LIM which is utilized in 160 km/h fast-speed maglev train and the LIM which is used in Changsha maglev express. The whole speed rang force calculation showed that with the new LIM the train has the ability to run up to 160 km/h.

Table 1. Design data and performance of the new LIM for Fast-speed Maglev Train and the original LIM for Changsha maglev express

Items	Design Data	Sign	LIM of Fast-speed Maglev Train	LIM of Changsha Maglev Express
Perfor-mance	Max.linevoltage (RMS)	V	220 V	220 V
	Max.primarycurrent	I_1	450 A	340 A
	Capacity	S	170 kVA	130 kVA
	Max.outputpower	P_m	48 kW	36 kw
	Max.thrust	F_m	2800 N	3100 N
	Max. speed	v_m	160 km/h	100 km/h

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Items	Design Data	Sign	LIM of Fast-speed Maglev Train	LIM of Changsha Maglev Express
Stator Parameter	Numberofphases	m	3	3
	Numberofpoles	2p	8	8
	Polepitch	t	225 mm	202.5 mm
	Lengthofstator	L	2020 mm	1820 mm
	Thicknessofironcore	H	220 mm	220 mm
	Heightofironcore	d_a	58 mm	58 mm
	Overalldimensions		2020×600×110 mm	1820×580×101 mm
	Numberofstatorslots		80	80
	Windingconstruction		doublelayerlapwinding	doublelayerlapwinding
	Wirematerials		silk-coveredaluminiumwire	silk-coveredaluminiumwire
	Coolingmethod		Naturalwindcooling	Naturalwindcooling

Fig. 3. Traction characteristic curve of the original LIM for Changsha maglev express (calculation with constant slip frequency 13.7 Hz)

As can be seen from Fig. 5, 6 and Tab. 2, the new LIM has better performance of equivalent stress and deformation than the original LIM.

PRODUCTION AND INSTALLATION OF THE LIMS

Since the new LIM is only 200 mm longer than the original LIM, the suspension bogie size of Fast-speed maglev train is unchangeable with respect to Changsha maglev express. With consideration of the support wheel and skids, some incidental modifications of the new LIM has been carried out (Fig. 7, 8).

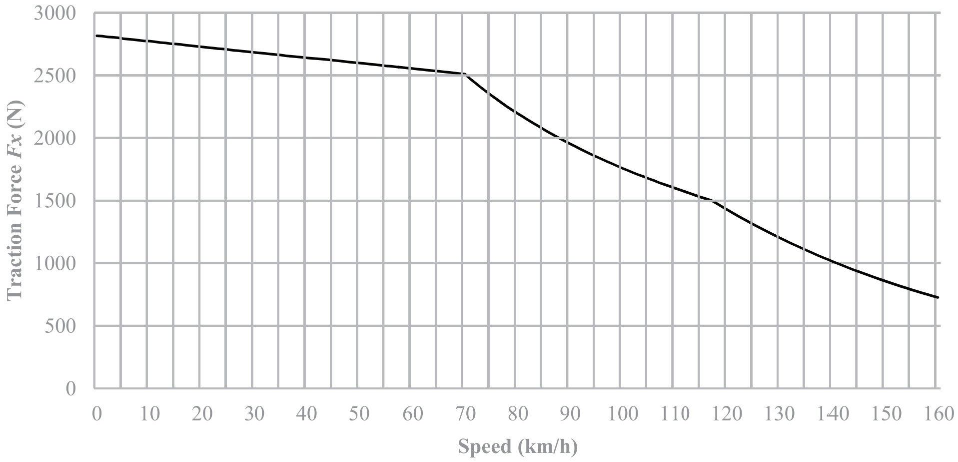

Fig. 4. Traction characteristic curve of the new LIM for Fast-speed maglev train (calculation with constant slip frequency 15 Hz)

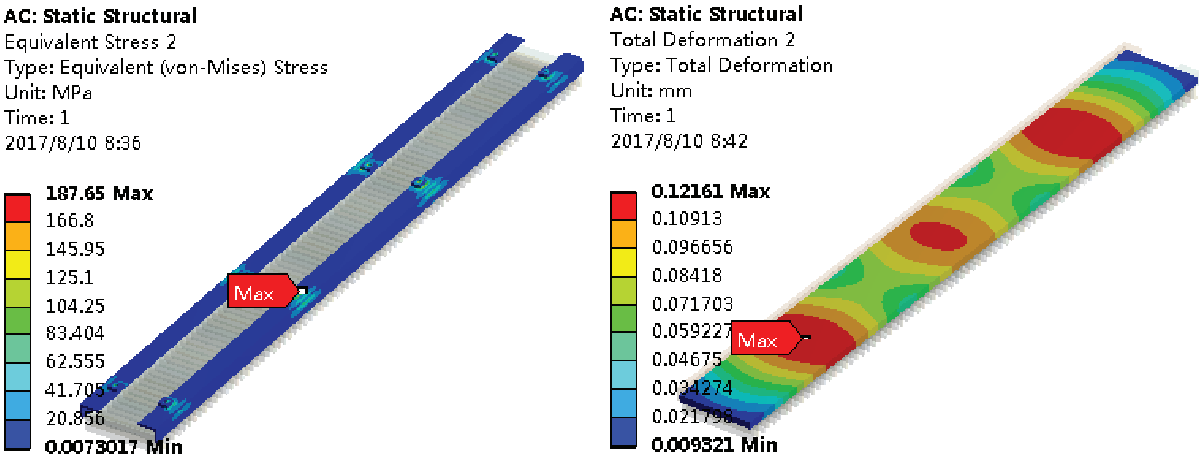

Fig. 5. Equivalent stress and deformation calculations of the original LIM for Changsha maglev express (impact acceleration value 15 g)

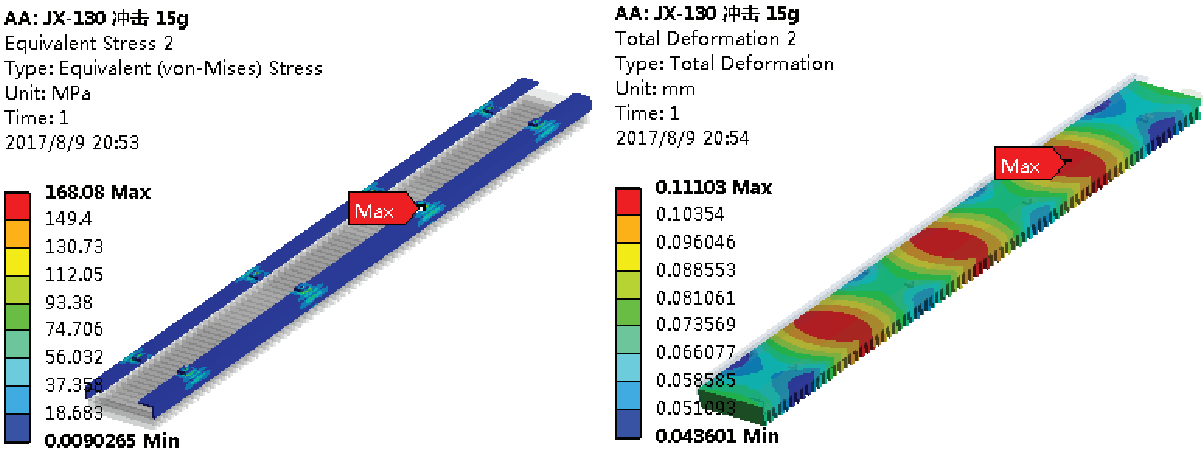

Fig. 6. Equivalent stress and deformation calculations of the new LIM for Fast-speed Maglev Train (impact acceleration value 15 g)

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Table 2. The Statistical results of equivalent stress and deformation

Model	Max. Equivalent Stress (MPa)	Max.Deformation (mm)	Yield strength of material (MPa)
Theoriginal LIM	188	0.122	235
Thenew LIM	168	0.111	235

Table 3. The Statistical results of traction and breaking

Operation	Items	The new LIM		The original LIM	
		Speed (km/h)	Thrust (N)	Speed (km/h)	Thrust (N)
Traction	Start-up	0	2816	0	3105
	Turning point	70	2508	41	2920
	Max. speed point	160	726	100	708
Breaking	Turning point end	5	2820	5	3198
	Turning point start	135	2744	85	3198
	Max. speed point	160	1593	100	1938

Fig. 7. The Original LIM (1820 mm)

Fig. 8. The New designed LIM (2020 mm)

The support wheels and skids of the Fast-speed maglev train are similar with the ones of Changsha Maglev Express, which are located by the end of the suspension bogie close to the end of the LIM windings (Fig. 9, 10).

The Fast-speed maglev train with the new LIMs is composed of 3 marshalling vehicles, andeach vehicleowns5suspension bogies. The input DC 1500 V is converted to alternative voltage and equally distributed tofive series connection LIMs. The maximum voltage foreach LIM is about AC 220 V. According to the propulsion calculation and whole-size model simulation with Finite Element Analysis (FEA), the maximum speed of the maglev train equipped with new LIMs is up to 160km/h, and the remainder acceleration value is 0.15 m/s^2.

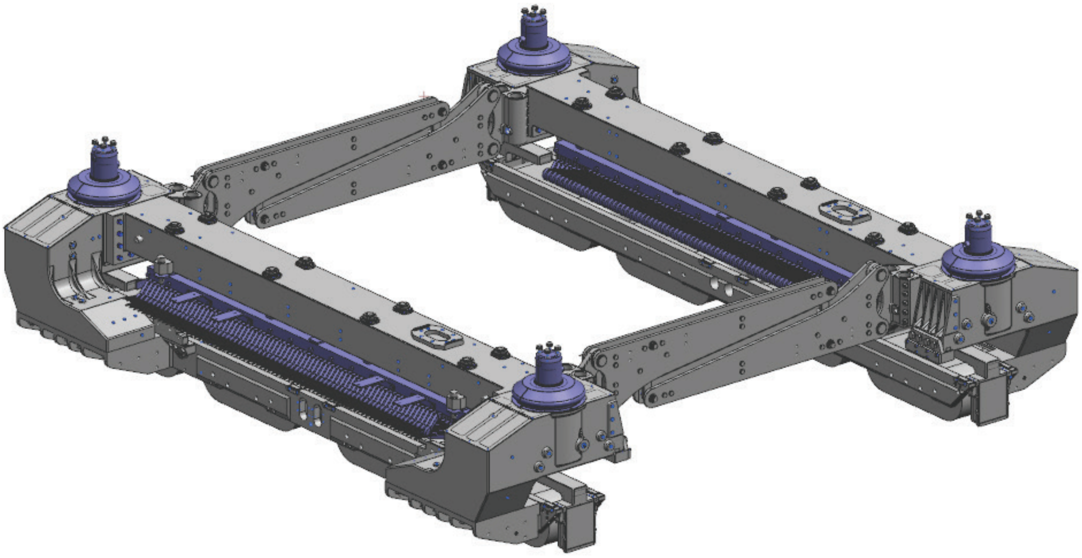

Fig. 9. The original suspension bogie applied in the Changsha Maglev Express

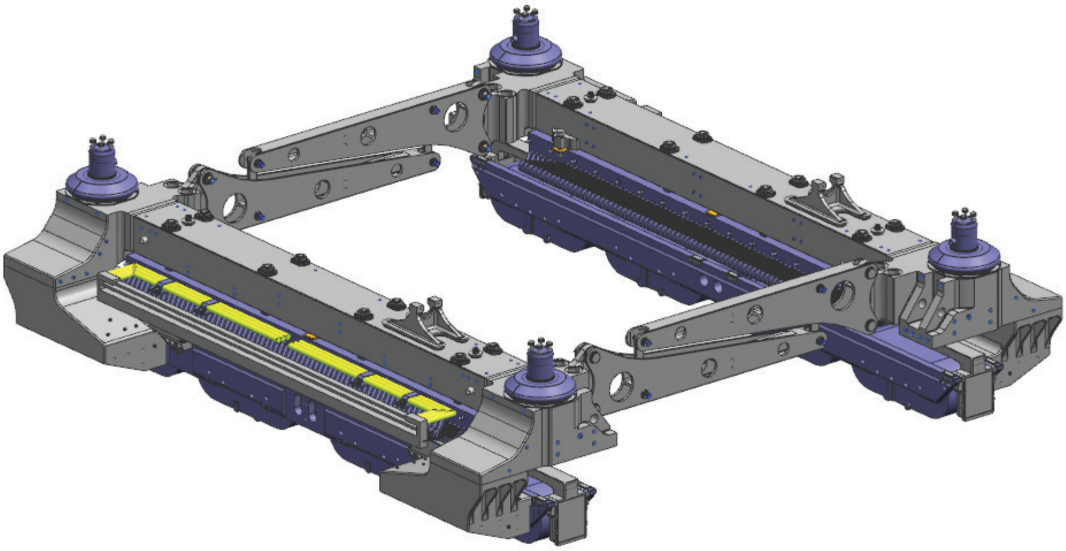

Fig. 10. The new designed suspension bogie for Fast-speed Maglev Train

CONCLUSION

The fast-speedmaglev train with three vehicles marshalling has been produced and tested on the Zhuzhoumedium-lowspeed maglev test line (Fig. 11) in the middle of 2018. The new designed LIMs' propulsion and suspension bogie dynamic performance weretotally verified, but due to the limitation that the length of test line is only 1.55 km, the maximum running speed was 70 km/h.

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Fig. 11. Zhuzhou Fast-speed maglev train with three vehicles marshalling (in 2018)

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EMPIRICAL INVESTIGATION OF POSSIBLE CONCERNS REGARDING THE USE OF MAGNETIC LEVITATION ELEVATORS

Aim: This study focused on an issue regarding an innovation of magnetic levitation elevators which was by different media coverage indicated as being unresolved: Are potential users of magnetic levitation elevators concerned about the safe use of these elevators and, if so, what kind of concerns exist?

Methods: To contribute a first scientifically sound assessment to this, a three-day face-to-face survey at the elevator test tower in Rottweil (Baden-Wuerttemberg), where aforesaid elevator technology is tested, has been conducted. (Touristic) visitors of the tower and the observation platform on it have been surveyed a standardized questionnaire.

Results: The results have shown that the average tendency of prospective conceivable users tends to be free of concerns. In addition, a share of about one-sixth has both expressed and concretized concerns. Those relate mainly to new characteristics of this elevator technology – absence of ropes, magnetic levitation, magnetic field presence – partially associated with known aspects such as power loss.

Conclusion: The study provides an explorative contribution to the topic described. Thusly it seems to be particularly interesting for both researchers willing to look further at this or similar areas and manufacturers or future clients of the technology in the context of, for instance, communicating its prospective implementations.

Keywords: Maglev Elevators, Concerns of Use, Multi, Prospective Use, Safety

INTRODUCTION

A levitation system based on magnetic levitation technology, which is intended to enable vertical as well as horizontal movement of cable-free elevator cars, has lately been attracting attention in industry, mobility sector and public. Based on the principle of the paternoster, the elevator system should allow several cabins to circulate independently of each other in a shaft circuit. According to its German developer the innovation can be an important factor influencing future mobility in cities in the context of advancing urbanization and rising skyscraper construction [1].

At the time of this study (November/December 2017) tests were carried out in a company-owned elevator test tower in Rottweil (Baden-Wuerttemberg) [2]. Yet, no persons were allowed to ride in tested prototypes, since qualifying certifications were still outstanding [3, 4].

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Safety aspects are generally considered to be one of the main challenges in the realization of the technology as new systems and interaction "beyond known concepts [5]" are necessary. Accordingly, when promoting the magnetic levitation elevator phrases like „Fokus auf Sicherheit [1]" („focus on safety") or safety as „Schlüsselbegriff [6]" („key term") are used.

While the general public was dominated by enthusiasm for the progress made possible through this elevator innovation, aspects of safety regarding the potential use occasionally sparked concerns in editorial reports. Accordingly, the following question appeared to be in need of an answer:

Are potential users of magnetic levitation elevators concerned about the safe use of these elevators and, if so, what kind of concerns exist?

In a scarcely considered scientific field this work – hereafter presented in highly compressed shape – should enable to formulate a first objective assessment regarding the existence of concerns and their possible manifestations.

METHODOLOGY & THEORETICAL APPROACH

In order to handle the topic adequately, the survey was chosen as the central methodology. More specifically, a three-day quantitative empirical investigation – realized by a standardized face-to-face questionnaire – was carried out to visitors of above-mentioned elevator tower in Rottweil.

Basically – not excluding own researching resources as a cause – no scientifically founded state of research on explicitly considered subject matter seemed to exist. Hence, it was necessary to both gain orientation on the basis of helpful theoretical topics and, in particular, develop guidelines as well as circumstances for the survey itself.

In Fig. 1 presented key content for the questionnaire arose based on findings from known concerns regarding elevator use, of the value of safety in the exercise of mobility, of technology acceptance tendencies and of individual risk assessment for the use of (new) mobility technologies – combined with an analytical consideration of the central issue.

Results of the subconscious and intuitive assessment of the use by a semantic polarity profile as well as of the open and concrete questioning of possible concerns should enable an answering of the central issue.

CONDENSED RESULTS

In total, 197 persons were questioned the complete questionnaire – almost two-thirds had already heard of the magnetic levitation elevator.

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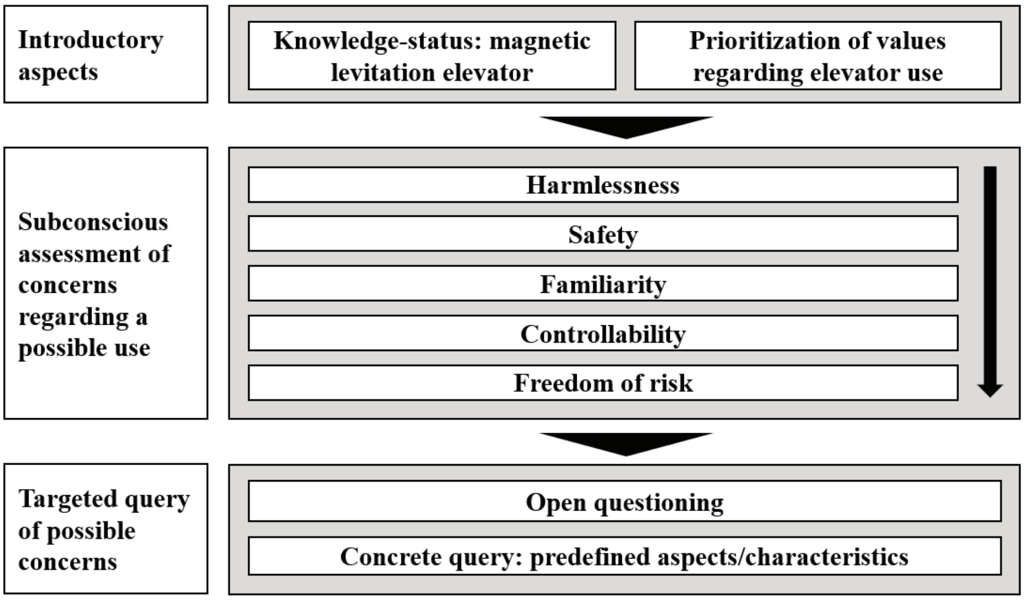

Fig. 1. Substantial-chronological structure of the questionnaire

Central aspects of the survey revealed the following compressed discussion approaches and results, thematically depicted according to predefined guiding questions.

- How important is the personal value of safety regarding the use of elevators?

Among five predefined values, safety was rated as the most important value in elevator driving by 50.2 % of the sample size. Furthermore, for 24.4 % of the respondents it was the second most important value while another 25.4 % put at least two other values above safety.

Thusly, in the overall trend safety appeared to be the dominant feature by some margin followed by speed, availability, ride comfort and cabin design. The findings suggested that a large proportion of potential users of maglev elevators would prefer safety against effectiveness and/or efficiency. Above all, 'being safe' or 'feeling safe' combined with 'moving quickly and ideally immediately' seems to be important to many people in terms of elevator usage.

- How does the average potential user subconsciously assess a possible ride with the maglev elevator regarding personal concerns?
- Are there any differences regarding concerns among potential users and, if so, how do they share proportionally?
- Are there any connections between a subconscious assessment of concerns and their concrete questioning and, if so, which ones?

As Fig. 2 shows, respondents rated a potential ride with the magnetic levitation elevator as rather harmless with a slight tendency towards the middle. Furthermore, a possible trip was averagely considered fairly safe. Beyond that, interviewees estimated a potential usage between undecided and rather unfamiliar with a slight bias towards the former. Irresolution was dominating in terms of the 'controllability' while the sample average, slightly tending towards the middle, estimated a conceivable ride as rather risk-free.

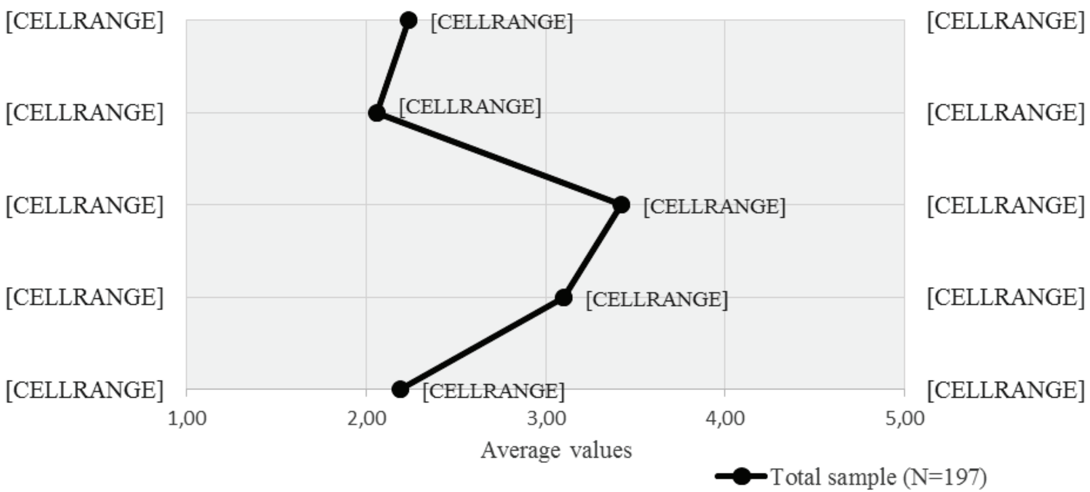

Fig. 2. Semantic profile of the total sample (N=197)
Question: „Please assess from your perspective a possible ride with the magnetic levitation elevator by using the following contrastive pairs“

Further analysis showed that the personal assessment of the 'harmlessness', 'safety' and 'freedom of risk' are positively linked in terms of judging a potential trip with a magnetic levitation elevator. Therefore – with a moderately correlated interrelation (r = 0.586, significance level 0.01) – respondents appear to be more likely to assess a possible use as rather safe if they also consider it to be rather harmless (and contrariwise). Similar statements can be made regarding the other connections of this triumvirate of dimensions.

In addition to the consideration of these overall trends, possible categorical differences should be taken into account via an individual calculation methodology.

Relating to the polarity profile as in Table 1, the results of each questionnaire were determined using the following formula:

$$y_n = (x_{n1} + x_{n2}) \times 1.0 + (x_{n3} + x_{n4} + x_{n5}) \times 0.5$$

Scores ranging from $y_n = 7.0$ to $y_n = -7.0$ were possible and every respondent could be assigned according to predefined categories of concerns. The outcome can be seen in Fig. 3.

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Table 1. Logic for the individual calculation methodology

	$x_n =$	2.0	1.0	0	−1.0	−2.0		Weighting
x_{n1}	harmless	☐	☐	☐	☐	☐	worrying	×1.0
x_{n2}	safe	☐	☐	☐	☐	☐	unsafe	×1.0
x_{n3}	familiar	☐	☐	☐	☐	☐	unfamiliar	×0.5
x_{n4}	controllable	☐	☐	☐	☐	☐	uncontrollable	×0.5
x_{n5}	riskless	☐	☐	☐	☐	☐	risky	×0.5

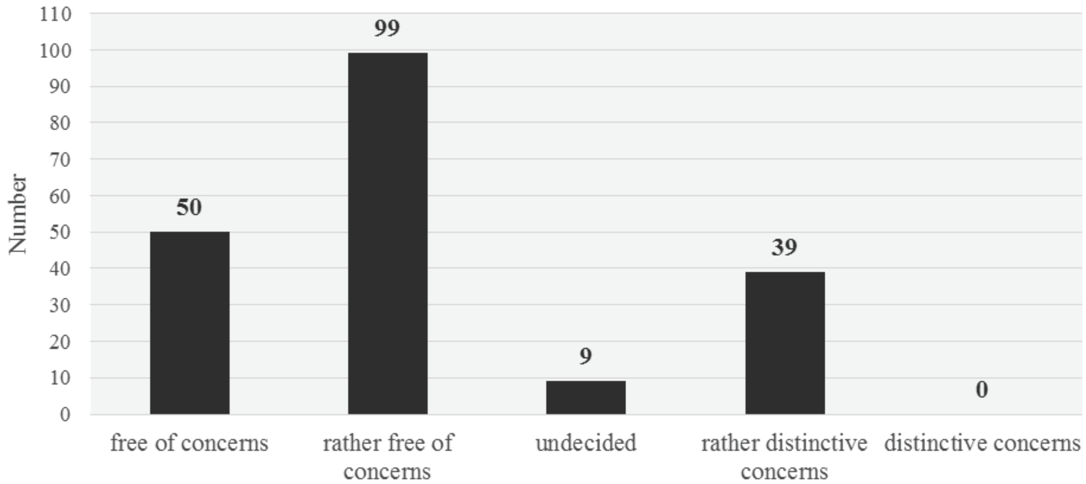

Fig. 3. Individual consideration of the total sample (N = 197)

In total, 25.4 % could be classified as persons who seemed fundamentally free of concerns on the basis of their subconscious assessment. 50.2 % appeared to be rather free of concerns while nine persons fell into the category ‘undecided’. Above that, 19.8 % of the sample appeared to have subconsciously expressed rather existing concerns by answering the polarity profile. Whereas apparently nobody showed strong concerns the following needs to be noted: an application of the calculation to the total sample resulted in a categorization as ‘rather free of concerns’.

Deeper analyzes have shown that among people with quite pronounced concerns in about four out of five were able to express these in concrete, thus to substantiate them.

- Which quantitative and qualitative characteristics can be determined by an open questioning of concerns? Are concerns expressed and, if so, which ones?

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The open questioning resulted in approximately one-third really concretizing aspects with more than half of them already being categorized as not free of misgivings. Below both causes for as well as manifestations of concerns are described.

Most frequently articulated were misgivings regarding suspected effects of power failure on the magnetic field stability (eleven times), followed by the absence of ropes (nine times) and doubts over the influence of magnetic fields on health (six times) of especially regular users and particularly on people with pacemakers (eight times). Furthermore, on a shared fourth place (six times each) felt uncertainty due to the innovation of the technology and therefore general risks associated with it as well as unspecified concerns relating to power loss would be expressed.

Followed by general doubt over the stability of such magnetic levitation (four times), concerns thanks to the pending cabins as well as felt uncertainty due to lacking knowledge about the technology itself and concerns relating to aspects of driving comfort came up as the divided eight place (three times each) of the most frequently mentioned aspects.

Eventually, with either two or less nominations followed: doubts about the technical/electronical functionality of the system; concerns over possible collisions or crashes of cabins; misgivings towards assumed possibilities of technical influence by "cyber-attacks"; reservations due to assumed negative leverage of magnetic field presence on electronic devices owned by users of the elevator.

- How are concrete and new aspects of magnetic levitation elevator technology assessed with regard to possible concerns?

Tangible aspects which seem to be novel to the user were – as Fig. 4 shows – all on average considered to be largely unobjectionable, especially the locomotion of elevator cars in the horizontal. Nevertheless, there were proportionate differentiations. The presence of magnetic fields, a large number of circulating cabins in the elevator shaft and the absence of cables appeared to be of concern by averagely about one-sixth, while the levitation of the cabins by magnets was considered to be the comparatively most alarming aspect.

Specially ‚Magnetic levitation of cabins‘ as well as ‚Absence of Ropes‘ could be ranked and defined as significant and correlative content-related (r = 0.592; level of significance 0.01) reasons for concerns. This relationship appears logical since both aspects are often highlighted in public reporting and appear to be related to one another: the lack of ropes results in a certain way from their replacement by the linear motor technology – ergo by ‚magnetic levitation'.

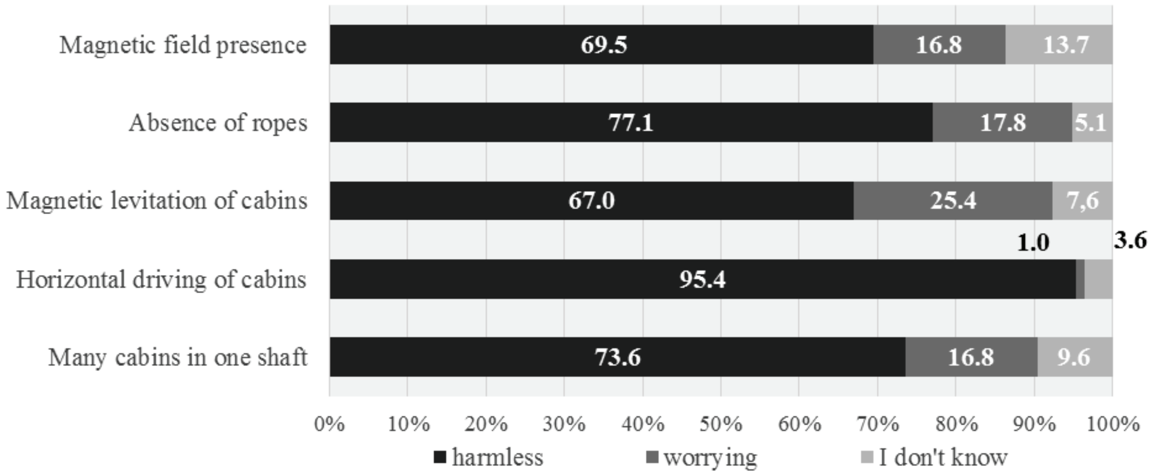

Fig. 4. Evaluation of predefined characteristics (N = 197)

Question: „How do you assess the following aspects of the magnetic levitation elevator?“

CONCLUSION

At the time of this study potential users in the overall trend appeared to be rather free of concerns about the safe use of magnetic levitation elevators. However, by an individual differentiation of this general bias, people with more pronounced concerns could be identified.

On closer inspection about a half of potential users could be categorized in said average trend, in about a quarter as completely free of misgivings and a small proportion as undetermined. As a result of subconsciously expressed reservations and clarification of concerns through naming, just under a sixth of potential users seem to have specific, significant concerns. After final compression of the data, those consist mainly of the following contentual nature:

- Health-related concerns due to suspected magnetic field presence
- Feelings of uncertainty due to mental perception of absence of ropes
- Concerns raised due to the magnetic levitation of the cabins, in particular with regard to doubted stability of the magnetic fields
- Uncertainty about possible effects of power outages in general and with regard to the stability of magnetic fields and cabin-maintenance

Using elevators has become part of everyday life for many people. Although there may be misgivings about conventional elevator systems, people have become accustomed to the use of elevators as a means of transportation – including potential disadvantages or perceived risks. This might be caused by the fact that characteristics and general conditions of the technology have changed little for a long time.

However, the magnetic levitation elevator technology will bring some new framework conditions whose actual perceptibility during the use itself remains

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to be seen but which are mentally both perceivable and conceivable for potential users.

While a large share of people in this respect seem to be free of thought, for some especially new characteristics and associated perceptions with it appear to lead to thoughts and assessments which primarily differ from traditional feelings related to elevators and partly eventuate in actual concerns.

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THEORETICAL BASE AND METHODS OF THE COMPLEX OPTIMIZATION OF MAGLEV

Background: In this study the feasibility of using Maglev transport through the determination of the limits of the effective application of the MLX01 and TRANSRAPID compared with railway systems was investigated.

Aim: Development of the technology of complex optimization of Maglev.

Methods: Resource-oriented optimization, system analysis, structured modeling, creation of the dynamic models, vector optimization, combined principle of optimization control, operation concept of the Maglev systems, economic aspects of the modeling, comparative analysis, determination of the borders of effective application of the compared transport technologies, research tools.

Results: Providing of maximum adapted configurations Maglev systems according to the conditions of their application. At the same time these configurations correspond to the state of the most stable equilibrium between all groups and the elements of the general optimization process.

Conclusion: This paper is scientifically justified work, which intended to accelerate the process of implementation Maglev technologies in the existing transport infrastructure.

Keywords: Maglev-system, optimization, system analysis.

1. INTRODUCTION

Currently, with the ever-growing competition in the world market of transport services and dynamically developing new transport technologies, will be able to compete only those maglev-systems that will use their technical and economic advantages. And if we take into account that modern maglev-systems are complex and high-tech multi-functional designs, which is constantly updated with new developments, then the existing evaluation methods were not always able to identify the maximum benefits of the aforesaid transport technologies.

Thus, a new tool has been proposed in this paper, which allows scientifically based methods to find the most optimal solution for maglev-system, depending on its application. This scientific instrument, as a full virtual model of the entire maglev-system, allows you to simulate any work processes of such a transport system, taking into account the introduction into it of new technical developments. As a result, at the lowest cost maglev-system ensures its maximum performance and the required traffic safety, which ultimately creates a good preconditions for considered maglev-system not only maintain a good position in the competition with other transport systems, but also to expand its scope of application.

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2. METHODS OF SOLUTION

2.1. Fundamental approaches

In order to improve the competitiveness of Maglev systems (Fig. 1) they were optimized by creating mathematical models based on the condition of maximum satisfaction of existing transport needs with minimum resource consumption.

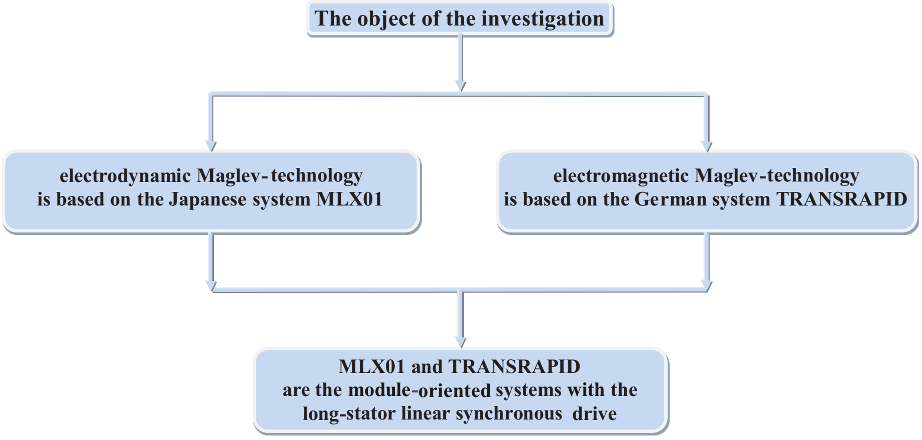


Fig. 1. The object of the study

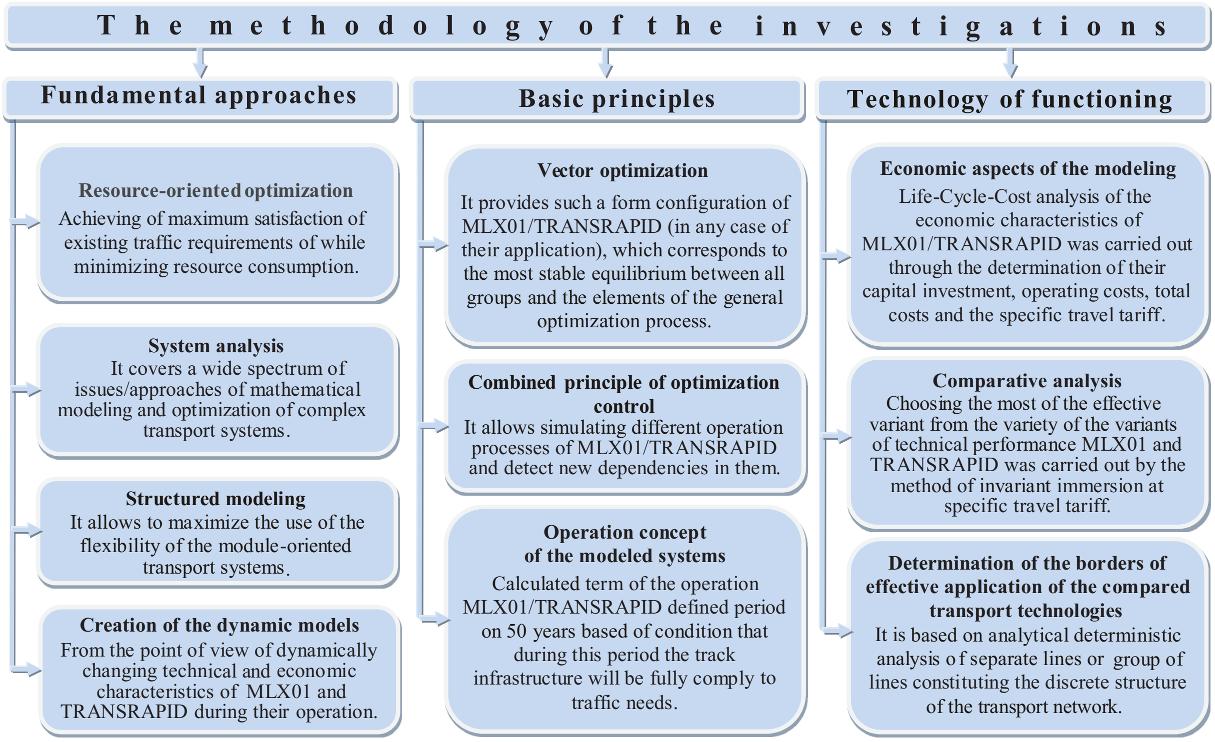
For this purpose, according to the systems theory, in the basis for the creating of the models of MLX01 and TRANSRAPID the system analysis method was applied to correct reflection the main features of these Maglev systems, their structure and properties, acting in this systems interactions and regularities, causal relationships inside the systems and methods of influencing them (Fig. 2).

Also, for the analysis and description of the existing complex algebraic problems, there was used the principle of structured modeling, based on the research of the hierarchical structure MLX01/TRANSRAPID and qualitative/quantitative relationships between their elements, which have an impact on the economic parameters of considered Maglev systems.

Using graph theory the possibility of configuration of module-oriented multivariate technical execution structure was investigated for MLX01/TRANSRAPID, depending on their capacity to adapt to the conditions of application for selected case of the building of a new line in terms of dynamically changing during its operation, technical and economic characteristics of these Maglev systems.

2.2. Basic principles

To eliminate the imbalance in the whole Maglev systems as a result of striving to improve the technical characteristics of one of its components or


The methodology of the investigations

Fundamental approaches

Resource-oriented optimization
Achieving of maximum satisfaction of existing traffic requirements of while minimizing resource consumption.

System analysis
It covers a wide spectrum of issues/approaches of mathematical modeling and optimization of complex transport systems.

Structured modeling
It allows to maximize the use of the flexibility of the module-oriented transport systems.

Creation of the dynamic models
From the point of view of dynamically changing technical and economic characteristics of MLX01 and TRANSRAPID during their operation.

Basic principles

Vector optimization
It provides such a form configuration of MLX01/TRANSRAPID (in any case of their application), which corresponds to the most stable equilibrium between all groups and the elements of the general optimization process.

Combined principle of optimization control
It allows simulating different operation processes of MLX01/TRANSRAPID and detect new dependencies in them.

Operation concept of the modeled systems
Calculated term of the operation MLX01/TRANSRAPID defined period on 50 years based of condition that during this period the track infrastructure will be fully comply to traffic needs.

Technology of functioning

Economic aspects of the modeling
Life-Cycle-Cost analysis of the economic characteristics of MLX01/TRANSRAPID was carried out through the determination of their capital investment, operating costs, total costs and the specific travel tariff.

Comparative analysis
Choosing the most of the effective variant from the variety of the variants of technical performance MLX01 and TRANSRAPID was carried out by the method of invariant immersion at specific travel tariff.

Determination of the borders of effective application of the compared transport technologies
It is based on analytical deterministic analysis of separate lines or group of lines constituting the discrete structure of the transport network.

Fig. 2. Structure of the research methodology

groups thereof, which can lead to their dominance due to the deterioration of the values of other elements of the system, the choice of most of the equilibrium state MLX01/TRANSRAPID carried out according to the vector optimization for the selected criteria through a complete solution of system of equations describing the calculated parameters of their technical and economic structure and operation technology. As a result, all unnecessary costs were cut off to provide maximum adapted configurations investigated Maglev systems according to the conditions of their application. At the same time these configurations will correspond to the state of the most stable equilibrium between all groups and the elements of the general optimization process.

According to the control theory and in order to identify new dependencies in the time carrying out simulative calculation was applied the combined principle of control of the optimization in models MLX01/TRANSRAPID, where the values of some parameters of their configuration and exploitation (which are considered as external control parameters) entered manually, and the value of all the other calculated parameters investigated Maglev systems are defined according to conditions of their application automatically.

The operating concept of MLX01/TRANSRAPID, used in the modeling was calculated for a period of 50 years. This period is equal to the period of operation of the track infrastructure of the line until its overhaul, taking into account changes in the intensity of seasonal/daily traffic and the continued growth of their annual volume. In the same time this schedule of trains and their number during this period have not changed over the years. The number of sections in the train configuration was only increased. Based on the maximum load on the line, which falls on the "peak hour" of the last calculation year of its operation, have been identified: type of track structure (single-track, double-track and single-track with bilateral passing track), the number of bilateral passing track and the number of station tracks at halt.

2.3. Technology of functioning

Economic aspects of modeling MLX01/TRANSRAPID are based on Life-Cycle-Cost analysis, according to which there were identified sum total costs as well as the specific travel tariff (as the main evaluation criterion) which was received from the calculation of the payback of the total costs to the time of credit payment.

The selection of the most effective variant of configuration MLX01/TRANSRAPID from the multitude ways of their technical execution (due to database diversity), as well as the choice between the investigated Maglev technologies and railway systems for each specific case their application, were carried out by the method of comparative analysis on specific tariff.

Thus, a deterministic analysis of individual lines or groups of lines constituting the discrete structure of the transport network, with a selection of the most efficient system from comparable transportation systems, allows to identify (according to the set theory) limits of effective application Maglev transport for each concrete case of its use and determine preconditions for optimal development existing transport infrastructure.

3. RESEARCH TOOLS

As a tool to achieve of the above purposes by scientifically-based methods, on the grounds of the principles of building of mathematical computer models, was developed the calculated application program that allows carry out the necessary volume of experimental calculations based of apparatus of methods of the optimization and the simulation modeling (Fig. 3).

Therefore, according to the aforesaid methodology for the calculation of technical and economic parameters MLX01/TRANSRAPID provided of their complex

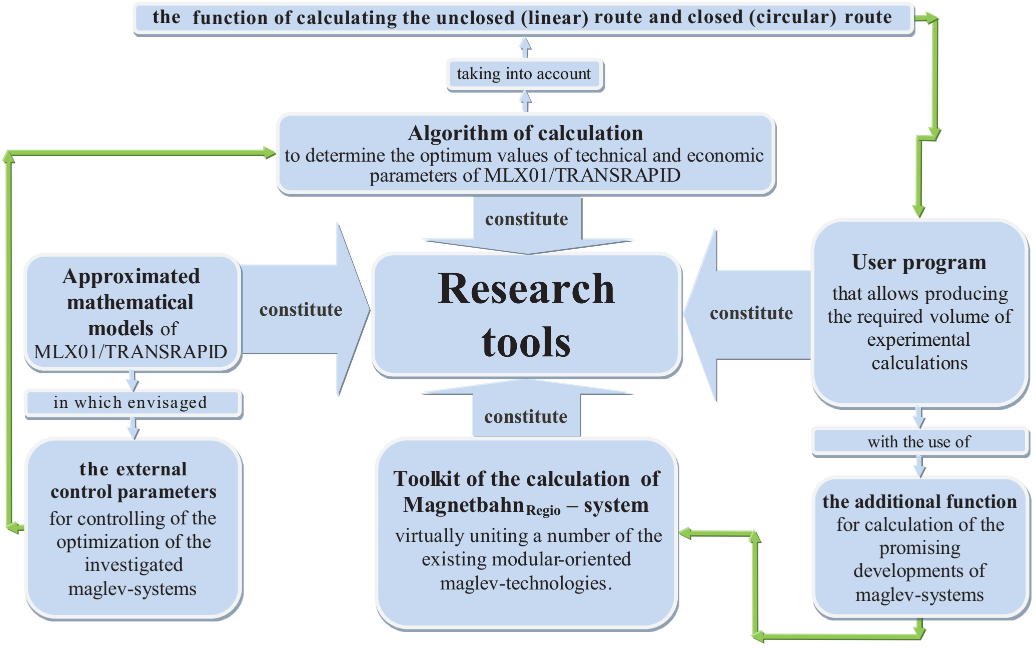


Fig. 3. Structure of the research tools

optimization, was written for each of these Maglev systems the separate algorithm for its mathematical model. For this the following data were used: test of model samples, experimental research and also theoretical research and design development.

However, due to deficit of information resources, caused by a strong structure considered Maglev systems and complicated functional connectivity in them, were used crude mathematical models MLX01/TRANSRAPID with limited modular execution (which takes into account the interaction only between their main components), for partial optimization these Maglev systems on average values of parameters condition of their application.

The principle of the combined method of control optimization MLX01/ TRANSRAPID was implemented in algorithm of the calculated program through two external control parameters: the maximum speed of the trains between two stops and the number of sections per configuration.

Also a function for calculating the linear routes and the circular routes was provided in the program. Circular route allows instead of network radially arranged of linear routes to construct a closed route which will consistently link all the stops.

In addition, the flexibility of input program parameters allows calculations not only for already developed system design as is MLX01 and TRANSRAPID, but also for prospective directions of their development, including for other long stator linear motors and suspension on the electric or superconducting magnets.

Thus, the potential of the program algorithm ensured the holding of the calculation of number of the existing modularly oriented Maglev systems with the possibility of organization simultaneous studies of two under consideration Maglev technology under identical or different conditions of their application.

4. INPUT DATA

In this study were conducted the calculation for MLX01 and TRANSRAPID on the condition of combined of cargo and passenger traffic for two separately selected virtual lines and for passenger traffic for six model lines, including well known projects TRANSRAPID (Fig. 4).

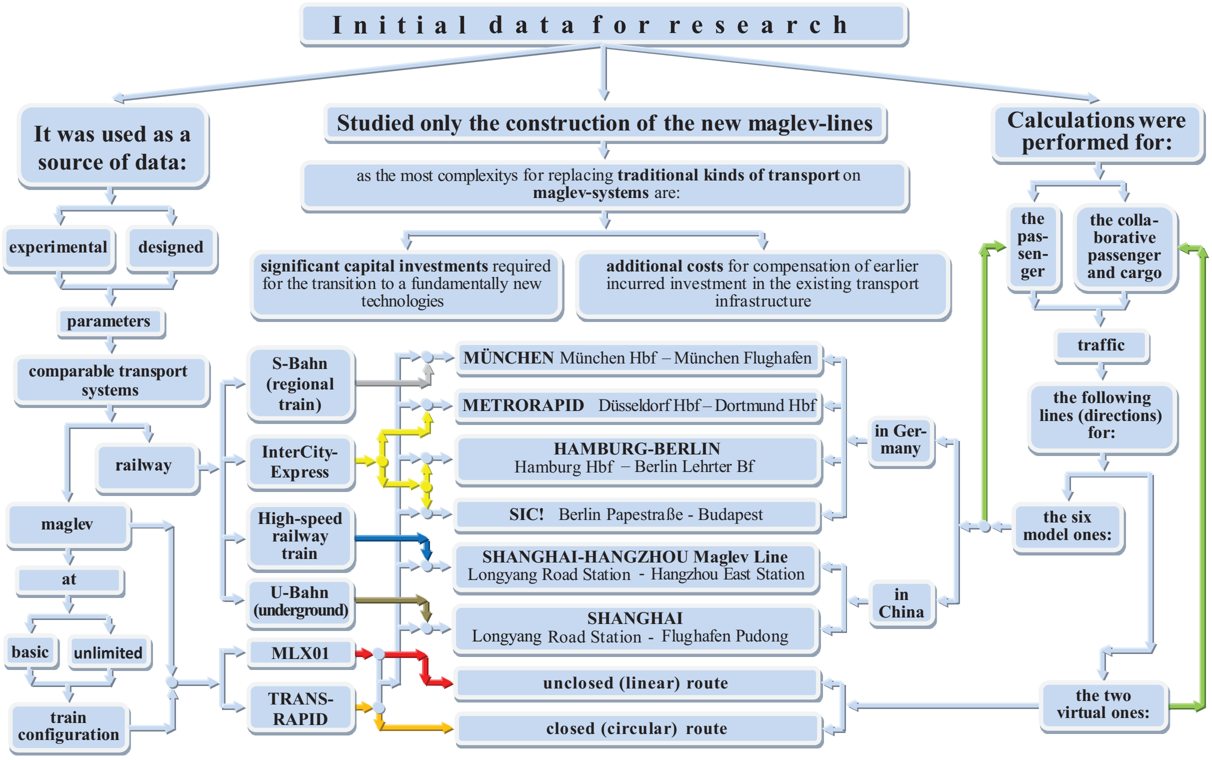


Fig. 4. Scheme of the baselines for the research

5. ANALYSIS AND ITS RESULTS

5.1. Results of the optimization TRANSRAPID

Eventually results of the optimization modeling TRANSRAPID showed one-third increase of the arithmetic average value of its economic efficiency (by reducing the total costs) compared with the previously calculated design data (according to standard methods) considered in the study of the lines (Fig. 5).

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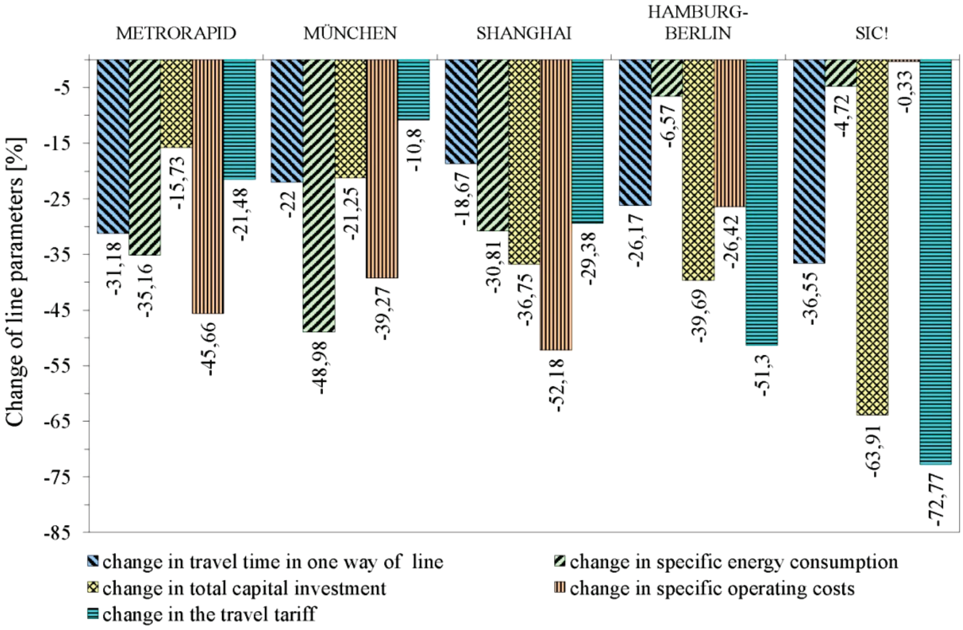
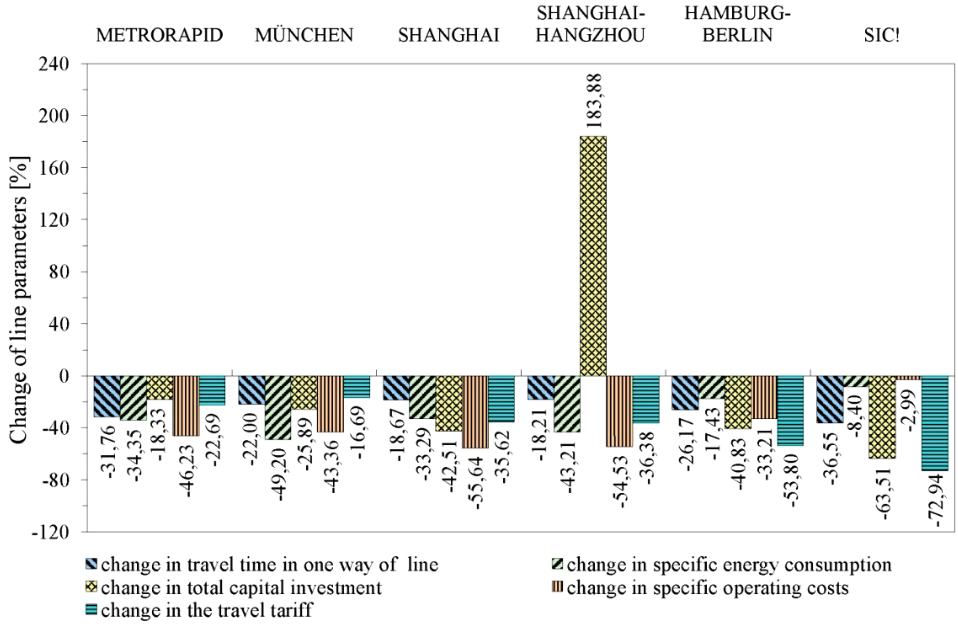


(a) At basic TRANSRAPID train configuration



(b) At unlimited TRANSRAPID train configuration

Fig. 5. A percent of change in line parameters on complex optimization of TRANSRAPID obtained by comparing of modeling results with the project data

5.2. Configuration of the track structure

So the optimization of the track structure by replacing a double-track by a single-track with bilateral passing tracks influenced on the decrease of costs of MLX01/TRANSRAPID and helped to identify perspective areas of their development such as further reduction of the minimal interval between traffic trains in the "peak hour" and design of turnouts for the operation of trains without reducing speed (Fig. 6).

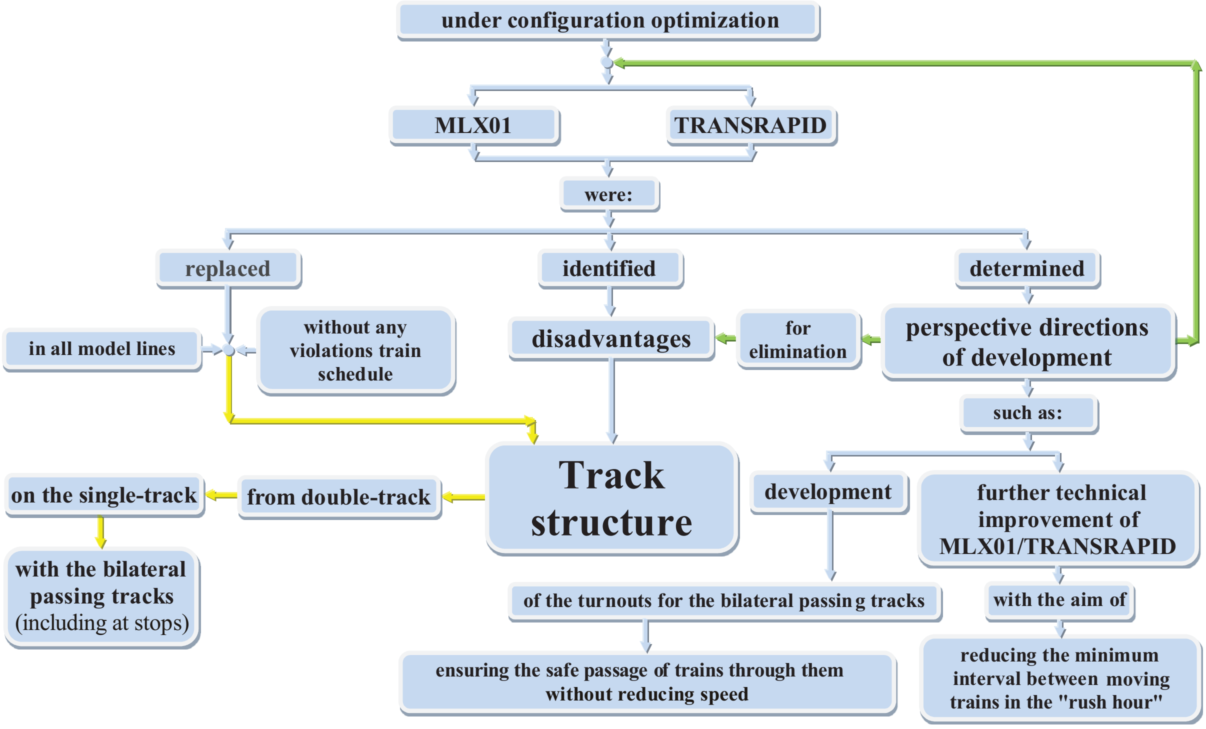


Fig. 6. Configuration of the track structure of MLX01 and TRANSRAPID

5.3. Train configuration

By a deterministic analysis the dependency of reduction of specific travel tariff from increasing of trains configuration MLX01/TRANSRAPID has been studied, according which the use of the long configuration Maglev trains proved optimal for all considered model lines (Fig. 7).

5.4. Optimal speed of train

By the method of the successive approximations the optimal speed for MLX01/TRANSRAPID on short distances between stops (typical of the regional traffic) was determined. It does not reaches its maximum of technical value, but in compared with the obtained economic effect leads only to a slight increase in travel time (Table 1).

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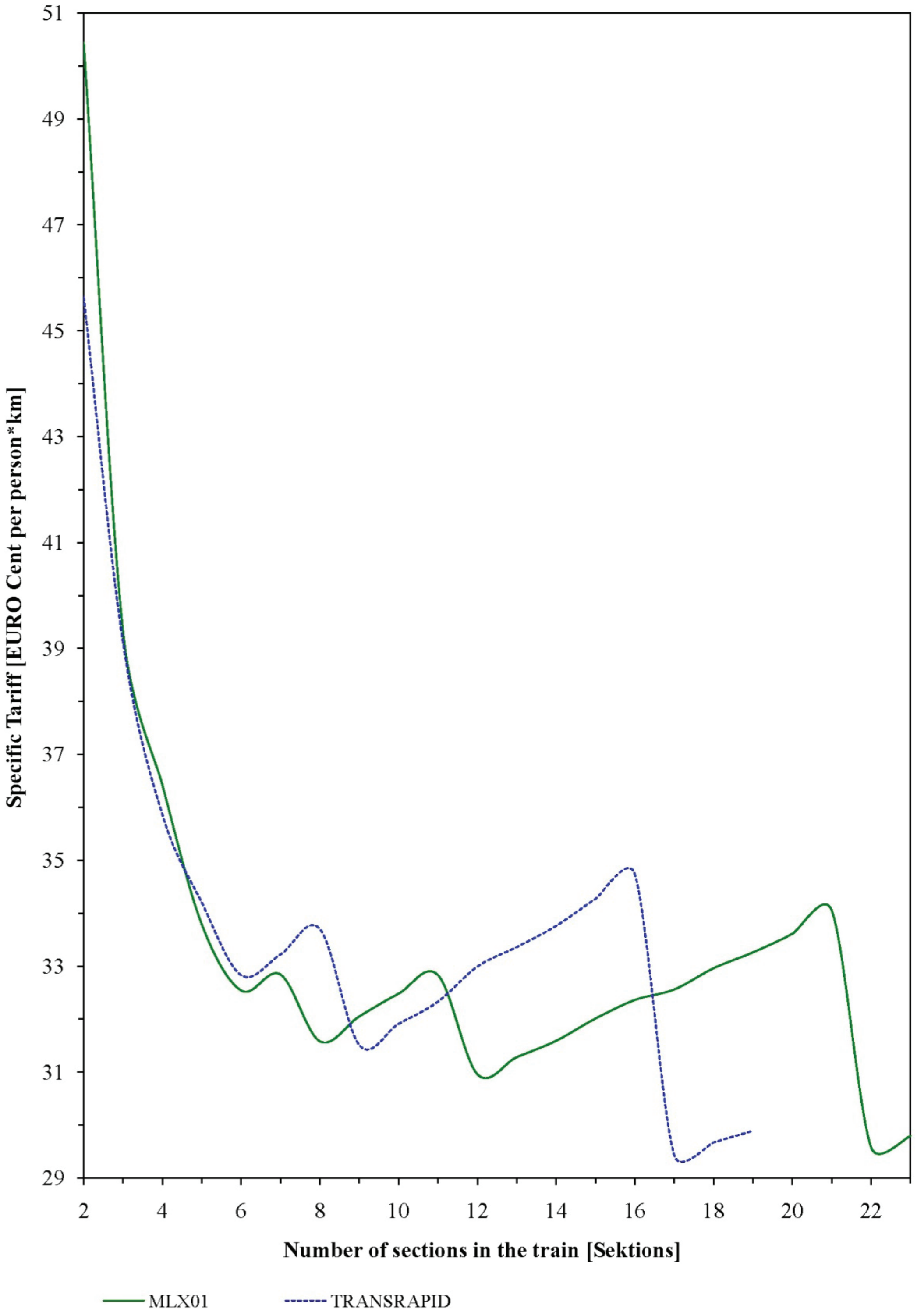

Fig. 7. Dependence of specific tariff on the train configuration

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Table 1. Parameters of MLX01 and TRANSRAPID, received by simulations

Parameter		**Unit**	**MLX01**		**TRANRAPID**	
			without the optimization of speed of the train	*with the optimization of speed of the train*	*without the optimization of speed of the train*	*with the optimization of speed of the train*
Maximum project speed of train		km/h	550	383	500	259
Maximum speed of train acceleration		km/h	412[a]	383	388[b]	259
Cruiser speed of train		km/h	162.8	161.6	161.6	134.6
Travel time between the end stops		min.	167.3	168.5	168.5	202.5
Travel time between the end stops		%	0.70		20.18	
Number of cars in the train	for the first year of line operation	sektions	4	4	2	2
	for the 50th year of line operation		10	10	6	6
Maximum capacity of the linear drive of train		MW	64.78	24.10	30.36	6.61
Specific energy consumption attributable to the transportation of 1 passenger per 1 km, taking into account energy recovery during braking train		Wh per person×km	72.5	70.4	53.5	36.2
Specific total capital investments per 1 km of line[c]		mil. EUR per km	35.62	23.70	27.65	14.98
Total costs at the time of repayment (the payment of the loan)[d]		billion EUR	52.84	43.09	37.41	25.50
Averaged operating costs for transportation of 1 passenger per 1 km		EURO Cent per person×km	4.67	4.36	3.16	2.51
Specific tariff for transportation of 1 ton of cargo per 1 km[e]		EURO Cent per t×km	83.96	68.47	56.13	38.26
Specific tariff for transportation of 1 passenger per 1 km[e]		EURO Cent per person×km	6.89	5.61	5.05	3.44
Economic effect after the optimization of the train speed		%	18.58		31.88	

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[a] Power of the linear drive accelerates the train with a constant acceleration on $1\ m/s^2$.

[b] On increase in power of the linear drive, its maximum speed exceeds 420 km/h because of the short distances between stops. The original engine power will increase by 2,7 times (82,88 MW); specific tariff will rise to 5,20 EURO Cent per person*km; the total costs will increase given to the payback period for 1,09 billion EUR (up to 38,5 billion EUR). Transit time between the final stop will be reduced to 1,25 minute. In comparison with the version of the optimized speed of the train excess engine power reaches 12,5 times, the cost of travel to 1,5 times.

[c] Excluding capital expenditures for the acquisition of additional rolling stock in connection with the growth of annual shipments.

[d] Taking into account the capital investments to purchase additional rolling stock in connection with the increase in the volume of annual traffic.

[e] Travel tariff were calculated taking into account factors: of the development experience of operating of the new lines, discounting (reduction of costs at different times) and additional profit.

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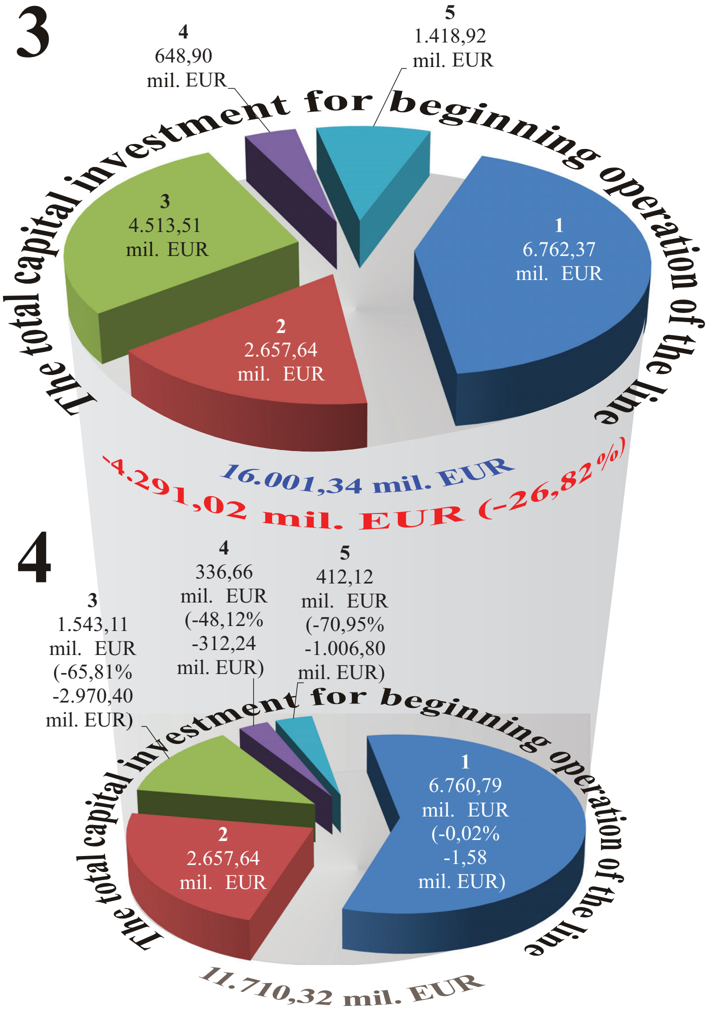
5.5. Application of the function of changing the unit costs from the volume of ordered quantity

Thus the correct calculation of economic values, expressed in application of the function of changing the unit costs from the volume of ordered quantity and using of the discount factor, led to an additional reduction in the cost of the investigated Maglev systems (Fig. 8, 9).



3 – total capital investment to the beginning of the line operation *before* the application a function of changing the unit costs from the volume of order quantity
4 – total capital investment to the beginning of the line operation *after* the application a function of changing the unit costs from the volume of order quantity
1 – costs for construction of the track of line and its infrastructure
2 – costs for acquisition of the plot of land for the construction of line
3 – costs for acquisition and installation of electrical equipment in the line track
4 – costs for acquisition of rolling stock line and the creation base of its service
5 – costs for creating of the line control system

Fig. 8. Structure of decline total capital investment of TRANSRAPID to the beginning of operation of the model line SIC!, after the application a function of changing the unit costs from the volume of order quantity

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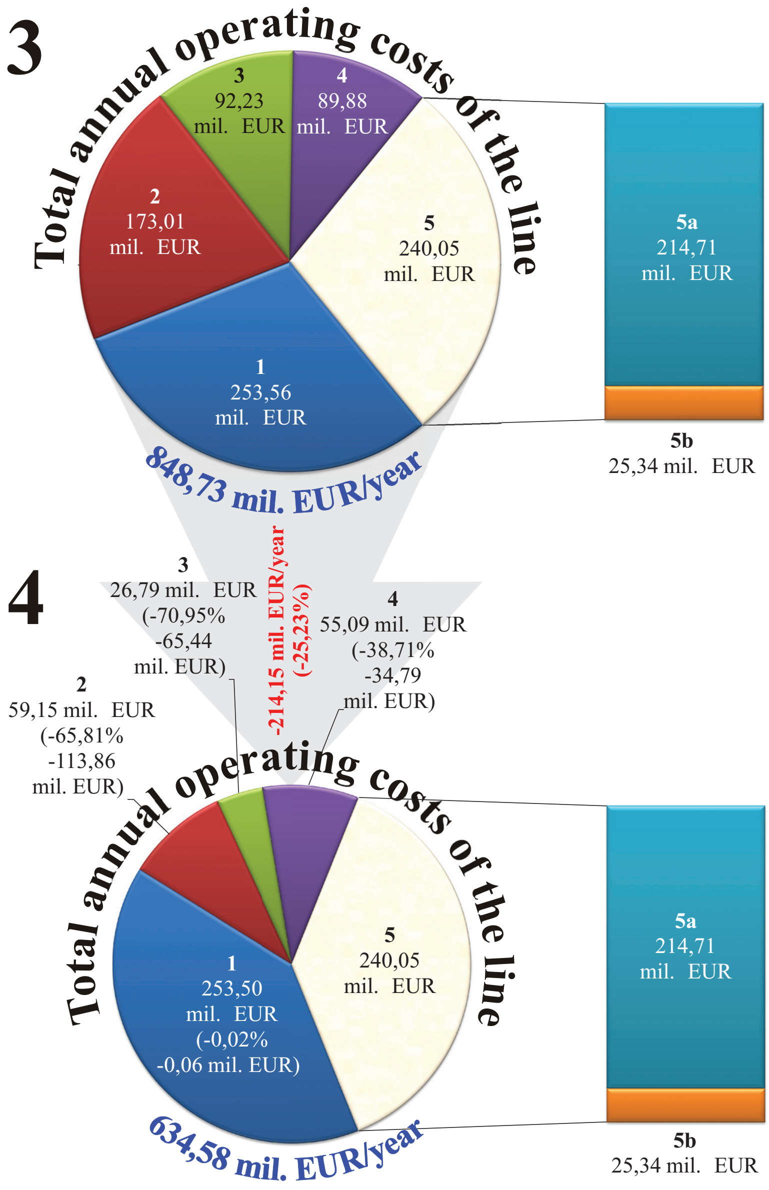

3 – the averaged total annual operating costs of the line *before* the application a function of changing the unit costs from the volume of order quantity
4 – the averaged total annual operating costs of the line *after* the application a function of changing the unit costs from the volume of order quantity
1 – the averaged annual costs for maintenance and repair of the track line in view of its infrastructure
2 – the averaged annual costs for maintenance, repair and renovation of electrical equipment of line
3 – the averaged annual costs for maintenance, repairs and renovation of the line control system
4 – the averaged annual costs for maintaining and repairing of rolling stock of line, including base his maintenance
5 – the averaged annual operating costs, which are not dependent on capital investments
5a – the averaged annual energy costs, that is consumed on the line
5b – the averaged annual costs for the payment of staff salaries of line

Fig. 9. The structure of the reduction of averaged total annual operating costs of TRANSRAPID for the model line SIC!, after the application a function of changing the unit costs from the volume of order quantity

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5.6. Control of quality calculations and determined the main factors/structure the costs reduction

In order to verify the results of the optimization (with a satisfactory result) a control of quality calculations was performed for the specific energy consumption of TRANSRAPID for model lines by comparing them with the experimental data of design lines (Fig. 10), and also were determined the main factors and the costs reduction structure for TRANSRAPID, critically were evaluated the accuracy of its economic calculations and the likelihood of the realization of the model project (Fig. 11–12).

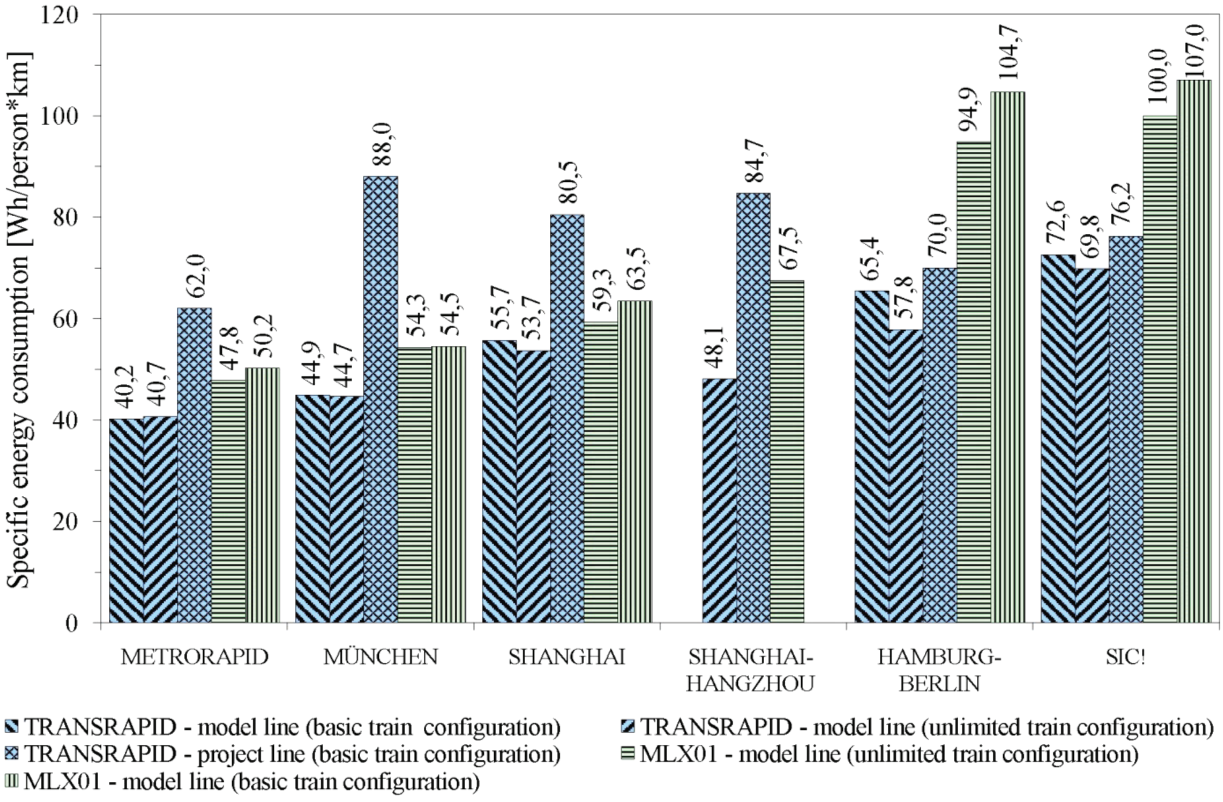
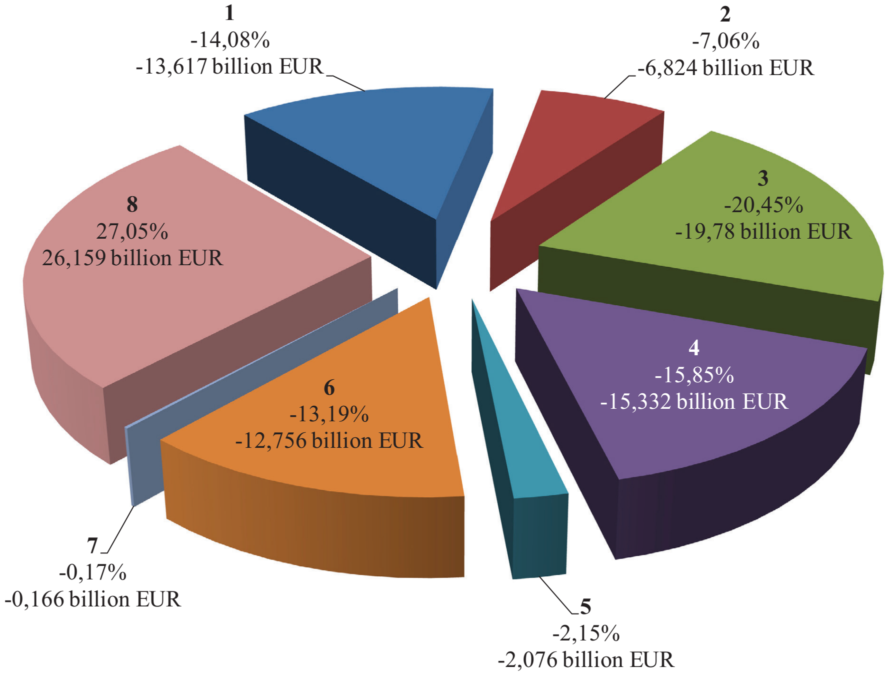


Fig. 10. Specific energy consumption attributable to the transportation of 1 passenger per 1 km, taking into account energy recovery during braking train

5.7. Determination of the limits of the effective application of TRANSRAPID and railway system

Since TRANSRAPID turned more effective than MLX01 for all model lines given in projects of traffic volumes, then at first was a comparative analysis of specific travel tariffs of railway system with project tariffs of TRANSRAPID, and



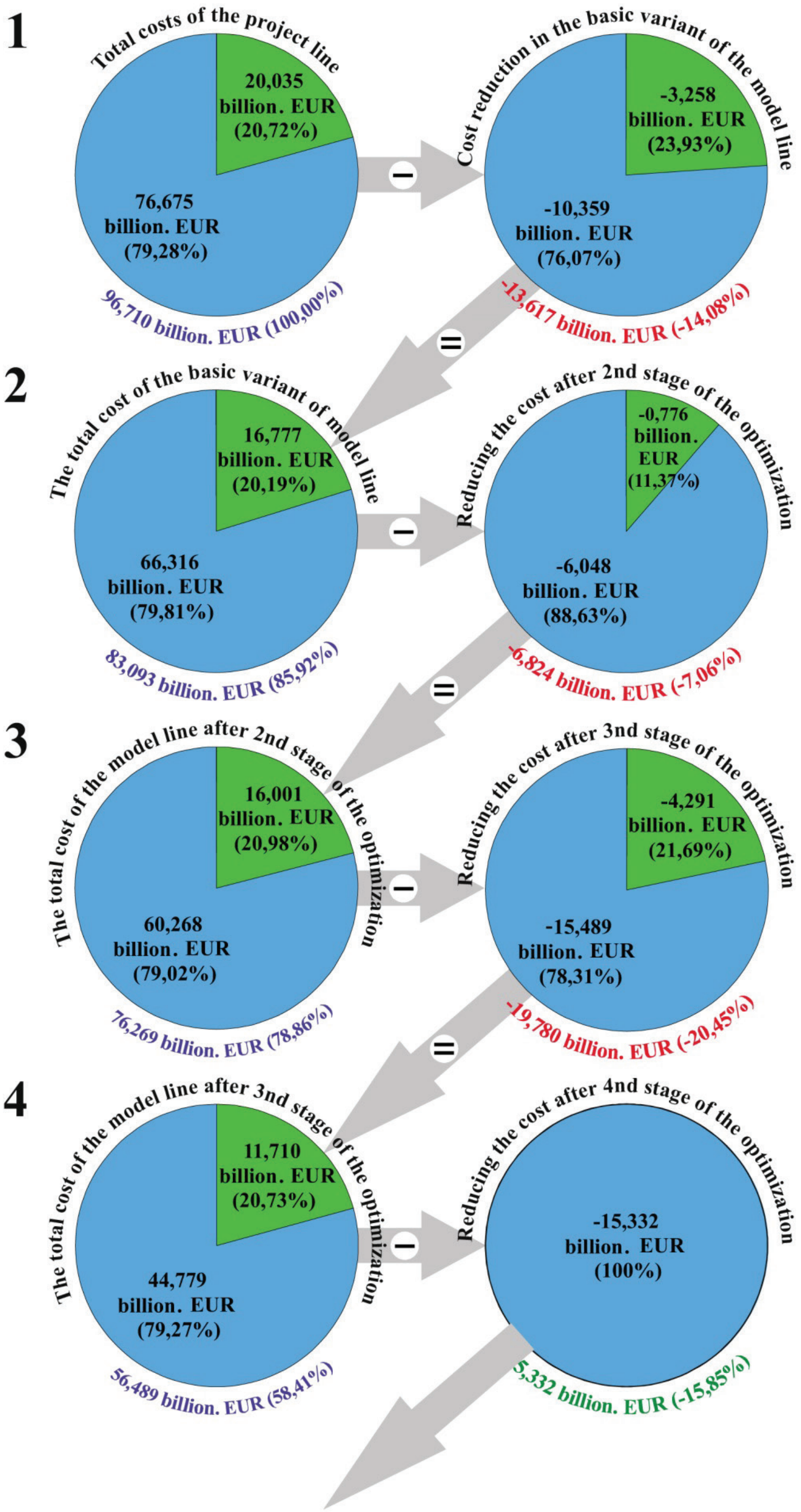
1– aggregate number of additional factors of optimization of the base variant of system execution of the model line (which is as close as possible to the initial design decision of the line), each of which separately has no significant impact on the reduction of its costs
2 – change of the basic train configuration from 4 to 10 sections
3 – application of functions of changing the price of piece goods of the volume of order quantity
4 – accounting of the discount factor
5 – phased acquisition of rolling stock of line during the whole period of its operation
6 – the use of single-track line with the bilateral passing tracks
7 – the use of single-track line with the bilateral passing tracks only on station tracks and change of the basic train configuration from 10 to 14 sections
8 – total costs of the optimized model line at the time of their recoupment

Fig. 11. The sequence of gradual reduction of total costs of TRANSRAPID in phasing out process of its optimization for the model line SIC!

then with the tariffs obtained as a result of its optimization, which led in 6 examined cases to a twofold the expansion of the limits of the effective application of Maglev transport: from 2 to 4 lines (Table 2).

5.8. Determination of the limits of the effective application of TRANSRAPID and MLX01

The limit of scopes of effective application between TRANSRAPID and MLX01 for a “city-airport” transport was determined over the maximum volume of the annual passengers’ flows, equal to 43,12 million passengers per year in both directions (Table 3).



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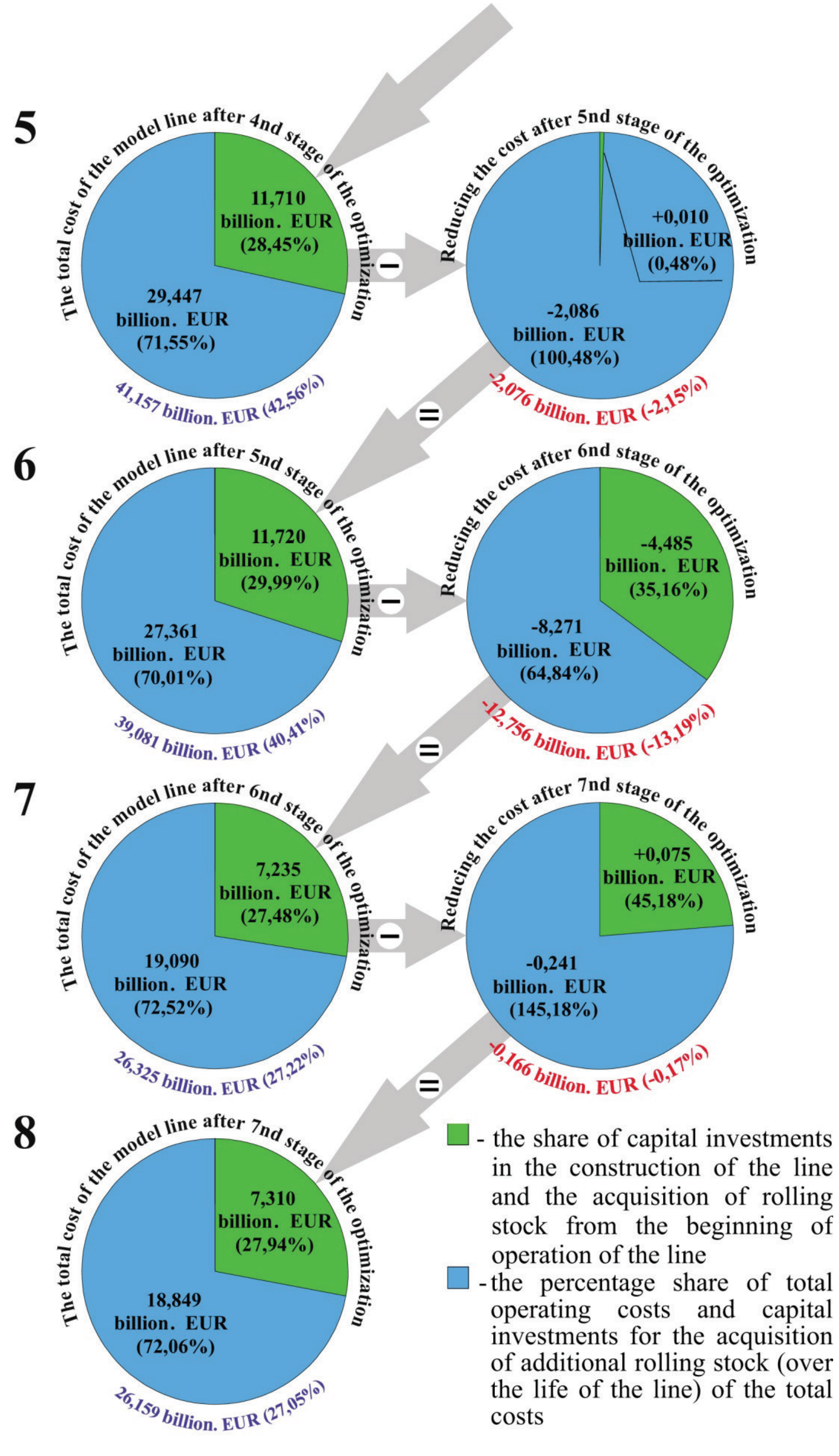

Fig. 12. Changing of the allocation of the proportion of capital investment and operating costs in the total costs structure of TRANSRAPID in phasing out process of its optimization for the model line SIC!

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Table 2. The boundary between areas of effective application of TRANSRAPID and railway system on value of specific tariff

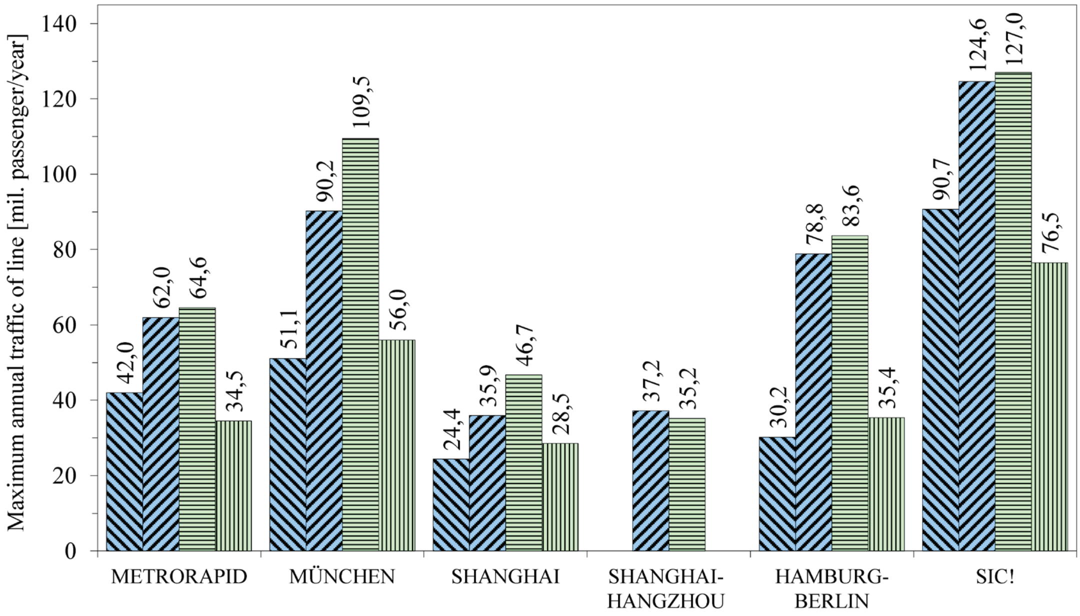
Parameter	**Unit**	**Project**					
		METRO-RAPID	*MÜNCHEN*	*SHANGHAI*	*SHANGHAI-HANGZHOU Maglev Line*	*HAMBURG-BERLIN*	*SIC!*
At comparison with design data	transport system	TRANS-RAPID	S-Bahn	U-Bahn	H/S Train	TRANS-RAPID	ICE (Inter-City-Express)
At comparison with modeling data		TRANS-RAPID	S-Bahn	U-Bahn	TRANS-RAPID	TRANS-RAPID	TRANS-RAPID

Table 3. The boundary between areas of effective application of TRANSRAPID and MLX01

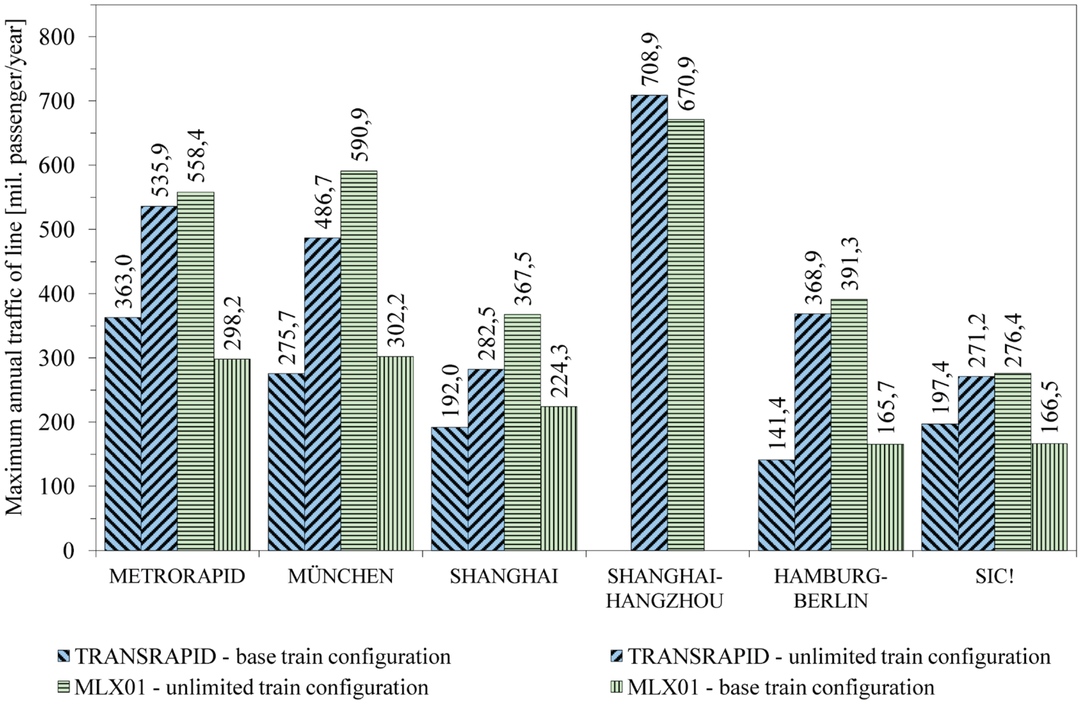
Parameter		Unit	**Project**					
			METRO-RAPID	*MÜNCHEN*	*SHANGHAI*	*SHANGHAI-HANGZHOU Maglev Line*	*HAMBURG-BERLIN*	*SIC!*
Limit annual passenger traffic in both directions in which the effectiveness of the changes in favor of MLX01	to first year of line operation	mil. pass. per year	no	7.99	10.30	no	no	no
	to 50th year of line operation		no	43.12	81.05	no	no	no
Specific tariff for transportation of 1 passenger per 1 km (the car of 2nd class)	TRANSRAPID	EURO Cent per person× km	missed	34.79	12.59	missed	missed	missed
	MLX01		missed	29.11	10.48	missed	missed	missed

5.9. Determination of the maximum allowable volume of traffic for transrapid and mlx01

In this case, in conformity with the maximum allowable volume of traffic (in terms of its satisfaction) was calculated threshold for the possible technical application of the provided in the project of configuration investigated Maglev systems. For TRANSRAPID it is from 271.2 to 708.9 million passengers per year, and for MLX01 it is from 276.4 to 670.9 million passengers per year (Fig. 13).



(a) To first year of line operation



(b) To 50th year of line operation

Fig. 13. Maximal annual passenger traffic in both directions provided the design configuration of the transport system

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5.10. Determination of the optimum distances between stops for MLX01 and TRANSRAPID

Besides, the optimum distances between stops for application of MLX01 and TRANSRAPID in a regional and suburban traffic were determined in the range of 10 to 15 km (Fig. 14).

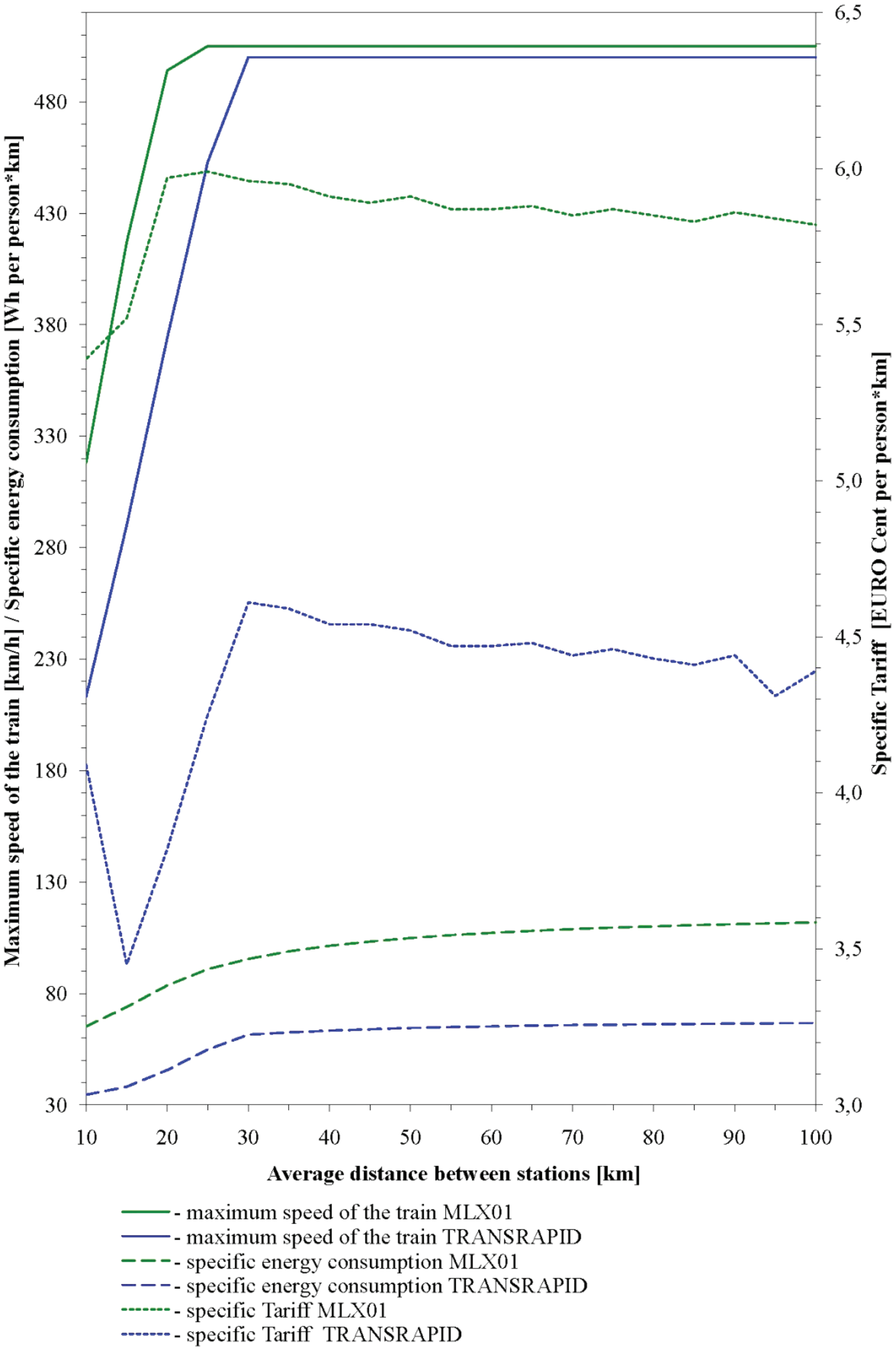

Fig. 14. Dependence of specific energy and specific tariff on the distance between stops

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5.11. Application of research results

The presented research results can be used for (Fig. 15):

- solving of technical and economic questions of vector optimization of Maglev systems, both in theoretical and in applied areas;
- studying of new economic processes/dependencies, occurring in Maglev systems in order of qualitative determination the directions of further perfection of the methods of their optimization;
- preliminary assessment of the effectiveness of introduction of innovation and the definition the most promising directions of the development of Maglev technologies with the aim of significant savings in time and resources to carry out further experiments, production of prototypes/experimental devices, and so on;
- carrying out a preliminary assessment of the feasibility of construction of the Maglev lines in a short time with the output the necessary design data;
- the correct determination of the limits of the effective application of Maglev systems in different conditions of their application, (that have multiparametric character), for compiling predictions to assess the development of transport networks and the development of clear practical recommendations for effective investment for the construction of Maglev lines.

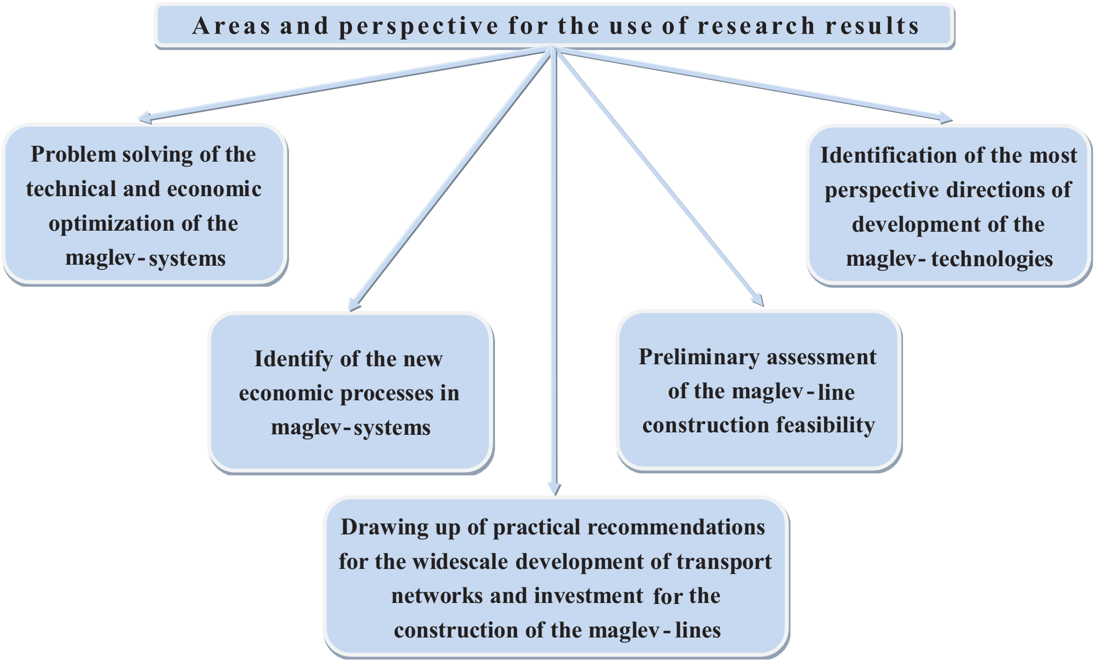

Fig. 15. The main aspects of the application of research results

6. CONCLUSION

This study is scientifically justified work, which intended to accelerate the process of implementation Maglev technologies in the existing transport infrastructure, which will lead to further improvements in the transportation process and environmental conditions, and also will give new impetus for the stage of development of transport (Fig. 16).

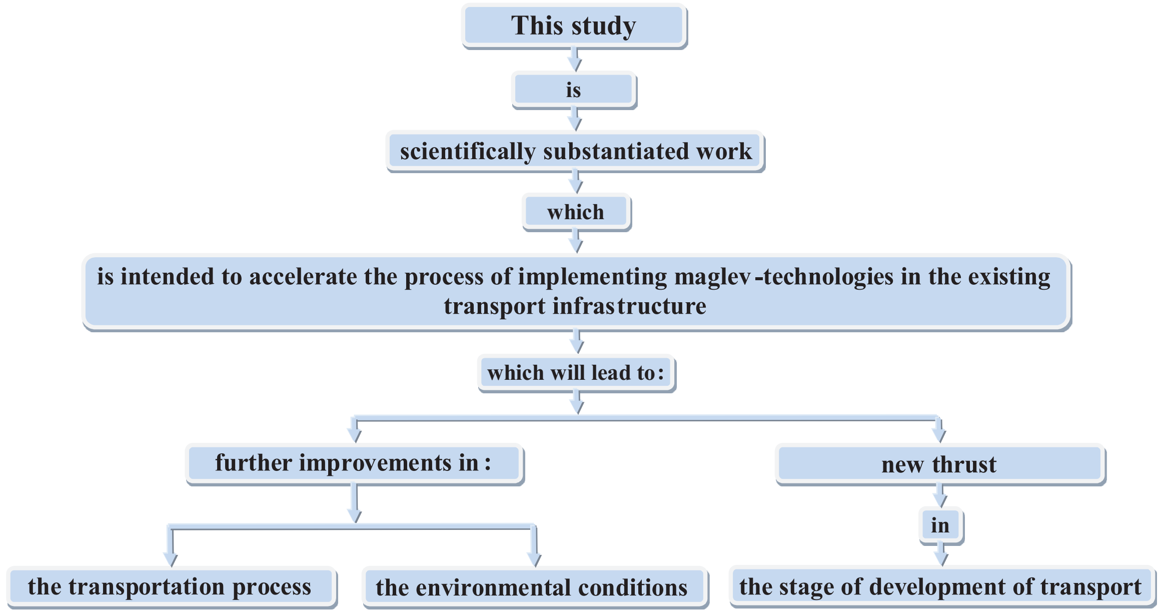

Fig. 16. Conclusion

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Lascher A. Theoretical Base and Methods of the Complex Optimization of Maglev. *Transportation Systems and Technology.* 2018;4(3 suppl. 1):173-194. doi: 10.17816/transsyst201843s1173-194Fig. 1. The last day of MagLev Conference in 2014

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RETROSPECTIVE AND PERSPECTIVES OF THE SUPERCONDUCTING MAGNETIC LEVITATION (SML) TECHNOLOGY APPLIED TO URBAN TRANSPORTATION

A review of the Superconducting Magnetic Levitation (SML) technology applied to urban transportation will be presented. The historical time line will be highlighted, pointing out the pioneering efforts at Southwest Jiatong University (SWJTU), China, followed by the Supra Trans project in IFW-Dresden, Germany, and the MagLev-Cobra project in UFRJ, Brazil.

Background: Details of the MagLev-Cobra project, the first, and until today the single one, applying the SML technology that counts with a real scale prototype, operating regularly in open air, will be disclosed. The inauguration of the MagLev-Cobra project was on the 1st October 2014, the last day of the “22nd International Conference on Magnetically Levitated Systems and Linear Drives (MAGLEV)” held in Rio de Janeiro. Curiously, this day coincides with the 50th anniversary of the successful operation of the Shinkansen in Tokyo. On the 1st October 1964, the first high-speed wheel and rail train in the world was inaugurated in time for the first Olympic Games that took place in Asia. This historical coincidence is a good omen for the MagLev-Cobra project. In fact, since October 2014, the system operates regularly for demonstration at the UFRJ Campus, every Tuesday. More than 12.000 visitors have already had the opportunity to take a test ride.

Aim: The Proceedings of the MAGLEV conferences, which first edition dates back to 1977 (http://www.maglevboard.net), are the documentary files of the importance of this achievement. Initially, the methods named Electromagnetic Levitation (EML) and Electrodynamic Levitation (EDL) were considered.

Methods: At the end of last century, due to the availability of Rare Earth Permanent Magnets and High Critical Temperature Superconductors (HTS), an innovative levitation method, called Superconducting Magnetic Levitation (SML), started to be considered. This method is based on the flux pinning effect property of HTS in the proximity of magnetic fields given by rare earth permanent magnets. The first experiments with SML, as expected, were small scale prototypes, or laboratory vehicles for one, two or four passengers, proposed mainly by researchers from Germany, China and Brazil. The Proceedings of the 16th MAGLEV, held in year 2000, confirms this fact. After 14 years of research and development, the team of the Laboratory of Applied Superconductivity (LASUP) of UFRJ achieved the construction of the first real scale operational SML vehicle in the world.

Results: This retrospective will be followed by a comparison with the EML technology, that has already four urban commercial systems, will be presented and the application niches delimited.

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Conclusion: The perspectives of the MagLev-Cobra project and the cooperation efforts with China to turn it a commercial experience will finish the paper. As will be explained, before the commercial application of the MagLev-Cobra technology, the system must be certified and the technical, economic and environmental viability for a first deployment concluded.

Keywords: Superconducting Magnetic Levitation, Urban Transportation, Superconductors, Rare Earth Permanent Magnets, Technology Readiness Level, Route for Commercialization.

INTRODUCTION

All big steps in the evolution of mankind can be related with the use in large scale of a new material to make objects. For instance: wood, bones, flint stones, iron, brass, steel. During the last century, the invention of the controlled semiconductor, in 1947, by Bardeen, Schockley and Brattain changed the world and inaugurated a new era that deserves to be referred in the future as the semiconductor era. Nowadays, a great variety of available new materials turns it difficult, even impossible, to select one to characterize the period, e.g.: graphene, carbon fiber, glass fiber, nanomaterials, superconductors and permanent magnets.

The Superconducting Magnetic Levitation (SML) technology is based on the use of high critical temperature superconductors (HTS) and rare earth permanent magnets, that dates back to 1987 [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 later than the available prototypes of EML and EDL 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 2002. This example was not only improved by Wang' fellow students [4, 5], but was also followed by prototypes in Dresden, Germany [6] and Rio de Janeiro, Brazil [7, 8]. These initial systems operated inside the laboratory, in controlled environmental conditions and just for demonstration. The first and until today the single prototype that operates outdoors, presenting the conditions of a real transportation system, is the MagLev-Cobra project, that will be described in the following.

THE MAGLEV-COBRA VEHICLE

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

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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 and the vehicle can carry 20 passengers at a speed of 12 km/h. Until today, more than twelve thousand persons experienced the ride [9, 10].

The graphical abstracted depicted in Fig. 3 summarizes the technology and a figure says more than thousand words.

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

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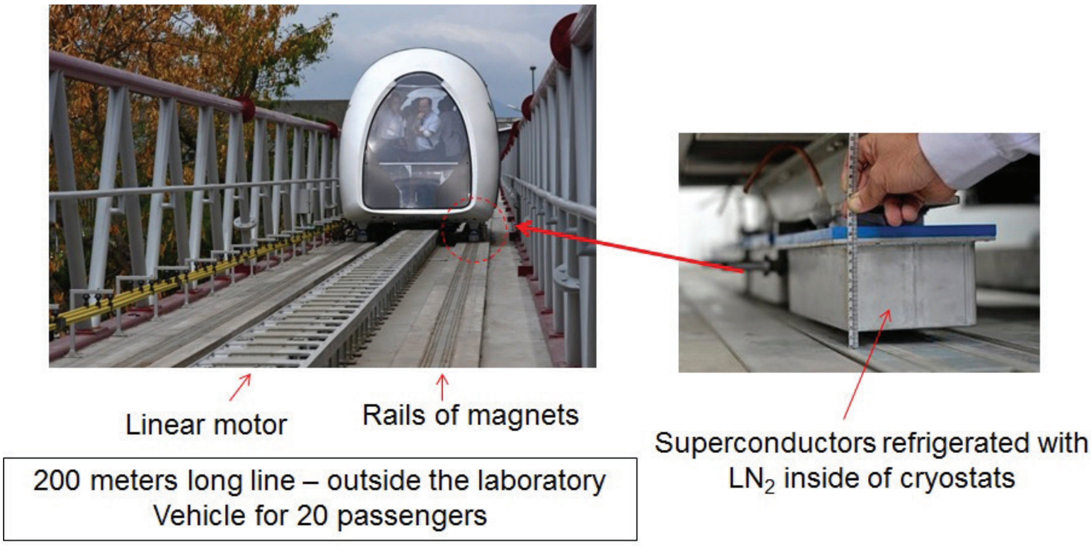

Fig. 3. Graphical abstract of the MagLev-Cobra project

NASA´S TECHNOLOGY READINESS LEVELS

According to the Technologic Readiness Level [11, 12] proposed by NASA and summarized in Table 1, the MagLev-Cobra has reached TRL7.

Table 1. NASA´s Technology Readiness Levels

Level	Description	Main characteristic
TRL1	Basic principles observed and reported	Small scale Proof of concept
TRL2	Technology concept and/or application defined	
TRL3	Proof of concept validation	
TRL4	Validation in laboratory environment	Full scale Laboratory environment
TRL5	Validation in a relevant environment	
TRL6	Validation in a relevant final environment	Full scale External environment
TRL7	Validation in an operational environment	
TRL8	“Mission qualified” trough test and demonstration	First product
TRL9	“Mission proven” trough successful operations	

In fact, for the large scale commercialization, which is not usually the main objective of NASA, a 10th level should be added, as proposed in Table 2.

Table 2. A new Technology Readiness Level to encompass the commercialization

Level	Description	Main characteristic
TRL10	Production, sales and marketing chain established	Series production

The efforts to reach each level increases considerably at each step. The number of person engaged in the activity and the amount of invested money progress geometrically at a rate greater than two. Therefore, to turn the SML Technology a final product, i.e. to reach TRL10, Brazil and China established recently a cooperation named "China-Latin American United Laboratory for Rail Transportation".

APPLICATION NICHE

The main cost of the SML technology rests on the Permanent Magnetic (PM) Rail. Since high speed implies necessarily large distance, which would represent a huge cost on PM, the application niches of SML are short distances, low speed (~70 km/h) urban transportation. For such applications, the EDL technology, which requires velocity to achieve levitation, does not offer a great appeal. In fact, presently, all commercially operated urban MagLev systems (HSST in Japan since 2005, ECO-Bee in South Korea since 2016, and Changsha and Beijing lines in China, since 2016 and 2017, respectively) uses EML technology.

The authors of this paper support that the SML method offers advantages in comparison with the EML solution for application in urban areas. The following items will support this statement based on two points: the simplicity and robustness of the levitation method; the simple and slimmer civil engineering construction.

COMPARISON EML X SML: 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. 4 turns this advantage of the SML technology evident.

COMPARISON EML X SML: 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. 5. As proof of this, the Brazilian prototype for 20 people weighs only 2.3 tons empty.

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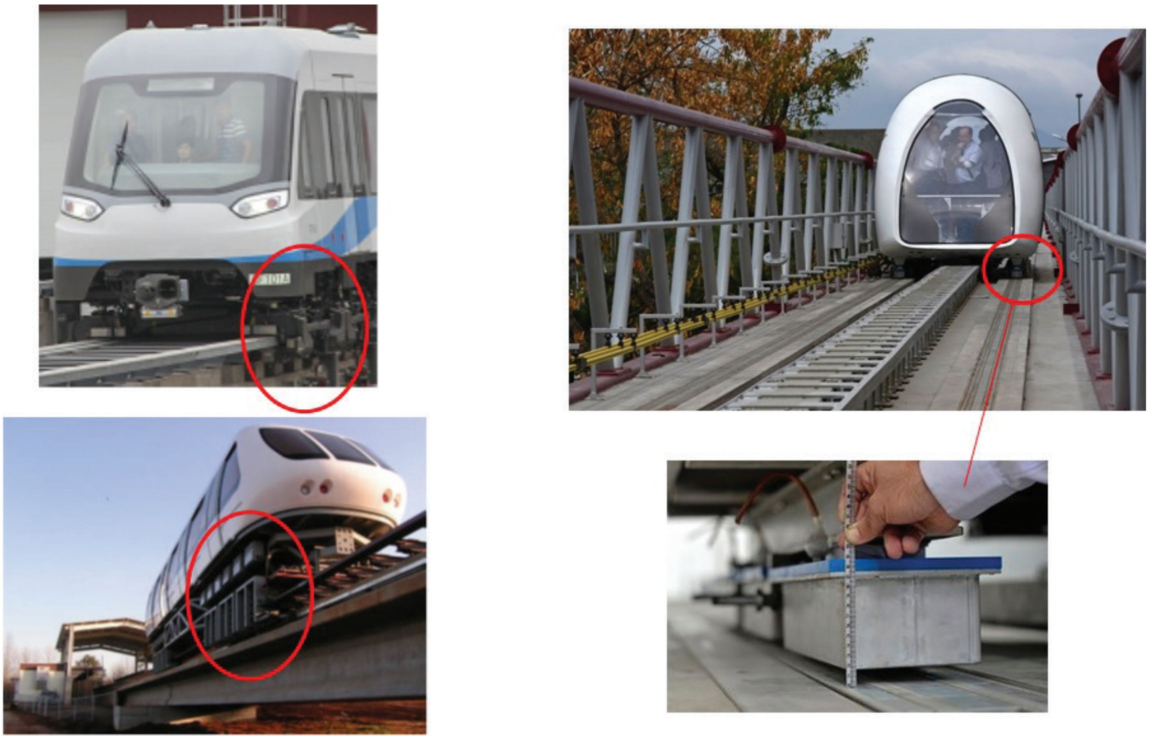

Fig. 4. The EML levitation method (two examples on the left side) in comparison with the SML levitation equipment (on the right)

Fig. 5. The EML civil engineering construction (three commercial lines) in comparison with the real scale prototype of the SML technology

ROUTE FOR COMMERCIALIZATION

To confirm the arguments presented in the last paragraphs, and climb levels TRL8, TRL9 and TRL10, an experimental line of the SML technology, one to two kilometers long, with curves, declivities and switches have to be constructed. The investment necessary is in the order of magnitude of 10^7 US$. Similar steps and levels of investment have been followed by other transportation systems. The participation of Public and Private capital, forming a Partnership, the so-called PPP, is under negotiation. Along this process, the production chain will be established and the flourishment of new companies are foreseen.

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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PROGRESS IN THE RESEARCH OF COPPER-OXIDE SUPERCONDUCTORS

Since H·Carvalin·Onnesse discovered the superconductivity of mercury in 1911, we have made progress in the research of the superconductor and the superconductor have evolved from single element, alloy to complex compounds with multiple elements.With the development of the research about new superconducting materials, the research of iron based superconductors, copper-oxide superconductor and magnesium boride superconductor is the latest research trend. So far the proved highest superconducting transition temperature of copper-oxide superconductor is 130 K under normal pressure and could reach more than 160 K under high pressure. Based on the experience accumulated in past decades, we propose some general introduction about the main structure type, the superconducting principle and the application of copper-oxide superconductor. It is expected that a positive effect would be made in the research of copper-oxide superconductor.

Background: Since H·Carvalin·Onnesse discovered the superconductivity of mercury in 1911, we have made progress in the research of the superconductor and the superconductor have evolved from single element, alloy to complex compounds with multiple elements.

Aim: The purpose of this paper is to explain the differences between copper oxide superconductors and conventional superconductors and their superconducting mechanism.

Methods: The superconducting mechanism and structure of copper oxide superconductors were analyzed by means of literature investigation, conceptual analysis and comparative study.

Results: In this paper, the different structure forms of copper oxide are analyzed, and its superconducting mechanism is described in detail. The applications of several main copper oxide superconductors are introduced.

Conclusion: Based on the experience accumulated in past decades, we propose some general introduction about the main structure type, the superconducting principle and the application of copper-oxide superconductor.It is expected that a positive effect would be made in the research of copper-oxide superconductor.

Keywords: High temperature superconductors, copper-oxide superconductor, superconducting principle, application

1. INTRODUCTION

Since 1911, when H. Carmaorin Annes discovered the superconducting properties of mercury, much progress has been made in the research of superconducting materials. In 1986, Bednorz and Mülle, the researchers of IBM company of Switzerland Zurich Institute, found that lanthanum barium copper oxide superconducting state system can be rendered at the temperature

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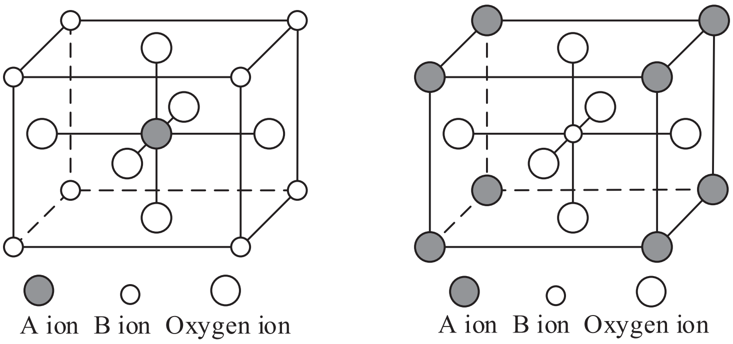
of 35 K, and high temperature superconductors were discovered. Since the discovery of high temperature copper-oxide superconductor, much progress has been made in the study of superconductivity. Although the mechanism of high temperature superconductivity is still unclear, physicists have put forward various superconducting mechanisms to explain the superconducting mechanism of copper-oxide superconductors after years of research.

2. CRYSTAL STRUCTURE OF COPPER-OXIDE SUPERCONDUCTORS

Almost all known high temperature superconductors are stacked with perovskite structures.

2.1. Perovskite structure

Fig. 1 is a schematic diagram of perovskite structure with two equivalent representations. In fig. (a) the B ion is in the center of the quadrangle of the cube, and the oxygen ion is in the center of the hexagonal surface of the cube; The unit cell in fig.(b) is obtained by moving a distance a/2+ b/2+ c/2)from the unit cell in fig. (a), (a,b,c are the crystal lattice constant). The A ion is in the center, the B ion is in the four corners of the cube, and the oxygen ion is in the center of the six sides of the cube.



（a）（b）

Fig. 1. Diagram of perovskite structure

2.2. Perovskite stacking mode

Fig. 2 shows two stacking patterns of perovskite: One is that one perovskite cell is stacked directly on the other, and the two units share the adjacent A-O surface, which is called rock salt layer. Another way is to put perovskite cells on top of the other. The difference is that the two perovskite cells have a displacement of a/2+b/2 to reduce electrostatic repulsion and increase the crystal binding energy. The adjacent A-O planes are no longer shared, which is called rock salt block.

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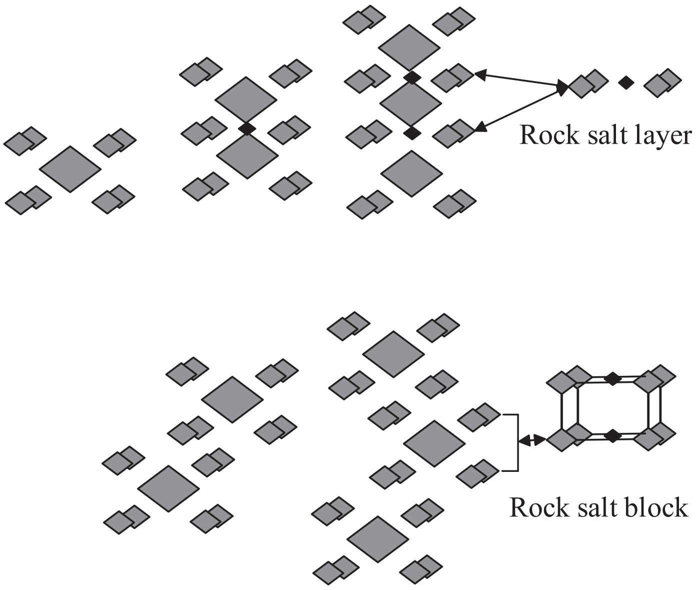

Fig. 2. Perovskite stacking mode

Most high temperature superconductors are stacked in the second mode, which is called R-P structure because it was first proposed by Ruddlesden and Popper. As shown in Fig. 3, the high-temperature superconductor structure is formed by inserting additional layers into the R-P structure, which are often rock salt layers. The general structure can be expressed as $A_mE_2B_{n-1}Cu_nO_{2n+m+2}$ by a four-integer representation (where A, E, R are various metal ions). In the representation of four integers, the m is generally the number of layers in the boundary layer at the junction of two units; the 2 is the number of layers adjacent to perovskite, the vast majority of them are two layers; the n^{-1} is the number of layers intercalated between copper oxygen surfaces and the n is the number of copper oxygen surfaces.

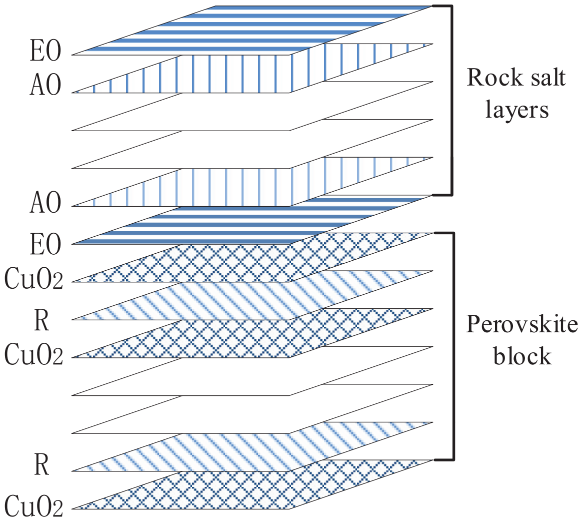

Fig. 3. layered structure of high temperature superconductors and its block method

After this representation, the physical images of the layered structure are displayed intuitively (Fig. 3). This layered structure can be seen as consisting of two blockss: $(EO)(AO)_m(EO)$ is called the storage reservoir area of electricity storage, also known as rock salt block. $(CuO_2)[(R)(CuO_2)]_{n-1}$ is called the conductive zone, also known as a perovskite block.

3. SUPERCONDUCTING MECHANISM OF COPPER-OXIDE SUPERCONDUCTORS

In explaining the superconducting mechanism of superconductors, we need to understand the causes of resistance and how superconductivity is formed.

3.1. Resistance causes

We know that the directional movement of electrons in conductors leads to the generation of currents, and when electrons move between atoms, the vibration of atoms is caused by the electromagnetic force between electrons and nuclei.It is well known that in normal conductors, some electrons are not bound to individual atoms, but can move freely through the lattice of positive ions. When the current is moving through the crystal lattice, especially when the electron in metal collides with the crystal lattice defect, and in the process of motion, it will interact with the crystal lattice vibration and bring about the macroscopic resistance phenomenon. This is the cause of the resistance.

3.2. Superconducting formation

By understanding the cause of the resistance, we can know that in order to form superconducting, it is necessary to eliminate the action of electromagnetic force and make the atom eliminate vibration, thus making the resistance zero to form superconducting.The existing scientific research has proved that at extremely low temperatures, the electrons in the atom are running at a low rate of electrons, and this kind of operation is not satisfied with the speed required for its normal operation. This is equivalent to the formation of an electron deficiency, so the core misappropriates adjacent extranuclear electrons, and then all cores continue to misappropriate adjacent electrons, thus forming a phenomenon of external electron sharing. The core takes the public electron as part of the electronic part of itself, and then uses its Coulomb force to transport the extra core electrons. Because of its own role, the electron flow is formed – superconducting current. Thus, the electron flows homewards during the period without interference of other motion forms, so that making its macroscopic resistance zero.

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3.3. PIntroduction to the classical BCS theory

The electrons with opposite spins and momentum in metals can be paired to form so-called “Cooper pairs”, which can move without loss in the lattice to form superconducting currents.The direct interaction between electrons is a mutually exclusive Coulomb force. If there is only a Coulomb direct action, electrons cannot be paired, but there is also an indirect interaction between electrons mediated by crystal lattice vibration (phonon). The interaction between electrons is attractive to each other, and it is this attraction that leads to the Cooper pair. In general, the mechanism is as follows: when electrons move in the crystal lattice, the positive charges on the adjacent crystal lattice will be attracted, resulting in the local distortion of the crystal lattice points, forming a local high positive charge region. This locally high positive charge region attracts spin opposite electrons, which are paired with the original electrons at a certain binding energy. This binding energy may be higher than the vibrational energy of the crystal lattice atom at very low temperatures, so that the electron pair will not exchange energy with the crystal lattice, and there will be no resistance to form the so-called “superconducting”. In traditional superconducting theory, the superconducting critical temperature depends on the interaction intensity of electron pair.

3.4. Study on Superconducting Mechanism of Copper-oxide Superconductor

The superconducting mechanism of oxide superconductors is one of the most important topics facing condensed matter physicists. This is because the interaction between electrons in this kind of material is so strong that the normal state electron motion behavior does not seem to be based on the Fermi liquid images of quasiparticle images and energy band theory to understand the knowledge. Although the superconducting state is due to the coacervation of Cooper pairs, many experiments show that the main inducement of the pair is probably not caused by electron-phonon coupling.

As to the mechanism of high temperature superconductivity, it is generally believed that electron pairs appear in the electronic system under the background of magnetic fluctuations, and then superconducting coacervation occurs. The most representative theoretical model is the resonance valence bond model proposed by Anderson, which is called Resonating-Valence-Bond, or RVB model. The RVB model considers that in the spin 1/2 system, the spin state is formed near the reverse spin, while the ground state is the quantum superposition state of the spin singlet, forming the so-called quantum fluctuation liquid (SpinLiquid). These adjacent pairs of spins in opposite directions are in quantum fluctuations, so they are more constrained than pure paramagnetic states, and the wave functions describing the opposite pair of spins are similar to the spin parts of the superconducting wave functions of a pair of spin monomorphic pairs. When there is a charge shift in the system, the phase of the spin singlet pair electrons of the RVB ground state is gradually correlated. When the temperature drops below the superconducting transition temperature, phase coherence will be established for the cruise electrons in the system.

It is very difficult to verify the RVB model directly by experiments because the measurement of quantum fluctuations in the RVB ground state leads to a new class of elemental excitations: Spinon (uncharged but with 1/2 spins) and holon (an electron charge but no spin). At present, experimental physicists are trying to find out whether these two new types of meta-excitation exist.

In 2016, physicists at the Brookhaven National Laboratory of the U.S. Department of Energy proposed a theoretical explanation for the high temperature superconductivity of copper oxide complexes. After manufacturing and analyzing thousands of samples of lanthanum strontium copper oxygen (LSCO) mixture, they found that the superconducting critical temperature of the material depends on the concentration of the electron pair in the unit volume of the material.

The magnetic and electrical properties of copper oxide materials were measured by mutual inductance technique to determine the thickness limit of copper oxide materials which can be penetrated by magnetic field. The data can be used to calculate the electron pair density.It is found that there is a good linear relationship between electron pair concentration and superconducting critical temperature. In other words, when there is no free electron pair in the material, the superconducting critical temperature of the copper oxide material should be absolute zero. Specifically, defects in the material prevent the free electron pair from moving, Specifically, defects in the material prevent the free electron pair from moving, leading to the material having to be cooled to a lower temperature to achieve superconductivity. The higher the free electron pair concentration is, the higher the superconducting critical temperature of the material is. According to mainstream superconducting theory, the critical temperature of superconducting depends on the interaction intensity of electron pair, not the concentration of electron pair.Therefore, the correctness of this new theory needs further study.

4. PROGRESS IN RESEARCH AND APPLICATION OF COPPER-OXIDE SUPERCONDUCTORS

Copper oxide superconductors have been developed for more than 30 years. The typical high-temperature bismuth superconducting materials $Bi_2Sr_2CaCu_2O_8$ (Bi2212 phase) and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi 2223 phase) have been widely used in the early stage because of their simple molding process and high critical superconductivity temperature.

At present, most of the high temperature superconducting motors (HTS motors) have been fabricated from a Bi 2223 high temperature superconducting material. High temperature superconducting motor has the advantages of high efficiency, large power, small volume and light weight. It is one of the most important applications of high temperature superconducting materials. Currently, several countries, such as the United States, Germany, Japan and China, have developed megawatt motors. Among them, the 36.5 MW HTS synchronous motor for ship propulsion developed by American Superconductor Corporation in 2007 has been delivered to the Navy. The weight of the motor is 75 t, which is 1/3 of the mass of the traditional motor of the same power. The torque density is 4 times that of the traditional motor, and it is the highest power HTS motor known at present. The 2 kW high temperature superconducting claw electrode DC motor developed by Northwest Nonferrous Metals Research Institute of China can be operated in the liquid nitrogen temperature region (77 K). The motor efficiency is 7 % higher than that of the traditional Z2 DC motor of the same power. However, although bismuth superconducting strips can meet the basic industrial needs, there are still some defects. For example, the Bi - based superconductor is anisotropic , and the irreversible field in the liquid nitrogen temperature region (77 K) is only about 0.2 t. In addition, the bismuth superconducting strips will use large amounts of precious metal silver. The cost of foundation is too high and is not suitable for mass application. These two limitations limit the application scope of bismuth superconductor.

The most widely used HTS material is YBCO. Compared with bismuth high temperature superconducting material, YBCO has much higher irreversible field than bismuth superconducting material. YBCO can maintain high critical current density at 77 K and high magnetic field produced by electric application.

However, the preparation process of YBCO is very complex: firstly, the conductive oxide coating (YBCO layer) is very brittle, the traditional extrusion molding method can not retain its superconducting properties; Secondly, due to the serious problem of weak connection in the YBCO layer, the critical current density of the polycrystal is very low, so it is necessary to eliminate the large angle grain boundary in the current transmission path, which makes it is more difficult in the fabrication process again. The manufacturing process of YBCO is to fabricate YBCO oxide coating on a flexible metal substrate, so YBCO high temperature superconducting material is also called coating conductor.The coating conductor is mainly composed of three parts: textured baseband, transition layer and superconducting layer, in which the manufacturing cost of textured baseband accounts for more than 60 % of the total cost.

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Shanghai Superconducting Technology Co., Ltd. and Shanghai Jiaotong University Joint Superconducting Research Institute optimize the production process of YBCO tapes. Through the production line autonomy, the cost is greatly reduced, and the finished product rate is greatly increased. At present, it has been used in superconducting motor, HTS magnetic separator, HTS current limiting energy storage and so on. Its structure is shown in Fig. 4. For example: Zhongtian technology superconducting current limiter project is using Shanghai superconducting YBCO strip.

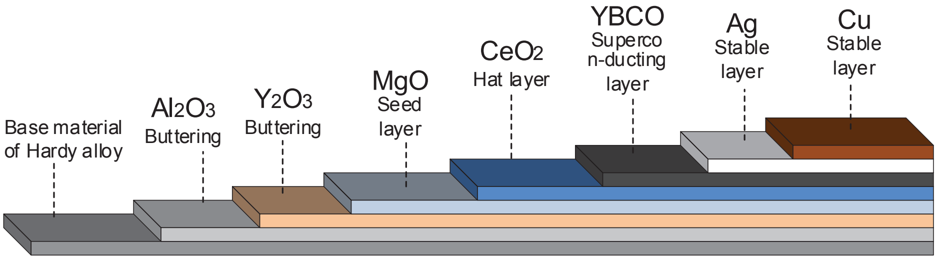

Fig. 4. Schematic show of the deposition process of coating conductor of YBCO

5. CONCLUSION

With the development of research, HTS will be widely used in various industries. For example: with the technology and technical problems of production of high temperature superconducting materials gradually resolved, high temperature superconductivity in low voltage high current power transmission transformer, current limiter and superconducting magnetic fluid technology is widely used in application; in addition, the direct use of completely diamagnetic effect and magnetic flux trapping effect of high temperature superconducting materials, new maglev technology will be developed and so on. At present, the development of superconducting materials has been written into “Made in China 2025” and included in the 13th Five-Year Plan of the New Materials Industry. Otherwise, China is promoting the reform of the national science and technology system, changing the national key R & D projects from the former Ministry of Science and Technology to enterprises. It is believed that HTS will be more and more widely used in the future with the attention and promotion of our country.

6. ACKNOWLEDGEMENT

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A NOVEL DESIGN OF ELECTROMAGNETIC LEVITATION SYSTEM FOR HIGH-SPEED MAGLEV TRAIN

Aim: To reduce the levitation energy consumption and alleviate the adverse effects caused by the over-heating of the electromagnet.

Methods: The design and manufacturing of hybrid electromagnet are introduced firstly. Secondly, the modification of driving chopper module together with a levitation control strategy and the design of an adsorption-prevention module are presented in details. Thirdly, a complete two-carriage maglev train is upgraded with the proposed hybrid electromagnet, choppers, and adsorption modules. Finally, an experiment is performed on a 1.5 km high-speed maglev test line to prove the efficiency of the proposed system.

Results: In this paper, a novel electromagnetic levitation system architecture and safety protection strategy for the high-speed maglev train are proposed.

Conclusion: A novel design of electromagnetic levitation system for high-speed maglev train is designed and implemented.

Keywords: High-speed maglev train, Levitation system, Hybrid permanent magnet and electromagnet, Chopper, Adsorption prevention.

1. INTRODUCTION

The high-speed maglev train is an intercity high-speed rail transportation tool with broad application prospects [1]. The first commercial high-speed maglev line in the world is located in Shanghai, China. The train was officially opened in 2002. It adopts the German TR08 technology and has been operating safely and stable for over 15 years. The successful operation of the Shanghai Maglev line shows the advantages of the maglev train, such as high speed, safety, stability, and low maintenance costs [2].

However, TR08 uses electromagnetic levitation technology without permanent magnet and keeps the train suspending on the track through pure electromagnetic attraction, which causes the following problems:

1. The levitation needs large current which causes serious over-heating of electromagnet [3].
2. The current is close to saturation and the payload capacity is limited.
3. The power supply equipment is very large and occupies too much vehicle space and quality.

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4. The over-heating affects the life expectancy of the electromagnet and the working environment of sensors [4, 5]. In order to solve these problems [6, 7], this paper presents a novel hybrid permanent magnet and electromagnet levitation system for high-speed maglev train. The permanent magnet can generate parts or all of the static levitation force, and the electromagnetic coil mainly plays the role of dynamic adjustment. Hybrid permanent magnet and electromagnet levitation system can significantly reduce the levitation energy consumption and the heating of electromagnet.

This paper mainly focuses on the hybrid permanent magnet and electromagnet levitation system for the high-speed maglev train. It includes the structural design of hybrid levitation electromagnet, the modeling of hybrid levitation system, the design of the levitation controller, the design of power drive module, strategies of adsorption prevention, and the evaluation experiments of a two-carriage maglev train.

2. DESIGN SCHEME OF HYBRID LEVITATION ELECTROMAGNET

Levitation force of high-speed maglev based on electromagnetic levitation is generated by the current in levitation electromagnet. The levitating cost is about 1000 W/t [8]. Fig. 1 is the schematic diagram of the levitation electromagnet for the high-speed maglev train.

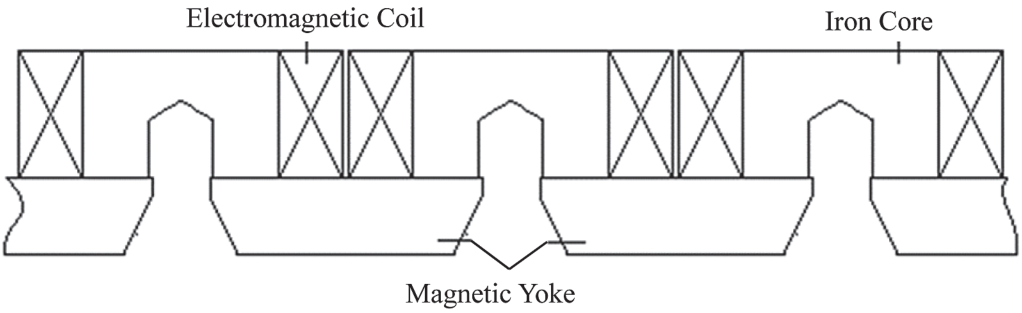

Fig. 1. The schematic diagram of levitation electromagnet

The hybrid high-speed maglev train levitation system proposed in this paper adds permanent magnet material (NdFeB) into the system except for the existing electromagnet. In order to make full use of the permanent magnet, the popular structure of the hybrid electromagnet is discussed first.

According to the different installation position of the permanent magnet, there are mainly three different schemes.

The first scheme: As shown in Fig. 2, the permanent magnet is installed in the middle of the core. In this way, the permanent magnet will not change the

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external dimensions of levitation magnets, and electromagnetic coils and yokes do not need to be changed. However, since the permanent magnet is added into the core, the winding of the electromagnetic coil become more difficult, so the core needs to be redesigned. Moreover, since the polar area of the permanent magnet is equal to the polar area of the iron core, the polar area of the permanent magnet cannot be selected flexibly.

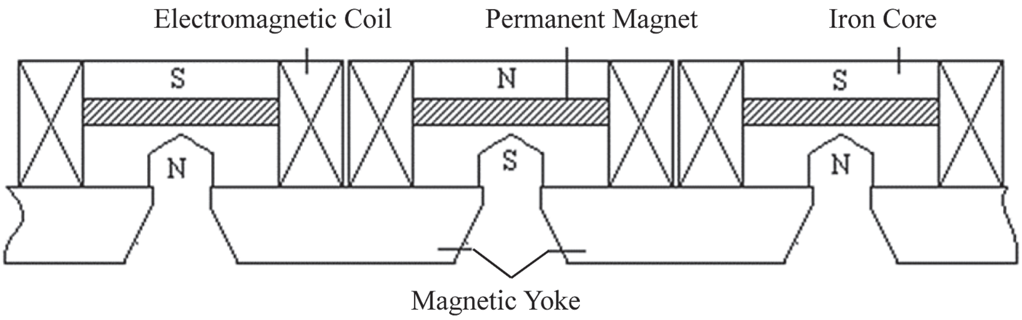

Fig. 2. The first PEM structural diagram.
The permanent magnet is installed in the middle of the iron core

The second scheme: As shown in Fig. 3, the permanent magnet is installed between the iron core and the yoke. In this way, iron cores, electromagnetic coils, and yokes do not need to be changed. However, the polar area of the permanent magnet is small, and it cannot be adjusted flexibly.

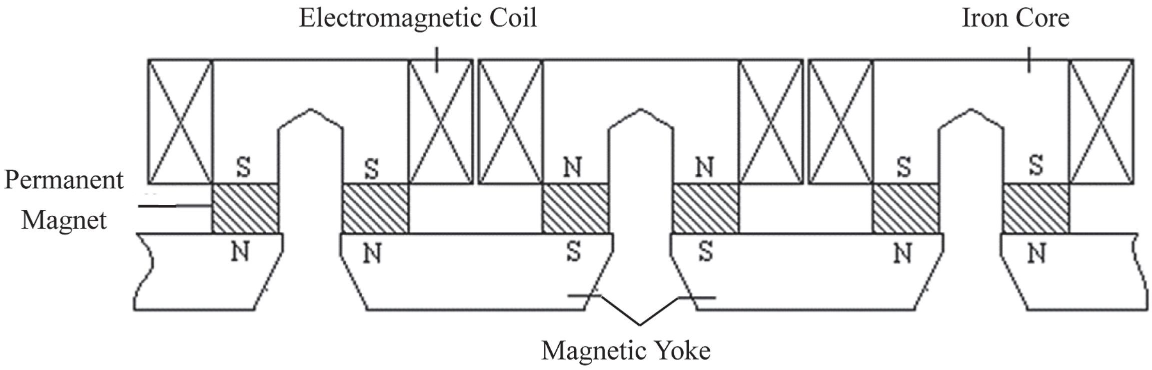

Fig.3. The second PEM structural diagram.
The permanent magnet is installed between the core and the yoke

The third scheme: As shown in Fig. 3, the permanent magnet is installed in the middle of the yoke. In this way, Iron cores and electromagnetic coils do not need to be changed, and the polar area of the permanent magnet can be selected flexibly. However, the yoke needs to be redesigned.

Adding the permanent magnet into the middle of the base yoke can not only increase the touching area of the permanent magnet, but also protect the permanent

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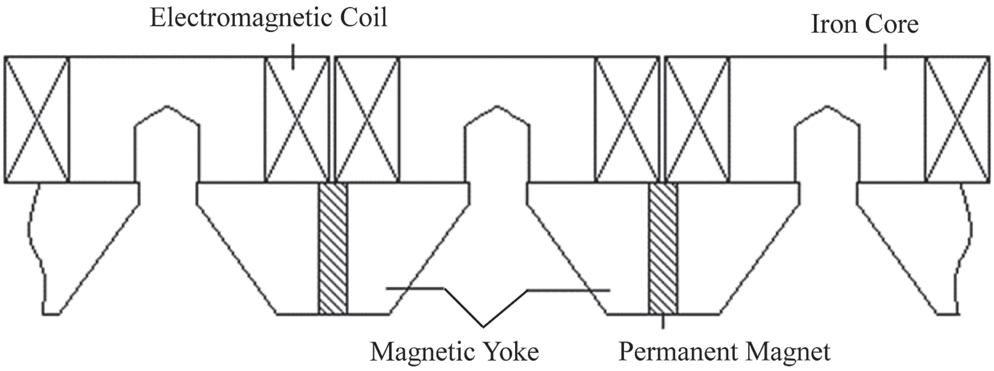

Fig. 4. The third PEM structural diagram.
The permanent magnet is installed in the middle of the yoke

magnet through the yoke. Compared with the way of installing permanent magnet above the core of the electromagnet, this installation way can avoid permanent magnet hitting the track and protect the electromagnet structure. Therefore, the structure of the hybrid permanent magnet and electromagnet adopts this installation mode. The calculation of the electromagnetic attraction in Fig. 4 can use the equivalent structure shown in Fig. 5. Variables are defined as follows: μ_0 denotes the permeability of vacuum, μ_r denotes the relative permeability of the permanent magnet, N denotes numbers of coil turns, i denotes the current in the coil, u denotes the control voltage at both ends of the coil, H_c denotes the coercivity of the permanent magnet, B_r denotes the remanence of permanent magnetic materials, H_m denotes the magnetic field strength at permanent magnet, H_z denotes the magnetic field strength at the gap, B_m denotes the magnetic induction strength at permanent magnet, B_z denotes the magnetic induction strength at the gap, Φ denotes the magnetic flux in magnetic circuit, $M_{\max}$ denotes the full load quality, $M_{\min}$ denotes the no-load quality, z denotes the levitation gap, z_m denotes the permanent magnet thickness, z_0 denotes the steady state levitation gap, S denotes the cross section area at the top of the core, S_m denotes the polar area of permanent magnet, F denotes the force between the permanent magnet and the orbit, $I_{\max}$

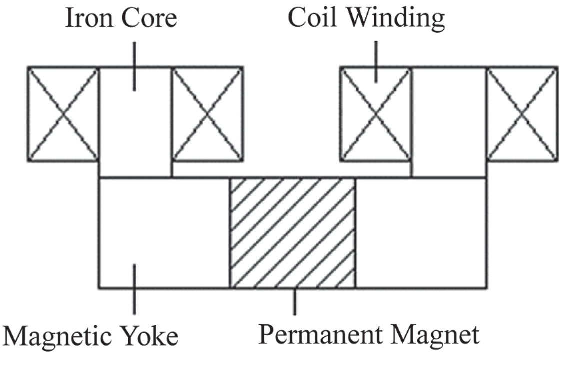

Fig. 5. The equivalent structure of the hybrid electromagnet

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denotes the allowed positive maximum current, $I_{\min}$ denotes the reverse maximum current, $I_{0\max}$ denotes the maximum current of steady state levitation, z_{00} denotes the gap of adsorption, z_{inital} denotes the floating gap.

The total reluctance of the closed loop R_m is calculated from the formula of reluctance:

$$R_m = z_m / (\mu_0 \mu_r \cdot S_m) + 2z / (\mu_0 \cdot S) \tag{1}$$

The total magnetic motive force U_m of the closed loop is shown below:

$$U_m = Ni + H_c z_m \tag{2}$$

According to the conversion relation between magnetic motive force and reluctance, magnetic flux Φ satisfies the following equation:

$$\Phi = U_m / R_m = \frac{Ni + H_c z_m}{z_m / (\mu_0 \mu_r \cdot S_m) + 2z / (\mu_0 \cdot S)} \tag{3}$$

According to the calculation formula of the magnetic induction force and magnetic force at the gap, the magnetic force F can be obtained by:

$$F = \frac{{B_z}^2}{2\mu_0} \cdot (2S) = \frac{\Phi^2}{\mu_0 S} = \frac{\mu_0 S (Ni + H_c z_m)^2}{(2z + z_m S / (\mu_r \cdot S_m))^2} \tag{4}$$

For the convenience of calculation, the formula of magnetic force can be simplified as:

$$F = \frac{K(\alpha i + 1)^2}{(z + \beta)^2} \tag{5}$$

3. LEVITATION MODELING AND THE DESIGN OF THE CONTROL ALGORITHM

In terms of control law design, the German scholar E. Gottzein first established the decentralized control mode of maglev train relying on mechanical decoupling and single point independent control. This mode is still in use today, and it determines the structure design and electrical control mode of high-speed and low-speed maglev train. In the mode of decentralized control, the study of suspension control is generally based on single point model. The suspension control law is designed by using multiple information, such as suspension gap, gap differential, electromagnet acceleration, acceleration integral, electromagnet current and voltage, and magnetic flux density of electromagnet. The mathematical model of the single point suspension system of the hybrid permanent magnet and electromagnet is shown follows:

$$\begin{cases} m\ddot{z} = mg + N_s - F = mg + N_s - \dfrac{K(\alpha i + 1)^2}{(z+\beta)^2} \;{}_{e} \\ u = Ri + \dfrac{d}{dt}(Li) = Ri + \dfrac{\mu_0 N^2 S}{2z + z_m S / \mu_r S_m}\dfrac{di}{dt} - \dfrac{2\mu_0 NS(Ni + H_c z_m)}{(2z + z_m S / \mu_r S_m)^2}\dfrac{dz}{dt} \end{cases} \tag{6}$$

Assuming the state variable as $x = [x_1\ x_2\ x_3] = [z\ z'\ i]$, the state equation can be obtained by:

$$\begin{cases} x_1' = x_2 \\ x_2' = -\dfrac{K(\alpha x_3 + 1)^2}{m(x_1+\beta)^2} + \dfrac{N_s}{m} + g \\ x_3' = \dfrac{-Rx_3(2x_1 + z_m S / \mu_r S_m)}{\mu_0 N^2 S} + \dfrac{2\mu_0 NS(Nx_3 + H_c z_m)}{(2x_1 + z_m S / \mu_r S_m)^2} x_2 + \dfrac{(2x_1 + z_m S / \mu_r S_m)}{\mu_0 N^2 S} u \end{cases} \tag{7}$$

The system model is a typical nonlinear system, which is usually complicated. A simple method is to linearize the system at the equilibrium point and get a linearized model. The stability of the linearized model near the equilibrium point can be considered as consistent with the stability of the original model.

Let $x' = 0$, the equilibrium point can be obtained by:

$$x_0 = [x_{10}\ x_{20}\ x_{30}] = \left[z_0 \quad 0 \quad \frac{1}{\alpha}[\sqrt{\frac{(mg+N_s)}{K}}(z_0+\beta) - 1] \right] \tag{8}$$

Linearize the system model at the equilibrium point, and the state space expression after linearization is obtained by:

$$\begin{cases} \Delta x' = A_S \Delta x + B_S \Delta u = \begin{bmatrix} 0 & 1 & 0 \\ a_{21} & 0 & a_{23} \\ a_{31} & 0 & a_{33} \end{bmatrix} \Delta x + \begin{bmatrix} 0 \\ 0 \\ b_{31} \end{bmatrix} \Delta u \\ \Delta y = C_S \Delta x = [1 \quad 0 \quad 0] \Delta x \end{cases} \tag{9}$$

where: $a_{21} = \dfrac{2K(\alpha i_0 + 1)^2}{m(z_0+\beta)^3}$,

$$a_{23} = -\frac{2K\alpha(\alpha i_0 + 1)}{m(z_0+\beta)^2},$$

$$a_{33} = \frac{-K(2z_0 + z_m S / \mu_r S_m)}{\mu_0 N^2 S},$$

$$b_{31} = \frac{2z_0 + z_m S / \mu_r S_m}{\mu_0 N^2 S}.$$

A cascade control idea is adopted in levitation control of maglev train in general, by introducing the current negative feedback, the current response speed is increased.By selecting appropriate feedback parameters, the current feedback link can be simplified as a proportional link with a gain of 1, which simplifies the complexity of controller design. Set state variable as $[x_1, x_2] = [z, z']$, the single point suspension system can be reduced to two order system. Then the state equation can be presented as follows:

$$\begin{cases} x_1' = x_2 \\ x_2' = -\dfrac{K(\alpha u + 1)^2}{m(x_1 + \beta)^2} \end{cases} \tag{10}$$

Let $x_1' = x_2' = 0$, the equilibrium point can be obtained by $x_{10} = z_0$, $x_{20} = 0$, $u_0 = i_0 = \frac{1}{\alpha}[\sqrt{\frac{(mg+N)}{K}}(z_0 + \beta) - 1]$. Linearize the state equation at the equilibrium point:

$$\begin{bmatrix} \Delta x_1' \\ \Delta x_2' \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ \dfrac{2K(\alpha i_0 + 1)^2}{m(z_0 + \beta)^3} & 0 \end{bmatrix} \begin{bmatrix} \Delta x_1 \\ \Delta x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ -\dfrac{2K(\alpha i_0 + 1)}{m(z_0 + \beta)^2} \end{bmatrix} \Delta u \tag{11}$$

According to optimal control theory for linear two order problems, the performance index is as follows:

$$J = \int_0^{\infty} \left[x^T(t) Q x(t) + u^T(t) R u(t) \right] dt \tag{12}$$

where Q, R are the weighting coefficients for state variables and control variables.

The optimal control variable to minimize the performance index is shown below:

$$u^*(t) = -R^{-1} B^T P x(t) = -K x(t) \tag{13}$$

where P is the unique solution of the Riccati algebraic equation:

$$PA + A^T P - PBR^{-1} B^T P + Q = 0 \tag{14}$$

4. DESIGN OF POWER DRIVE MODULE

The difference between the hybrid permanent magnet and electromagnet levitation system and the normal electromagnet system is that even if there is no current in the coil, the hybrid electromagnet still has attraction force. Because of the magnetic force of the hybrid electromagnet can make the electromagnet adsorbed on the track when failures occur. As shown in Fig. 6, the bi-directional chopper must be used in the hybrid levitation system, and the chopper drive circuit must

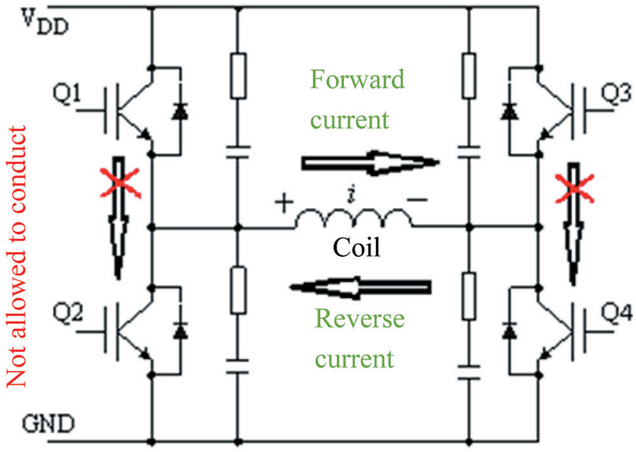

Fig. 6. A bi-directional chopper for hybrid levitation system

be able to output voltage in two directions. The two power switches in the upper part and the lower part of the bi-directional chopper are connected in a branch. In order to avoid direct connection, the opening period of the two devices must have no overlap. In this way, it can avoid the burning of the power components. So the safe and reliable driving of the power switch tube must be solved.

In order to avoid the direct connection between the upper and lower bridge arms, a chopper drive circuit with perfect function and high reliability should be selected. The external RC network generates suitable dead time to avoid simultaneous conduction of upper and lower bridge and main power supply short circuit. Drive circuit has perfect short circuit protection, over current protection and power monitoring function. If abnormal occurs, the block signal will be enabled and the chopper will turn off four power switches at the same time.

5. DESIGN OF ADSORPTION PREVENTION

Because the adsorption fault can cause great damage to levitation system and affects the safety of the maglev train, it is necessary to design the adsorption protection module for the permanent magnet. In order to improve the reliability of protection strategy, this paper designs a novel adsorption prevention module from the perspective of control algorithm and mechanical design.

5.1. Adsorption preventing by control algorithm design

By improving the design of the levitation controller and chopper, the system can have the function of adsorption prevention. The structure of the designed adsorption prevention system is shown in Fig.7.

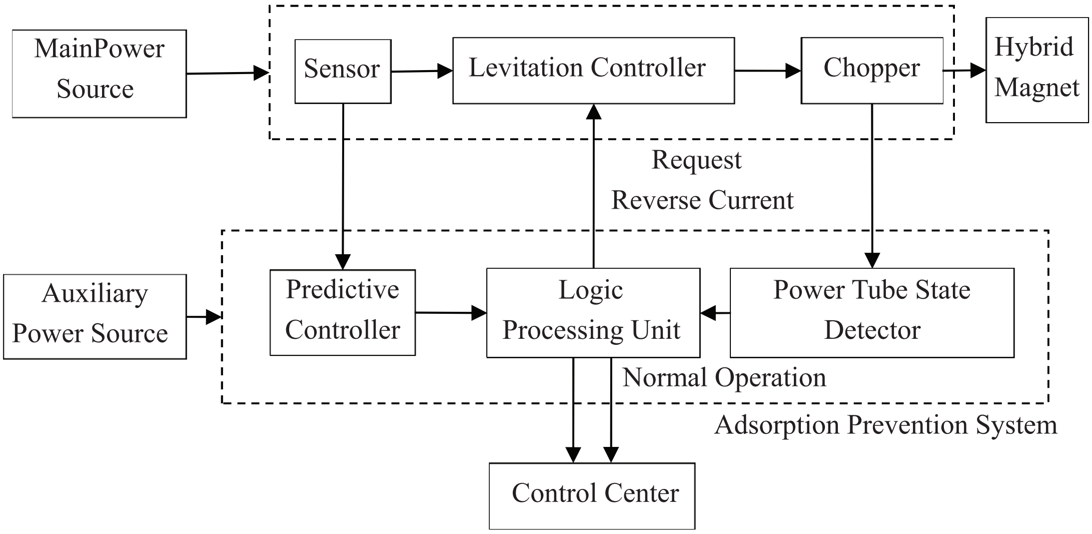

Fig. 7. The Schematic diagram of the proposed adsorption prevention system

The adsorption prevention system consists of a predictive controller, a power transistor state detector, and a logic processing unit. Under normal circumstances, the adsorption prevention system predicts the gap and monitors the chopper state, and the levitation controller adjusts the current according to the algorithm. When there is a risk of adsorption, the levitation controller outputs the reverse current to reduce the attraction between the magnet and rail track.

The realization of the adsorption prevention system through the digital circuit is shown in Fig. 8. The DSP predicts the effect of levitation control. When the actual value is quite different from the predicted value, the DSP judges that the levitation control has failed and sends a protection order to the CPLD. The CPLD is used to generate PWM waves and outputs fault-oriented safety PWM.

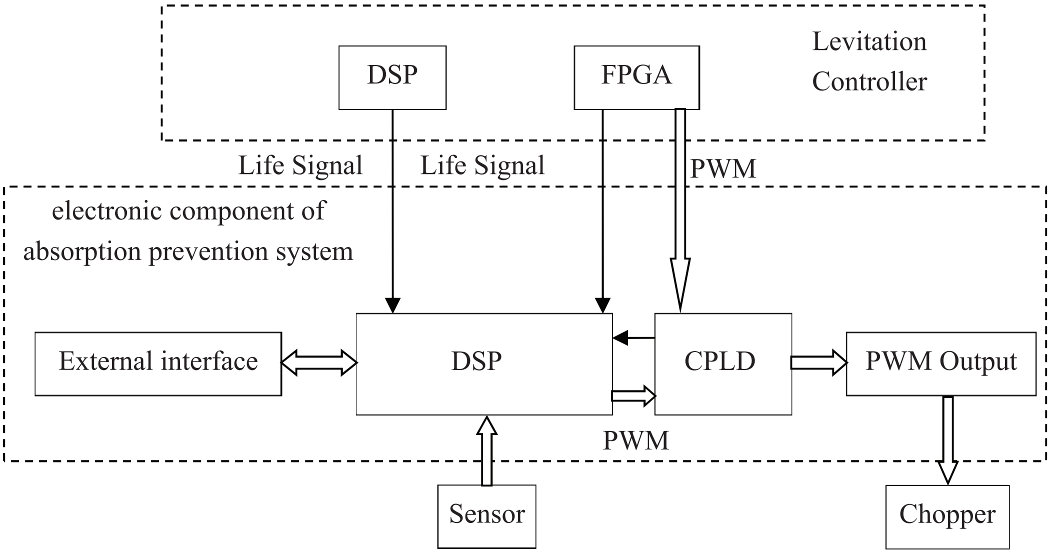

Fig.8. The hardware structure of the adsorption prevention system

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5.2 Adsorption preventing by mechanical design

Except for the control method, design a novel mechanical structure is another method to keep a minimum gap between the electromagnet and the track when absorption failure occurs. In this way, the direct collision between the magnetic pole and the track can be avoided, and the repair difficulty is greatly reduced after adsorption failure occurs. The specific mechanical design method is to add pads on both ends of the electromagnet. The pad is 3.5mm higher than the magnetic pole, which ensures there is a 3.5mm minimum gap between the electromagnet and the track.

6. EXPERIMENTAL RESULTS

In order to ensure the safety of the system, a lot of experiments need to be performed before it can be put into usage. Experimental tests mainly focus on ensuring system security. The tests include the static levitating and landing test carried out in the garage, the normal suspension of the system, artificially disturbance applied for the levitation electromagnet to evaluate the proposed adsorption prevention methods, and implementing the tests on the track outside the garage. Those key experiments are performed and evaluated in this section.

6.1. Levitation experiment

The static levitating and landing test is carried out in the garage. Fig. 9 shows the assembled high-speed maglev train based on hybrid permanent magnet and

Fig. 9. The high-speed maglev train based on hybrid permanent magnet and electromagnet in Shanghai

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electromagnet in Shanghai. Fig. 10 shows the experimental result of the maglev suspension. After the levitation command is issued, the levitation electromagnet gradually rises to the target position, meanwhile the levitation gap decreases gradually and keeps at the target value. Fig. 11 shows the test result of the landing process. After the landing command is issued, the electromagnet rapidly falls to the initial position, and the levitation gap gradually increases from the target value to the initial value.

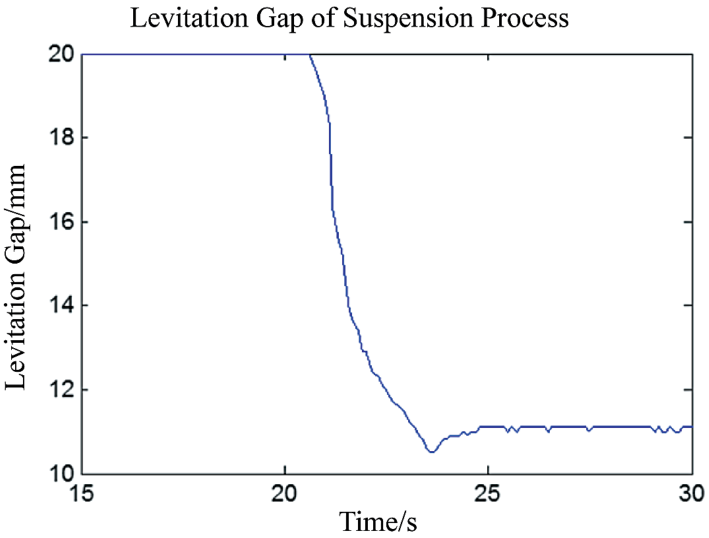
Levitation Gap of Suspension Process

Fig. 10. Levitation gap during the maglev suspension

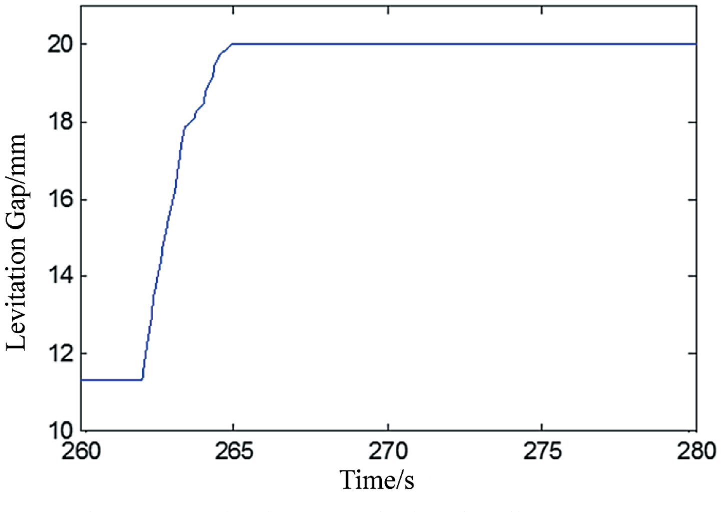

Fig. 11. Levitation gap during landing process

6.2. Operation experiment

The traction test of 2 maglev trains based on the hybrid permanent magnet and electromagnet on 1,5 km track is also carried out, the test result is shown in

Fig. 12. The levitation gap remains stable during this process, and the amplitude of the electromagnet fluctuates within 3 mm.

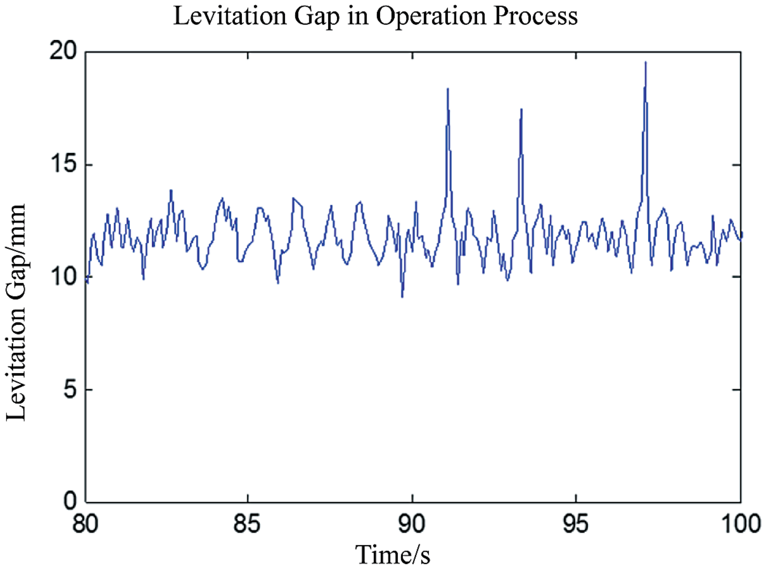

Fig.12. Levitation gap during running test

7. CONCLUSIONS

The hybrid permanent magnet and electromagnet levitation system has two characteristics, one is energy conservation, and another one is payload capacity. In order to make full use of these two advantages, the hardware design and control algorithm need to be modified in order to solve new problems of the hybrid permanent magnet and electromagnetic levitation system. In this paper, a two-marshaling maglev train based on the hybrid permanent magnet and electromagnet levitation is reformed, the stable levitation of the train is achieved, the closed loop traction test is carried out, and the feasibility of high-speed maglev train based on the hybrid permanent magnet and electromagnet levitation technology is verified.

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THE SIMULATION AND ANALYSIS FOR A NEW CONCEPT OF THE STATOR POWER SUPPLY MODE OF A MEDIUM SPEED MAGLEV SYSTEM

Aim: The Aim of this paper is to demonstrate the structure of the proposed new stator power supply mode.

Methods: analyze the results of some simulation work to see whether the new concept could meet the requirements of the medium speed maglev transportation system or not. The study is based on some simulation work which is done by the software tool developed in the research work in "The 11th Five-year plan" of China.

Results: The calculation results indicate that, from the point of view of top speed, that say 200 km/h, the structure of the new concept could meet the requirement of the medium speed system, but further studies are demanded for the engineering application.

Conclusion: The advantage of this structure is to reduce the demand for the capacity of the inverters and eliminate the requirements for the cable lines and the stator switches. However, the disadvantage is also explicit. The structure is more complex than its high speed peer, and thus need more complex control strategies. And the structure is more fixed and thus maybe need more invest at the beginning of an engineering project.

Keywords: medium speed transport, power supply mode, medium power converter, simulation, long stator synchronized linear motor

INTRODUCTION

Since 40s of last century, Maglev transportation technology has been studied and developed for over 70 years. The application speed mainly focuses on two areas: below 120 km/h or higher than 430 km/h. For the slow speed range, the short stator linear induction motor is applied, for example the HSST demonstration line in the Tsukuba World Exposition and the Changsha Maglev Express Line. As for the high speed range, the long stator linear synchronous motor is the better choice. Transrapid Maglev technology, which is used in Shanghai Maglev Project, and SCMaglev technology, which will be used in Chuo Shinkansen Project, are both this type of linear motor.

Recently, some Chinese government officials and experts are seeking for a transportation type around 200 km/h operation speed to solve the relatively short inter-city traffic problem, which demand more strong acceleration capability than

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traditional wheel rail technology to shorten the accelerating periods, and then make the whole travel time reasonable. The long stator synchronous motor therefore is taken into account. The new concept structure of the stator power supply mode, which is just designed for this medium speed system, proposed firstly by CRRC Zhuzhou Locomotive Co., Ltd. Then the research work is supported by Ministry of Science and Technology of China in “The 13th Five-year plan”.

This paper describes the details of this new structure. The main idea is to degrade the capacity requirement of the motor, and put more general industrial converters into consideration. The paper reveals the feasibility of this new concept from the point of view of speed requirements. Other details about the engineering adaption are still under further research.

In the following description, the new structure of the power supply mode is introduced firstly. Then the simulation results based on the same motor parameters as Shanghai Maglev Project are presented. After analyzing the advantages and disadvantages of the system, some conclusions are drew at the end of the paper.

THE NEW CONCEPT OF POWER SUPPLY STRUCTURE

The proposed structure is presented in Fig. 1. Basically, the linear motor, including the materials, size, the stators and the rotors on the train, is as same as the one applied in Shanghai Maglev Project. The main difference is the connection types.

Fig. 1a shows the supply mode when the system is configured 4-car trains. There are two long stator sections in (a). Each section locates on one side of the boundary line and is divided into two groups of subsections, which are named Stator Unit in the figures. The color blue stands for one group of stator units and red stands for another. One stator units is about two carriages long. The stator units in the same group are arranged at intervals and connected directly by stator cables. As a result, the total length of one stator units group is about half of one stator section.

The situation of 6-car trains is present in Fig. 1b. The difference between (a) and (b) is that each stator section is divided into three groups of stator units. As can be seen in (b), the color green on the track means the third group of stator units. The stator units from the three groups is arranged in sequence along the track, and therefore each group of stator units is about one third of the stator section length. According to the same principle in Fig. 1c, if the system demand for 8-car trains, the stator section will consist of four groups of stator units, each of which is about one forth long of the stator section. The fourth group is color orange in (c). The length of stator units in (b) and (c) is same as that in (a), which is about two carriages long of the train.

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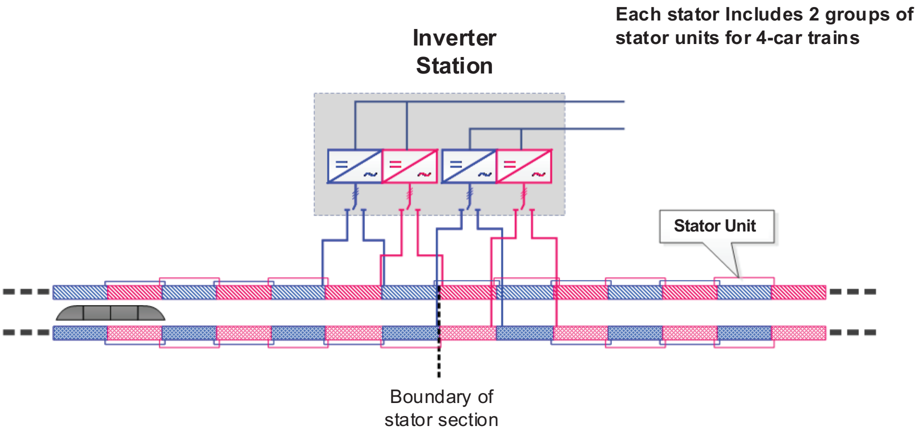
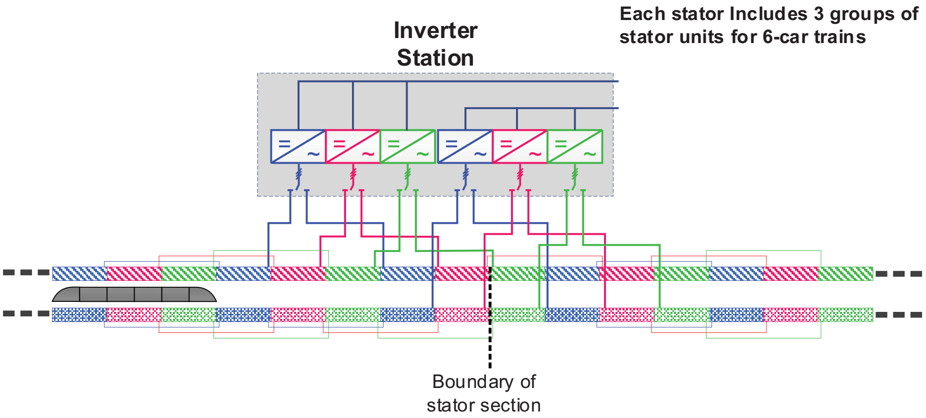
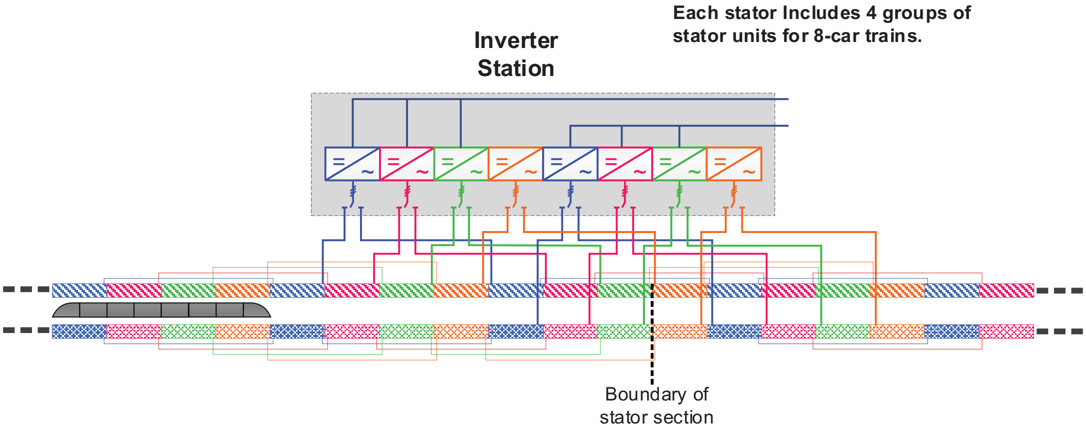


(a) Tvehicle contains 4 cars



(b) The vehicle contains 6 cars



(c) The vehicle contains 8 cars

Fig. 1. The sturcture of the new concept power supply mode:
Same color means belonging to the same stator unit group which is excited
by the inverter in the same color

Another important issue that needs to be addressed is about inverters, which are located by the track near the boundary of stator sections, and shared by two adjacent stator sections through the output switches. Compared with the arrangement in Shanghai Maglev Project, this kind of design saves the feeder line

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cables along the tracks, and thus avoids the voltage drops on the feeder cables. The trackside switch stations now should be called propulsion/inverter stations, for the stator switches are replaced by inverters now. In Fig. 1, Each group of stator units is corresponding to one inverter that is in the same color.

Fig. 2 gives an example of the whole structure of the new concept, which is a draft of the propulsion system for a medium speed test line. There are two inverter stations and a power station. The rectifiers in power station transform the 20 kV input AC voltage to 3000 V DC voltage, and then supply the DC power to trackside inverters.

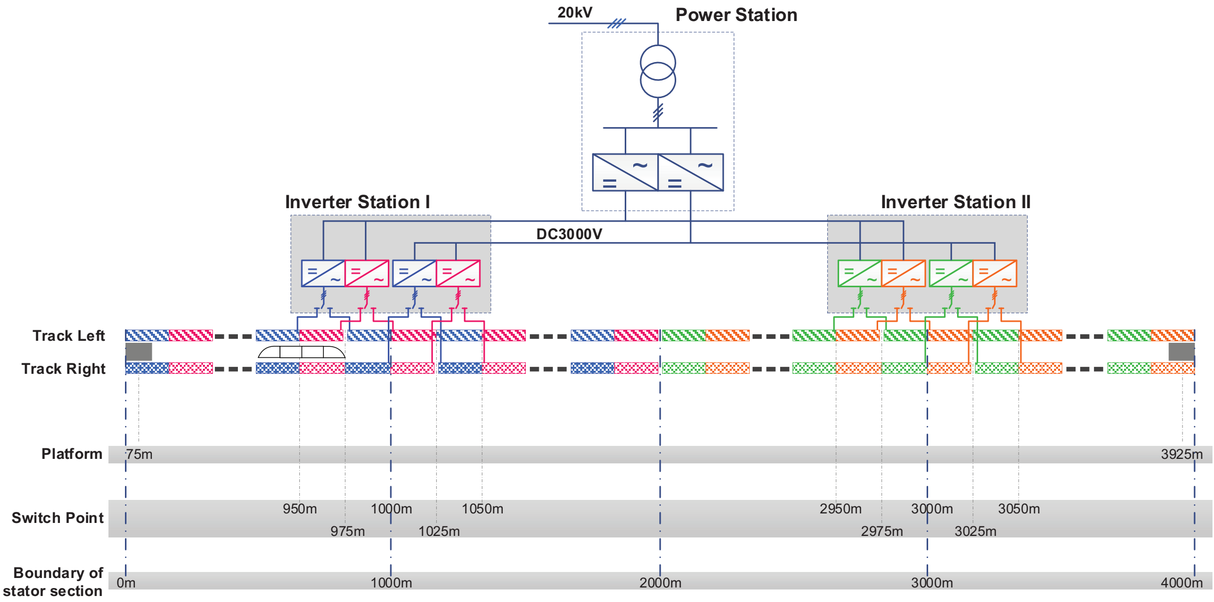

Fig. 2. A draft outline of the propulsion system for a medium speed test line

SIMULATION RESULTS

The track line in Fig. 2 is about 4 km long, which is constraint by the onsite geographical conditions and the project budget. To evaluate the acceleration capability of and the electrical characteristics of the new power supply mode, the length of the track is set to 5 km (for 1000 m stator section) or 8 km (for 2000 m stator section) to ensure that the propulsion system has enough distance to reach 200 km/h. In addition, the plane and vertical curves of the track are neglected too. The other simulation conditions are listed in Table 1.

Since every two stator sections corresponding to one trackside inverter, the length of the stator section is the crucial data for the cost of inverters. In consequence, the behavior of the propulsion capability with different lengths of the stator section is concerned. The different numbers of the carriages of the train are also taken into account in the calculation. All trains are full loaded. The simulation

Table 1. Simulation Conditions

Items	Contents	
Track	Length: 5 km / 8 km without plane and vertical curves	
Vehicle	Number of cars	4-car, 6-car or 8 car 1.5 m/car
	Weight	Each empty car: 24.5 t end 24 middle; Each full car: 31.2 end 31.2 middle
Inverter	Current Limit	1200 A
	Voltage Limit	2200 V (Line Voltage)
Stator Section Length	1000 m / 2000 m	

results with 1000 m and 2000 m stator section are presented respectively in the following paragraph. All the simulation work is carried out by the software named MaglevPDS, which is a research achievement in the "The 11th Five-year plan".

1. 5 KM TRACK FOR 1000 M STATOR SECTION

The speed and acceleration profiles with are shown in Fig. 3. The acceleration capability data is listed in Table 2.

Fig. 4 is the power profiles for each numbers of carriages. The relative power data is listed in Table 3.

Table 2. List of Acceleration Capability Data (1000 m stator section, 5 km track)

Number of cars	Running Time (s)	Accl. Distance (km)	Accl. Time (s)	Max. Accl. (m/s^2)	Average Accl. (m/s^2)
4*	180	2.94	104	0.673	0.534
4**	198	3.01	105.2	0.673	0.528
6	180	2.79	101.4	0.632	0.548
8	181	2.78	101.6	0.591	0.545

* A 4-car train can not reach 200 km/h with 5 km track. The maximum speed is 198.6 km/h.

** If the track is extended to 6km, thetrain can reach 200 km/h.

Table 3. List of Power Data (1000m stator section, 5km track)

Number of cars	Max. Power for Each Inverter (MW)	Maximum Total Power (MW)
4	2.00	8.01
6	2.17	13.02
8	2.10	16.77

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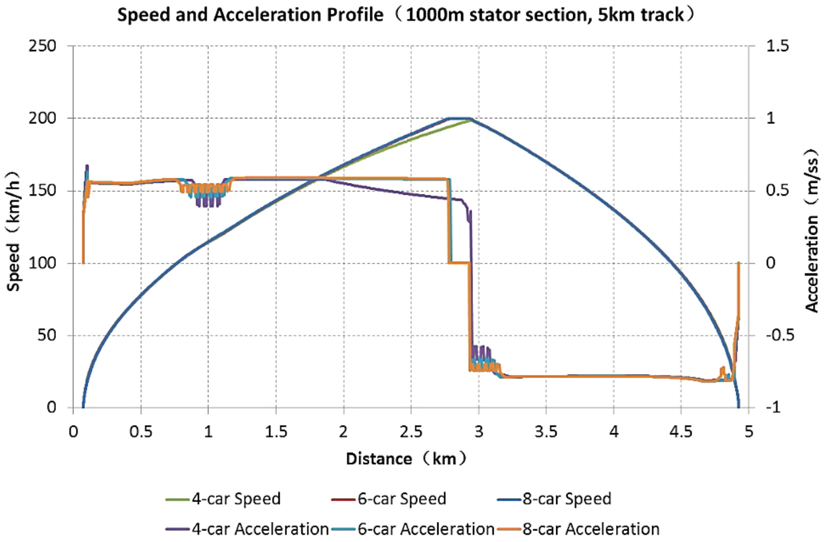

Fig. 3. Speed and acceleration profiles for 1000 m stator section with 5 km track

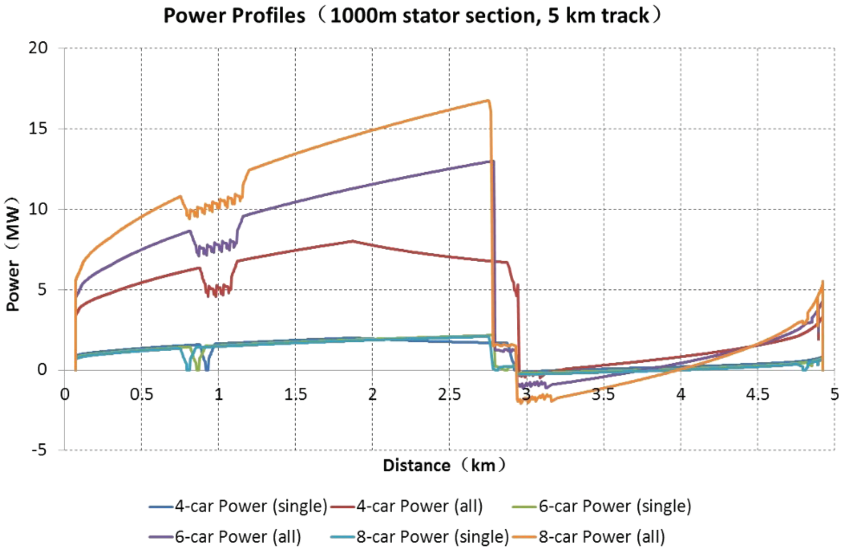

Fig. 4. Power profiles for 1000 m stator section with 5 km track

2. 8 KM TRACK FOR 2000 M STATOR SECTION

The speed and acceleration profiles with 2000 m stator section and 8 km track are shown in Fig. 5 and the acceleration capability data is listed in Table 4. Fig. 6 is the power profiles for each numbers of carriages. The relative power data is listed in Table 5.

ANALYSIS

The simulation results demonstrate that this new concept of power supply mode can meet the requirement of 200 km/h top speed, and can be one of the alternative designs for the medium speed system.

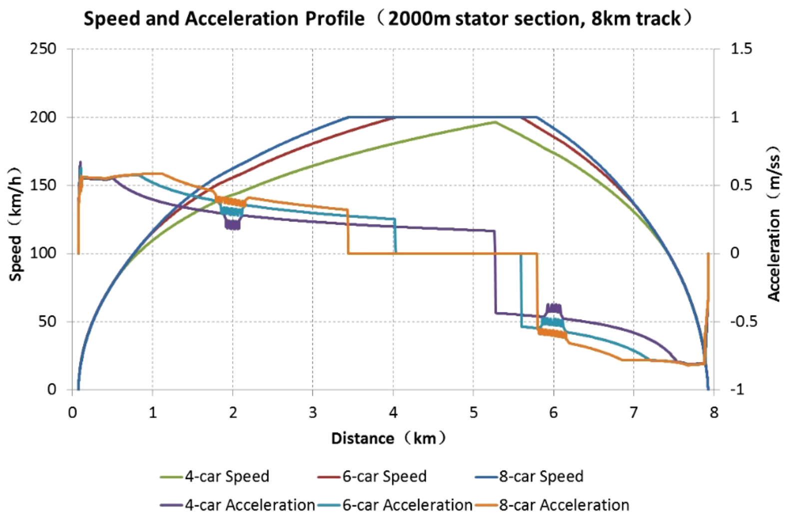

Fig. 5. Speed and acceleration profiles for 2000 m stator section with 8 km track

Table 4. List of Acceleration Capability Data (2000 m stator section, 8 km track)

Number of cars	Running Time (s)	Accl. Distance (km)	Accl. Time (s)	Max. Accl. (m/s2)	Average Accl. (m/s2)
4*	248	5.27	156.8	0.673	0.348
4**	266	5.60	162.7	0.673	0.341
6	239	4.03	127.3	0.632	0.436
8	237	3.44	114.8	0.589	0.484

* A 4-car train can not reach 200 km/h with 8 km track. The maximum speed is 196.5 km/h.
** If the track is extended to 9 km, thetrain can reach 200 km/h.

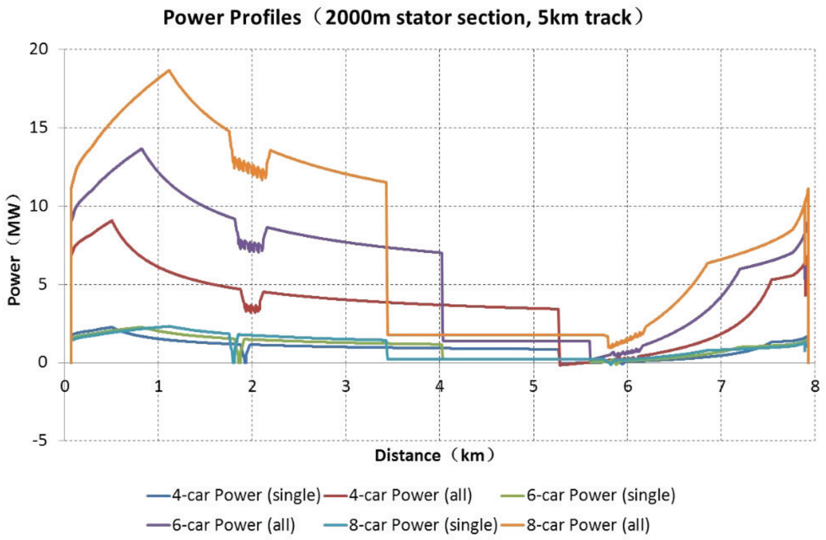

Fig. 6. Power profiles for 2000 m stator section with 8 km track

Table 5. List of Power Data (2000 m stator section, 8 km track)

Number of cars	**Max. Power for Each Inverter (MW)**	**Maximum Total Power (MW)**
4	2.27	9.07
6	2.28	13.67
8	2.34	18.68

A special feature of the system is that the longer the train is, the more strong acceleration capability the system has. Since for the similar length of the stator section, longer train means shorter stator units group. For example, a 4-car train corresponding to 2 groups of stator units, which indicate one half of the stator section length for each group. While a 8-car train indicate one fourth for each group. This feature is more explicit in 2000 m stator section situation.

Another feature can be seen from the above results is that the output power of each single inverter is almost at the same level, no matter what the number of the carriages of a train is. That is because the inverters are located beside the track, the main part of the output voltage is the back EMF of the train. While each inverter only corresponds to two cars of the train, no matter how many the carriages the train has. Therefor the structure is easy to standardize and generalize.

From the data listed in Table 1, the capacity of inverters in this paper is around 4.5 MVA, which is less than 1/3 of the capacity of the high power converters used in Shanghai Maglev Project. That mainly benefits from the reduced top speed and the trackside inverter strategy. Since the voltage requirement is degraded, the output voltage of the inverter is sufficient for the system, and the output transformers are not necessary. The trackside stator switches are also removed which is another advantage of the trackside inverter.

This structure also has some obvious defect. The greatest one is the dependency between the stator connection type and the number of the carriages of a train. Due to the difficulty of change the connection type after the project put into operation, the inverters for the longest train must be allocated at the beginning of the formal operation. That indicates the project should invest more money for a long term planning at its initial term.

Additionally, because of the more complex structure, the stator section switch principle is more complex too, which indicate the control system need more resource to switch between stator sections.

Another disadvantages is about the 3000 V DC line. Since the DC cables are layout along the track, the voltage will drop on the cables. If the ripple of the DC voltage is too large, the output voltage of the inverter will be affected.

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CONCLUSION

This paper demonstrate a new concept power supply mode for the medium speed transportation system. Some simulation research results are presented and the advantages and disadvantages are analyzed. It is verified that the new concept structure is reasonable and feasible for a medium speed system, but further research is required before the concept put into reality.

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UML BASED TEST CASES GENERATION FOR THE CENTRALISED CONTROL SYSTEM OF HIGH SPEED MAGLEV

Background: The high speed maglev centralized control subsystem (CCS), which realizes the display, automatic train operation (ATO) and diagnose. The CCS is an important security assurance for train operation. System testing (ST) can detect design defects early and performed effective repair to improve the efficiency of the system' on-site coordinated operation. Therefore, the quality of test cases directly determines the achievements and efficiency of CCS, and it is necessary to be tested before put it into use.

Aim: The generation of test case of centralized control subsystem is proposed.

Methods: In order to meet the requirements of the system, the first step is operating the extraction of functional features. Then, the unified modeling language is using to develop the test model in this paper. Then the corresponding unified modeling language models, use case diagram, state diagram, activity diagram and sequence diagram, are developed. The state diagram of operation process is using to describe the state transition during the period from initial state of the OTS to the completion of the operation. The activity diagram of train operation process focuses on the control relationship during the period from one activity to another, which can describe the interaction exactly between OTS, DCS and VCS. The sequence diagram, behavior of use case, focuses on the sequence of information sent by objectives, in which a group of objectives and information transfer are presented. And according to these models, the test cases of the specified case are generated.

Results: The generated test cases are all executed in the developed lab-test system. The results show that the generated test cases can fully simulate the common situations of the operation scene, and effectively improve the test efficiency and test quality. We designed the experiments as followings: 85 test cases for terminal system design of operator, 68 test cases for train automatic operation design, 31 test cases for central diagnostic system design. All of the designed test cases are examined through the test platform, covering all main scenes in operation process. The errors or detects found in tests are solved by finding the reasons and modifying the code, etc. Finally, the pass rate of the method proposed in this paper is 100 %.

Conclusion: The UML based method of test case generation implements the generation process and achieves the test cases and verification for CCS. Through the test practice, test cases designed can fully simulate all kinds of common situations in the operation site. What's more, the test cases also realize early detection of errors and defects in the system and repair them. It is useful to improve the efficiency on-site testing process, to reduce the cost of time and test quality. The method can provide theoretical basis and reference for further testing of high speed maglev CCS.

Keywords: centralized control subsystem, safety, unified modeling language, function features, test cases generation, use case diagram, state diagram, activity diagram, sequence diagram

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INTRODUCTION

The high speed maglev centralized control subsystem (CCS), which realizes the display, automatic train operation (ATO) and diagnose, is an important security assurance for train operation. System testing (ST) can detect design defects early and performed effective repair to improve the efficiency of the system' on-site coordinated operation. Therefore, the quality of test cases directly determines the achievements and efficiency of CCS, and it is necessary to be tested before put it into use.

As the core of test work, the test case has a direct impact on the efficiency of test. Tsai [1] proposed a test cases generation for data processing system, which mainly generates test data from the specification. Hall [2] studied the test cases generation method and presented Z specification based test cases generation method. The rapid expansion of object-oriented technology, the method of unified modeling language (UML) based test cases generation has attracted more and more attention. The method is focus on the selection of the dynamic model such as state diagram, sequence diagram, activity diagram and collaboration diagram to generate the test cases covering the test requirements for the guidelines. A.J. Offutt [3] et al. proposed a test case generation method based on UML state diagram and four test coverage criteria, developed the first tool that can automatically generate test cases. Ji Lili [4] extended the expression in terms of limitation of the transfer condition with Boolean type on the UML state diagram presented by A.J. Offutt. F. Falk [5] discussed a method based on UML sequence diagram and introduced the SeDiTeC tool. Wang Linzhang [6] et al. used UML collaboration diagram to integrated test cases generation method, and the test cases were generated by designed model. Chris Rudram [7] expended the semantics and grammar of UML activity diagram and proposed a formalized activity diagram. Zhang Mei [8] et al. designed a three-level conversion process from the UML activity diagram model to the test outline model, then test cases model. However, most of studies focused on single model diagram, there is less analysis about the combination model of multiple diagrams.

The high speed maglev CCS is the key security guarantee, and testing the system is a necessary process for its operation. This paper proposed a test case generation method by extracted system functional feature for CCS. Then, the generated test case examples are all executed on the test platform to achieve the verification of CCS.

FUNCTIONAL FEATURES EXTRACTION

The purpose of the functional test on system is to verify the ability that the system meets all functional requirements. Nonetheless, the transition from every

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requirement to corresponding test case will cause a large number and repeated test cases, which not only increase the cost but also reduce the efficiency of test. Therefore, it is necessary to extract and purify the system functional requirements for functional test.

Functional features are the functional entities that are extracted based on the system functional requirement and come from a set of requirements. Multiple test cases can be designed for one functional feature. In order to meet the comprehensiveness and legitimacy of the functional features, every requirement from system functional set is reflected in at least one functional feature, and each functional feature is come from system functional requirements. The relationship of system requirements, functional features and test cases is shown in Fig. 1.

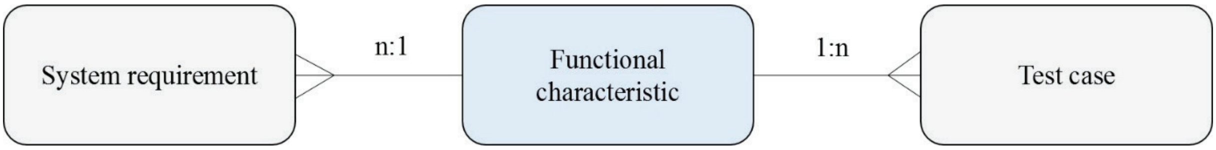

Fig. 1. Relation between system requirement, functional characteristic and test case

METHOD OF FUNCTIONAL FEATURES EXTRACTION

Firstly, all the required functions and attributes of the system requirements are analyzed, and are grouped according to the characteristics for forming one or more corresponding requirement functional groups. Then, after analyzing and summarizing these requirements, the functional features are obtained. The main purpose of the functional verification of CCS is to verify whether the system meets all of the requirements in requirements specification. The process of extracting functional features of CCS is shown in Fig. 2.

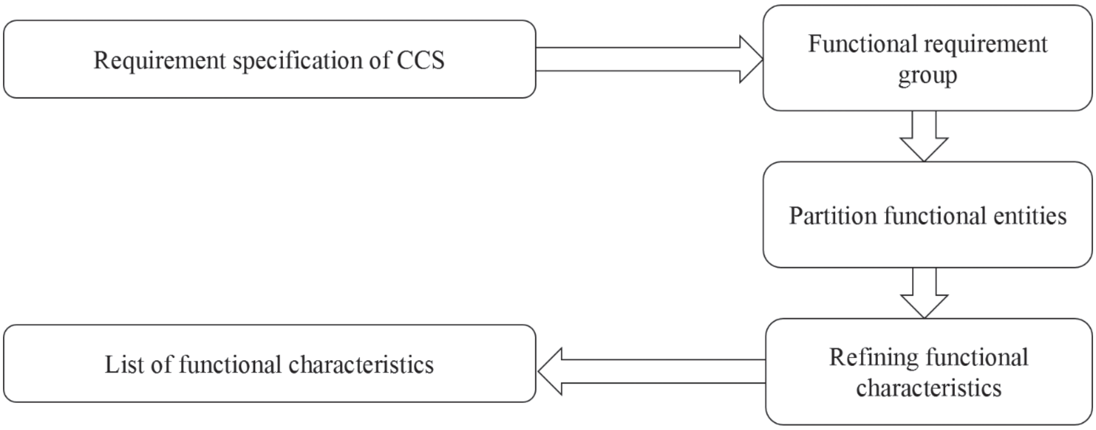

Fig. 2. Functional characteristics extraction process of centralized control system

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RESULT OF EXTRACTION

Based on the process of functional features extraction proposed, according to the functional requirements of CCS, operator terminal system, automatic train operation system and center diagnostic system were extracted. The results are shown in Table 1.

Table 1. Results of functional characteristics extraction

CCS	Functional characteristics			
Operator Terminal System	operator register	user change password	state display	relevant operation(CR)
	add new user	delete user	start or close	labeling information
	loading data	handle inspection message	operation procedure	find parts
Operator Terminal System	generate orders	execute orders	performance requirement	video check
ATO	operator register	handle ATO state	response control(DCS)	operation schedule
	TN number	operator control	system test	Dual redunda-ncy control
	performance requirement	train operation	–	–
Centralized Diagnostic System	start system	login and logout	overhead information	user management
	delete or assign fault	fault list	data profiling	handle message
	performance requirement (DTS)	–	–	–

UML BASED TEST CASES GENERATION

Operation Scene Analysis of CCS

Scenario technology can be used as a basis for system modeling at the test design stage. It can describes customer requirements and system functions, and is useful to design test cases. Each subsystem of the Centralized Control System has its own functional requirements. According to the system functional features, the operating process of Centralized Control System can be divided into several relatively independent scenarios. Each scenario contains numerous operations and information interaction. The main scenarios include: system rights management, order generation operation of operator terminal system, CR operation of operator terminal system, view display of operator terminal system, system coordination and interaction, train schedule operation, operation scheme operation, status change of ATO, operation monitoring of DCS order, train management, diagnostic information operation and the operation process of train, etc.

Operation Scene Modeling of CCS

Modeling the operation scene of CCS describes its internal state changes and information interaction from outside world in detail during the operating process, which also providing an important conference for guidance of test cases generation. In this paper, modeling and analysis are carried out based on each functional scene of CCS. This paper use illustration, sequence diagram, state diagram and activity diagram based on UML to express the action sequential logic of CCS from different angles. The following takes the typical scene of single-zone train operation as an example, the detailed modeling process proposed. Moreover, the modeling process of other scene is similar to single-zone train operation.

Use case diagram of operation process

As can be seen from Fig. 3, the test case diagram of single-zone train contains three participants: operator, DCS and VCS. These participants use cases to realize information interaction and complete functional requirement for current scene.

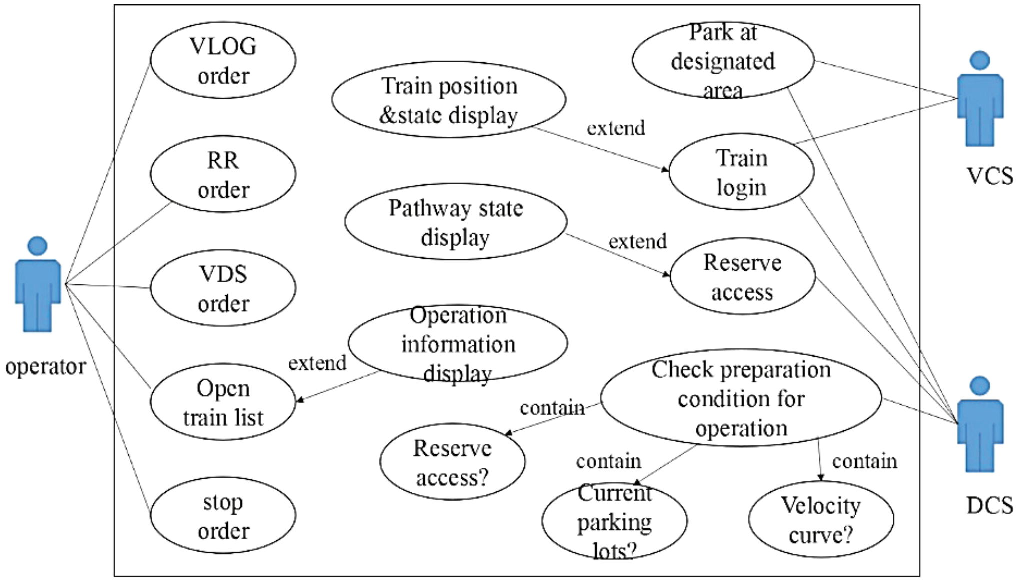

Fig. 3. Use case diagram of operation process

State diagram of operation process

The state diagram of operation process describes the state transition during the period from initial state of the OTS to the completion of the operation, as

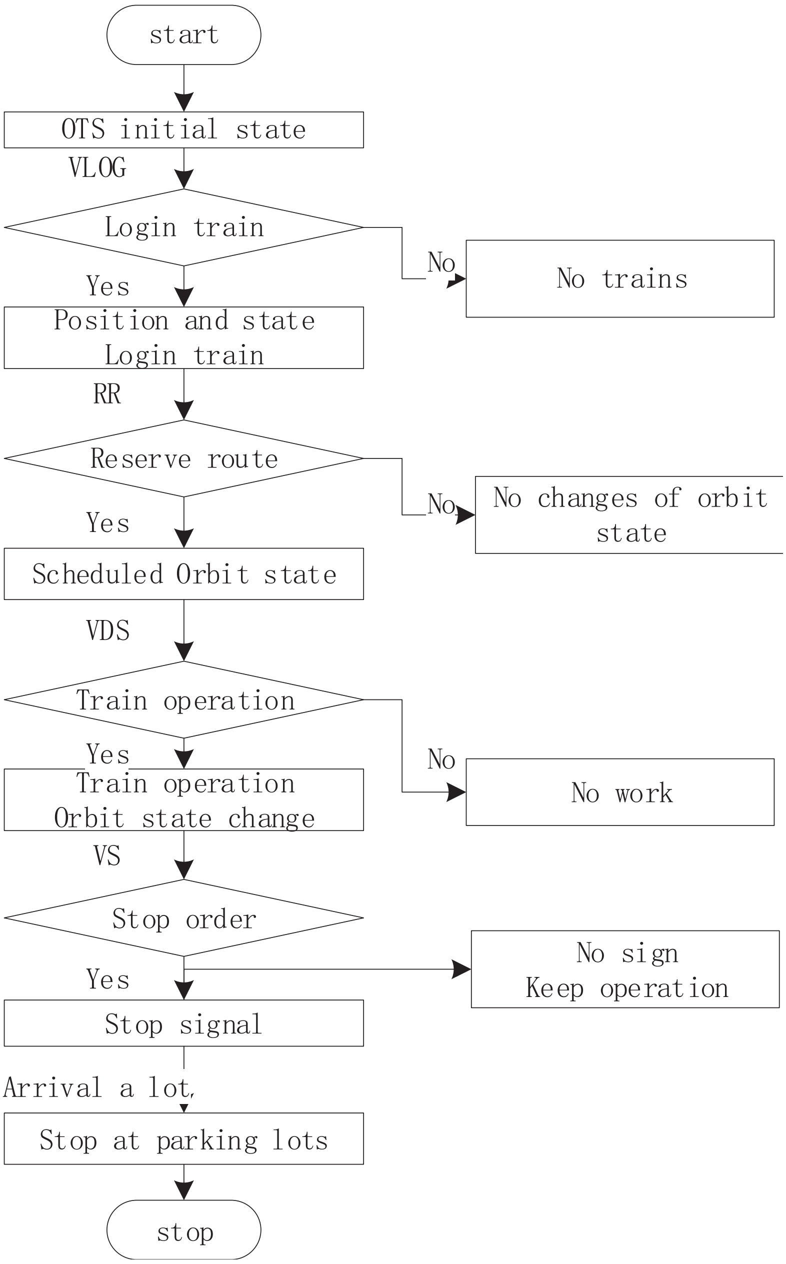

Fig. 4. State diagram in operation procedure

is shown in Fig. 4. In Fig. 4, the state diagram starts from initial state of OTS, undergoing a series of processes such as registering train, scheduling a route, setting train operation and parking instructions. During this state diagram, the state of OTS and trigger events caused by transition are presented gradually.

Activity diagram of operation process

The activity diagram of train operation process focuses on the control relationship during the period from one activity to another. As is shown in Fig. 5, a control flow between actives of train operation process is formed, which can

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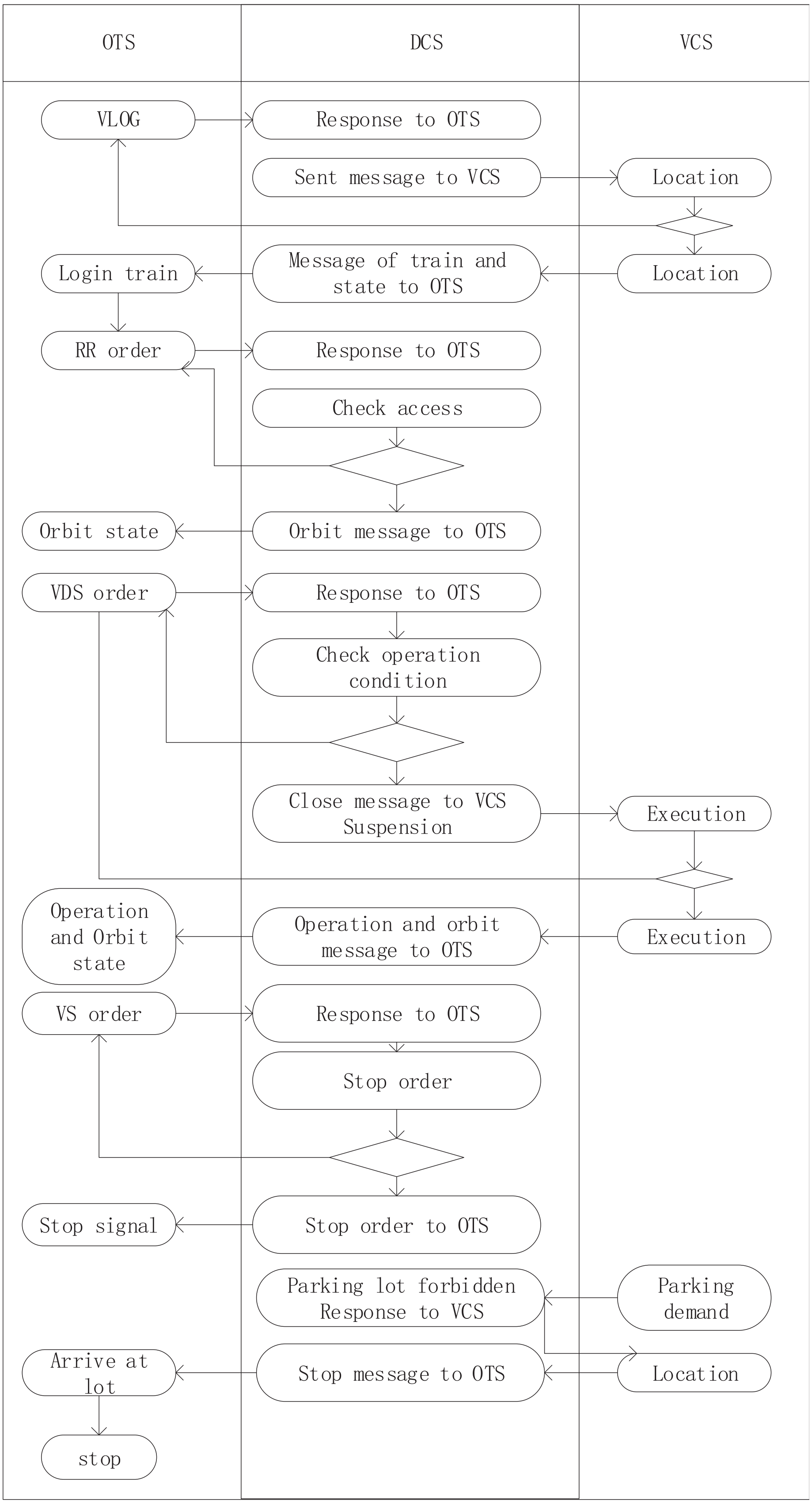

Fig. 5. Activity diagram in operation procedure

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describe the interaction exactly between OTS, DCS and VCS by activity diagram. In addition, the purpose of this control flow is a presentation of system behavior.

Sequence diagram of operation process

Sequence diagram, behavior of use case, focuses on the sequence of information sent by objectives, in which a group of objectives and information transfer are presented. The sequence diagram only shows a specific scenario of use case. The normal execution of sequence diagram during system operation process for every kind of order is given in Fig. 6. During the operation process, approaches to information interaction with each other based on time schedule about OTS, DCS and VCS are expressed in Fig. 6.

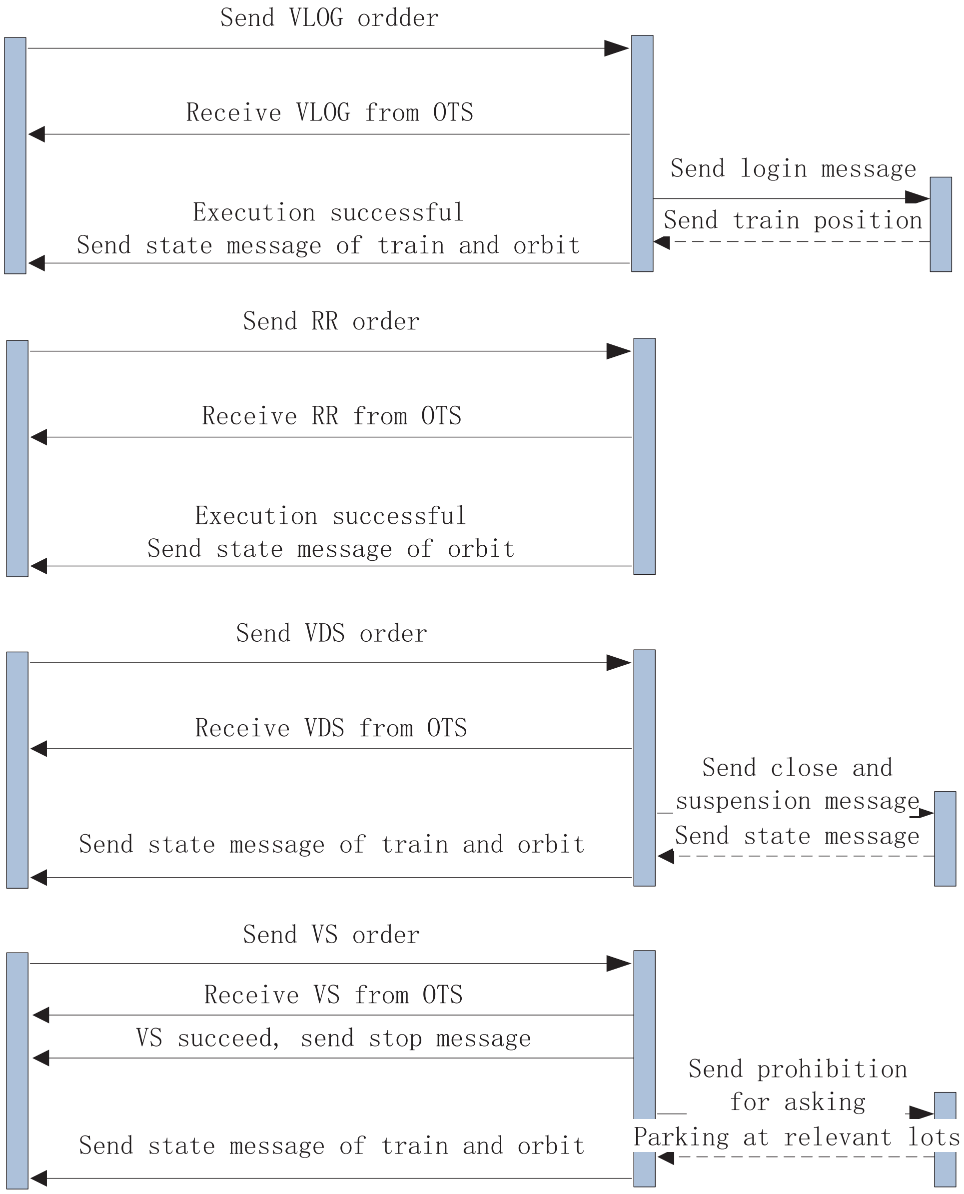

Fig. 6. Sequence diagram

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EXAMPLE VERIFICATION OF TEST CASE

The process of test case based on modeling diagram is shown in Fig. 7:

Step 1: select relevant modeling diagram for operation sub-scene

Step 2: confirm specific equipment involved in current scene based on use case diagram

Step 3: determine the number of test cases required to cover all of the state diagram according to state diagram

Step 4: confirm the procedure of every test case based on activity diagram

Step 5: confirm the information interaction between equipment involved in test procedure based on sequence diagram

Step 6: write the test cases document based on the standard format of test cases designed

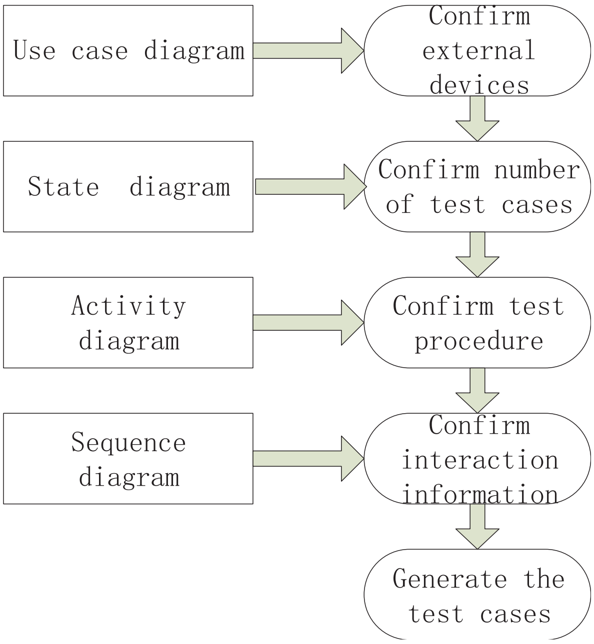

Fig. 7. Test case generation based on modeling

There are a large number of test case sets in CCS. The single-area train operation process is taken as an example to illustrate the process of generating test cases based on its modeling diagram. First of all, according to the use case diagram, there are three external participants involved in the scene: operator, DCS and VCS. The function of participants is to finish the test cases generation and observation of test results. Then, according to the state diagram, the state changes of OTS in this scene can be seen in Fig. 5. The rule in state diagram is maximum coverage of states. In this paper, five test cases is involved. Finally, activity diagram and sequence diagram will provide specific operation procedures and information interaction during every procedure. Table 2 shows the result designed based on the normal condition of order execution.

Table 2. Test case for train operation

Number	OTS_SYS_001_A	**Designer**	
Title	Train operation process		
Description	This test case is used to deliver message from OTS to DCS. Step1:login train on the orbit Step2:reserve route for specified train Step3:send start order Step4:set stop order		
Precondition	OTS start, data has been loaded at Operating partition, CR-allowance		
Post condition	The corresponding partition displays the data changes in the process view, Changes in train data logged into the list		
Test procedure	**Operation(input)**	**Expected outcome**	**Test result**
1	Right click “train login orbit”, select VLOG order	Display train login dialog box	
2	Login information Click “OK”	VLOG order in input field Button highlight	
3	Click “handle”	CR procedure, Red orbit for login train, train number	
4	RR order	Reserved route become green Direction arrow	
5	Right click “login train orbit”, VDS order	VDS order in input field, handle button highlight	
6	Click “handle”	Execution, operation and state changes displayed in view	
7	CD View-View- train list	Train list, train’ velocity and position vary with operation	
8	Right click to orbit VS order	VDS order in input field, “handle” highlight	
9	“handle” button	Execution, display corresponding stop signs, stop at parking lots	
Conclusion			
Tester		**Test date**	

In this paper, method of test case generation method finally designed: 85 test cases for terminal system design of operator, 68 test cases for train automatic operation design, 31 test cases for central diagnostic system design. The designed test cases are all examined through the test platform, covering all main scenes in operation process. The errors or detects found in tests are solved by finding the reasons and modifying the code, etc. Finally, the pass rate of the method proposed in this paper is 100 %.

CONCLUSION

A UML based method of test case generation is proposed in this paper, and implements the generation process to achieve the test cases and verification for CCS. Through the test practice, test cases designed can fully simulate all kinds of common situations in the operation site. In addition, the test cases also realize early detection of errors and defects in the system and repair them. It is useful to improve the efficiency on-site testing process, to reduce the cost of time and test quality. The method proposed can provide theoretical basis and reference for further testing of high speed maglev CCS.

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PROGRESS MADE AND PROSPECT OF CHINA'S MAGLEV TRANSPORTATION TECHNOLOGY STANDARDIZATION

Background: In order to standardize maglev transportation engineering and its operation, the research of maglev transportation technical standards becomes important. Based on the analysis of the growth of rail transit, the acceleration of maglev transportation engineering, the China's standardization regulation and the maglev transportation technology standardization practice,

Aim: This paper proposes the basic principles for establishing maglev transportation standard system and the framework of maglev transportation technical standard system, introducing China's maglev transportation technology standardization mechanism, its achievements, prospects and experiences.

Results: By the end of 2017, China had developed 12 maglev transportation technical industry and provincial standards.

Conclusion: There are 12 maglev transportation technical industry standards and social organization standards under development.

Keywords: Maglev, transportation, engineering, technology, standard, standardization, system framework.

1. INTRODUCTION

The development of urbanization in China and the increasing demand for public transportation facilities have promoted the development of rail transit in China and the application of technological research and engineering in China's maglev transportation system. The standardization of maglev transportation technology has received attention from standardization bodies at all levels and the related enterprises and institutions. It has achieved initial results. The application and the commercial operation of maglev transportation bring a more urgent demand for maglev transportation standards.

2. URBANIZATION PROMOTES RAPID DEVELOPMENT OF RAIL TRANSPORTATION

By the end of 2017, the permanent urban population in China had reached 813.47 million, and the urbanization rate of permanent residents had reached 58.52 %. In the past five years, the average annual increment of permanent urban

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population was 13 million [1]. To meet the public travel demand, the construction and operation of China's conventional railways, high-speed railways, and urban rail transit have been rapidly developed.

2.1. Rapid development of rail transit construction and operation

By the end of 2017, the mileage of China's railways has reached 127 000 kilometers, including 25 000 kilometers of high-speed railways [2]. The mileage of urban rail transit reached more than 5 000 kilometers.

In 2017, the number of passengers sent by railways reached 3.08 billion [3], an increase of 46 % from 2.11 billion people in 2013, the passenger volume of urban rail transit reached 18.48 billion person-times [4], which was an increase of 69.2 % from 10.92 billion person-times in 2013.

2.2. Maglev Transportation Technology Gets New Development Opportunities

Maglev transportation brings advantages due to its technical characteristics and gets better development opportunities in the comprehensive system of rail transit in China.

The high-speed maglev transportation with a maximum speed of up to 500 km/h and constant-current magnetic levitation has unique advantages. It can greatly increase passengers' long-distance travel efficiency in long-distance travel of over 1 000 kilometers. Medium and Low speed maglev transit has low noise and strong climbing ability. The advantage of small turning radius has potential for development in urban public transportation and tourism and tourist routes.

Based on the technological advantages of maglev transportation technology, maglev transportation technology research has been highly valued in China, and the application of maglev transportation engineering has also entered the initial stage of development. By the end of 2017, the operating mileage of China's maglev transportation had reached 57.9 kilometers, including the 29.1 kilometers Shanghai high-speed maglev demonstration line, the 18.6 kilometers Changsha Maglev line, and the 10.2 kilometers Beijing S1 line.

3. ESTABLISHING A FRAMEWORK FOR MAGLEV TRANSPORTATION TECHNICAL STANDARDS

The engineering development of maglev transportation puts forward requirements for maglev transportation technical standards. The standardization

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of maglev transportation technology requires the establishment of a maglev transportation technical standard system. It should follow the principles:

1) Comply with national laws, regulations and mandatory standards.

2) Based on current international standards, national standards and industry standards.

3) Focus on the unique technology of maglev transportation.

According to the basic classification of Chinese standards, standards can be divided into two categories: product categories and engineering construction. The basic structure and format of product standards follow the requirements of GB/T 1.1-2009 *Directives for standardization – Part 1: Structure and drafting of standards* [5]. The basic structure and format of engineering construction standards follow the *Engineering Standards Preparing Regulations* (Jian Biao, 2008, No. 182) [6].

According to the technical application scope of standard technical content, standards can be divided into basic standards, general standards and specific standards.

The basic standards for maglev transportation technology are mainly related national basic standards, basic industry standards, and basic standards specific to maglev, such as terminology standards. The general standard is the general technical requirements for the systems, subsystems of maglev transportation technology; the specific standards are the technical requirements for the design, manufacture, installation, acceptance, operation and maintenance of various subsystems, specialized or key equipment and components.

The development of maglev transportation technical standards should focus on the maglev vehicles, tracks, turnouts, propulsion and power supply system, operation control, and maintenance technologies. Therefore, it is needed to construct the maglev transportation technical framework (shown in Fig. 1).

The establishment of a maglev transportation technical standard system can provide guidance for the application, establishment, research and drafting of maglev transportation technical standards.

4. PROGRESS MADE AND PROSPECT OF MAGLEV TECHNOLOGY STANDARDIZATION

In order to promote the engineering of maglev transit, China has given full play to the enthusiasm of maglev transportation technology standardization at multi-level standardization bodies and related research, design, manufacture, construction, installation, operation and maintenance units, and has developed some maglev transportation technology standards.

4.1. Build multiple levels of maglev technology standardization working mechanism

According to different levels and types of China's standards, the development of basic standards and general standards for maglev transportation technology is usually supported by national, industry and provincial standardization bodies, the development of specific standards of maglev transportation technology is usually supported by social standardization bodies and companies. Therefore, according to the level and type of standard to be developed, the chief development organization should submit standard project application to standardization bodies, and form the standard working group according to the professional characteristics of each relevant unit and the willingness to participate in the standard preparation.

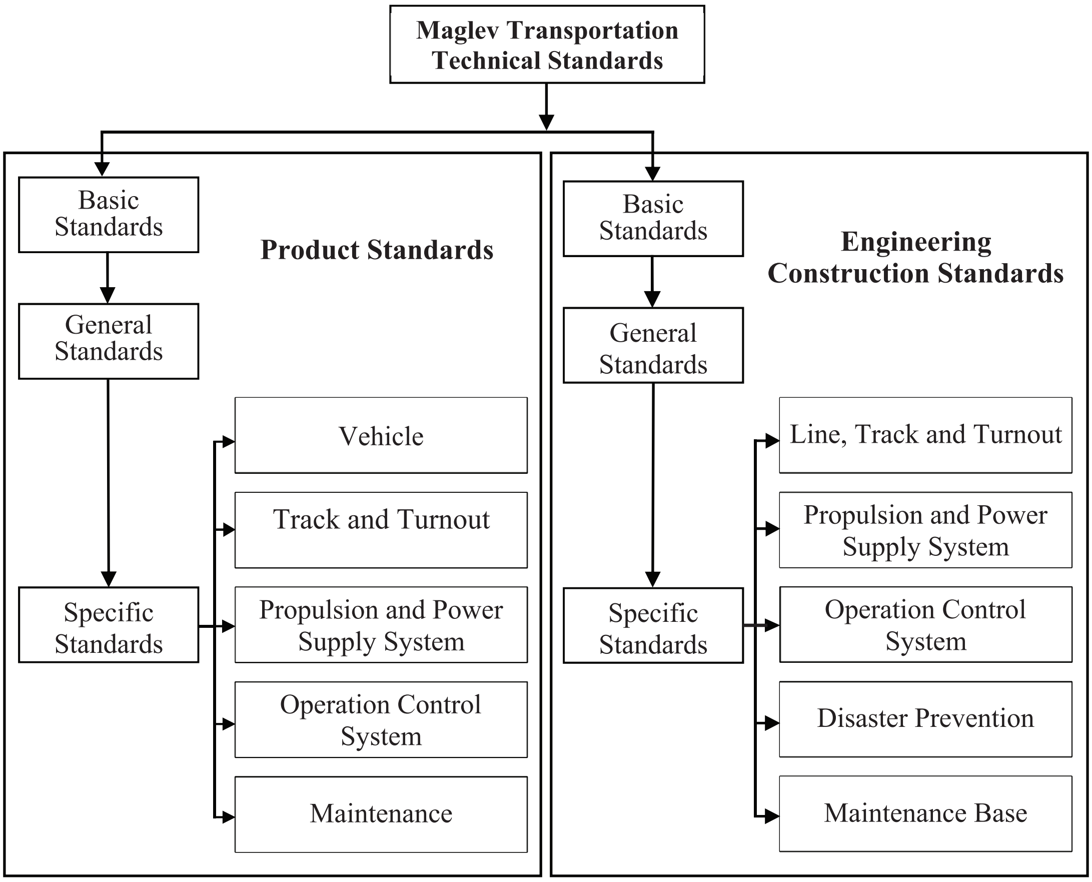

Fig. 1. Maglev Technical Standard System Framework

4.2. Progress in maglev technology standardization

Since 2006, China's maglev transportation technology related research, design, manufacture, construction and operation units have actively carried out

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research and drafting of maglev transportation technology standards. At present, 2 high-speed maglev transportation industry standards have been issued (see Table 1), 10 medium and low speed maglev transportation industry and provincial standards have been issued (see Table 2).

Table 1. Issued standards of high-speed maglev transportation

No	Standard title	Standard code
1	High-speed maglev transportation construction standard (for trial implementation)	JianBiao 161 – 2012
2	General specification for high-speed maglev vehicle	CJ/T 367 – 2011

Table 2. Issued standards of medium and low speed maglev transportation

No	Standard title	Standard code
1	General technical specification for medium and low speed maglev vehicle	CJ/T 375 – 2011
2	Technical specification for electrical system of medium and low speed maglev vehicle	CJ/T 411 – 2012
3	Technical specification for medium and low speed maglev turnout	CJ/T 412 – 2012
4	Technical specification for medium and low speed maglev transport rail row	CJ/T 413 – 2012
5	Technical specification of system for the levitation control of medium and low speed maglev transportation vehicle	CJ/T 458 – 2014
6	Technical code for automatic train control of medium and low speed maglev transit	CJJ/T 255 – 2017
7	Power supply technical code for medium and low speed maglev transportation	CJJ/T 256 – 2017
8	Code for design of medium and low speed maglev transit	CJJ/T 262 – 2017
9	Standard of Hunan for design of medium and low speed maglev transit	DBJ43/T 007 – 2017
10	Standard of Hunan for quality acceptance of medium and low speed maglev transit engineering	DBJ43/T 201 – 2017

The publication and implementation of these standards and related enterprise standards laid the foundation for the advancement of maglev transit engineering.

4.3. Maglev Transportation Technology Standardization Prospect

With the support of standardization bodies at all levels and the efforts of all related units, maglev transportation technology standardization will be further

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strengthened. There are 12 maglev transportation technical standards under development (see Table 3).

Table 3. Standards of maglev transportation under development

No	Standard title
1	Standard of high-speed maglev transit
2	Code for quality acceptance of medium and Low speed maglev track engineering
3	Code for quality acceptance of medium and Low speed maglev turnout system engineering
4	Code fo rtest of medium and Low speed maglev train
5	General technical specification for medium and low speed maglev vehicle bogie
6	Technical specification of electromagnet for medium and low speed maglev vehicle
7	Rules for inspecting and testing of medium and low maglev vehicle after completion of construction
8	Technical code for detection of medium and low speed maglev turnout
9	Code for quality acceptance of medium and low speed maglev automatic train control system engineering
10	Technical specification of suspension system for medium and low speed maglev vehicle
11	Technical specification of contact rail for medium and low speed maglev transit power supply
12	Technical specification of brake system for medium and low speed maglev train

In order to regulate and guide the activities related to the research, design, manufacture, construction, and operation of maglev transportation technology, various maglev transportation technology related units have also developed company standards related to maglev transportation technology.

It can be predicted that in the next few years, with the advancement of China’s maglev transportation technology research and engineering, China’s maglev standardization work will develop faster.

5. EXPERIENCE

1) The promotion of maglev transportation engineering has become an increasingly urgent requirement for maglev transportation technology standards.

2) Maglev standardization should be based on relevant research, experiments and engineering practices.

3) The standardization of maglev transportation technology should give full play to the respective advantages of each research, manufacturing, design,

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construction and operation unit, Multiple units may joint for maglev transportation standard development.

4) Strengthen the international exchange of maglev transportation technology standardization.

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STUDY ON RELIABILITY ANALYSIS OF SUSPENSION CONTROLLER OF THE MEDIUM AND LOW SPEED MAGLEV VEHICLE

Suspension controller is the core device of suspension system of the medium and low speed maglev vehicle, its reliability directly affects the stability, reliability and safety operation of the whole medium and low speed maglev train. Reliability analysis is of great theoretical and practical value for improving the performance of the suspension controller.

Taking Hunan Changsha maglev express as an application case, based on the mechanism and functional structure of the suspension controller, the reliability of the suspension controller is analyzed and studied. According to the Chinese standard GJB/Z 299C, the reliability prediction handbook for electronic equipment, the reliability of the suspension controller is calculated and analyzed by synthesizing the stress analysis method, the component counting method and the RBD reliability block diagram method. The reliability weak points of the suspension controller are analyzed, and the design optimization proposal is suggested to improve the suspension controller reliability.

Background: Medium and low speed maglev traffic has gained wide attention and engineering application in China. It is very necessary to study the reliability of the medium and low speed maglev train.

Purpose: The purpose of this paper is to carry out reliability research on the levitation control system of medium low speed maglev train.

Methods: The stress analysis method, component counting method and RBD reliability block diagram method are used to calculate and analyze the reliability of the suspension controller.

Results: The reliability quantitative analysis results of the suspension controller are analyzed, and the reliability weakness of the suspension controller is analyzed and studied. A design optimization proposal to improve the reliability of the suspension controller is proposed.

Conclusion: Through the reliability prediction analysis of the suspension controller, the reliability and weakness of the suspension controller can be determined, which provides theoretical guidance for the improvement of the design scheme and the performance optimization of the maglev train suspension controller.

Keywords: Medium and low speed maglev vehicle, Suspension Controller, Reliability Analysis, Reliability Prediction, Maglev Transportation

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1. INTRODUCTION

On Dec. 26th, 2015, China's first medium and low speed maglev railway, Changsha Maglev Airport Express line began trial operation, and officially began commercial trial operation one year later. Because of its obvious advantages, such as small turning radius, low noise, high comfort and so on, the medium and low speed maglev train has attracted wide attention of the rail transit field. Whether such a new rail transit mode is safe and reliable, especially whether the suspension system of maglev train which is quite different from the traditional wheel rail train can operate reliably, has become the key concern of maglev train operation. Therefore, the study of the reliability of the suspension controller has a very important practical value in engineering practice.

Reliability block diagram (RBD) uses the blocks and connections to draw the influence of each component on the functional characteristic of the system when failures occurred. In RBD, the blocks represent the different component units of the system, and the connections depict the interconnection of the components. The reliability block diagram shows the failure logic of the system by using interconnected blocks. It helps to evaluate the overall reliability of the system by analyzing the impact of the failure rate of each component in the system. Reliability prediction is the method of estimating products reliability under given working conditions. Based on the empirical data of some similar products or the reliability data of the units that make up the product, we can estimate the reliability parameters value of the product under given working or non-working conditions when there is no test data for the products. The commonly used methods include: component counting method, stress analysis method, mathematical model method, upper and lower limits method, Monte Caro method and so on.

When the internal structure of the suspension controller, detailed list of components, stress environment and other information are known, the failure rate of the product can be calculated accurately by using the stress analysis method. And then we can quantify the reliability of the product. For the components that cannot be determined temporarily, we can use the element counting method to estimate roughly.

In the case of reliability analysis, the reliability block diagram of the components inside the suspension controller should be analyzed first. Based on this, the mathematical model of system reliability prediction is obtained. The failure rate of each component module is calculated by component counting method or stress analysis method. By this method, the failure rate data of each module can be obtained, and the influence of internal structure on the reliability of the overall suspension controller can be taken into account.

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2. ANALYSIS OF THE FUNCTION STRUCTURE AND WORKING MECHANISM OF THE SUSPENSION CONTROLLER

The functional structure of suspension controller for the low-speed maglev trains is shown in Fig. 1.

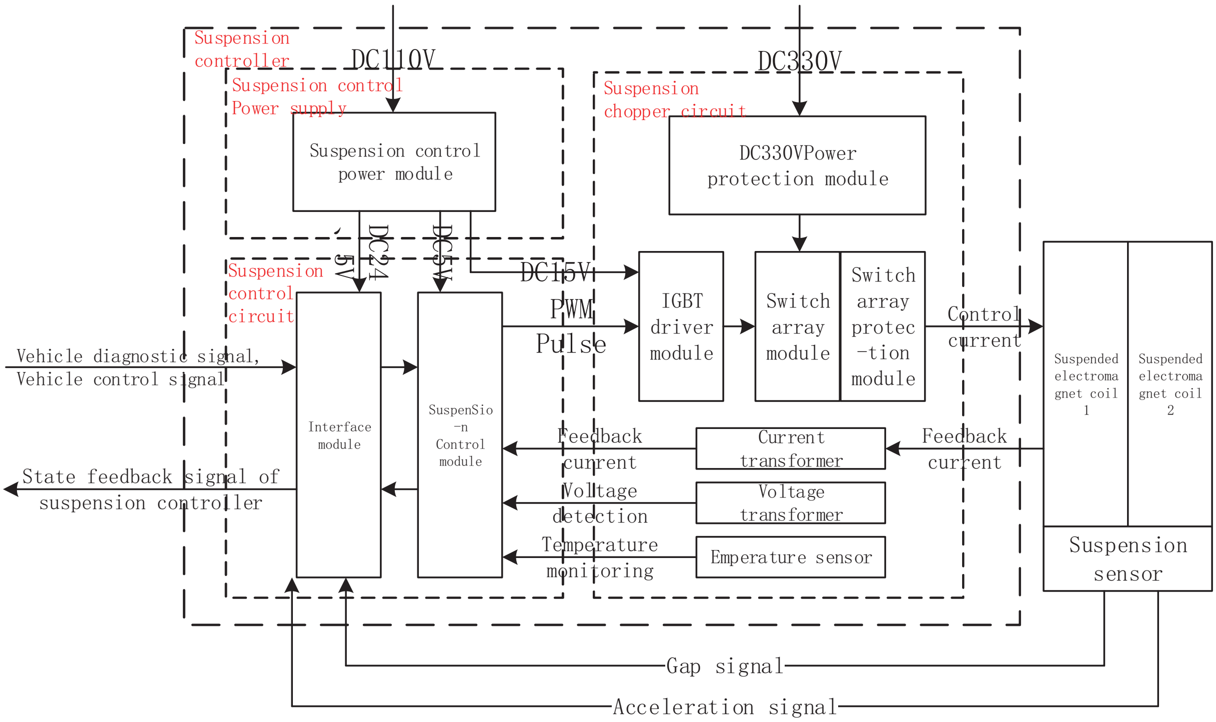

Fig. 1. Suspension controller structure diagram of the medium and low-speed maglev trains

The working principle of the suspension controller is a typical closed-loop control principle. The suspension sensor can measure the real time gap between the suspended electromagnet and the F rail and the vertical acceleration of the point. And the current sensor can measure the amount of current flowing through the electromagnet. The measured gap signal, acceleration signal and current signal are fed back to the suspension control module through the interface module of the suspension control circuit. Accordingly, the suspension control module is processed by the suspension algorithm, and the current needed by the electromagnet is calculated. The output PWM (Pulse Width Modulation) signal is sent to control the IGBT driving module. The IGBT driver module controls the turn-on and turn-off of the IGBT switches to output the main power supply. By turn-on and turn-off the DC/DC chopping principle of the DC330V module, the current required on the electromagnet is realized, thus the suspension gap is controllable. Furthermore, the suspension controller can also receive on-board control and diagnosis information via on-board network, and feedback the current state of the suspension control point to the superior train network. Thus the monitoring and control of the suspension system is realized via the vehicle network.

The interface module is an information exchange component to the suspension controller, which includes CAN interface unit, installation position interface unit, control network levitation control signal and state feedback signal interface unit, logic operation unit, the blank spring control unit, PWM pulse signal and drive board interface unit, reset signal circuit unit and 24V sensor power supply control unit, contactor control unit, power preprocessing unit and so on.

The suspension control module is the most important part of the suspension controller. The feedback signals and control signals are calculated and processed by the suspension control algorithm. In addition, the suspension control module can also implement the functional coordination of other modules of the suspension controller. It is mainly composed of signal filter unit, AD conversion unit, DSP processing unit, memory unit, arithmetic logic unit and power preprocessing unit.

3. RELIABILITY MODELING AND RELIABILITY PREDICTION ANALYSIS OF THE SUSPENSION CONTROLLER

3.1. Reliability modeling of the suspension controller

From the description of the functional structure of the suspension controller, we can see that any module failure will lead to the fail of whole controller, only when all these modules can work properly, can the suspension controller fulfill the requirements. The medium and low-speed maglev controller belongs to the RBD reliability model of pure series structure, as shown from Fig. 2 to Fig. 4.

The components of the suspension controller are connected in series, so the mathematical model formula of the series system mentioned above is calculated by formula (1).

$$R_s(t) = \prod_{i=1}^{n} R_i(t) \tag{1}$$

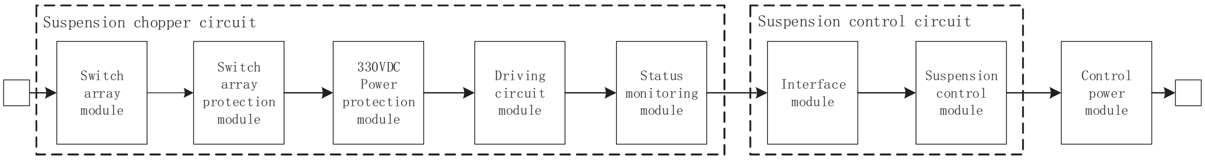

Fig. 2. RBD model of suspension controller

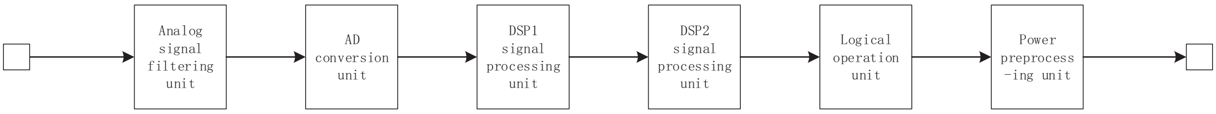

Fig. 3. RBD model of suspension control module

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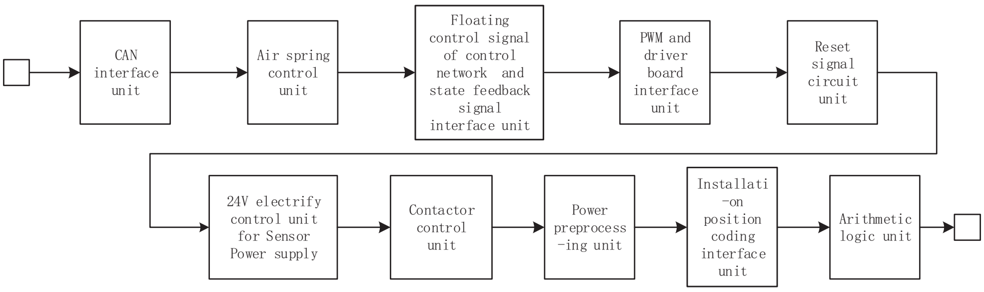

Fig. 4. RBD model of suspension controller interface module

The failure rate of most electronic products in accidental failure period follows exponential distribution. The formula of total failure rate of suspension controller is shown as formula (2).

$$\lambda_s = \prod_{i=1}^{n} \lambda_i \tag{2}$$

The average mean time to failure interval time (MTTF) of the suspension controller can be calculated by formula (3).

$$\mathrm{MTTF} = \frac{1}{\lambda_s} \tag{3}$$

3.2. Reliability prediction of the suspension controller

After the establish of the reliability model of suspension controller for medium and low-speed maglev vehicle, the reliability analysis of suspension controller can be carried out as follows:

1) Determine the type and number of the components used in the unit.

According to the design data of the suspension controller circuit diagram , we can sort out the information of the components of each module unit, such as types, quantities, models and so on, which can facilitate the next work and finding the components data list for standby.

2) Determine the quality grade of components.

The quality grade of components is determined according to the selection, purchase, batch inspection and control of components. Due to the high quality requirements of the devices used in the levitation controller of low-speed maglev trains, the quality grades of the components are all in a higher grade.

3) Determine the ambient temperature.

Changsha Maglev Express Line located in Changsha City, Hunan Province in a subtropical monsoon climate. The annual average temperature in the urban area of Changsha is 17.2°C. In each county, the temperature is between 16.8–17.3 °C, so the ambient temperature of the suspension controller worked should be 17 °C.

4) Identification of environmental categories.

In GJB/Z 299C, the application environment of electronic equipment is divided into more than ten categories. The vehicle body of medium and low-speed maglev trains is suspended on the track and has no obvious tremble. It can be regarded as steady ground movement and the environmental category is codenamed as G_{M1}.

The reliability prediction stress analysis method has many parameters and large data volume. For each component, after finding the basic data of each component, the failure rate of each component can be calculated according to the reliability model.

3.3. Reliability prediction results of the suspension controller

With the help of professional reliability analysis software Isograph RWB11.0, each component parameter can be input, and the failure rate of each component can be obtained by consulting the built-in reliability prediction manual standard. The predicted results of the components in the suspension controller are as follows:

1) Suspension chopper circuit

From the data of reliability prediction, it can be seen that the failure rate of other parts in the suspension chopper circuit is higher than 700 FITS except for the switch IGBT driving module. The electrolytic capacitance of switch array protection circuit, (587.00 FITSs) and IGBT (215.82 FITS) have a high failure rate.

2) Interface module

The parts of high failure rate in the interface module are 24V sensor power supply unit and power preprocessing unit. Among them, the fuses (760 FITS), TPS75733 voltage regulation chip (186,26 FITS) contribute more failure rates.

Table 1. Reliability Prediction Results of Suspension Chopper Circuit

Number	Description	Failure rate (Fits)	Quantity (/N)	N x Failure rate(Fits)	MTTF (h)
1	Suspension chopper circuit	4446.92	1	4446.92	2.25E+05
1.1	Switch array module	722.04	1	722.04	1.39E+06
1.2	Switch array protection module	1196.64	1	1196.64	8.36E+05
1.3	330VDC Power protection module	930.58	1	930.58	1.08E+06
1.4	IGBT Driver module	39.10	1	39.10	2.56E+07
1.5	Status monitoring module	1558.56	1	1558.56	6.42E+05

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Table 2. Reliability Prediction results of Interface Module

Number	**Description**	**Failure rate (Fits)**	**Quantity (/N)**	**N x Failure rate(Fits)**	**MTTF (h)**
2.1	interface board	4933.27	1	4933.27	2.03E+05
2.1.1	CAN interface unit	409.21	1	409.21	2.44E+06
2.1.2	Air spring control unit	96.81	1	96.81	1.03E+07
2.1.3	Feedback signal unit	190.08	1	190.08	5.26E+06
Number	**Description**	**Failure rate (Fits)**	**Quantity (/N)**	**N x Failure rate(Fits)**	**MTTF (h)**
2.1.4	PWM and driver board interface unit	6.02	1	6.02	1.66E+08
2.1.5	Reset signal circuit unit	3.25	1	3.25	3.08E+08
2.1.6	24V Sensor power unit	1702.77	1	1702.77	5.87E+05
2.1.7	Contactor control unit	381.00	1	381.00	2.63E+06
2.1.8	Power preprocessing unit	1578.34	1	1578.34	6.34E+05
2.1.9	Installation position coding interface unit	36.88	1	36.88	2.71E+07

3) Suspension control module

Table 3. Reliability Prediction Results of Suspension Control Module

Number	**Description**	**Failure rate (Fits)**	**Quantity (/N)**	**N x Failure rate(Fits)**	**MTTF (h)**
2.2	Suspension control module	6570.66	1	6570.66	1.52E+05
2.2.1	Input analog signal filtering unit	417.07	1	417.07	2.40E+06
2.2.2	DSP1 signal processing unit	1059.20	1	1059.20	9.44E+05
2.2.3	Arithmetic Logic Unit	1168.60	1	1168.60	8.56E+05
2.2.4	Power preprocessing unit	1516.32	1	1516.32	6.60E+05
2.2.5	DSP2 signal processing unit	867.55	1	867.55	1.15E+06
2.2.6	AD Conversion unit	1541.93	1	1541.93	6.49E+05

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Except for the input signal filter unit in the suspension control module, the failure rates of other parts are all high, and most of the components in each unit are integrated chips. For example, the CPLD chip (1168.60 FITS) and the AD converter chip (739.08 FITS), IS61Lv6416 asynchronous static random access memory(514,35 FITS), EEPROM memory chip (372,96 FITS) and so on.

The overall reliability of the suspension controller is expected to be shown in Table 4.

Table 4. Reliability Prediction Results of Each Module of Suspension Controller

Number	Description	Failure rate (Fits)	Quantity (/N)	N x Failure rate(Fits)	MTTF (h)
1	Suspension chopper circuit	2888.36	1	2888.36	3.46E+05
2	Suspension control circuit	11503.93	1	11503.93	8.69E+04
3	Suspension control power	5582.78	1	5582.78	1.79E+05

According to the reliability block diagram of the suspension controller shown in Fig. 2. the working failure rate of the whole suspension controller can be calculated, and the result is 21533,63 FITS.

$$\lambda = 21533.63 \times 10^{-9} / h \tag{4}$$

Therefore, the average failure interval of the suspension controller is:

$$\mathrm{MTTF} = \frac{1}{21533{,}63 \times 10^{-9}} = 4.644 \times 10^{4} h \tag{5}$$

According to the reliability prediction results, the least replaceable units, components or components of the suspension controller for the medium and low-speed maglev trains can be sorted in accordance with the contribution of failure rate, and the main components that affect the reliability of the suspension controller can be found out.

Table 5. Sorting of Components with High Failure Rate in Suspension Controller

Component name	Type of components	Failure rate of single component /FIT
CPLD	XC95144XLTQ100	1168.6
Fuse	RUE185, BS88	760.00
AD Conversion chip	AD7864	739.08
Electrolytic capacitor	epcosB43310	587.00
Asynchronous static random access memory	IS61Lv6416	514.35

It can be seen from Table 5 that the programmable logic device CPLD chip has a great influence on the reliability of the suspension controller in the medium and low-speed maglev trains. According to the device analysis, the methods and measures to improve the reliability of the suspension controller can be put forward as follows:

- Device screening:

The inherent reliability of electronic components depends on the reliability design of the products, The average life of components with early failure is much shorter than that of normal products. The reliability of electronic devices is based on the reliability of electronic components. If the components of early failure are installed with equipment, the failure rate of early failure of equipment will be greatly increased, its reliability can't meet the requirements, but also pay a great deal of cost to repair. Therefore, the components with early failure should be excluded as much as possible before the electronic components are installed with equipment. For this reason, the components should be screened. Based on the experience of screening at home and abroad, the total failure rate of components can be reduced by 1 ~ 2 orders of magnitude through effective screening, so the screening of components is an important means to ensure reliability.

- Derating design:

The so-called derating design of equipment is that make the working stress of components or equipment properly lower than the rating specified of components or equipment, so as to reduce the basic failure rate and improve the reliability. Among them, the reliability of electronic products is sensitive to its electric stress and temperature stress. The commonly used derating parameters are voltage, frequency, input current, power consumption and junction temperature. For all kinds of electronic components, there is an optimal reduction range, in which the variation of working stress has a significant impact on the failure rate of components, and is also relatively easy to achieve in design, and will not be realized in the volume of the equipment. The derating criteria and application guidelines for all types of components are in accordance with the national military standard GJB/Z35 "Derating criteria for electrical, electronic and electromechanical parts".

- Structural optimization:

The starting point of improving reliability from the structure level is to increase the redundancy of the integrated circuit appropriately, so that we can avoid the negative impact of failure rate accumulation on the reliability of the suspension controller. The key modules of the circuit can be designed redundant within the limits of space and cost.. Take the control card as an example, suppose that the design of the suspension control card has a backup redundancy module, its failure

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rate can be reduced from 6904 Fits to 47 Fits and the reliability of 1000 hours was increased from 0.99312 to 0.99995 (calculated on the basis of the reliability of 1000 h). It can be seen that the reliability of the levitation controller of the low-speed maglev trains can be greatly improved by increasing the redundancy of the easy failure module structure.

- On-line diagnosis and status detection:

Improving the reliability of suspension controller from the system level depends on the further development of on-line testing and fault diagnosis technology. We can set test points at key nodes of important devices, such as the key output pin of the chip, voltage output of the control power circuit, and set up a digital code for each test point. By extracting and analyzing the circuit eigenvalues under the working state of each test point, judging whether the circuit is invalid or not on line. According to the feedback code of the online fault diagnosis system, the "focus" of the fault can be accurately tested. Even further, we can introduce the technology of fault prediction and health management (PHM). And by analyzing the difference or similarity between the circuit to be tested and the standard fault-free circuit, we can judge the health state of the circuit under test and predict the potential failure form. The reliability of the suspension controller is raised to a new level from a preventive point of view.

4. CONCLUSION

Based on the engineering application of the first medium and low-speed maglev railway in China, this paper analyzes the reliability of suspension controller for Changsha Maglev Express Line synthetically by using the component counting method and the stress analysis method. By analyzing the reliability prediction of levitation controller, the weak points of reliability of suspension controller can be determined. And it provides theoretical guidance for the design improvement and performance optimization of maglev train suspension controller.

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DATAFLOW ANALYSIS OF VEHICLE SAFETY COMPUTERS REGARDING HIGH-SPEED MAGLEV TRANSPORTATION BASED ON DATA PRIORITIES

To analyze the dataflow of vehicle safety computers regarding high-speed maglev transportation, it is considerable to add data priorities to the dataflow model of vehicle safety computers to improve the accuracy. With regard to vehicle safety computers, we choose VSC1 as our research object. First, we give a brief summary for the interface relationships of VSC1. Next, we analyze the data priorities of VSC1 in detail. After that, we present the dataflow model of VSC1 with priorities. Finally, we make a brief conclusion. The structure of the abstract of an article is strictly arranged and should encompass the following points:

Background: Dataflow model of Vehicle Safety Computers regarding high-speed maglev transportation.

Aim: To analyze the dataflow of vehicle safety computers with data priorities.

Methods: interface analysis, data priority analysis and dataflow chart.

Results: The dataflow model of VSC1 with data priorities is presented.

Conclusion: Adding data priorities to the dataflow model of vehicle safety computers to improve the accuracy is fulfilled. The recommended number of words in the abstract is 500.

Keywords: high-speed maglev; vehicle safety computer; dataflow; data priority, inteface analysis, dataflow accuracy, ATP

INTRODUCTION

Vehicle safety computers (VSCs) are the onboard part of the operation control system (OCS) regarding high-speed maglev and responsible for control and safety protection for maglev trains. They are always located at two sides of maglev trains. Relative to the traditional railway signal systems, they are same as ATP (Auto Train Protection). For ATP, the software safety integrity level (SIL) of ATP function is SIL-4 [1]. In a word, vehicle safety computers are safety critical software systems, always based on embedded hardware system, and their requirement of real-time and safety are very high.

Due to the complexity of software systems and especially the importance of non-functional requirements including performance, security, or compliance with

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law increases, to ensure quality properties is hard and often shifted to the operations phase. Fixing issues found in this phase is, however, costly. The data flow analysis enables early detection of requirement violations regarding privacy laws, external service providers, and throughput requirements on the architectural level [2].

With regard to the data flow analysis of vehicle safety computers, three papers are related to this, all written by myself. In [3], the information flow is analyzed and the software architecture is designed for the vehicle control system (VCS). In [4], the information flow analyzed for the OCS. In [5], the information flow is analyzed for the forced stop management of the OCS. However, all these papers are omitted one important point that various data has various priority. To improve the accuracy of dataflow analysis for vehicle safety computers, integrating the data priority is necessary.

How to improve the accuracy of dataflow analysis, some approaches are presented by means of data priorities. In [6], the accuracy improvement of dataflow analysis for cyclic stream processing applications scheduled by static priority preemptive schedulers is presented. In [7], the temporal analysis of static priority preemptive scheduled cyclic streaming applications using CSDF models is introduced. It is worth mentioning that both papers are concerned with big data.

What are executed on vehicle safety computers are consist of dataflow processing applications which regularly contain cyclic data dependencies due to the presence of feedback loops and bounded FIFO buffers. In order to analyze the dataflow of vehicle safety computers with high accuracy improvement, it is considerable to add data priorities to the dataflow model of vehicle safety computers. Therefore, this paper presents the dataflow model with data priorities for vehicle safety computers.

INTERFACE ANALYSIS OF VEHICLE SAFETY COMPUTERS

For each of maglev trains, there are two vehicle safety computers in it. One is vehicle safety computer No.1 (VSC1), and the other is vehicle safety computer No.2 (VSC2). Both vehicle safety computers locate at two ends of a maglev train, i.e. driver's cabs. Once VSC1 loses the control to a maglev train, VSC2 can make a safety stop of the train. In others word, VSC2 is a standby of VSC1. They are slightly different in functionalities and interfaces. To simplify the dataflow for vehicle safety computers, we only choose VSC1 to analyze the interfaces and data priorities.

VSC1 has physical interfaces to vehicle electrical facilities, which are Locating Unit, Onboard Controller, Driver Console, Forced Stop Button and Braking Unit. By means of Locating Unit, VSC1 can get locating data of a maglev train,

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such as position, speed and direction. By means of Onboard Controller, VSC1 can control vehicle's doors, suspension, etc., and get their feedback. By means of Driver Console, VSC1 can receive a driver' instructions. By means of Forced Stop Button, VSC1 can get a forced stop signal once a driver push the button. By means of Braking Unit, VSC1 can active eddy-current braking unit when the speed profile is infringed.

VSC1 also has physical interface to the Radio System, which fulfill logical interface to decentralized safety computers (DSC). Fig. 1 shows the interfaces of VSC1.

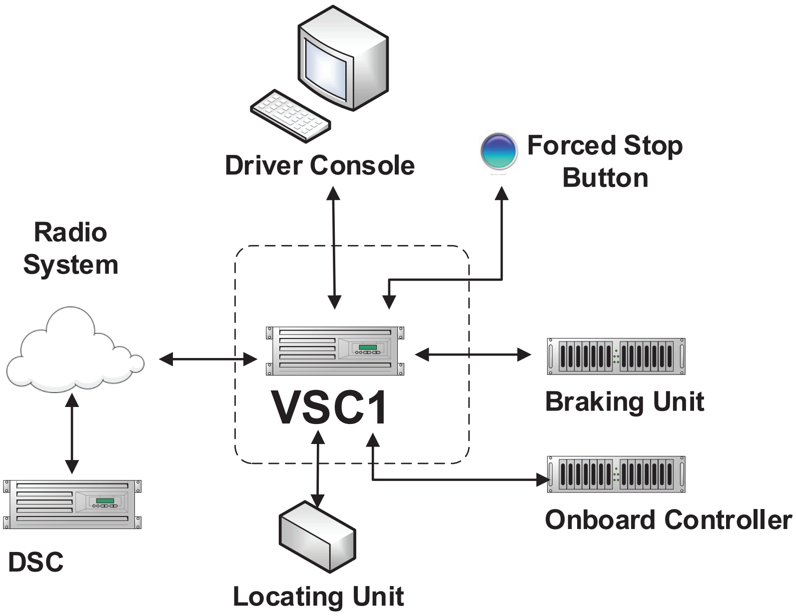

Fig. 1. The interfaces of VSC1

DATA PRIORITY ANALYSIS OF VSC1

During the processing cycle of VSC1, various data coming from different data sources may happens at the same time. Because the importance of data is different, VSC1 should distinguish the data priority so that it can process the most important data first.

Table 1 gives the complete analysis of data priorities for VSC1.

DATAFLOW ANALYSIS OF VSC1 WITH DATA PRIORITY

VSC1 has three main function modules:

1. The Safety Locating module: It receives location data from Locating Unit and generates safety location data. In the meantime, it maintains a storage area to

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Table 1. Data Priorities Analysis of VSC1

Interface Object	**Interactive Data**	**Data**	**Interface Object**
Braking Unit	signal of braking level	VSC1 Braking Unit	VSC1 outputs corresponding braking force level according to the scale of over-speed. Before VSC1 executes a brake, VSC1 needs send a propulsion shutoff request to the interactive DSC. The processing priority is P1.
Locating Unit	location data	Locating Unit→VSC1	After receiving the location data VSC1 generates safety location data. If VSC1 detects that the speed profile is violated for the current stopping point, VSC1 sends a request of propulsion shutoff to the interactive DSC, and then sends a brake signal to the Braking Unit. VSC1 also sends the safety location data to the interactive DSC in order to perform under-speed protection. The processing priority is P2.
Forced Stop Button	forced stop signal	FS→VSC1	After receives a forced stop signal, VSC1 performs a forced stop by prohibiting stopping point stepping, and the train will stopped at the current stopping point. The processing priority is P3.
Onboard Controller	vehicle status	OBC→VSC1	VSC1 detects whether a forced stop signal occurs which is generated by Onboard Controller. If so, VSC1 implements a forced stop by prohibiting stop point stepping, and the maglev train will stop at the current stop point or a service station. VSC1 also sends the vehicle status data the interactive DSC. The processing priority is P4
	vehicle control signals	VSC1→OBC	By sending vehicle control signals to OBC, VSC1 control the suspension, doors, etc. The processing priority is P5.
DSC	stopping point stepping request	VSC1→DSC	VSC1 initiates stopping point stepping to the interactive DSC to fulfill continuous operation. The processing priority is P6.
	line data	DSC→VSC1	VSC1 receives line data from the interactive DSC to generate speed profiles for the following stopping points. The processing priority is P6.
	instructions and status from DSC	DSC→VSC1	DSC manages and controls VSC1 by sending instructions and status data. VSC1 also sends the status data o Driver Console for display. The processing priority is P7.
	requests and vehicle status	VSC1→DSC	VSC1 sends requests and vehicle status to DSC for collaboration and sharing. The processing priority is P7.
Driver Console	operation status	VSC1→DC	VSC1 Sends the operation status to DC for display. The processing priority is P8.
	driver's instructions	DC→VSC1	VSC1 transparently forwards driver's instructions to DSC for train control in driver mode. The processing priority is P8.

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store the safety location data, such as speed, positon and direction of a maglev train. Moreover, it distributes the safety location data to the Vehicle Protection module, the Speed Profile Monitoring module, and DSC.

2. The Vehicle Protection module: It receives control instructions (such as opening doors, levitating the maglev, etc.) from DSC and send corresponding signals to Onboard Controller. Meanwhile it receives feedback from Onboard Controller and detects whether any forced stop signal occurs. In addition, it receives the forced stop signal from Forced Stop Button. Once a stop signal is detected, it sends an instruction that prohibits stopping point stepping to the Speed Profile Monitoring module. It receives driver instruction from Driver Console and transparently transmits to DSC. In the meantime, it maintains a storage area to store the vehicle status data, like status of doors, suspension of a maglev train. Moreover, it distributes the vehicle status data to the Speed Profile Monitoring module and DSC.

3. The Speed Profile Monitoring module: It is the core module of VSC1 and depends on three kind of data: safety location data from the Safety Locating

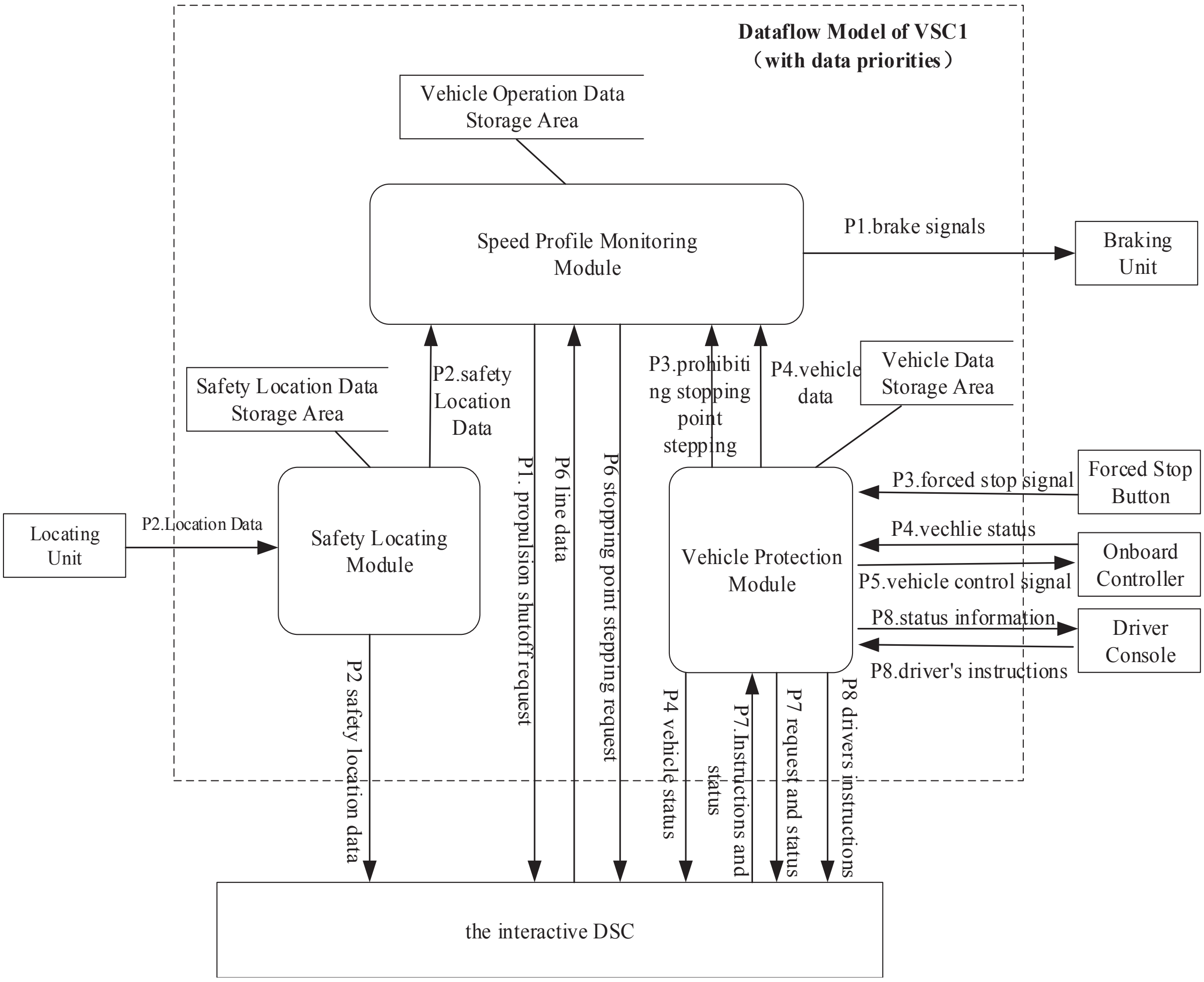

Fig. 2. The dataof VSC1 with data priorities

module, vehicle data from the Vehicle Protection module, and line data from DSC. In the meantime, it maintains a storage area to store the operation data. It is responsible for monitoring the speed profile according to the current stopping point. When the speed profile is infringed, it actives eddy-current braking after sending a request to DSC to perform a propulsion shutoff.

According to the function modules and data priority analysis of VSC1, we present the dataflow model with data priorities as Fig. 2.

CONCLUSION

Vehicle safety computers are safety critical systems and the safety integrity level are same as ATP. If the data priority is omitted, the dataflow model for vehicle safety computers will be less accurate.

To simplify the problem for vehicle safety computers, we choose VSC1 as a representative for vehicle safety computers to analyze.

The interfaces to VSC1 include Locating Unit, Onboard Controller, Driver Console, Forced Stop Button, Braking Unit and DSC.

The various data from different interactive sources include signal of braking level, location data, forced stop signal, vehicle status, vehicle control signals, stopping point stepping request, line data, instructions and status from DSC, requests and vehicle status from VSC1, operation status and driver’s instructions. Their processing priorities are assigned from P1 to P8 according to the importance analysis.

VSC1 has three main function modules: The Safety Locating module, The Vehicle Protection module and The Speed Profile Monitoring module. The three function modules of VSC1 have their dataflow and storage area respectively. According to the analysis of data priority and data process, the data flow model of VSC1 is established.

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RESEARCH ON MECHANISM OF EDDY CURRENT IN RAIL OF MAGLEV AND OPTIMUM DESIGN OF ELECTROMAGNET

Aim: Due to the movement of medium-low speed maglev vehicles, eddy current is generated in the rail, leading to reduced levitation force. This detrimental effect becomes more prominent with increasing velocity. In order to reduce the influence of eddy current effect, the electromagnet is optimized to meet the requirement of vehicle speeding up from 100km/h to 160km/h.

Methods of the studies: To maintain a constant levitation force, the current must also increase accordingly resulting in higher power consumption and heat generation. In this paper, a mathematical model is established by analytical method, focusing on the mechanism and influencing factors of eddy current. Three-dimensional transient magnetic field magnet model is analyzed by the ANSYS electromagnetic simulation software Maxwell.

Results: The levitation force is related to five parameters, such as speed, length of the electromagnet, rail height, rail thickness and air gap. According to the finite element simulation results, when the train speed is 160 km/h, the levitation force of the end electromagnet is reduced by about 21.9 %. The levitation force of optimized electromagnet increases by 27 % under the same current, which can compensate for the drop of levitation force caused by eddy current. The levitation force is 41.4 kN at the speed of 160 km/h, which is slightly larger than the 39.6 kN of the former electromagnet static levitation force, which can meet the requirements.

Conclusion: The result confirms that optimization methods proposed above are valid and effective.

Keywords: Medium-low speed maglev vehicles; Electromagnet; Eddy current; Levitation force

1. INTRODUCTION

Electromagnetic levitation and linear induction motor systems are commonly used in medium and low-speed maglev systems. China’s first medium and low speed commercial line “Changsha maglev express line” was officially opened and operated at a speed of 100 km/h in May 2016. Another 160 km/h line is being planned. When train speed increases to 160 km/h, the eddy current becomes significant, resulting in reduced levitation force.

In this paper, a mathematical model of electromagnet is established, and the mechanism and influence factors of the eddy current are analyzed. The electromagnet model is analyzed by three-dimensional transient magnetic field of professional electromagnet simulation software Maxwell. The method of compensating the eddy current effect is put forward according to the decrease of the levitation force.

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2. MECHANISM OF EDDY CURRENT

According to Faraday's law of electromagnetic induction, the movement of a conductor in a changing magnetic field or a conductor in a magnetic field can cause an induced electromotive force or an induced current in the conductor, and this phenomenon is called the eddy effect. Non-laminated steel rails are normally used in the low speed maglev system and eddy current in the rail is easily induced by moving magnets[1]. The eddy current will weaken the air gap magnetic field and reduce the levitation force.

Japanese scholar Yamamura has performed a theoretical analysis on the eddy current effect of the train electromagnet. The analytical solution of the suspension force is given under the conditions that magnetic flux leakage, rail nonlinearity and orbital flux saturation are neglected. Its model and calculation formula are as follows [2]:

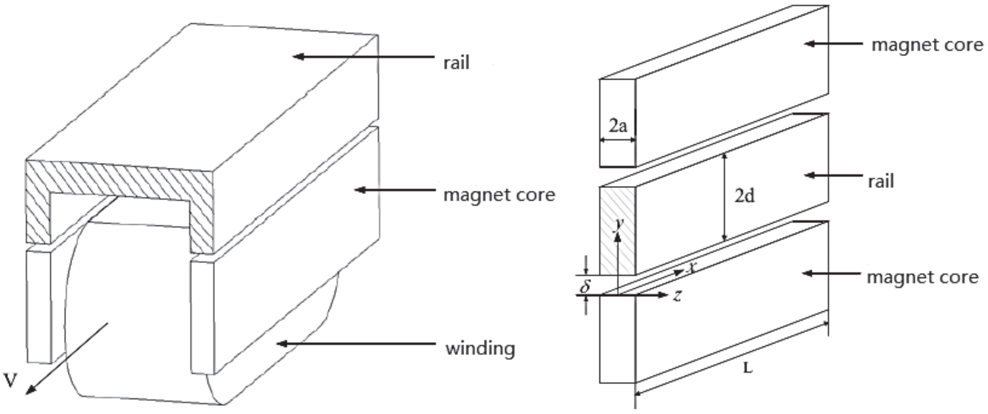


Fig. 1. Simplified model of electromagnet

$$F_{yo} = \frac{1}{\mu_0}\int_0^L dx \int_{-a}^{a} B_0 dz = aLB_0^{\,2} / \mu_0 \tag{1}$$

$$F_y = F_{yo}\sum_{n=1}^{\infty} C_n^{\,2} \frac{1}{2L\left[L - \dfrac{1}{a_n(1-e^{-a_n L})}\right]} \tag{2}$$

$$C_n = \frac{4}{(2n-1)\pi}\sin\frac{\pi(2n-1)}{2} \tag{3}$$

$$\gamma_n = \frac{(2n-1)\pi}{2a} \tag{4}$$

$$a_n = \frac{1}{2(-K+\sqrt{K^2+4\gamma_n^{\,2}})} \tag{5}$$

$$K = \frac{\sigma \mu_0 d v}{\delta} \tag{6}$$

F_y – levitation force, F_{yo} – stationary levitation force, μ_0 – magnetic permeability in vacuum, B_0 – magnetic flux density in air gap, L – length of iron core, $2a$ – rail thickness, d – single-side rail height, δ – levitation gap, σ – electrical conductivity.

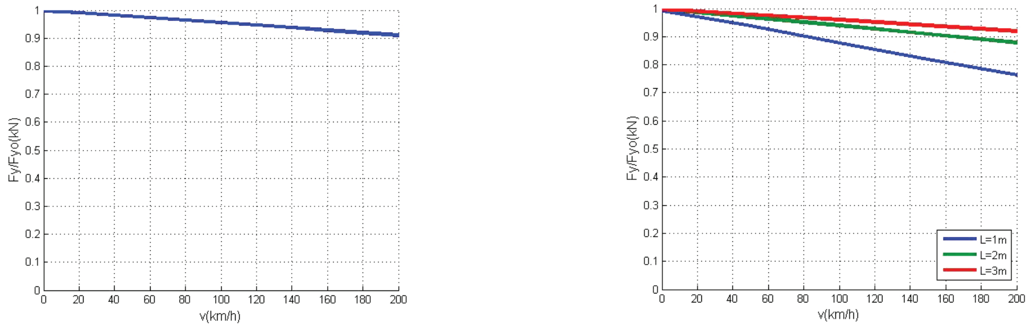
From the calculation formula, it can be concluded that the levitation force is related to five parameters, such as speed, length of the electromagnet, rail height, rail thickness and air gap. Fig. 2 shows the variation of levitation force F_y / F_{yo} with velocity [3, 4].

Fig. 2 (a) shows that the levitation force of electromagnet decreases with the increase of train speed.

Fig. 2 (b) shows the influence of electromagnet length on the eddy current effect to levitation force.

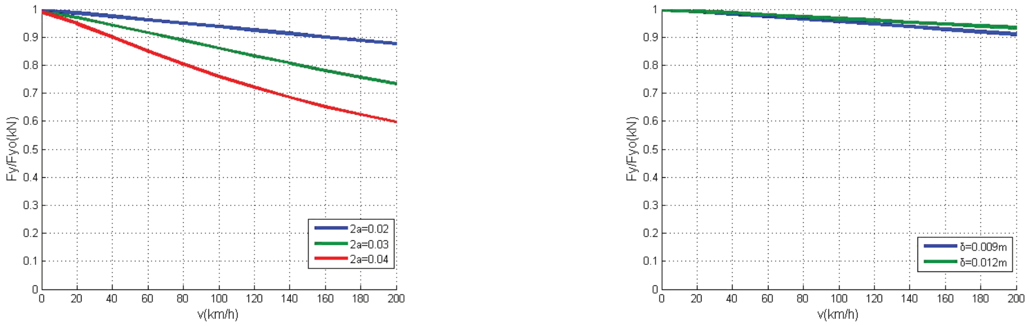
Fig. 2 (c) shows that larger the rail thickness, smaller the influence of the eddy current on the levitation force.

Fig. 2 (d) shows the influence of the eddy current on the levitation force with different values of air gap.



(a) levitation force – speed

(b) levitation force – speed with different lengths of electromagnet



(c) levitation force – speed with different rail thickness

(d) levitation force – speed with different air gaps

Fig. 2. F_y / F_{yo} decreases with increasing speed

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3. FINITE ELEMENT SIMULATION

Electromagnet parameters are show in table 1.

Table 1. Electromagnet parameters

Parameters	**Values**
Rail thichness (2a)	0.028 m
Magnet Length (*L*)	2.72 m
Air gap (δ)	0.009 m
Ampere-turns (*i*)	15 360 A

The three-dimensional transient simulation model of electromagnet is established by Maxwell simulation software. As shown in Figure 3, the moving object is an electromagnet, the electromagnet is moving in the direction of the X axis. The V shows the direction of the electromagnet in Figure 3, and the simulation assumes that the electromagnet and the rail have no lateral misplacement and side rolling.

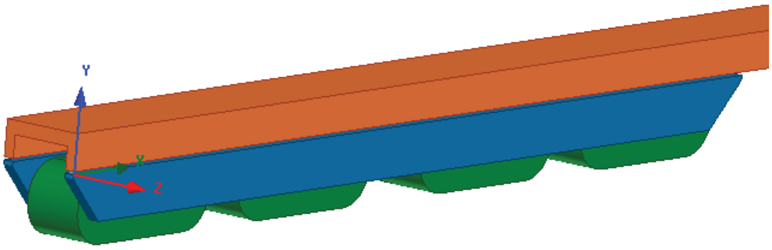

Fig. 3. Simulation model of electromagnet module

The Jz distribution of lateral density of rail eddy current density at different speeds is shown in Fig. 4. The eddy current density at the two ends of the electromagnet is larger than that of in the middle part of the electromagnet. The eddy current at both ends is in opposite direction and increases with the speed. The peak position at both ends does not vary with speed. The front end of the eddy current is in the negative direction along the Y axis and the back end is in the direction of the Y axis. This indicates that the eddy current weakens the front magnetic field of the electromagnet and strengthens the magnetic field at the end of the electromagnet [5].

The density of magnetic flux By distribution of the vertical component in the air gap at different speeds is shown in Fig. 5. The By of the electromagnet decreases with increasing eddy current in the front of the air gap, and the By changes very little at the end. Comparing the air gap flux density at different speed, it indicates that the average magnetic flux density is smaller in the air gap when the velocity

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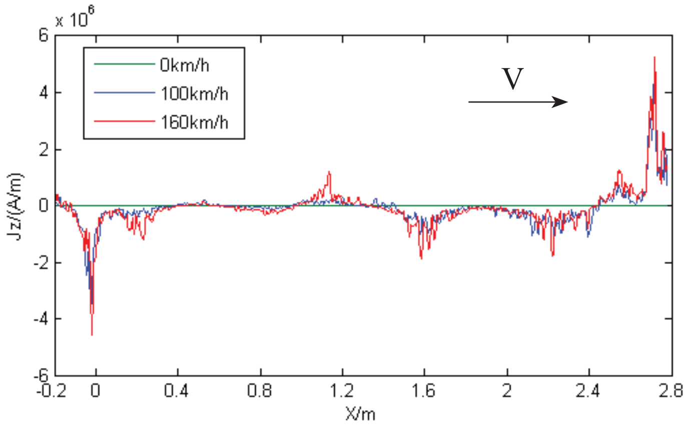

Fig. 4. Distribution of eddy density lateral component Jz at different speeds

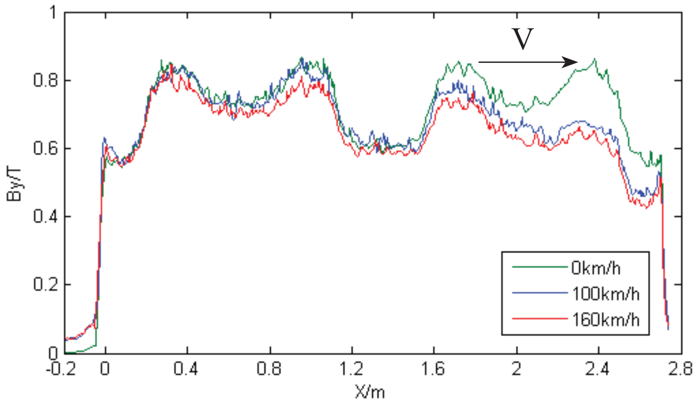

Fig. 5. Distribution of vertical component by of air gap flux density at different speeds

is larger. The decrease of the air gap means that flux density will directly reduce levitation force. The higher the speed of the electromagnet, the more significant the effect of eddy current, the more the lead force is reduced [5].

The levitation force of the electromagnet model is calculated, and the results of the finite element simulation is shown in Table 2. When the speed is 160 km/h, the levitation force of the electromagnet decreases by 21.9 % compared with 0km/h. The current may increase by about 6A to meet the requirements, with the same air gap and vehicle weight. The increasing current will lead to higher temperature which can damage the electromagnet. Therefore, reducing the effect of eddy current is the key to achieve higher speed.

Table 2. Simulation results

Speed, km/h	Levitation force, kN	Descent range, kN	Descent rate comparing to stationary, %
0	39.6	0	0
100	33.9	5.7	14.4
160	30.9	8.7	21.9

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4. OPTIMUM DESIGN OF ELECTROMAGNET

In order to compensate the influence of eddy current effect on the levitation force, the electromagnet must be optimized. According to the analytical results mentioned above, influence of the eddy current on the levitation force can be reduced by three parameters: electromagnet length, the rail height and rail thickness. The rail height is determined by the overall scheme of the line, which is generally difficult to change. Although the influence of the eddy current on the levitation force can be reduced through decreasing the rail thickness, the levitation force will also be reduced. The purpose of this paper is to compensate the eddy current effect on the levitation force by extending the core length and adding extra coils.

Based on the original electromagnet scheme, length of iron core at the front end is increased and an electromagnet coil is also added, as shown in Fig. 6.

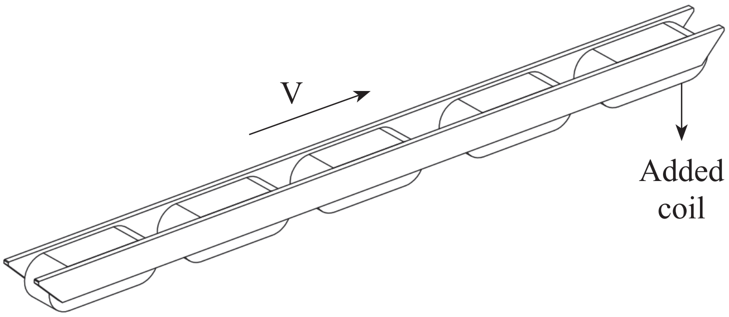

Fig. 6. The optimized electromagnet

The levitation force of the optimized electromagnet increases at speed of 0 km/h, which can still meet the requirement of vehicle weight after the eddy current is weakened. The benefits of the scheme are as follows: simple structure, easy maintenance, constant installation interface and flexible disassembly and assembly according to the actual demand of the train.

The optimization electromagnet simulation model is established, and the simulation results are shown in Table 3.

Table 3. Simulation results on levitation force of electromagnet

Speed, km/h	**levitation force, kN**	**Descent range, kN**	**Descent rate comparing to stationary, %**
0	50.4	0	0
50	48.2	2.2	4.4
100	45.1	5.3	10.5
160	41.4	9.0	17.9
200	39.3	11.1	22.1

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The levitation force is 41.4 kN at the speed of 160 km/h, which is slightly larger than the 39.6 kN of the former electromagnet static levitation force, which can meet the requirements.

5. CONCLUSION

Reducing the effect of eddy current on levitation force is the key to further speed up the low speed suspension train. Starting from the analytical method, the generation mechanism and influencing factors of rail eddy current effect are analyzed. The three-dimensional transient magnetic field simulation of the electromagnet model is carried out by the Maxwell software, and the decrease of levitation force at different speeds is obtained. According to the simulation results, the electromagnet is optimized. A method of extending the iron core length and adding extra coils in the front of electromagnet is proposed to compensate the loss of the levitation force.

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CONSTANT SWITCHING FREQUENCY MODEL PREDICTIVE CONTROL FOR PERMANENT MAGNET LINEAR SYNCHRONOUS MOTOR

Aim: This paper proposes constant switching frequency model predictive control (CSF-MPC) for a permanent magnet linear synchronous motor (PMLSM) to improve the steady state and dynamic performance of the drive system.

Methods: The conventional finite control set model predictive control (FCS-MPC) can be combined with a pulse width modulation (PWM) modulator due to an effective cost function optimization algorithm which is from the idea of dichotomy. In the algorithm, all the voltage vectors in the constrained vector plane are dynamically selected and calculated through iteration. The whole system including control algorithm and mathematical model of PMLSM is built and tested by simulation using MATLAB/Simulink. Besides, the control algorithm is tested in the FPGA controller through FPGA-in-the-Loop test.

Results: With the modern digital processors or control hardware such as digital signal processors (DSPs) or field programmable gate arrays (FPGAs), the algorithm can be easily executed in less than 10-micro second. This is very proper for industrial applications. The proposed control algorithm is implemented on FPGA and tested by FPGA-in-the-Loop method. The proposed control algorithm can improve the performance of drive system greatly.

Conclusion: The proposed CSF-MPC for PMLSM not only keeps the same dynamic transient performance as FCS-MPC but also greatly decreases the torque ripple in steady state. Furthermore, CSF-MPC is also robust to parameter variations. Simulation and FPGA-in-the-Loop results illustrate that CSF-MPC has an attractive performance for PMLSM drives.

Keywords: Permanent magnet linear synchronous motor (PMLSM), Model predictive control, Field programmable gate arrays (FPGAs), Dichotomy, Constant switching frequency, Voltage vector.

INTRODUCTION

Linear machines are widely used in industry systems which require fast response and large thrust. Without an intermediate conversion mechanism, a linear machine can directly convert electrical energy into mechanical energy in a linear motion [1]. This is the most attractive characteristics of linear machines. Recently, Permanent magnet linear synchronous motors (PMLSM) drive systems develop very fast because of some advantages such as low losses, fast dynamic performance and high thrust performance.

PMLSM drive systems have wide applications in industrial automation production lines and industrial transmissions such as machine tools. With the

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continuous development of equipment manufacturing technology, on the one hand, PMLSM drive system requires higher control bandwidth and dynamic response; on the other hand, it needs higher steady state accuracy and better static characteristics. These technique demand make advantage control strategies of PMLSM more desirable [2, 3]. Recent years, with the rapid development of control platform devices, such as DSP (digital signal processor) and FPGA (field programable gate array), model predictive control (MPC) becomes attractive in control of electrical drive systems for some advantages such as good dynamic response and straightforward inclusion of nonlinearity and restrictions in the model and control [4, 5]. For application in power electronics and electrical drives, MPC can be concluded into two categories: continuous control set MPC (CCS-MPC) and finite control set MPC (FCS-MPC).

For CCS-MPC, generalized predictive control (GPC) is a typical control strategy belong to this category [6]. GPC is established on linear models and extended to including constraints. In order to receive a required accuracy, the prediction of GPC usually need at least several steps. Moreover, the calculation is normally so large that it can only be realized by off-line calculation. Furthermore, GPC degrades accuracy while control of nonlinear systems such as electrical drive systems. FCS-MPC considers only finite set of possible switching states of power converters and solves the cost function for each of them and selects a switching state which minimizes the cost function. Easy to be implemented and good dynamic response are the two remarkable advantages of FCS-MPC. Therefore, it becomes rather popular in control of power electronic systems in these years [6, 7]. However, only one switching state to be applied in a sampling interval makes a variable switching frequency. Meanwhile, a relatively large control error is generated in each switching interval especially for two level converters. Hence, a large current ripple and wide range harmonics frequency are unavoidable.

Recently, many research works try to solve above men9tioned problems of FCS-MPC. In [8], based on a fixed hysterics bandwidth, multi-step prediction is adopted to select a proper switching state so that it keeps a constant torque ripple bandwidth. In each sampling interval, following an active switching state, a zero state will be inserted in the control interval to decrease the current ripple [9]. While in [10], a cost function for minimum torque ripple is directly defined to calculate the switching point. Based on duty cycle control, an improved model predictive control for current control is proposed in [11]. In [12], dichotomy solution algorithm for cost function is proposed which provide an effective approach to solve some of these problems.

This paper proposed a dichotomy solution based constant switching frequency model predictive control (CSF-MPC) for PMLSM. The d and q axes currents are

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both predicted based on the fundamental model of PMLSM using Euler formula. The optimal voltage vector can be chosen in the whole voltage vector plane since the dichotomy solution algorithm is used. Through FPGA-in-the-Loop test, the advantages of proposed CSF-MPC compared with conventional FCS-MPC is proved. Mathematical model of PMLSM is described in the next section of this paper. Then, Section III presents conventional FCS-MPC for PMLSM. The proposed control algorithm is elaborated in Section IV. After FPGA-in-the-Loop test, we conclude the paper in Section VI.

MATHEMATICAL MODEL OF PMLSM

In this work, a simplified mathematical model of PMLSM which includes no magnetic saturation is considered. Due to the inductances of PMLSM are normally varied with position information, we mainly consider the mathematical model in synchronous rotating frame, i.e., d-q coordinate. Firstly, the d-q frame voltage equations can be described as:

$$u_d = R_s i_d + \frac{d\lambda_d}{dt} - \frac{\pi v}{\tau}\lambda_q \tag{1}$$

$$u_q = R_s i_q + \frac{d\lambda_q}{dt} + \frac{\pi v}{\tau}\lambda_d \tag{2}$$

where, u_d, u_q are the d-q axis voltage; i_d, i_q are the d-q axis current; λ_d, λ_q are the d-q axis flux, respectively. R_s is the resistance of on phase PMLSM primary winding; v is the moving speed of the mover; τ is the pole pitch.

The flux linkage equations in d-q frame can be written in the following equations:

$$\lambda_d = L_d i_d + \lambda_f \tag{3}$$

$$\lambda_q = L_q i_q \tag{4}$$

where, L_d, L_q are the d-q axis inductances, respectively; λ_f is the flux linkage produced by permanent magnet.

Correspondingly, the electromagnetic thrust of PMLSM is deduced as the following equation:

$$F_e = \frac{3\pi}{2\tau} n_P [\lambda_f i_q + (L_d - L_q) i_d i_q] \tag{5}$$

For multi-pole linear motors, n_P denotes pole-pairs.

Because the air gap is relatively large for the linear machines, the inductance value in d and q frame could be seen as the same. This means $L_d = L_q = L_s$. Therefore, the equation of electromagnetic thrust can be simplified as

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$$F_e = \frac{3\pi}{2\tau} n_P \lambda_f i_q = k_f i_q \tag{6}$$

In equation (6), k_f is the coefficient of electromagnetic thrust.

The equation used to model the dynamics is presented in (7), where m is the mass of linear movement part; F_l is the load resistance; D is the system friction coefficient.

$$m\frac{dv}{dt} = F_e - F_l - Dv \tag{7}$$

CONVENTIONAL FCS-MPC FOR PMLSM

Similar with conventional direct torque control (DTC) proposed in the 1980s which is continuously developed and improved by ABB cooperation, FCS-MPC also considers finite switching states of power converters. Therefore, the optimization problem is reduced to evaluate all possible switching states and select the one which minimizes the given cost function. Based on this idea, the complex model predictive control optimization strategy of three-phase two-level inverter is simplified to optimize only eight possible switch states. Although the calculation burden will increase exponentially when the prediction horizon increases, one step prediction usually receives satisfied performance.

In the d-q synchronous rotating frame, the d-axis and q-axis current state space equations of PMLSM are respectively described as

$$\frac{di_d}{dt} = \frac{1}{L_s}[u_d - R_s i_d + \frac{\pi v}{\tau} L_s i_q] \tag{8}$$

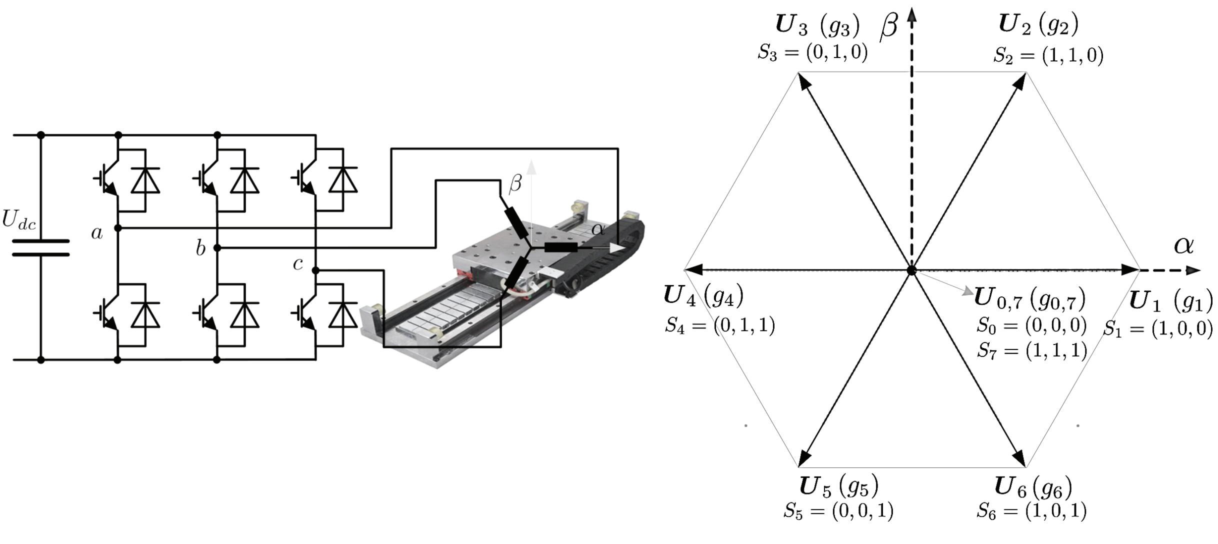

Fig. 1. PMLSM drive system: three-phase two-level inverter and its eight voltage vector state

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$$\frac{di_q}{dt} = \frac{1}{L_s}[u_q - R_s i_q - \frac{\pi v}{\tau} L_s i_d - \frac{\pi v}{\tau}\lambda_f] \tag{9}$$

In order to calculate predicted current in the next sampling interval, Euler formula is used to discretize the current equations. This means the approximated d-axis and q-axis current can be presented by the following equations

$$i_d(k+1) = i_d(k) + \frac{T_s}{L_s}[u_d(k) - R_s i_d(k) + \frac{\pi v(k)}{\tau} L_s i_q(k)] \tag{10}$$

$$i_q(k+1) = i_q(k) + \frac{T_s}{L_s}[u_q(k) - R_s i_q(k) - \frac{\pi v(k)}{\tau} L_s i_d(k) - \frac{\pi v(k)}{\tau}\lambda_f] \tag{11}$$

Where, $i_d(k+1)$ and $i_q(k+1)$ are the predicted d and q axes current in the next sampling interval, respectively; $i_d(k)$ and $i_q(k)$ are the measured feedback d and q axes current at present sampling interval; T_s is the sampling period; $u_d(k)$ and $u_q(k)$ are the d and q axes voltage, $v(k)$ is the speed all at present time.

Conventional FCS-MPC replaces the inner current control loop of field-oriented control (FOC) by model predictive control method. The speed control loop keeps the same to use proportional integration (PI) controller. For conventional FCS-MPC, equation (10) and (11) are firstly used to calculate the one step prediction value for d and q axes current. Then, through calculation of cost function (12), the voltage vector which is able to minimize the cost function will be selected as the optimal voltage vector and applied to the inverter. Fig. 2 shows the control structure of conventional FCS-MPC for PMLSM drive system.

$$g = |i_d^* - i_d(k+1)| + |i_q^* - i_q(k+1)| \tag{12}$$

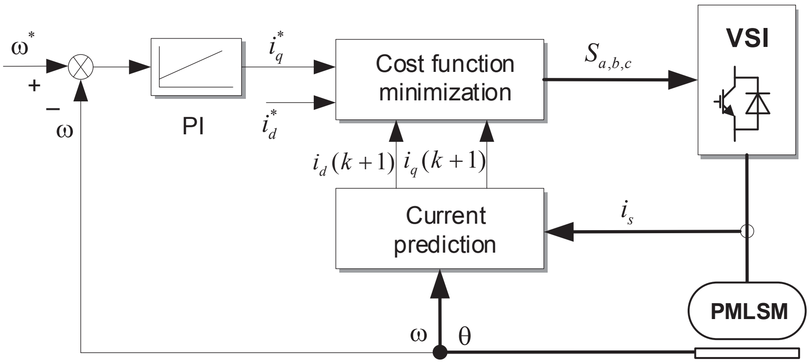

Fig. 2. Conventional FCS-MPC (predictive current control) for PMLSM drive system

PROPOSED CSF-MPC FOR PMLSM

Though the concept of FCS-MPC is straightforward and it is easy to implement this control strategy, FCS-MPC for PMLSM will present large steady

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state current and torque errors. To improve its performance, this work proposes a dichotomy solution based constant switching frequency model predictive control (CSF-MPC) for PMLSM. The structure of CSF-MPC for PMLSM drive system is presented in Fig. 3. We can see the difference between conventional FCS-MPC and proposed CSF-MPC for PMLSM drive system (Fig. 2 and Fig. 3) is PWM module is required of CSF-MPC. The reason is that the output voltage vector of CSF-MPC is quasi-continuous, so PWM module can be applied to the control system. Due to the proposed dichotomy solution algorithm, the optimal voltage vector in each sampling interval can be acquired in time. In the proposed CSF-MPC, the over current protection is added in addition,

$$G = \left| i_d^* - i_d(k+1) \right| + \left| i_q^* - i_q(k+1) \right| + g_I \tag{13}$$

$$g_I = \begin{cases} 0, & if\ i_s < I_{s.\max} \\ \infty, & else \end{cases}$$

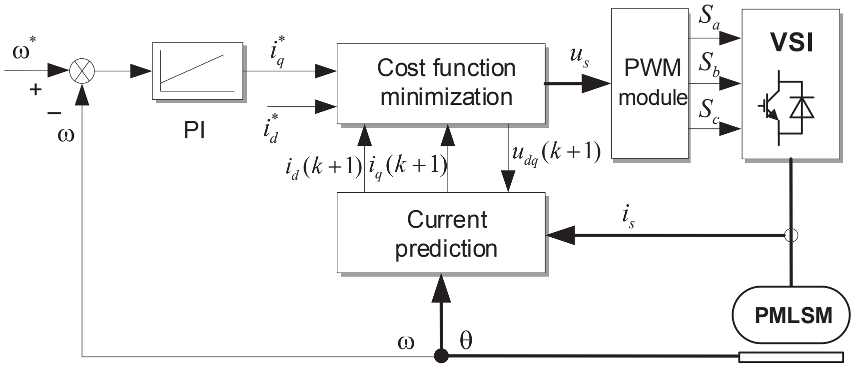

Fig. 3. Proposed CSF-MPC for PMLSM drive system

The idea of the cost function solution algorithm is from dichotomy. As presented in Fig. 4, the voltage vector search area is the voltage circular plane with a radius of U_m – the maximum available voltage. In each sampling interval, with $U_m / 2$ amplitude and $\pi / 4$ phase different of each other, eight voltage vectors are selected as the vector candidates at the initialization. At the first step of the iteration, one of the eight vectors is selected as the optimal vector based on the cost function.

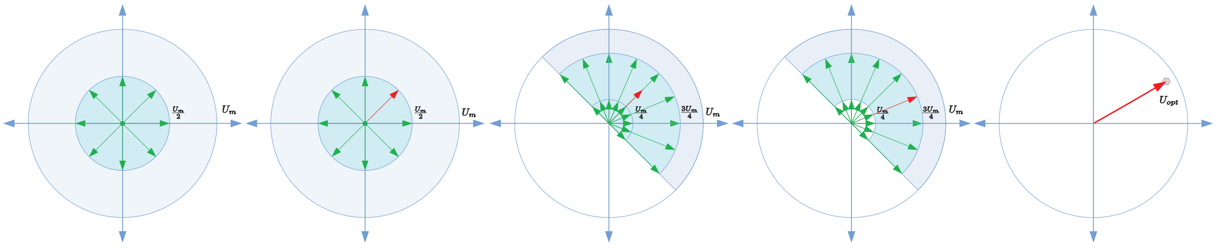

Fig. 4. Dichotomy solution algorithm process for cost function

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In the next step, based on the optimal vector selected in the last step, 18 new voltage vectors, whose amplitude and phase angle are added or subtracted by half of last step optimal voltage vector, are selected to solve the cost function. Therefore, the search area decreases to half of the last step. After 14 steps iteration, the optimal voltage vector is selected as the reference vector for PWM modulator.

FPGA-IN-THE-LOOP TEST RESULTS

For the FPGA-in-the-Loop test, the plants including power converters, PMLSM and mechanical load are simulated in the MATLAB/Simulink in the computer. The control algorithm which is described as VHDL is working in the real FPGA board, for instance, Altera DE2-115 development board is used in this work. When the test is working, both the plants and control algorithm are working in real time connected with each other through Ethernet communication. Using this test method, the control algorithm can be completely tested as tested in the real test bench. The researchers do not need to pay too much time on hardware system. Therefore, the development time of control algorithms could be dramatically decreased. The whole FPGA-in-the-Loop test platform is described in Fig. 5. The parameters of PMLSM is shown in table I.

Fig. 6 presents the FPGA-in-the-Loop test results of both control methods. For the test, the speed is set to 125 rad/s, the thrust load is set to 190 N and 380 N before and after 0.1S. The sampling frequency of conventional FCS-MPC is 40 kHz, which can insure the maximum switching frequency is no more than 20 kHz. The fixed switching frequency is 10 kHz for the proposed CSF-MPC for PMLSM. It is clear to see that conventional FCS-MPC for PMLSM has larger current ripple compared with CSF-MPC. The current performance of CSF-MPC for PMLSM is elegant.

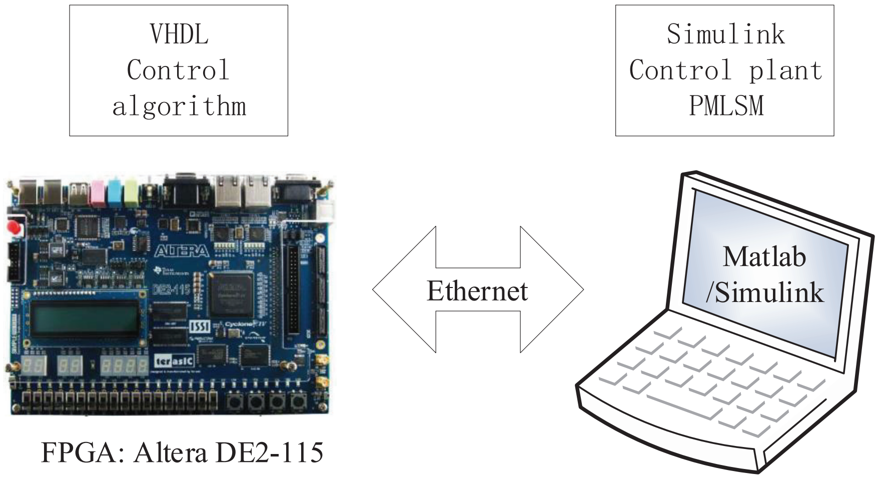

Fig. 5 Overview of FPGA-in-the-Loop test platform

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Table 1. Parameters of PMLSM

Parameter	Value	Unit of measurement
Rated power	1050	W
Maximum power	2030	W
Current effective value	4.6	A rms
Maximum current effective value	24.6	A rms
Resistance	3.1	Ω
Capactance	32.2	mH
Back EMF constant	26	Vrms/(m/s)
Maximum speed	3	m/s
Maximum acceration	50	m/s^2
Continuous thrust	180	N
Pole pitch (2τ)	32	mm

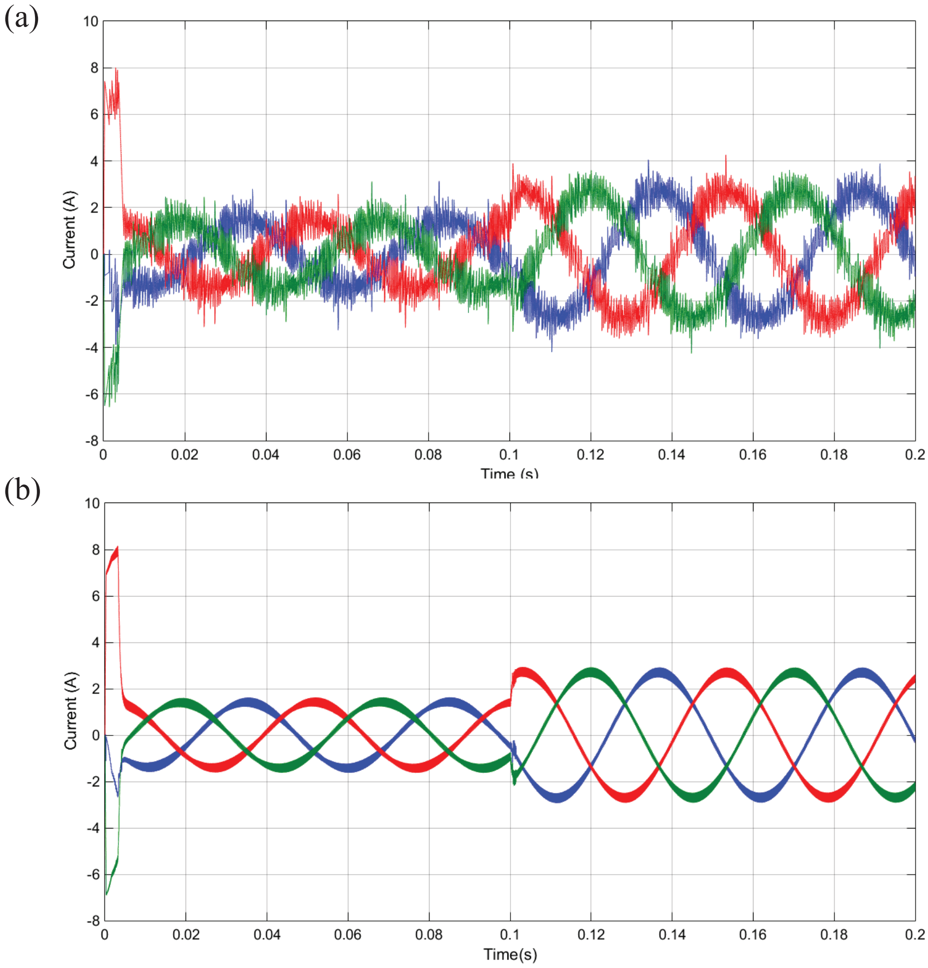

Fig. 6. FPGA-in-the-Loop test results comparison:
(a) conventional FCS-MPC; (b) proposed CSF-MPC

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CONCLUSION

CSF-MPC which is based on current prediction and control is proposed for PMLSM drive system. D and q axes currents are the control target in the control algorithm. Due to the effective dichotomy solution algorithm, the required optimal voltage vector can be selected on the whole voltage vector plane. So PWM modulator can be combined with conventional FCS-MPC method to generate the optimal voltage vector. This is reason why current ripple is dramatically reduced. With the novel FPGA-in-the-Loop test method, the effectiveness of proposed CSF-MPC of PMLSM is proved and the test results are rather excited. The next step of this work will improve the algorithm further and test it on the real test bench.

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MEASUREMENT OF THE RESIDUAL STRESS FOR THE BOGIE FRAME OF MAGLEV VEHICLE BASED ON BARKHAUSEN EFFECT

Background: The effect of residual stress resulted from the manufacturing process on the performance of bogie frame has been attracting more and more attention with the increasing of running speed of maglev vehicle, which could develop cracks on the frame and compromise the operational safety.

Aim: It is necessary to determine and understand the distribution rules of residual stress on the bogie frames.

Methods: Barkhausen effect is one of the effective methods used to measure residual stress.

Results: This paper presents a experiment system designed for residual stress detection and the principle of electromagnetic stress detection is expounded, finite element simulation analysis on magnetization device is carried out, and the effect of magnetization under different excitation conditions is analyzed.

Conclusion: The feasibility of the online magnetic detection method of internal stresses in bogie frame is verified through the simulation, which would provided the basis for bogie frames internal stresses detection.

Keywords: bogie frames; maglev vehicle; Barkhausen effect; residual stress; nondestructive examination.

INTRODUCTION

The demand for train speed increase by users is increasing under the premise of the continuous development of medium-low speed maglev train. The operating environment of the maglev train is becoming more and more complicated when the train running speed is increased to 160–200 km/h. As the most critical part of the whole vehicle, the maglev train bogie supports the weight of the vehicle and transmits traction and braking force, which operating status is directly related to the safety of the entire vehicle. As the speed of the medium-speed maglev train increases, the traction force will increase appropriately on the basis of the original low-velocity traction force. The resulting stress and impact dynamic load

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of the bogie traction transmission will cause a surge of local stress, which result in increase in the stress and impact dynamic load of the bogie traction transmission causes a surge in local stress. Therefore, it is necessary to carry out non-destructive testing analysis of the internal stress distribution of the frame components and the service period of the materials.

Fig. 1. Maglev train of Changsha Maglev Express

Non-destructive testing technology is playing an important role in the high-level maintenance of urban rail vehicles. Nowadays the NDT methods mainly include magnetic powder, X-ray, ultrasonic and electromagnetic non-destructive testing. Among them, electromagnetic non-destruction has its unique advantages compared to other types of testing [1]. However, general electromagnetic nondestructive testing technology can't meet the current situation of steering frame maintenance. Magnetic Barkhausen noise on measurement of residual stresses in the nondestructive testing is a new technology [2]. In 1919, the German physicist Barkhausen the first time discovered the Barkhausen effect. He observed ferromagnetic hysteresis loop of materials and found: curve is not smooth, see changes which jitter level amplified, known as the Barkhausen transition. Non-destructive testing techniques based on the Barkhausen effect have little research on magnetic floatation [3–4]. Therefore, the development of the Barkhausen detection system for the bogie frame is particularly important.

This paper presents a experiment system designed for residual stress detection and the principle of electromagnetic stress detection is expounded, finite element simulation analysis on magnetization device is carried out using ANSYS Maxwell, and the effect of magnetization under different excitation conditions is analyzed. The feasibility of the online magnetic detection method of internal stresses in bogie frame is verified through the simulation, which would provided the basis for bogie frames internal stresses detection.

1. DETECTION PRINCIPLE

The Barkhausen effect is a sudden discontinuous motion of the magnetic domain wall when the ferromagnetic material is magnetized to release elastic stress – strain wave phenomenon. The voltage pulse generated by this effect on the surface receiving coil of the sample is called Barkhausen noise, which is abbreviated as MBN [5].

According to the ferromagnetic theory, when the external magnetic field H = 0, the material is magnetically neutral and the domain walls are in equilibrium. When an external magnetic field is present, the domain wall displacement gradually increases from the reversible wall shifting stage. The strength required to move the domain wall to the demarcation point is the critical magnetic field strength H_0:

$$H_0 = \frac{1}{2\mu_0 M_s \cos\theta}\left[\frac{dE}{dx}\right]_{\max} \tag{1}$$

where μ_0 is the magnetic permeability of material, M_s is the saturation magnetization, θ is the small angle at which the magnetic domain moment is rotated by the action of the external magnetic field in the direction of easy magnetization, E is the domain wall energy per unit area, x is the displacement.

Wall shift occurs when the magnetic field strength increases slightly above H_0. As the strength of the magnetic field continues to increase, the domain wall again jumps, with dE/dx further increasing. Therefore, as the strength of the magnetic field increases, several hopping domain wall movements may occur. All Barkhausen jumps in a complete magnetization process come together to form MBN.

During the magnetization of the material, microscopic defects and residual stresses inside the material can hinder the movement of the magnetic domain walls. In the process of magnetic domain wall displacement, it is necessary to overcome the potential energy barrier caused by uneven stress, impurities, holes and other factors inside the material. Therefore, the characteristics of the MBN signal can reflect the magnetic domain structure and motion law of the ferromagnetic material, which in turn reflects the microstructure and stress state of the material [6–8].

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When the induction coil is placed on the surface of the material, it can receive the Barkhausen noise generated by the material during the magnetization process [9–10]. Through the acquisition and analysis of the noise signal, the relationship between the residual stress and other characteristics and the characteristic value of the Barkhausen noise signal is studied.

2. TESTING TECHNIQUES AND INSTRUMENTS

The functional blocks of the testing instruments are shown in Fig. 2. The excitation detecting sensor comprises a U core magnet and a probe. The magnetization device is composed of a U core magnet and an exciting coil wound on the magnet. To produce Barkhausen noise, a magnetizing field is generated and applied to a ferromagnetic material through an electromagnet [3, 4]. The material reacts to the magnetic field and emits Barkhausen noise, which are captured by a probe consisting of a coil of conducting wire. The signal is filtered and amplified. The amplitude is calculated and the data is digitized for display and output to storage meanwhile.

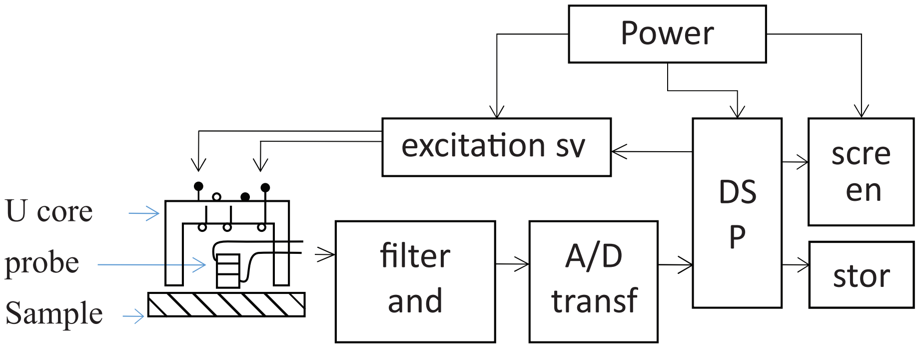

Fig. 2. The functional blocks of the testing instruments

3. ESTABLISHMENT OF FINITE ELEMENT SIMULATION MODEL

The simulation model is shown in Fig. 3. It mainly includes U-shaped magnetic core, excitation coil, and steel plate to be tested. Material properties assigned to the established electromagnetic mechanism: The magnetic core is made of cold rolled non-oriented silicon steel lamination, the material of the excitation coil is copper, the material to be tested is made of carbon steel, The geometric parameters of the excitation coil and specimen are listed in Tables 1, and 2. The boundary is set to the boundary of the balloon, and the inner and outer gaps of the sensor device are set to air.

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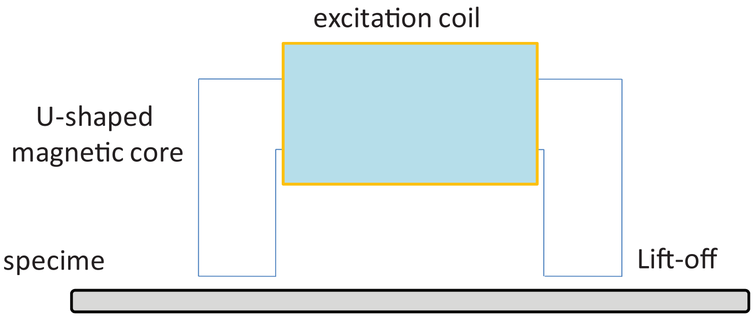

Fig. 3. Simulation model for excitation device

Table 1. Properties of the excitation coil

Turns	**Cross-section Shape**	**Material**	**Current source**
300	Rectangular	Standard Copper (Permeability = 1 Mu; Conductivity = 5.8e007 S/m)	1.0 A (Strand; Total)

Table 2. Dimension and properties of the conductive sample

Width (mm)	**Thickness (mm)**	**Cross-section Shape**	**Material**
50	5	Rectangular	Iron (Permeability = 4000; having B-H curve)

Maxwell 3D software performs meshing methods automatically, adaptively and manually. The software recommends that the user manually split the data to more accurately analyze the static characteristics. Fig. 2 shows the result of manual splitting, defining the total number of cells of the core and the grid to be tested as 10 000. The mesh of the coil and air is adaptively split.

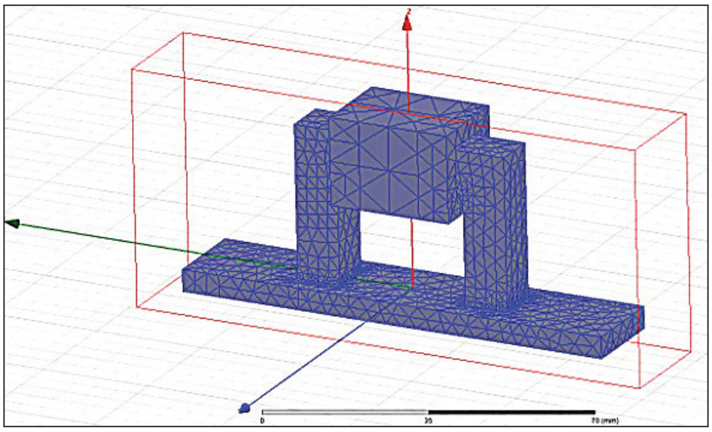

Fig. 4. Meshed model

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4. NUMERICAL RESULTS

4.1. Magnetic Field Distribution

The excitation coil is applied with a current of 1.0 A, observe the distribution of the magnetic field lines in the magnetic permeability loop and the magnetic induction intensity distribution of the surface layer of the sample material. The magnetization effect is shown in Fig. 5 and Fig. 6, wherein Fig. 5 shows the magnetic field distribution of the magnetic permeability loop. Fig. 6 shows the magnetic induction distribution of the sample. It can be seen that the magnetic magnetic yoke and the sample material constitute a conduction magnetic circuit, and the surface layer portion of the sample reaches the magnetization effect. Therefore, the excitation device design meets the requirements, and the excitation effect on the test piece can be achieved.

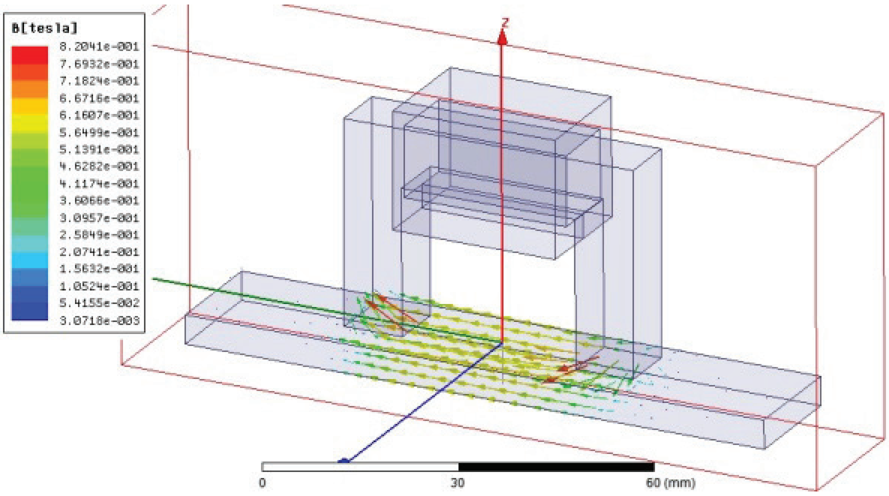

Fig. 5. B-vector map of steel plate

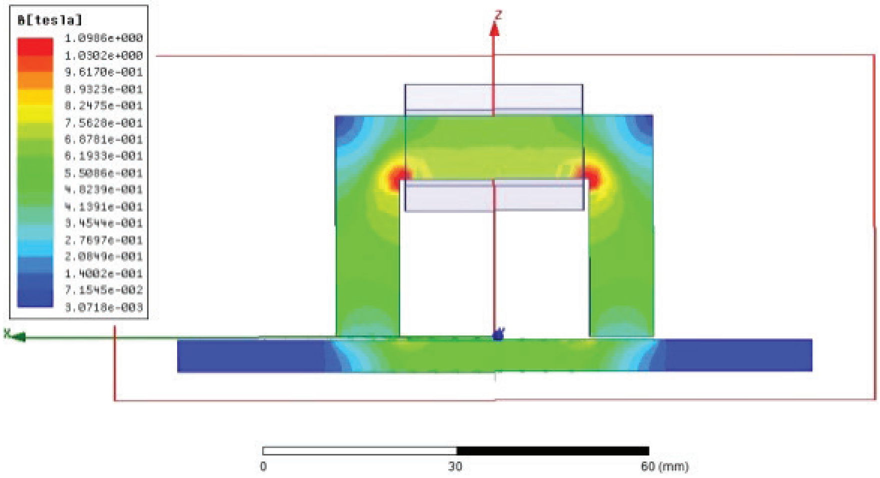

Fig. 6. Mag-B field map of xz plane

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4.2. The Effect of Lift-off on Excitation

Lift-off is a problem that has always been faced and needs to be solved in electromagnetic testing, and it has also become one of the main factors hindering the further development of electromagnetic defect detection technology. Lift-off refers to detecting the distance between the sensor and the tested part. When the relative position between the detecting sensor and the test piece changes, the degree of interaction between the detecting sensor and the test piece changes, and the detecting sensor and The effect of the change in distance between the test pieces on the detection of the sensor signal is called the "lift-off effect". In the Barkhausen excitation simulation experiment, and the aipgap is 0 mm–1.0 mm, as shown in Fig. 7, the consequence of lift-off on the excitation effect. As the lift-off distance increases, the magnetic field induction intensity in the steel plate decreases exponentially, which is due to the increased distance between the detection sensor and the test piece, and the degree of interaction is weakened. Therefore, in order to improve the excitation effect of the Barkhausen effect excitation probe, the lift distance should be reduced as much as possible.

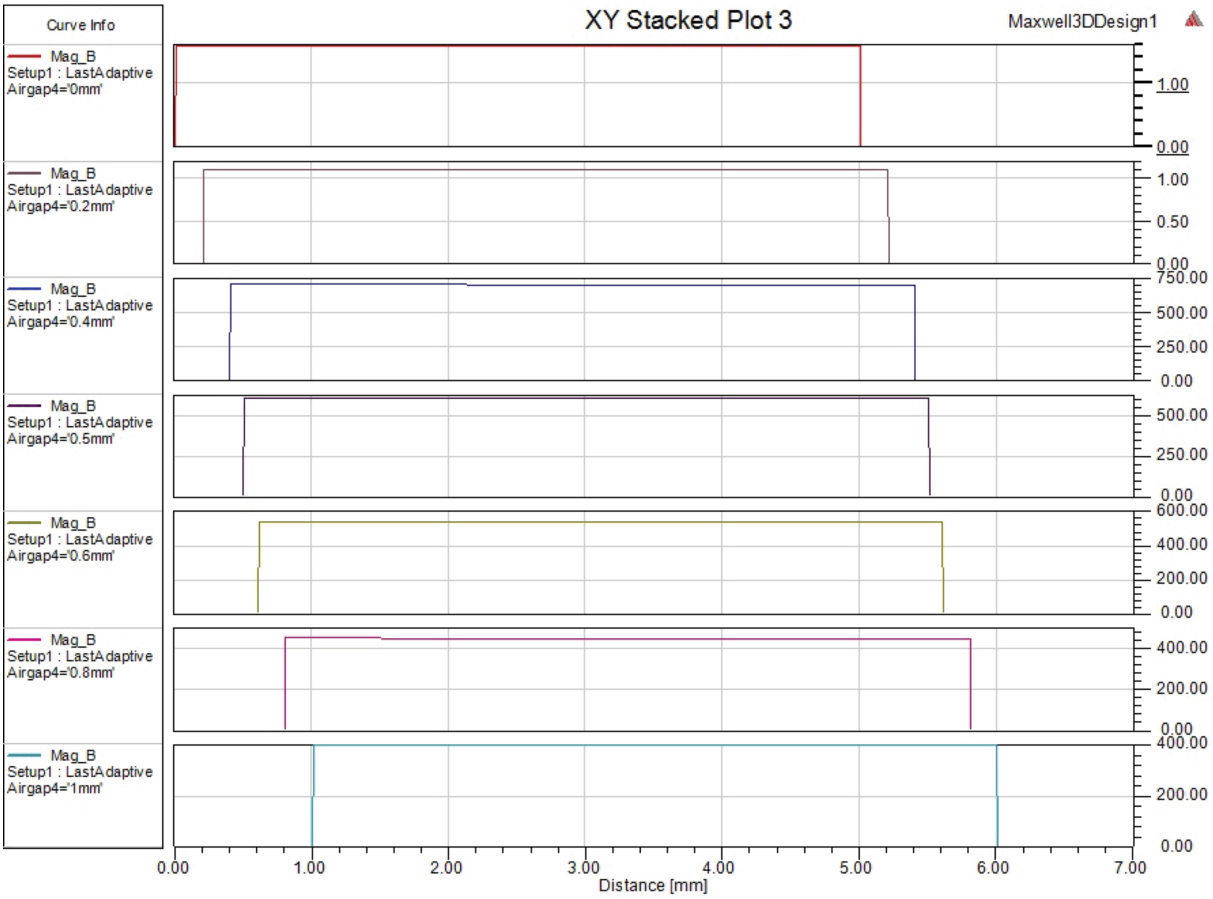

Fig. 7. Lift-off effects to sample for the airgap increased from 0mm to 10 mm

CONCLUSION

The feasibility of using the Barkhausen effect for detecting stress of bogie frame is investigated. According to the Barkhausen effect detection principle, an excitation detection sensor device is designed for the force-receiving parts of the medium-speed maglev train bogie frame. The electromagnetic field finite element analysis software is used to analyze the part of the designed magnetization device. From the above simulation analysis results, it can be concluded:

1) It can be seen from the magnetic line and the magnetic induction intensity map that the magnetic yoke and the material to be tested constitute a magnetic magnetic circuit, and the surface layer of the test piece achieves the magnetization effect. Therefore, the magnetizer meets the design requirements.

2) Lift-off is a key issue in electromagnetic testing. As the lift-off distance increases, the magnetic field induction intensity in the steel plate decreases exponentially. Therefore, in order to improve the excitation effect of the Barkhausen effect excitation probe, the lift distance should be reduced as much as possible.

The theoretical study demonstrates the feasibility of the proposed approach. Experimental validation of the inspection process is currently underway.

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THE TOTAL SOCIAL COSTS OF CONSTRUCTING AND OPERATING A MAGLEV LINE USING A CASE STUDY OF THE RIYADH-DAMMAM CORRIDOR, SAUDI ARABIA

Background: Introducing Magnetic Levitation (Maglev) technology in a developing country is a big challenge that needs huge investments in infrastructure, operations and maintenance. Background information about the development of Maglev worldwide to date is included.

Aim: Determine a methodology to estimate the full cost of travel and provide insights into the working model developed to include the calculations of the total social costs of building a new Maglev line for the Riyadh-Dammam corridor in Saudi Arabia and understand in what circumstances it is a suitable technology to use.

Methods: The Spreadsheet Total Cost Model (STCM) is used to determine the calculations of operator costs, user costs, and environmental costs. However, the operator costs are related to infrastructure construction and maintenance costs, and costs associated with the acquisition, operation and maintenance of Maglev rolling stock. The user costs are dependent on the journey time, including access/egress time, waiting time, and in-vehicle time. The value of time is considered in order to get the user costs calculated. The external costs include air pollution, noise pollution, accident, and climate change per passenger-km.

Results: The travel demand has to be forecasted in order to determine the total social costs, using the elasticity approach between the the proposed HSR and Maglev lines in terms of their number of trips and the generalised journey times. In addition, the generalised journey time is based on the in-vehicle time and service interval penalty. The Maglev system is operated at the capacity limit and the change in service is therefore forecasted to increase the Maglev demand by 24.6 % (3.25 million passengers). In terms of the total infrastructure costs, the infrastructure construction and maintenance costs are included and computed to be about € 835.4 million per year, using the capital recovery factor (0.06) based on 35 years of operation and a 5 % social discount rate. The acquiring, operating, and maintaining train's unit cost is included in the calculation of rolling stock to achieve results of € 22.4 million, € 22.5 million, and € 40.9 million, respectively. In terms of the user costs, the access/egress time is computed as of 33 minutes, using the car, while the in-vehicle travel time and waiting time are resulted of 61.8 minutes and 7.8 minutes, respectively. The external environmental costs are based on accidents, and climate changes of € 8.87 million per year and € 8.13 million per year, respectively. However, the total social costs of Maglev line are computed as € 1.18 billion for 16.45 million passengers per year. This gives an average social cost of € 71.9 per passenger. The comparable figures for High-Speed Rail (HSR) are € 1.10 billion for 13.21 million passengers per year, giving an average social cost of € 83 per passenger.

Conclusion: In conclusion, the Riyadh-Dammam Maglev system introduces a new intercity system into Saudi Arabia and brings new competition in the intercity transit market as a part of the future transport developments in the country. The average social cost for HSR is around 16 % higher than Maglev – but that is more proven technology.

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Keywords: Magnetic Levitation, High-Speed Rail, Operator Cost, User Cost, External Cost

INTRODUCTION

Maglev is defined as a system in which the vehicle runs levitated by using electromagnetic forces between coils on the ground and superconducting magnets on board the vehicle [1]. The Maglev technology is also a form of transportation that uses electromagnetic force to suspend the guides and propels vehicles. The term of Maglev refers to both of vehicles and the railway system, while the meaning of levitation refers to a technology that uses Maglev to push vehicles with magnets instead of wheels [2, 3]. The Maglev can also be defined as an innovative technology, using magnetic field to make a gap between the guideway and vehicle. The vehicles of Maglev have no wheels, transmission and axles, and use non-contact magnetic levitation, guidance and propulsion systems. Moreover, these vehicles move along magnetic fields, which are established between the vehicle and its guideway [4].

In this case, the vehicle levitation will be kept at a constant distance of 10 mm from its guideway by an electronic control system. Maglev trains move more smoothly and quietly with less friction than wheeled mass transit systems whilst there is only a small percentage needed for the power of levitation of the overall energy consumption and most of the energy consumed goes to overcome air resistance [2]. The Maglev works after the electromagnets that are located on the underside of the train pull it up to the ferromagnetic stators (current) on the track and levitate the train, while the magnets on the side keep the train from moving from side to side. In order to keep the train one cm from the track, the computer changes the amount of current [3]. In term of transferring of energy to the vehicle, contactless transfer (e.g. linear generator, inductive power transfer, transformer action, and gas turbine generator) is considered for high-speed Maglev whilst the catenary is the chosen technology for low speed Maglev with a DC voltage of 1500 VDC. In this case, the linear generator is used at high-speed Maglev that created by flux harmonics induced in the wires which are inserted in each motor pole [5].

OVERVIEW OF MAGNETIC LEVITATION

A. Main Principles of Maglev Trains

Maglev train floats on a magnetic field and it is propelled by Linear Induction Motor (LIM) or Linear Synchronous Motor (LSM) [3]. With Maglev technology, the magnets are used to levitate a vehicle a short distance away from a guideway

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and create both lift and thrust. However, there are three different principles of Maglev as shown in Fig. 1 that are necessary to be considered, including levitation, propulsion, lateral guidance. These three principles are magnetic forces used in most current design [2]. The levitation of the train is mainly dependent on the train's speed, as its coils are connected under the guideway through facing each other and constituting a loop.

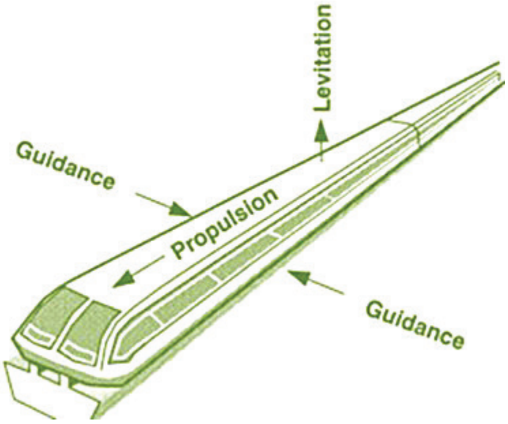

Fig. 1. The basic principles of magnetic levitation [6]

In this case, there are two main types of Maglev trains based on the technique used for levitation technologies. First, the electromagnetic suspension (EMS) as shown in Fig. 2 is based on using the magnetic attraction force between electromagnets and guideway [7]. However, the magnets of the vehicles wrap around the iron guide ways and get it lifted by the attractive upward forces. Furthermore, the resulting attractive electromagnetic forces are usually independent of the speed, as there could be lift forces at a zero speed at the end of the vehicle. In this case, the EMS requires a small gap of magnetic air of ≤ 25 mm [5]. The speed usually becomes higher and maintaining control is difficult because of the small air gaps used in the EMS. There are two types of levitation technologies in EMS that either the levitation and guideway can be integrated as in the Japanese HSST system, and the Korean UTM system, or separated such as the German Transrapid system. In terms of the rating of electric power supply, the separated type is larger than the integrated one, as it is difficult in integrated types to control guidance and levitation simultaneously because of the increasing interference for high-speed operation between levitation and guidance that is caused by speed increases [7]. On the other hand, the number of electromagnets and controllers is reduced for low-speed operation and low cost, while the difference of reluctance automatically generates the guiding force. In the integrated type, the rating of electric power supply is smaller than that in the separated type [7]. The EMS technology is defined

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as classical and that includes the German Transrapid system, the Chinese CMS system, the Japanese HSST system, and the Korean UTM system [5, 8]. In the EMS system, a magnetic circuit is excited by a current-carrying coil, consisting of a ferromagnetic rail fixed to the track and an iron core in the vehicle [9].

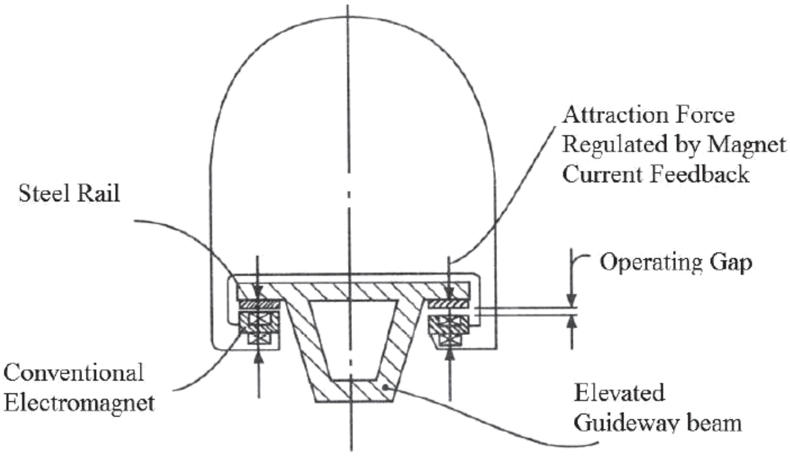

Fig. 2. Electromagnetic Suspensions [9]

Second, there is the electrodynamic suspension (EDS) that has been developed by Japanese engineers as shown in Fig. 3 and used the same polarity of magnets to levitate the trains by repulsive force from the induced currents located in the conductive guide ways and keep the two objective apart [5, 7]. Moreover, the repulsive forces are originally due to the temporal variation of a magnetic field in a conductor that are exerted by both rail and train [3, 5]. Moreover, the repulsive force is in the track is either created by conducting strips in the track or an induced magnetic field in wires [3]. However, the EDS technology is very reliable for the load variation and so stable magnetically, which needs enough speed to obtain induced currents for levitation [7]. In the EDS technology, the magnetic air gap is considered to be large (≤ 80 mm) and there is no repulsive damping forces at zero speed. The actual technology same as the Japan JR-Maglev (MLX) is based on superconductivity in order to match large air gap, as the system requires bogie at low speed (≤ 100 km/h) [5]. Into the vehicle of the EDS system, a current carrying coil is built and the flux produced by the current flowing in the on-board coil induces currents either in conducting aluminium sheet or in passive coils located in the guideway [9].

The main difference between EMS and EDS Maglev trains is that the EMS uses standard electromagnets and when a power supply is present, the coils only conduct electricity. On the other hand, the EDS Maglev train uses super-cooled coils as a kind of superconducting electromagnets to conduct electricity even after

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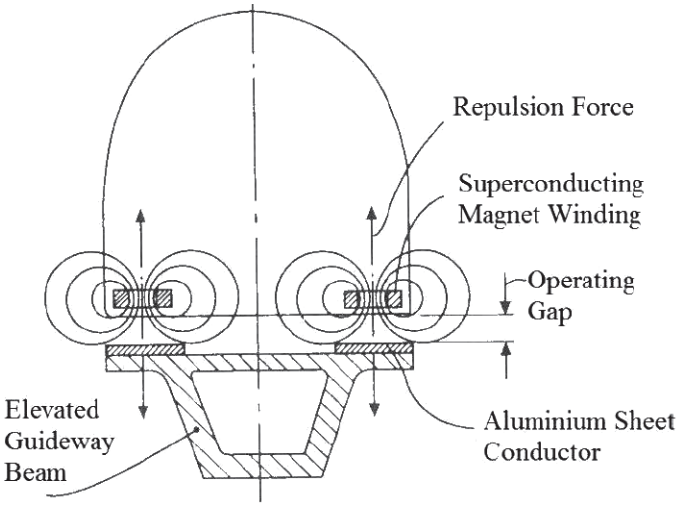

Fig. 3. Electrodynamic Suspensions [9]

the power supply has been turned off [10]. However, this system can increase the speed of the train, but it is not strong enough to move the train vehicle from a stationary position all the way around the track. In order to control the air gap between the track and the train, the EDS system compared with the EMS system enables a larger suspension gap of up to 10 mm and it is inherently stable during the operation. On the other hand, the EMS system requires constant control to levitate at a standstill, as it is an inherently unstable system [8]. In this case, some of the characteristics of EMS and EDS systems are presented in Table 1.

Table 1. Characteristics of EMS and EDS systems [9]

Characteristic	**EMS**	**EDS**
Type of Mode	Attraction Mode	Repulsive Mode
Magnets	Iron cored electromagnets	Superconducting coils
Guideway	10-15 mm	100-150 mm
Guideway components	Laminated strips	Aluminium strips
Stability	Inherently unstable	Dynamically stable
Feedback control	Necessary to maintain dynamic stability	Necessary
Compatible drive system	Linear Induction Motor	Linear Synchronous Motor
Example	Transrapid	MLX

However, the majority of the Maglev trains are electromagnetic suspension type whilst the guideway for most of them are elevated, U-shaped, and double track, with spans and track gauges of 24.8 m and 2.8 respectively as shown in Table 2.

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Table 2. Guideway structures and suspension systems [4]

Maglev systems	**Shanghai, China**	**HSST, Japan**	**Transrapid, Germany**	**JR, Japan**	**Korea**
Suspension	EMS	EMS	EMS	EDS	EMS
Section	I-shaped	U-shaped	U-shaped	U-shaped	U-shaped
Guideway	Elevated	Elevated	Elevated (at grade)	Elevated (at grade)	Elevated
Track gauge	2.8 m	1.7 m	2.8 m	2.8 m	2.8
Span length (elevated)	24.8 m	30 m	24.8	–	25–30 m
Guideway structure	Double track	Double track	Double track	Double track	Double track

The propulsion system involves two main types. First, linear induction motor (LIM), which use the propulsion systems to analyse its properties of force and power consumption, and travel through deep underground tunnels. The LIM has many advantages over other systems of conventional propulsion such as the ability to climb steep gradients, and excellent acceleration and deceleration. In this case, the control equipment of LIM is installed under the deep underground GTX (Great Train Express) bogie whilst its reaction plate is installed on the rail [11]. Second, the propulsion by a Linear Synchronous Motor (LSM) has the magnetic source within itself whilst its motion is in synchrony with a traveling magnetic field that is produced by either switched currents or AC. However, the levitation-propulsion modules of the LSM are located on each side of the vehicle whilst one of this system's disadvantages, it requires data of the on-board magnets for the exact position to guarantee that the vehicle is matched with the traveling magnetic wave in the guideway produced by the stator winding [12]. In the superconducting Maglev system, the north and south poles of magnetic field is produced by passing current through the propulsion coils located on the ground to propel the vehicle forward by the attractive force of opposite poles. In addition, the repulsive force can also act for the same poles between the superconducting magnets built into the vehicles and the ground coils [13]. The active part of the motor for the low speed Maglev is located inside the vehicle, while it is placed on the infrastructure for the high-speed Maglevs such as Trasrapid and JR-Maglev [5].

The lateral guidance system controls the train's ability to stay on the track and use the system of electromagnets that is located in the undercarriage of the Maglev train to stabilize its movement from the left and right sides of the train track [14]. In this case, the concrete or steel beams supporting by concrete substructure have been used in building the guideway of Maglev line, which can be determine in

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three ways. First, it can be elevated to avoid conflicts with existing infrastructure of other transport modes and ground surface activities. Second, in tunnels in order to direct the guideway under densely populated areas. Finally, at-grade where safety can be maintained and land is available [15]. In the EDS system, the principle of null-flux coils provides the guidance, which is mainly achieved by cross coupling the conducting coil mounted on the guideway and it is also used as the framework of linear synchronous motor for propulsion (9). On the other hand, the guidance in the EMS mode is provided by the magnetic guidance forces that are generated by the interaction of separate sets of electromagnets carried by vehicles and ferromagnetic rails on the sides of the guideway structure [9]. The vehicles can be kept in the centre of the guideway at all times by exerting a repulsive force and attractive force on both of the nearer and further sides respectively, especially when the vehicle moves off centre to either side [13].

B. Magnetic Levitation in Various Countries

Magnetic Levitated systems are seen on the worldwide market that is mainly depending on the mechanical air gap between the track and the train, and speed of the transportation systems [5]. In this case, the super-speed Maglev systems are limited to two Maglev types such as the German and Chinese Transrapid systems, and the Japan MLX system. However, the Maglev vehicles structure is closer to airplane structure than HSR, even if compared to the latest development of Japanese railway and French AGV. None of the Maglev trains has a double deck approach for passengers, which might be considered in the future as a handicap in relation with station length and capacity [5].

1. China

a. Shanghai Maglev Line

In 1999, many Chinese experts believed that would be a great achievement for China to construct a High-Speed Maglev system in Shanghai, as there was no operational Maglev lines worldwide at that time and that would mean the country would be the first in developing and constructing Maglev line [16]. However, the Shanghai Maglev Transportation Development Company (SMTDC) was founded in August 2000 to accomplish the construction and operation of the project, using the German Transrapid for its guideway. The construction of the Shanghai Maglev line started in March 2001, while the demonstration and operation of its opening was in December 2002 to become the first Maglev system in operation. In addition, the commercial operation of the Shanghai Maglev line began in 2004 and it showed to people how possible high speed can be reached with Maglev trains. The length of Shanghai Maglev line is 30 kilometers with trains running every ten minutes from the

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Pudong International Airport (PIA) to the Lujiazui Financial District for operations hours between 6:45 a.m. and 9:40 p.m. [16]. Moreover, this system has three sets of five-section TR-08 trains with an average capacity of 100 passenger per section, as the double track route starts from the station located in the Longyang Road and ends at the station of PIA. As a result, the total cost of the Shanghai Maglev project was €1.3 billion[1] in 2004 prices, as the Transrapid system was the most appropriate Maglev system for China based on the its large population and vast land [16].

Fig. 4. The Shanghai Maglev Train [17]

The Shanghai Maglev system contains four main parts, including the vehicle, the guideway, operation control, and power supply. The vehicles of this system are electromagnetic for elevation and population, and include on-board batteries, levitation control system, and an emergency braking system [16]. Along the path, the guideway directs the trains and spreads the load onto the ground from the train. For the entire Maglev system, the operation control system is needed to operate it whilst the Linear Synchronous Motor is used. However, the LSM is a highly efficient motor and it requires an active guideway, which significantly increasing the system costs [18]. On the other hand, the power supply for the Shanghai Maglev system includes the substations, switch stations, other power supply equipment, and trackside feeder cables [16].

b. Changsha Maglev Line

China operated the Changsha Maglev system on May 2016 that runs from Changsha's south railway station to the local airport for a length of 18.55 km and a maximum speed of 100 km/h. In addition, the travel time for the Changsha Maglev line is about 19 min 30 sec, and it might reduce the amount of traffic in the

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[1] The operating cost is mainly based on the Shanghai Maglev train with a capacity of 444 seats.

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areas along the line [16]. The Changsha Maglev system uses the electromagnetic suspension (EMS) and Linear Induction Motor (LIM) propulsion system, as the Maglev train has three vehicles, including one middle car and two head cars that can run in both directions. In addition, each vehicle consists of 10 electromagnetic modules and 20 suspension points [19]. This line uses Chinese Maglev technology and has only one intermediate station at Langlizhen, consisting a fleet of three-car trains and each 48m-long train has an average capacity up to 363 passengers [20].

Fig. 5. The Changsha Maglev Line [21]

The total cost of the Changsha Maglev project is between € 18.4 million and € 30.7 million, with an average of € 2.5 of a one-way ticket in 2015 prices [22].

2. South Korea

The Korea Institute of Machinery and Materials (KIMM) was given funding in 1989 to start a research and development project for a low-to-medium Maglev system, using EMS system and LIM propulsion. The KIMM and Hyundai Rotem developed this system, as they enhanced their UTM-02 model to attain the nominal air gap of 8 mm. However, the Incheon Airport Maglev line (IAM) had been using as a test project since 2007, while this type of system allows the Maglev to work without noise and vibration, and the need for the wheels [16]. The length of the IAM line is 6.1 km and includes of six stations, with a design speed up to 110 km/h and a maximum speed of 80 km/h. Moreover, the line contains four Maglev trains and each train consists of two carriages to carry up to 230 passengers and the operation hours between 9:00 a.m. and 6:00 p.m. with 15 min intervals. The total cost of the project was about € 280 million, while the construction cost was € 28.8 million per kilometre in 2006 prices. South Korea started passenger operations in

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early 2016 on the IAM line, making the country as the second nation worldwide to launch urban Maglev technology [16].

Fig. 6. The Incheon International Airport Maglev [23]

Now, South Korea has the ability to sell their Maglev technology, as different countries worldwide have expressed their interest in adopt this technology such as Russia, Malaysia, the United States, and Indonesia [16].

3. Japan

a. MLX-JR-Maglev

The JR-Maglev is a Maglev system developed by the Japan Railway Technical Research Institute, while the JR-Maglev MLX01 is one of the latest design of Maglev trains in Japan. In the Yamanashi prefecture, Japan has built a demonstration line as part of the planned new Chuo Maglev Shinkansen line (CMS). The proposed CMS line is connecting Tokyo and Osaka via Nagoya, as the president of JR Central, Masayuki Matsumoto disclosed in 2007 that the service of commercial Maglev would aim to begin in the year 2025 between Tokyo and Nagoya [24].

In 2003, a three-car train of MLX01 achieved a maximum speed of 581 km/h, which was faster than any wheeled trains and compared to the TGV speed record of 574.8 km/h set in 2007, which the Japanese Maglev technically able to reach higher speeds. The Japanese Maglev trains mainly use the modern superconducting magnets to allow for the repulsive type of EDS and a larger air gap [24]. In this case, the Maglev system is expected to run through nine prefectures when the total line goes into operation, and the prefectures include jointly governments group of Tokyo and Osaka to promote the construction of the line. One of the reasons why the Japanese use the EDS system is the wider air gap, especially the magnets of a Transrapid system in the EMS air gap of only one cm could touch the stator in the case of an earthquake. However, the Japanese system has an air gap of about

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Fig. 7. Japanese MLX Maglev Train [25]

10 cm and is self-stable and using a Linear Synchronous Motor (LSM) system for the driving system. In terms of the guideway, the construction costs has estimated of € 30 to € 70 million per kilometer in 2003 prices as shown in Table 3 [24, 26].

Table 3. The projected Chuo Maglev Shinkansen Line [26]

Construction Line	**Chuo Shinkansen**
Section	Tokyo - Osaka
Total Length	438 kilometres
Length of open Section	126 kilometres
System	Superconducting Maglev system
Maximum Operation Speed	505 km/h
Travel Time	67 minutes
Construction Cost (including vehicles)	30 to 70 million euros
Traffic Demand (in 2045) (billion passenger-km)	41.6

b. Linimo Maglev Line

The Japanese Linimo Maglev line was constructed to comply with the World Expos 2005 and run from the Higashiyama Subway line at Fujigaoka to the World Exposition’s satellite grounds at Yakusa. The Aichi Rapid Transit Company (ARTC) operates the Linimo Maglev system, while its vehicles levitate at 8 mm above the guideway and be able to reach a top speed of 100 km/h. Moreover, the length of the Linimo Maglev line is 8.9 km and has nine stations, which transported about 31,000 daily passengers during the World Exposition. After the ending of the Exposition’s event, the number of daily passengers dropped to 12,000 passengers, as the Linimo serves the local community from 5:50 a.m. to 12:05 a.m. every day [16]. This Type of High-Speed Surface Transport (HHST) runs with closely stations on an elevated guideway, as it has 15 min of the end-to-end trip time, and 6 minutes and 10 minutes of headways during the peak and off peak period respectively [27].

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The Linimo Maglev is the first HSST Maglev commercial train in Japan and the second worldwide that is propelled by LIM and used the attractive force of normal conductive magnetics for its levitation. In addition, the vehicle is provided by the guidance and levitation system for the primary suspension, while the air springs and lateral mechanical linkages are used for the secondary suspension [28]. The construction of the Linimo Maglev project costs approximately €471 million and about €311 million for train in 2009 prices, as the line has a minimum operating radius of 75 meters and a maximum gradient of 6 % [29].

Fig. 8. The Linimo Maglev Train [30]

4. United Kingdom

The Birmingham International Maglev shuttle was the first commercial maglev train that opened in 1984, connecting the airport terminal of Birmingham International Airport with the nearby the railway station for a total length of

Fig. 9. The Birmingham International Maglev shuttle [33]

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600 meters [31]. It ran at speed of 25 mph, using LIM for its propulsion and levitated by electromagnets [32].

This system flew at the impressive attitude of 15 mm along its 600 m track and worked for 11 years before it was closed in 1995 due to design and maintenance problems. One of the problems was arisen to a contractor who decided individually that the Maglev vehicle needed to be stronger, which required an extra layer of glass fiber and would make the cost of replacing and maintaining too high. In this case, the electromagnets could not lift the train off the track with the additional weight and that led to build an entirely new vehicle [32].

C. Advantages and disadvantages of Maglev

Speed is one of the advantages of Maglev as it is a floating train and travels extremely fast so that it can reach speeds up to 500 km/h (or 300 mph). Moreover, it has more wide potential for further development, as it overcomes the main obstacles for increasing the speed of HSR, including the existence of mechanical contacts between rail and wheels as well as in the power supply system [34]. In this case, Maglev could match gate-to-gate air travel time on routes of less than 1000 kilometers, as it can accelerate and decelerate up to 1.5 m per second, and reach 300 km/h in around 5 km compared with 30 km for a HSR [35].

It is also less noisy because there are no wheels running along which makes it quieter than normal trains, and it uses 30 % less energy than normal trains. Moreover,

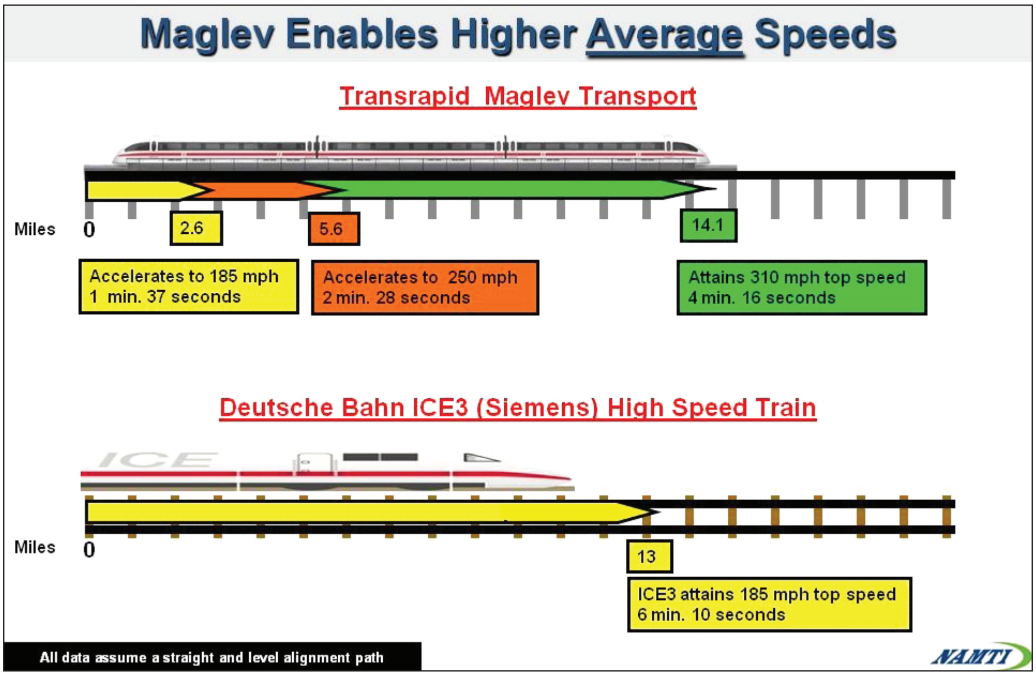

Fig. 10. Maglev Enables Higher Average Speed [36]

Maglev and its track would require very little maintenance and it is recognized as the primary advantage because the train never touches the track and the wear and tear of parts is minimal. In theory, this means the Maglev trains and track would need no maintenance at all, or the cost is very little for maintaining the rail, since checkups and frequent repairs are not required [37, 38]. Moreover, a Maglev can reach to 300 km/h in only 5 km after stations and going uphill and greater gradients will be applicable [37]. The energy consumption of Maglev transport can use the renewable sources such as wind and solar power. It is also weather independent and can carry enormous traffic loads of both goods and people with less cost than the present modes of auto, rail, bus, and air. Moreover, the train and track operating costs are the long-term advantages of a Maglev train as they are much lower along with less wear and tear costs associated with the moving parts of a conventional train [39]. Since, there is no contact with the tracks of Maglev trains, they will never be delayed and they are operational during any weather conditions, compared to HSR that can get stuck in severe snowfall [38]. As a result, the developers of Maglev claim that their system can reach higher speeds with lower energy consumption, attract more passenger, lower life cycle costs, and produce less vibration and noise than other transport modes, including HSR [40].

On the other hand, there are several disadvantages of Maglev trains. First, the Maglev guide paths are more costly than conventional steel railways, as the Maglev guideways are not matched with the infrastructure of existing rail and a new set of tracks is needed to build for the Maglev system from scratch. Second, the unsuitability with existing infrastructure. For example, the Maglev trains would not be able to achieve whatever the high-speed trains can do of going for a fast run on the high-speed line and come off it for the rest of the journey. In this case, it is very difficult to construct Maglev lines commercially workable unless there are two very large destinations being connected, as the high-speed rail can serve other nearby cities beside the two main cities by running on normal railways that branch off the HSR line. Another disadvantage of Maglev train's design is the weight of the large electromagnets in many EDS and EMS designers. From technical view, Maglev has enormous switching difficulties, in order to direct a vehicle from one track to another perfectly. In terms of energy consumption, larger train cars of Maglev are difficult to levitate and that require more energy and making the system less efficient [37].

BACKGROUND OF THE CASE STUDY

The Kingdom of Saudi Arabia (KSA) is located in the continent of Asia as shown in Fig. 11, in the Middle East region, with an estimated size of 2.21 million square kilometres, of which about 95 % is dominated by desert. KSA shares its borders with Kuwait, Jordan, and Iraq to the north, Oman and Yemen to the south, United Arab Emirates, Qatar, Bahrain, and the Persian Gulf to the east, and the Red Sea to the west [41]. The discovery of oil changed the kingdom from a pre-industrial country to a modern industrial country and has made it as one of the rich developing countries and its wealth comes from the oil revenue. In Saudi Arabia, the demographic surveys are one of the most important sources of data, which is necessary for development planning in the social and economic fields, at the national and domestic levels. The population of Saudi Arabia increased by 16.54 % (4.5 million people) from 27.2 million people in 2010 to 31.7 million people in 2016, with an average annual increase of 2.52 % [42].

Fig. 11. Map of Saudi Arabia [43]

Saudi Arabia is among the 25 largest economies in the world in terms of GDP (billions of $) in 2016 that can be described as modest compared with the United Kingdom in its experience in the railway industry [44]. The conventional train for the Riyadh-Dammam corridor was opened for public service in 1981 and managed by the Saudi Railway Organization (SRO). It traverses the desert dunes via Al Hofuf and Abqaiq, covering 449 km with a journey time of 4 hours and 30 minutes.

The track gauge is 1,600mm and the line is equipped with the European Train Control System (ETCS) Level 1, the first implementation of this technology in the Arab world. The SRO increased the frequency between Riyadh and Dammam starting from September 2018, to 82 trips per week, 88 trips between Dammam and

Hofuf, and 68 between Riyadh and Hofuf; a total of 238 trips per week compared to 35 trips in each direction per week [45]. Saudi Arabia has an ambition of making a bigger railway network, as there are railway projects coming into life in the eastern and western regions of the country. The upcoming projects include the Harmain High Speed Rail (partly operating) connecting Mecca and Medina via Jeddah and Rabigh; North-South Rail (partly operating) linking Riyadh with Qurayyat via Majmah, Qassim, Hail, and Al-Jouf; and the Landbridge rail (planned) between Riyadh and Jeddah, and Dammam with Jubail [46].

This case study of Riyadh-Dammam line, Saudi Arabia has modal comparisons of total travel time, total travel costs (fares), and service frequency. The conventional rail service took about 4 hours and 15 minutes, travelling via two intermediate stations, Abqaiq and Hofuf as shown in Fig. 12 within a distance of 454 km and different travel fares for different classes. On the other hand, the approximately 412 km corridor is travelled also by plane in only one hour, with extra time required for check-in, boarding, and baggage collection.

Fig. 12. Riyadh-Dammam corridor, using different transport modes

METHODOLOGY

A. Spreadsheet Cost Model

The methodology of this paper is to provide an estimate of the total social costs of a new Maglev line worldwide and apply it in the case study of Saudi Arabia for the Riyadh and Dammam corridor, using a Spreadsheet Cost Model that is based on Microsoft Excel. However, the estimated total social costs are based on the total annual volume of passengers assumed and included three main categories.

First, the operating costs that include infrastructure construction and maintenance costs, and the acquisition, operation and maintenance of rolling stock. With regard to the acquisition, the price of the Maglev trains is determined by their technical specifications, including the capacity and the unit cost of acquiring trains. On the other hand, costs of labour, energy consumed to run the trains, and the number of trains operated on a specific line are determined with respect to the operating costs. In the case of maintaining rolling stock, the costs are related to the fleet size, labour, materials and spare part, train usage (related to the total distance covered by each train every year). Second, user costs that are mainly dependant on door-to-door travel costs, including access, waiting, in-vehicle and egress time, and excluding money costs. Finally, external social costs include air pollution, accidents, noise and climate change.

The operator cost is mainly based on the infrastructure construction cost of Maglev line that can be calculated into two parts. First, the infrastructure construction cost is mainly dependent on the proportion of the construction costs spent on planning and the length of the Maglev line, as multiplying it by the capital recovery factor is necessary. In this model, the capital recovery factor is used to convert from present cost to an annual cost as shown in equation 1 [47].

$$A = P[\frac{i(1+i)^n}{(1+i)^n - 1}] \tag{1}$$

However, the capital recovery factor is used in the infrastructure construction cost to convert it to the annual cost as shown in equation 2.

Infrastructure construction cost

$$(IC_C) = L[c_c(1+\rho)] \times [\frac{i(1+i)^n}{(1+i)^n - 1}] \tag{2}$$

where:

IC_C = The infrastructure construction costs of Maglev line (€/kilometre)

L = The length of a given Maglev line (kilometres)

c_c = The unit construction cost of a given Maglev line (€/kilometre)

ρ = The proportion of the construction costs spent on planning (percentage)

P = The present value of costs of the Maglev line (€)

A = The annual value costs (€/year)

Second, the infrastructure maintenance cost is already in an annual unit and it can be calculated as shown in equation 3.

Infrastructure maintenance cost

$$(IM_c) = L \text{ x } c_m \tag{3}$$

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where:

IM_c = The infrastructure maintenance costs of Maglev line (€/year).

$\boldsymbol{c_m}$ = The unit cost of regular maintenance of a given Maglev line (€/kilometre)

The rolling stock costs are considered for the different three categories: acquisition, operation and maintenance of the trains needed to run the services of the corridor. The acquisition cost of rolling stock is determined by main factors related to its technical specification, including the capacity (number of seats), the delivery and payment conditions, the contractual relationship between the rail operator and the manufacturer, in terms of price. In this case, some of the rail operators have their rolling stock designed internally, while other preferred contracting out. However, the capacity of Maglev is represented by the maximum number of trains needed during a specified period of time, which can be handled on the particular line, and the size of Maglev rolling stock operating (seats). The forecasting travel demand is needed in order to estimate the total social costs of proposed Maglev line worldwide. However, the regression model has been applied on determining the travel demand for the proposed HSR line between Riyadh and Dammam, two large cities in Saudi Arabia within a length of 412 kilometres. In this case, the travel demand of Maglev line can be forecasted by using the elasticity approach between the proposed HSR and Maglev lines in terms of their number of trips and the generalised journey times as shown in equation 4.

$$\text{Forecast change } (\mathrm{F_c}) = \frac{\mathrm{T_M}}{\mathrm{T_{HSR}}} = \left(\frac{\mathrm{GJT_M}}{\mathrm{GJT_{HSR}}}\right)^E \tag{4}$$

where:

$\mathbf{T_M}$ = The number of trips by Maglev (trains)

$\mathbf{T_{HSR}}$ = The number of trips by HSR (trains)

$\mathbf{GJT_M}$ = The generalised journey time by Maglev system (minutes)

$\mathbf{GJT_{HSR}}$ = The generalised journey time by HSR system (minutes)

$\boldsymbol{E}$ = The elasticity of generalised journey time

In this case, the generalised journey time is based on the in-vehicle time and service interval penalty that can be calculated as shown in equation 5 and 6:

$$\mathrm{GJT} = \mathrm{IVT} + \text{Service Interval penalty} \tag{5}$$

$$\mathrm{GJT} = \frac{\text{Distance}}{\text{Speed}} + \frac{60}{\text{Service frequency}} \tag{6}$$

However, the frequency is mainly dependent on the total number of daily services per direction, which is obtained from the projected demand and the

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effective occupation capacity of train, which can be calculated by multiplying the train capacity by the average load factor per service frequency on the line during a time as shown in equation 7.

$$F_t = \frac{Q_t}{O_d \times Q_e} \tag{7}$$

where:

$\mathbf{F_t}$ = The transport service frequency on the corridor during time (train/hour)

$\mathbf{t}$ = The t-th year starting from the beginning of the period of (n) years of operation of a given Maglev line (year)

$\mathbf{Q_t}$ = The projections of the (one-way) daily demand (passenger)

$\mathbf{O_d}$ = Operating daily hours (hour)

$\mathbf{Q_e}$ = The effective occupation (seats)

In addition, the effective occupation is calculated as shown in equation 8.

$$Q_e = l \times c \tag{8}$$

where:

$\mathbf{l}$ = Load factor (percentage)

$\mathbf{c}$ = Train capacity (seats)

The number of passenger per day and direction in year can also be calculated as shown in equation 9.

$$Q_t = \frac{ID_a}{N \times days / year} \tag{9}$$

where:

$\mathbf{Q_t}$ = The projections of the (one-way) daily demand (passenger)

$\mathbf{ID_a}$ = Initial annual demand (passengers/year)

$\mathbf{N}$ = Number of direction

The number of train per day-direction (train) can be determined as shown in equation 10.

$$NS = \frac{Q_t}{Q_e} \tag{10}$$

In this case, the number of trains per day is needed in order to calculate the service frequency per hour as shown in equation 11.

$$F_t = \frac{Q_t}{O_d \times Q_e} \tag{11}$$

The total number of trains needed for the Maglev corridor can be calculated as shown in equation 12, which is mainly related to the number of passengers and frequency.

$$RS_t = (1.5) \times \tau \frac{Q_t}{O_d \times Q_e} \tag{12}$$

where:

RS_t = The number of trains acquired in the t-th year of the observed period (train)

τ = The operation cycle time of the Maglev train (hour/train)

v = Average commercial speed (kilometres/hour)

The operation cycle time of the Maglev train is necessary to be determined using 40 seconds for both start and end journey in order to calculate the number of acquired trains as shown in equation 13.

$$\tau = 2 \times (L / v) + (20 + 20) / 60\text{min} \tag{13}$$

In order to purchase new rolling stock, the process of contracting, designing, building, delivering and testing them usually takes several years, especially if the demand projections are known in advance. However, the cost of Maglev rolling stock usually depends on the number of seats, as it is better to choose a train with large capacity seats in order to reduce the maintenance cost as well as the number of departures. In this case, acquisition cost can be calculated by multiplying the number of trains every year by their average capacity and the unit cost per seat, as shown in equation 14.

$$RSC_A = [RS_t \times c_A \times \overline{q}] \times [\frac{i(1+i)^n}{(1+i)^n - 1}] \tag{14}$$

where:

RSC_A = The acquisition costs of rolling stock (€/year)

c_A = The unit cost of acquiring a rolling stock (€/seat)

$\overline{q}$ = The average seat capacity of a train (seat)

The operating costs of rolling stock mainly depend on the expected traffic level, as labour cost on board the train, energy cost, and sales and administration costs are included. In the equation 15, a number of trains per day and operation hours is considered in the operating cost of rolling stock to meet ridership, while the value 2 representing the number of directions.

$$RSC_O = 2 \times c_O \times F_t \times \overline{q} \times L \tag{15}$$

where:

RSC_O = The operating costs of rolling stock (€/year)

c_O = Average unit cost of operating a rolling stock (€/seat-km)

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The maintenance costs of the Maglev rolling stock are related to the number of trains, their utilization during a given period and the average unit maintenance cost and can be calculated as shown in equation 16.

$$RSC_M = c_M \times u_t \times \overline{q} \times RS_t \tag{16}$$

where:

RSC_M = The maintenance cost of rolling stock (€/year)

u_t = The average utilization of a train in the t-th year of the observed period (km/seat)

C_M = The unit cost of maintaining rolling stock (€/seat-km)

The user cost is mainly based on time related to the journey is taken into account in order to calculate the total social cost. In transportation studies, the user travel time is broken into several components including walking (access/egress) time, waiting time, and in-vehicle time. In Fig. 13, the access time is the total time spent to reach a Maglev station (A) from the origin point, while the egress time is the total time spent from Maglev station (B) to the destination point. On the other hand, the line-haul represents the in-vehicle time and the waiting time spent in station.

Fig. 13. The structure of the total journey time

The access time as normally the time taken from one's door (e.g. home, work, etc.) to the first transportation infrastructure used in the city (A). It is the time spent by the traveller in getting to a metro, bus station, rail station, airport terminal, etc. For travelling by Maglev, the access time could mean the time spent on a bus, metro, or in the car (e.g. private or taxi) [48].

On the other hand, the egress time is defined as the time taken from the first transportation infrastructure used in the city (B) to the final destination. In this case, the main difference between access and egress time is mostly for travel to/from Maglev station and the egress time was found as 32% higher than access time, which may due to greater familiarity at one's origin with the transportation options rather than at the destination for a long distance trip. Access/egress times can also include other access options beside car such as any transit service (e.g. bus, metro, etc.) and by walking. In some studies, the coefficient for walking time has valued as almost twice that of in-vehicle travel time [48].

In this case, the access/egress travel time per passenger is mainly dependent on the average access/egress distance and average travel speed that can be calculated as shown in equation 17.

$$T_{AE} = \frac{D_{AE}}{V_{AE}} \tag{17}$$

where:

$\mathbf{T_{AE}}$ = The average access/egress time per passenger (hour)

$\mathbf{D_{AE}}$ = The average access/egress distance to/from the Maglev station (kilometre)

V_{AE} = Average travel speed (kilometre/hour)

The total access/egress time needs to be on an annual basis and can be calculated by multiplying the average access/egress time per passenger by the total number of passenger per year. In this case, the average access/egress time has to be multiplied by a factor of 2 in order to account for both the access/egress to and from the Maglev station as shown in equation 18.

$$TT_{AE} = 2 \text{ x } Q_t \text{ x } T_{AE} \tag{18}$$

where:

$\mathbf{TT_{AE}}$ **=** The total annual passenger access/egress time (hours)

$\mathbf{Q_t}$ = Passenger demand in the time period t per direction (passenger / year)

The waiting time is determined as one of the most important factors of the total user cost for all public transport modes, as it starts counting when a passenger arrives at the rail station when the passenger boards the train. However, the waiting time is a very critical element for judging the service of the passenger, as the passenger of railway usually faces different types of waiting due to different reasons. For example, the waiting time might be longer if trains running behind schedule and most trains meet with some delay during rush hours. The value of time is almost expressed relative to the driving time in the case of waiting for trains, which it means passengers rate one minute of waiting as equivalent to 2.5 minutes of driving [49]. The average waiting time can be estimated as a fraction of the headway, while the average of headway is calculated by dividing the length of the operating day by the service frequency (50). As a result, the passenger waiting time can be calculated by taking the half of the headway as shown in equation 19.

$$T_{WT} = \frac{1}{2} \times \text{Headway} \tag{19}$$

where:

$\mathbf{T_{WT}}$ = The average waiting time per passenger (hour)

$\mathbf{F_t}$ = The transport service frequency on the corridor during time (train/hour)

In order to obtain the total user cost of the Maglev passengers on an annual basis, the total annual waiting time is calculated by using the annual demand, as shown in equation 20.

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$$\mathrm{TT_{WT}} = \mathrm{Q} \times \mathrm{T_{WT}} \tag{20}$$

where:

$\mathbf{TT_{WT}}$ = The total annual passenger waiting time (hours)

$\boldsymbol{Q}$ = Passenger demand in the time period t (passenger / year)

The in-vehicle time for Maglev is mainly dependent on the average length of the journey, the average operating speed $(\mathbf{v})$. As there are no intermediate stops along the Maglev, the dwell time is excluded in this section, and the average in-vehicle time can be simply calculated by dividing the average journey length by the average speed as shown in equation 21.

$$\mathrm{T_{IV}} = \frac{\mathrm{L}}{\mathrm{v}} \tag{21}$$

where:

$\mathbf{T_{IV}}$ = The average in-vehicle time per passenger (hour)

$\boldsymbol{L}$ = The average length of a given Maglev line (kilometres)

$\mathbf{v}$ = The average operating speed (km/h)

The annual HSR passenger's in-vehicle time can be calculated by using the average passenger journey length, the average operating speed of Maglev, and the annual passenger demand as shown in equation 22.

$$\mathrm{TT_{IV}} = \mathrm{Q_t} \times \mathrm{T_{IV}} \tag{22}$$

where:

. = The total annual passenger in-vehicle time (hours)

$\boldsymbol{Q_t}$ = Passenger demand in the time period t per direction (passenger / year)

The Value of Time (VOT) is important for management and evaluation of transport investment decisions and considered as one of the key inputs related to travel demand models. It also is defined as the price that travellers as willing to pay in order to acquire an additional unit of time, while the value of time savings is the willingness to pay for time between two different transportation alternatives [51]. The VOT is also counted as one of the most important outcomes that can be extracted from the experiment of stated preference, which concerning for the willingness to pay, in order to save time. The value of time for personal journeys varies usually by circumstances, which ranges between 20 % and 90 % of the gross wage rate within an average of around 50 % and generally much higher for business travel. In this case, the value of walking time (access/egress) and waiting time is 1.6 to 2.0 times the in-vehicle time [52].

The values of time for private trips were estimated of €10/h, €12/h and €6.5/h for rail, car and coach respectively, based on Stated Choice data using for the Swedish national forecasting model in price level 2008 [53]. For business journeys, the value of time is dependent on the cost saving, which considers the benefit of time saving in terms of cost savings to the employer (54). However, the value of time savings may be more valuable on longer distance trips, as it is noted and recommended in the Netherlands and Sweden. On the other hand, lower value of time can be applied to time savings on shorter distance trips, as the value of time for employee in time savings requires an appropriate valuation of leisure time (54). Small, Verhoef (52) defined the value of time as a fraction of the wage rate. For example, the value of time is equal to 1.33 of the wage rate per hour for work trips and business in terms of cost to employer whilst it values of one-third for shorter commuting (less than one hour round trips) and two-third for longer trips that is applied (52, 55). In this case, the average hourly wage rate is calculated as shown in equation 23.

$$\mathrm{AWR} = \frac{\text{average monthly wage rate}}{\text{average working hour per month}} \tag{23}$$

The total user cost in the previous sections are mainly related to generalised time, including walking time, waiting time and in-vehicle time, while it is converted to generalised cost by multiplying by the value of time, as shown in equation 24.

$$\mathrm{TUC} = [(\mathrm{w_{AE}} \times \mathrm{TT_{AE}}) + (\mathrm{w_{wt}} \times \mathrm{TT_{WT}}) + \mathrm{TT_{IV}}] \times \mathrm{VOT} \tag{24}$$

where:

TUC = The annual total user costs (€/year)

$\mathbf{W_{AE}}$ = The factor to represent the weighting perception of access/egress time vs. in-vehicle time (number)

$\mathbf{W_{wt}}$ = The factor to represent the weighting perception of waiting time vs. in-vehicle time (number)

VOT = Value of in-vehicle time for Maglev (€/hour)

The external environmental cost is defined as the costs generated by transport users but paid by surroundings, the environment, people, and the society as a whole, including air pollution, noise, accidents and climate change (56). The external costs associated with society and the transport user cannot be considered without policy intervention, as they usually refer to the difference between internal costs and social costs. In this case, the internal costs directly accepted by the transport user, such as energy cost of the vehicle, transport fares and taxes, wear and tear, and own time costs [57]. However, the external costs of transport modes strongly depend on parameters such as location, peak/off-peak time, and vehicle characteristics [57]. Moreover, the cost calculation of external environment uses the vehicle-kilometre and the unit environmental cost used in previous environmental cost studies, which can measure the external costs due to the operating performance of the transport technology [58]. As a result, the external environmental costs can be calculated by multiplying the sum of unit costs of air pollution, noise pollution, accident, and climate change by the total passengers per kilometres as shown in equation 25.

$$\text{Total External Costs}\left(\text{TEC}\right)=\left(\text{UAP}_c+\text{UNP}_c+\text{UA}_c+\text{UCC}_c\right)\ \text{x PKM} \quad (25)$$

where:

$\mathbf{UAP_c}$= Unit air pollution costs per passenger-kilometre (€/pkm)

$\mathbf{UNP_c}$= Unit noise pollution costs per passenger-kilometre (€/pkm)

$\mathbf{UA_c}$ = Unit accident costs per passenger-kilometre (€/pkm)

$\mathbf{UCC_c}$= Unit climate change costs per passenger-kilometre (€/pkm)

PKM= Total Passenger per kilometres

The unit cost for the external costs per vehicle – kilometre needs to be identified by using the Purchasing Power Parity (PPP) rate, which is defined as an economic theory that is constructed to consider the values of currency rates and the PPP of different countries.

A. Results

In order to forecast the initial annual demand for the first year of operating the Maglev system for the proposed line, the generalised journey time for both Maglev and HSR need to be determined with using the elasticity of – 0.9 for non-London ticket holders over 20 miles [59]. The Transrapid Maglev system is chosen, as its technical stability and reliability have shown at both of the Shanghai, China and in Emsland Test Track Line, Germany. However, the service frequency of HSR was based on an initial demand of 18 089 per day and calculated as of 3.21 trains an hour, which could be rounded to 4 trains per hour to give a headway of 18.7 minutes. This would result in an equivalent time penalty of around 16.2 minutes, using the interpolation based on Table 4.

Table 4. Service Interval Penalties (in minutes) [Source: (59)]

Service Interval	Equivalent Time Penalty
5	5
10	10
15	**14**
20	17
30	21
0	23
60	27

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In order to introduce operational flexibility and in light of the above, it is assumed that four trains an hour are operated and this gives an equivalent time penalty of 14 minutes as shown in Table 5. It is also used to determine the generalised journey time of Maglev system for an operating speed of 400 km/h, as there is no interchange related to the Riyadh-Dammam proposed corridor of a length of 412 km.

Table 5. Forecasting Service Frequency Changes

Category	**HSR**		**Maglev**	
	Service	**GJT Units**	**Service**	**GJT Units**
In-vehicle travel Time	83 min	83 min	62 min	62 min
Service frequency	4 per hour	14	4 per hour	14
Interchange	0	0	0	0
Total GJT		97 min		76 min

As a result of the elasticity based on generalised journey time, the forecast change in demand is shown in equation 26.

$$F_c = [\frac{76}{97}]^{-.09} = 1.246 = \frac{4}{3.21} = 1.246 \tag{26}$$

This means that Maglev would be operated at the capacity limit and the change in service is therefore forecast to increase the Maglev demand by 24.6 % (3.25 million passengers) and resulted of 16 453 694 passengers. With increasing the number of travel demand of Maglev line, the number of daily service is reached to 69 trains per day-direction compared to 58 trains for HSR, as the service frequency increased from 3.21 for HSR to 3.81 trains per hour for Maglev system and rounded up to be 4 trains per hour for both as shown in Table 5 previously. The construction cost of Shanghai Maglev line is about €30 million per kilometre. However, the Transrapid Maglev high-speed train commonly consists a passenger capacity of 438 seats per train, using a standard seating layout. On the other hand, the annual unit cost of maintaining the proposed Maglev line is € 12 300 per track-km, as one of the reasons of this lower cost is no frictions. In terms of purchasing, operating, and maintaining the Maglev trainset, the average unit costs are € 49 233/seat, € 9.74/seat-km, and € 0.011/seat-km respectively as shown in Table 6.

With the unit costs of infrastructure, construction and maintenance shown previously in Table 6 and using the capital recovery factor (0.06) based on 35 years of operation and a 5 % social discount rate, the total infrastructure costs (including maintenance) is computed to be about € 835.4 million per year. The number of

Table 6. Estimated Costs in 2009 year's prices [Source: (60-64)]

Category	Cost Value	Unit
The unit construction cost of a given Maglev line	30 000 000	€/km
The unit cost of regular maintenance of a given Maglev line	12 300	€/year
The unit cost of acquiring a Transrapid	49 233	€/seat
Average unit cost of operating a Maglev trainset[1]	9.74	€/seat-km
Average unit cost of maintaining a Maglev trainset	0.011	€/seat-km

acquired Maglev trains is about 17 trains, as it is mainly based on the operation cycle time, value of risk of failing (1.5) and the service frequency of four trains per hour. In addition, the acquiring, operating, and maintaining train's unit cost is included in the calculation of rolling stock to achieve results of € 22.4 million, € 22.5 million, and € 40.9 million respectively. In terms of the user costs, the access/egress time, waiting time, and in-vehicle time are mainly based on the value of time related to business and commuting trips. In this case, the distances and travel speed to/from Maglev stations based on speed limit in cities are calculated within average of 24.9 km and 45 km/h respectively in order to obtain the access/egress time of 33 minutes, using the car. Moreover, the in-vehicle travel time is based on the length of 412 km and 400 km/h and resulted of 61.8 minutes whilst the waiting time is based on half of headway and resulted of 7.8 minutes. In terms of external environmental costs, it is assumed that there is no air pollution or noise pollution caused by the Maglev train. In addition, the same external costs of HSR will be used for Maglev system in terms of unit accident that is resulted of € 1.31/1 000 passenger-kilometres due to similar number of incidents, as the total passenger-kilometre is 6.77 billion. In this case, the average accident cost of Maglev line is € 8.87 million per year. Maglev also uses more energy per kilometre than HSR and hence will have a greater climate change impact of € 8.13 million per year, compared to HSR of € 4.38 million per year.

CONCLUSION

In the conclusion, there is a number of key findings have resulted and shown as follows:

- The Riyadh-Dammam Maglev technology system introduces a new intercity system into Saudi Arabia and brings new competition in the intercity transit market as a part of the future transport developments in the country.
- The forecast demand of the proposed Maglev system for Riyadh-Dammam corridor is increased by 24.6 % and resulted of 16.45 million passengers in the

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first year of operation compared to the HSR forecast demand of 13.21 million passengers.

- The total operator cost resulted from constructing and maintaining of infrastructure, and the acquiring, operating and maintaining of the rolling stocks is € 921.24 million per year, which is higher than HSR of € 867.78 million per year.
- The total user cost resulted from access/egress times, waiting time, and in-vehicle time is € 245.50 million per year, which is higher than HSR of € 216.77 million per year.
- The total external environmental cost of Maglev only resulted from accident, and climate change is € 17 million per year whilst the air and noise pollution are excluded in this paper due to insufficient data. In this case, the total external costs of accident and climate change for Maglev is higher than HSR that is resulted of € 11.5 million per year.
- The total social costs of Maglev line is €1.18 billion based on forecasting demand of 16.45 million passengers, given an average social cost of €71.9 per passenger.
- On the other hand, the total social costs of HSR line is € 1.10 billion based on forecasting demand of 13.21 million passengers, given an average social cost of € 83 per passenger.
- In other words, the average social costs for HSR is around 16 % higher than Maglev- but that is more proven technology.

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HIGH-SPEED VACUUM AIR VEHICLE

Background: There are a number of problems in the prior art, those are topics of research inputs like ranges of the drag force generated by the vehicle, lift force at high vehicle motion velocities for compensation of the vehicle weight, aerodynamic aspects of operation of the vehicle.

Aim: Stream-wise stability of vehicle motion and levitation as well as braking of the vehicles and supersonic speed are not achieved in any mode of transportation. But this present invention relates to high-speed magnetic levitation transportation using compressed air chamber in the transportation vehicle.

Materials and methods: The present invention relates more particularly related to high-speed vehicle levitated in a vacuum tunnel by using electromagnetic levitation, as this vehicle will move from one place to another in a vacuum environment and this vehicle will levitate above track with the help of electromagnets.

Results: The important thing is its motion, which is possible due to reaction force of high pressure air, coming out from compressed air chamber present in vehicle.

Conclusion: It can give us the acceleration as per load requirement and it can achieve supersonic speed in few seconds.

Keywords: Magnetic levitation, Electromagnets, Magnetic track, High-speed vacuum vehicle, Air train, Transportation, Compressed air train.

INTRODUCTION

Along with the increase of population and expansion in living zones, automobiles and air services cannot afford mass transit anymore. Accordingly, demands for innovative means of public transportation have increased. In order to appropriately serve the public, such a new generation transportation system must meet certain requirements such as speed, reliability, and safety. In addition, it should be convenient, environmentally friendly, low-maintenance, compact, light-weight, unattained, and suited to mass transportation. We human waste our precious life time for travelling from one place to another. So we need a high-speed transport system which will save our time. Yes, we have such kinds of transport systems like airways, which can reach up to one thousand km/h and we also have present magnetic levitation technology which cannot reach sonic speed. Here

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with this invention, transportation method will be safe, quick, efficient and, most significantly, high-speed. And it can change the future scenario of transport method. We also have Hyperloop system, but that idea limits the speed of transportation as it consists of the air compressor in front.

DETAILED DESCRIPTION

Here Fig. 1 shows exemplary representation of mechanism for formation of compressed air and vacuum creation mechanism according to one of the embodiment of the invention. Here we have used vacuum tunnel as shown in Fig. 1, inside this tunnel vacuum will be created with the help of vacuum pump. This pump will suck air from tunnel. Next, we will compress air with the help of air compressor.

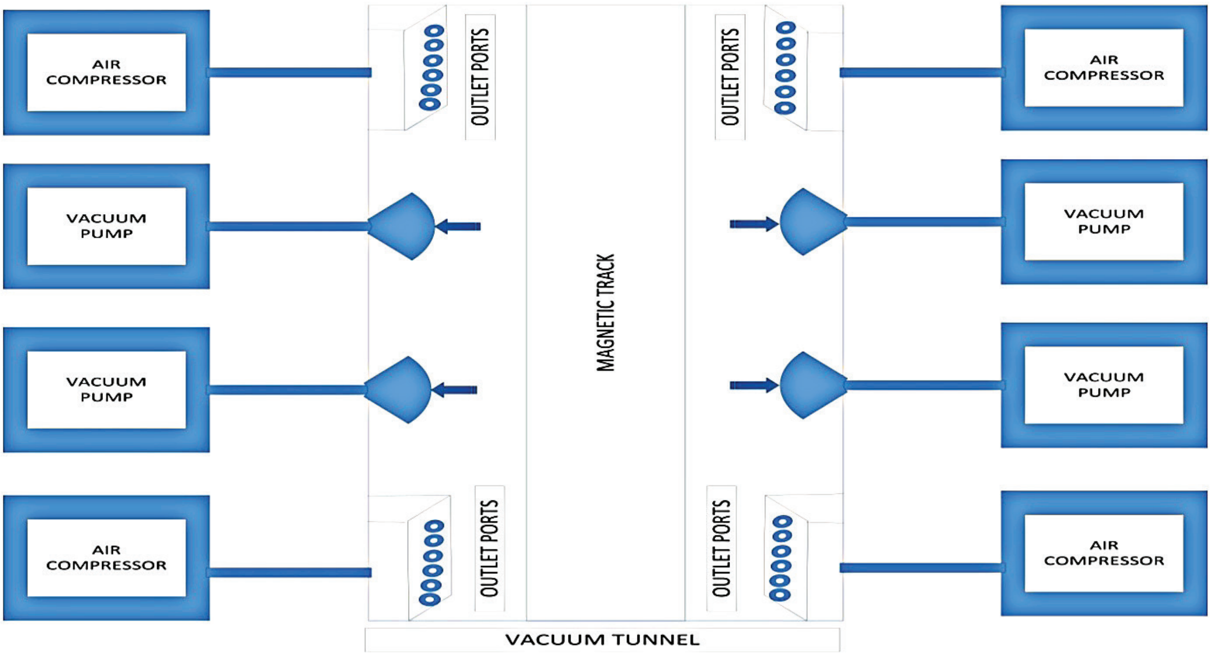

Fig. 1. Setup for vehicle motion on magnetic track

Here outlet ports as shown in Fig. 1 are the part of the air compressor to transfer compressed air to vehicle. And in Fig. 1 magnetic track is the track on which vehicle will levitate and move.

Fig. 2 shows detailed view of vacuum tunnel. Now we come to a vehicle which will levitate above the track and move with a very high speed.

In Fig. 3, we have explained the basic components of a vehicle, such as battery area, crew cabin and passengers' room. And here we have also used high reusable silicon insulation (HRSI) tiles as it does not allow heat transfer in passenger

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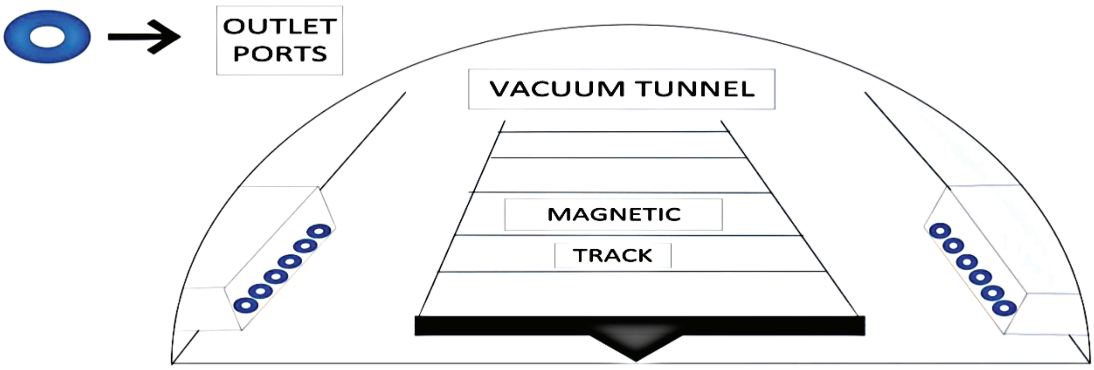

Fig. 2. Inside View of tunnel

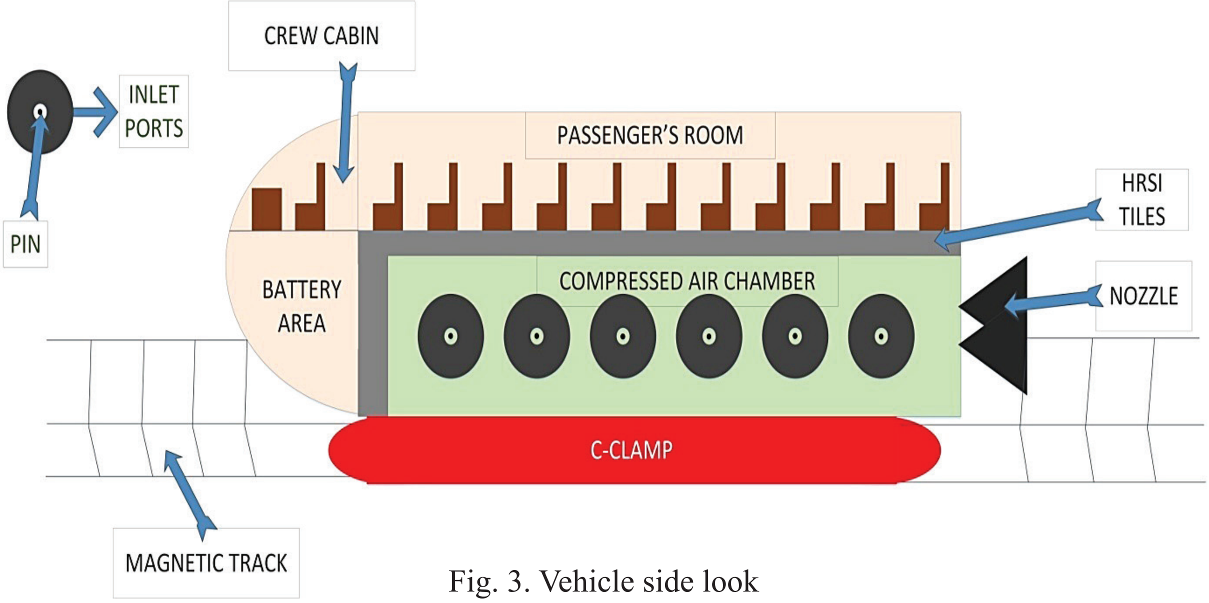

Fig. 3. Vehicle side look

sitting area for safe journey. Here C-clamp is the base of the vehicle, which makes vehicle levitate above the magnetic track. Here compressed air chamber is the closed chamber in which compressed air is filled. Here inlet ports are shown which are used to fill compressed air chamber with compressed air.

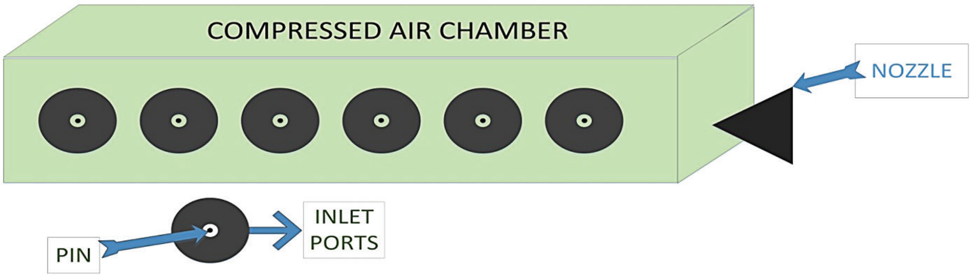

Fig. 4. Look of compressed air chamber

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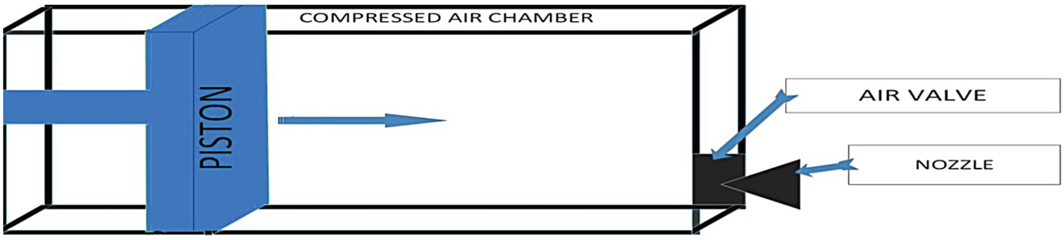

Fig. 4(a). Forward motion of piston

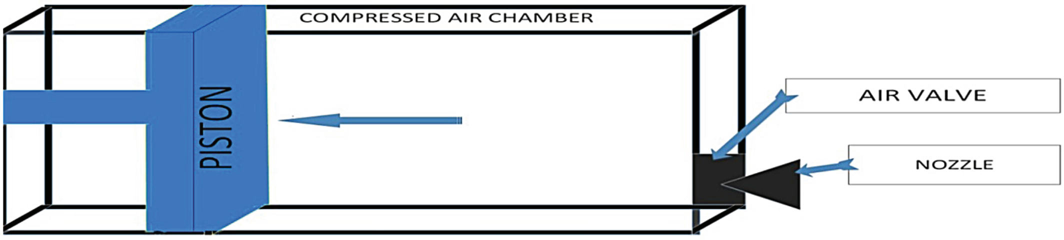

Fig. 4(b). Backward motion of piston

Inside view of compressed air chamber look is shown below in Fig. 4(a) and Fig. 4(b).

Now we will discuss the mechanism of motion of vehicle in forward direction. The outlet ports, as shown in Fig. 1, will transfer compressed air to inlet ports, as shown in Fig. 3, of the vehicle. As the pin, as shown in Fig. 3, gets pushed inside, the entry of compressed air into compressed air chamber starts. This charging of compressed air chamber is done when the vehicle is in rest. See Fig. 4 (2D view of chamber), as compressed air gets inside compressed air chamber, it accumulates until the chamber is full, and then we will release compressed air with the help of valve as shown in Fig. 4(a) and Fig. 4(b), and to enhance effect we have used nozzle which will allow releasing compressed air. As we need a constant pressure throughout exit of the compressed air, we have used a piston. Fig. 4(a) and Fig. 4(b) represent forward and backward motion of the piston. And when compressed air comes out from compressed air chamber via nozzle in control of valve with constant pressure, it provides a huge reaction force which will accelerate our vehicle in opposite direction of the air coming out. Once it gets a required velocity, the valves will be shut off by the command from crew cabin, as shown in Fig. 3, and hence the vehicle will maintain its velocity as it will be in the environment of negligible friction. Compressed air chamber should be made in such a way that it can tolerate high temperature and high pressure.

Here a clear look of nozzle is shown below in Fig. 4(c) and a proper explanation of all the parameters shown in Fig. 4(c) is given as well.

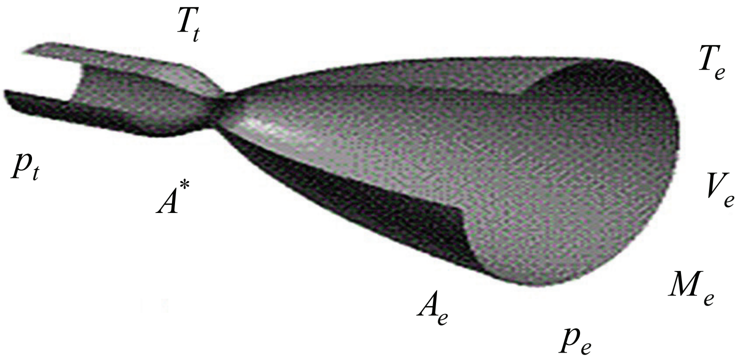

Fig. 4(c). Close view of nozzle

Parameters are explained below as follows:

T_t – Total temperature of compressed gas inside compressed air chamber;
T_e – Temperature of gas on its way out from nozzle;
A^* – Area of cross-section of choked flow region;
A_e – Area of cross-section of exit;
p_t – Total pressure of compressed gas inside compressed air chamber;
p_e – Pressure of gas on its way out from nozzle;
p_o – Free stream pressure;
M_e – Exit Mach number;
V_e – Exit velocity.

Fig. 5 shows an exemplary representation of magnetic levitation and braking system according to the present invention. In Fig. 5, the C-clamp has two L-shaped electromagnets named as C-clamp levitation electromagnets, attached to its base side. And the other L-shaped electromagnet, named track levitation electromagnet, attached to the upper side of the magnetic track. The four track

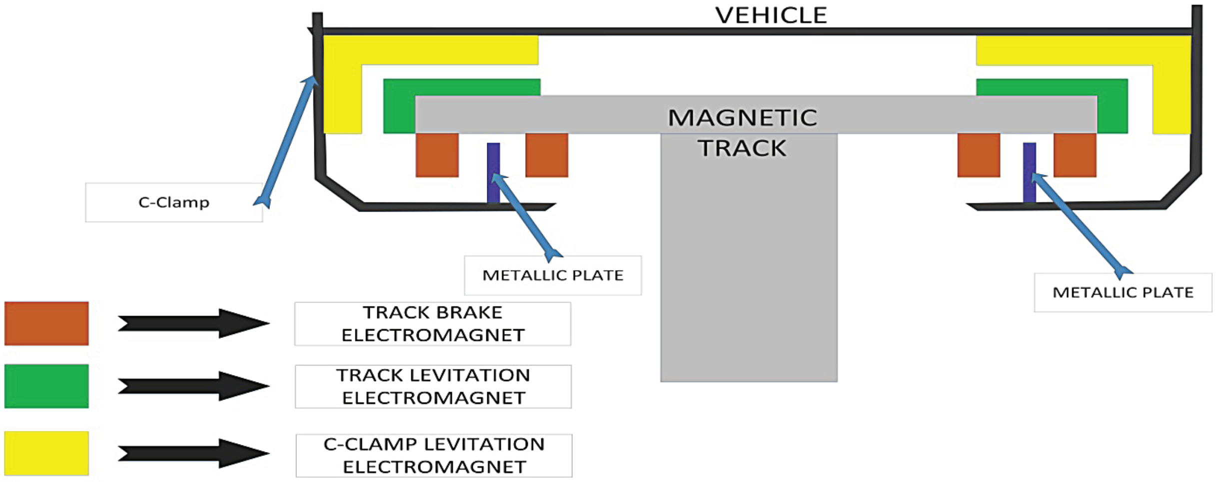

Fig. 5. C-Clamp Analysis

brake electromagnets are placed at the lower side of the magnetic track. The C-clamp has a metal sheet. The metal sheet is attached to the C-clamp in such a manner that it is placed between at least two track brake electromagnets at the lower side of the magnetic track. This metal sheet is covered with a diamagnetic cover. This cover can be covered and uncovered by control of the vehicle by its control system in crew cabin, as shown in Fig. 3, during braking and levitation of vehicle.

These C-clamp levitation electromagnets of C-clamp and track brake electromagnets of the magnetic track both generate similar poles and develop repulsive force during the normal position of the vehicle. The repulsive force is developed in such a manner that the vehicle loses its contact with the magnetic track and it starts levitating above the magnetic track. If the weight of the vehicle changes then intensity of these electromagnets also changes accordingly automatically.

As Fig. 5 shows, during braking of the vehicle, the four track brake electromagnets of the magnetic track and metal sheets attached to C-clamp come in action. The metal sheets are kept in a diamagnetic envelope until braking is not required. When the vehicle transportation control system, present in crew cabin, as shown in Fig. 3, provides signal to retard motion of the vehicle, then the vehicle transportation control system creates north-south poles in each pair of electromagnets. It is done in such a way that metal sheet lies in between north and south poles of two track brake electromagnets of the magnetic track. As metal sheets are attached to the vehicle body, hence it cuts the magnetic field created by track brake electromagnets of the magnetic track. During this activity, the flux is changed in metal sheets which create eddy currents as described by Faraday’s law of induction. By Lenz’s law, the circulating currents in the metal sheet create their own magnetic field in the sheet. Thus metal sheet will experience a drag force from the track brake electromagnets of the magnetic track. So it opposes its motion. The kinetic energy of the moving vehicle is dissipated as heat is generated by the current flowing through the electrical resistance of the metal sheet. By the reason of this activity, the metal sheet should bear a high temperature.

The whole magnetic track is divided into segments, and when the vehicle comes near segment electromagnets get active accordingly. Now as our vehicle will face negligible air friction and negligible friction from track, so it is highly efficient. Here in this vehicle we will coat its body with diamagnetic substance so that magnetic field does not affect inside the vehicle.

Fig. 6 is responsible for reversing the direction of vehicle clockwise or counterclockwise with rotating disk.

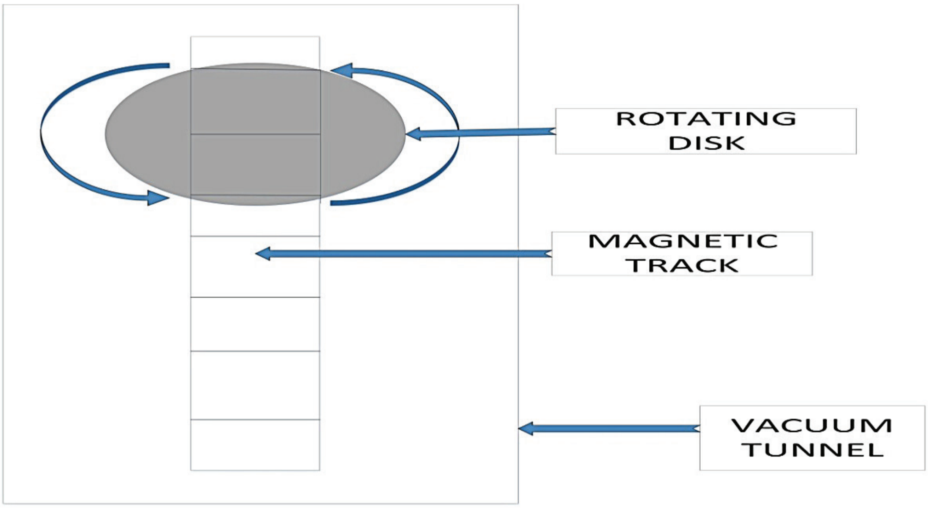

Fig. 6. Changing direction of vehicle

ANALYSIS

Analysis of detailed description
T_t – Total temperature of compressed gas inside compressed air chamber;
T_e – Temperature of gas on its way out from nozzle;
A^* – Area of cross-section of choked flow region;
A_e – Area of cross-section of exit;
p_t – Total pressure of compressed gas inside compressed air chamber;
p_e – Pressure of gas on its way out from nozzle;
p_o – Free stream pressure;
M_e – Exit Mach number;
V_e – Exit velocity;
m^* – Mass flow rate;
R – Gas constant;
γ – Specific heat ratio.
Mass flow rate:

$$m^* = \frac{A^* p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{1}$$

Area ratio:

$$\frac{A_e}{A^*} = \left(\frac{\gamma+1}{2} \right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1 + \frac{\gamma-1}{2} M_e{}^2 \right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M_e} \tag{2}$$

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Temperature ratio:

$$\frac{T_e}{T_t}=\left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{-1} \tag{3}$$

Pressure ratio:

$$\frac{p_e}{p_t}=\left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{-\frac{\gamma}{\gamma-1}} \tag{4}$$

Exit velocity:

$$V_e=M_e\sqrt{\gamma R T_e} \tag{5}$$

Force applied on the vehicle:

$$F=m\times V_e+(p_e-p_o)A_e \tag{6}$$

Now taking values of following parameter.

- $R = 287$ JKg^{-1}K^{-1} (For air)
- $M_e = 2.5$
- $\gamma = 1.4$ (For air)
- 1 atm = 101 325 N/m^2
- Now from ideal gas law $p_t V = mRT_t$

Pressure of the air inside compressed air chamber

- Taking p_t = 2.5 atm = 2.5×101325 N/m^2 = 253312.5 N/m^2
- Taking $V = L\times B\times H$

L = Length of compressed air chamber (17 m)
B = Width of compressed air chamber (2 m)
H = Height of compressed air chamber (4 m)
So, V = 136 m^2

- Now m = mass of air; [1 mol = 0.02897 Kg (For air)]
- Mole of air in chamber = $\dfrac{136}{22.4\times 10^{-3}}$
- Mass of air (m) = no. of moles × 0.02897 Kg = $\dfrac{136}{22.4\times 10^{-3}}\times 0.02897 =$ 175.8892857 Kg

Now $T_t = \dfrac{p_t V}{mR}$

Temperature of air inside Compressed air chamber

$$=\frac{253312.5\times 136}{175.8892857\times 287} = 682.45535\ \text{K}$$

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- Now taking equation 3, the temperature of air at Exit from vehicle:
- $T_e = T_t\left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{-1} = 682.45535(1+0.2(2.5)^2)^{-1} = 303.313488$ K.
- Now taking equation 5, the exit Velocity:
- $V_e = M_e\sqrt{\gamma RT_e} = 2.5\sqrt{1.4\times 287\times 303.313488} = 872.7519674$ m/sec
- Now taking equation 2, the radius = 2 *m* of choked flow Region
- $A^* = \pi r^2 = 4\pi = 12.56637$ m^2
- Exit area of cross-section of Nozzle:
- $A_e = A^*\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}\frac{\left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M_e} =$

$$=12.56637\left(\frac{1.4+1}{2}\right)^{-\frac{1.4+1}{2(1.4-1)}}\frac{\left(1+\frac{1.4-1}{2}(2.5)^2\right)^{\frac{1.4+1}{2(1.4-1)}}}{2.5} =$$

$$= 12.56637\times 2.6367187 = 33.133985 \text{ m}^2$$

- Now taking equation 1, here it is Mass Flow Rate:

$$m^* = \frac{A^* p_t}{\sqrt{T_t}}\sqrt{\frac{\gamma}{R}}\left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}}$$

$$m^* = \frac{12.56637\times 2.5\times 101325}{\sqrt{682.45535}}\sqrt{\frac{1.4}{287}}\left(\frac{1.4+1}{2}\right)^{-\frac{1.4+1}{2(1.4-1)}} = 4925.02765914 \text{ Kg/sec}$$

Now taking equation 4, the pressure of the air on its way out from the vehicle

$$p_e = p_t\left(1+\frac{\gamma-1}{2}M_e{}^2\right)^{-\frac{\gamma}{\gamma-1}}$$

$$p_e = 2.5\left(1+\frac{1.4-1}{2}(2.5)^2\right)^{-\frac{1.4}{1.4-1}} =$$

$$=2.5 \times 0.058527663466 = 0.146319158665 \text{ atm}$$

- Now taking equation 6.

$$F = m^{*} V_e + (p_e - p_o) A_e \text{ [Here } p_o = 0$$

$$= (4925.02765914 \times 872.7519614) + (0.14631915 \times 101325) \times 33.133985$$

$$= 4298327.549464 + 491237.433022$$

$$= 4789564.982486 \text{ N} = 4789.564982486 \text{ kN}$$

This amount of force will act on the vehicle if we provide parameter as stated above. As per our requirement related to high or low force on vehicle we can adjust parameter accordingly.

- For levitation of the vehicle.

$$F = \frac{AB^2}{2\mu_0}$$

A – Total area of magnet under bogie.
B – Magnetic flux density.
μ_0 – Permeability of the vacuum.
As shown in Fig. 7, when $F > mg$ then levitation of vehicle occurs.

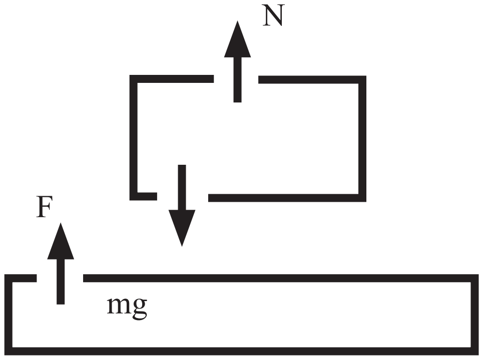

Fig. 7. Levitation

CONCLUSION

We were able to successfully demonstrate the feasibility of high-speed vacuum air vehicle. As with this technology vehicle will face negligible friction due to which force will only act to accelerate the vehicle. Dimension of the track and vehicle should be accurate in order to get better results. As per our requirement

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that is high or low force on the vehicle we can adjust parameter accordingly. With this technology we can achieve very high speed with safety ensured, and this technology can be utilized for not only train application but also for aircraft launching systems and spacecraft launching systems.

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THE MODEL FOR STUDY OF INFLUENCE OF MAGNETIC FIELDS ON BIOLOGICAL OBJECTS (WITHIN THE RUSSIAN MAGLEV PROJECT)

Aim: methodological aspects of the study influenced static magnetic fields (SMF) used in the technology “Russian Maglev” on the organisms are improved.

Materials and methods: organotypic culture of animal tissue fragments was studied under the influence of an experimental setup generating a homogeneous SMF with characteristics similar the “Russian Maglev”.

Results: area index (AI) for liver, heart, prostate, renal tissue of explants in the control and under the action of SMF did not differ. SMF significantly reduces AI of explants the immune tissue of the spleen and the cerebral cortex.

Conclusions: 1. the influence of SMF has a negative impact on the proliferative activity in organotypic culture of the cerebral cortex and spleen; 2. the biological model for examination of influence SMF on organisms intended for approbation of means of physical protection is presented.

Keywords**:** static magnetic field, organotypic tissue culture, “Russian Maglev”, biological model, cell proliferation, means of physical protection.

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МОДЕЛЬ ДЛЯ ИЗУЧЕНИЯ ДЕЙСТВИЯ МАГНИТНЫХ ПОЛЕЙ НА БИОЛОГИЧЕСКИЕ ОБЪЕКТЫ (В РАМКАХ ПРОЕКТА «РОССИЙСКИЙ МАГЛЕВ»)

Цель: совершенствование методологической базы для изучения влияния на организм человека постоянных магнитных полей (ПМП), используемых в технологии «Российский Маглев».

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Материалы и методы: органотипическое культивирование фрагментов тканей животных, на которые воздействовали экспериментальной установкой, генерирующей равномерное ПМП с характеристиками аналогичными отечественной разработке «Российский Маглев».

Результаты: значения индекса площади (ИП) для эксплантатов тканей печени, сердца, простаты, почки в контроле и под действием ПМП не различались. ПМП значительно снижало ИП эксплантатов иммунной ткани селезенки и коры головного мозга.

Выводы:

1. воздействие ПМП отрицательно действует на пролиферативную активность органотипической культуры ткани коры головного мозга и селезенки;

2. представлена биологическая модель оценки влияния ПМП на организмы, предназначенная для апробации средств физической защиты.

Ключевые слова: постоянное магнитное поле, органотипическая культура тканей, «Российский маглев», биологическая модель, пролиферация клеток, средства защиты.

INTRODUCTION

The main attention in the modern scientific literature is paid to operational developments and problems of magnetic levitation transport systems, the energy analysis of the technologies used and developed, the search for optimal technical solutions for safety. The project “Russian Maglev” (RM) is used the system of static magnetic levitation in contrast to electrodynamic (Maglev) and electromagnetic (Transrapid) levitation systems [1]. In this regard, the issues of medical safety of the “RM” have special features, although in the overall structure of the problems they are given insufficient attention. Therefore, it is important to establish the locations and levels of field characteristics around the “RM”, to conduct model medical and biological studies to establish the impact of non-radiation physical fields on various systems of the body, to develop evidence-based proposals and recommendations for the establishment of regulatory norms in this type of transport, to protect against harmful fields effects on passengers and service personnel.

The aim of this work was to study the characteristics of the main sources of static magnetic fields (SMF) used in the technology of “RM” and affecting the human body. The studies in organotypic tissue culture for the differentiated assessment of SMF impact on the organs of different mammalian systems were carried out. It should be noted that the cell and tissue cultures in biological research is increased common as relatively simple model systems is possible to successfully solve many problems the impact of various environmental factors on different organisms.

Organotypic tissue culture is the most appropriate and convenient method for a rapid quantitative assessment by level influenced physical factors on biological

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objects [2, 3]. This is due to the change in the number of cells is the result of stimulation or inhibition of cell proliferation, and this change serves as a criterion for the primary integral assessment of biological activity, including SMF. The advantage of this method is that the explants retain the same hierarchical subordination of the cellular composition of the tissue, as well as in the whole body. In the organotypic culture the strictly dosed effect directly on the cells by SMF is possible to have. This excludes the effect of the whole body nervous, hormonal and other effects. The classical test system is the organotypic culture of various rat tissues.

MATERIALS AND METHODS

The effect of SMF on cell proliferation processes in organotypic tissue culture from different organs mature male rats of the Wistar population ("collection of laboratory mammals of different taxonomic affiliation", Pavlov Institute of Physiology RAS supported by the program of bio-resource collections Federal Agency of Science Organizations from Russia) were studied. The 747 explants of the tissues of the cerebral cortex (n=182), spleen (n=184), kidney (n=95), heart (n=96), prostate (n=92) and liver (n=98) were studied in the experiments. Explants were placed in Petri dishes with a nutrient medium pH=7.2 containing saline (0.9 %) 50 ml, MEM 50 ml, fetal bovine serum 10 ml, glucose (5 %) 1 ml, gentamicin (4 %) 0.5 ml. Petri Dishes with explants were placed in a CO_2 incubator at 36.8°C [4, 5].

The experimental Petri Dishes were exposed in a special camera with a magnetizing device consisting two magnetic poles-concentrators (flat ferrite magnets Y22H ($Fe_2O_3 \cdot SrCO_3$)) with an anisotropic magnetic structure and a platform of non-magnetic material for placing Petri dish with explants of the studied tissue. Concentrators formed a spot of homogeneous SMF, the structure and the amount of induction was controlled by the device Teslameter f 4354/1 at the location studied tissue. The magnitude of the intensity and control of the uniformity of the field in the spot was established and regulated by the mutual location of the concentrators. The measurement error did not exceed 2.5 %. Petri dishes with samples of different tissues was placed between the working ends face of the magnet poles where were within three days at a constant temperature and atmosphere with a homogeneous SMF (~200 mT). The value of the SMF induction value in the experiment corresponds to the SMF intensity in the railway car of the project "RM" at one meter from the floor [6].

The data of two experiments for each tissue included the control Petri dishes without SMF exposure and experimental Petri dishes the with SMF were

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obtained. To quantify the impact of SMF on the development of explants used for morphometric method comparing the control and experimental Petri dishes. For this after the explants were visualized using a microtelevision attachment (series 10, MTN-13, Alpha-Telecom), was calculated area index (AI) using PhotoM 1.2 software.

In the cultivation there is migration cells into the growth zone (GZ) from the Central zone (CZ) of the explant estimated by AI calculating by the formula (1) relationships area (S) the explant (S_{GZ+CZ})) to the area of the central zone (S_{CZ}).

$$AI = \frac{S_{GZ+CZ}}{S_{CZ}} \tag{1}$$

Then, the values of AI were averaged separately for the control AI and experimental dishes AI_E. The Average value of AI_C was taken as 100 %, and the difference of average values (ΔAI) expressed in percent by the formula (2), demonstrates the amount and direction of influence on proliferation of cells.

$$\Delta AI = \frac{AI_E - AI_C}{AI_C} \cdot 100\ \% \tag{2}$$

The reliability of the differences of AI explants in the control and experimental dishes after checking for compliance with the normal distribution of the data was evaluated using t criteria for independent samples. Statistically significant differences were taken at the level of p less than 0.05.

RESULTS AND DISCUSSION

According to previously studied and presented the characteristics of the main sources of SMF in the technology “RM” [6], the magnetic induction exposed to the human body increases from < 1 to 300 mT when approaching the source of MF from 0.7 to 0.1 m, respectively. The data obtained are compared with the current Russian normative and technical documents: SanPiN 2.2.4.3359-16 “Sanitary and epidemiological requirements for physical factors in the workplace” (unfortunately, the regulatory standards in the Russian Federation on transport have not yet been developed). According to the literature data, non-specific reaction by the type of General adaptation syndrome were caused in the human body after exposition of SMF. There is possible specific, similar to the meteotropic, reaction, proceeding with a change in vascular tone. There is a belief that the magnetic factor is not the direct cause of the disease, it only provokes it or contributes to the aggravation of

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the existing pathological process. People with meteosensitivity may have functional disorders that affect the quality of life. At the same time, the specific dynamics of physiological parameters in different people may be vary [7].

However, the results of screening studies exposure on different organs by SMF the same intensity in the literature could not be found. In addition, only a number of studies have described the study of the characteristics of SMF having the greatest biological effect. There is the most suitable method organotypic tissue culture for the screening study of the action of biologically active factors [8].

According our experimental data uniform SMF with induction of ~200 mT has different effects on the cells of different mammalian tissues. In the Table 1 presents the average values of AI for the explants organotypic tissues culture: liver, heart, prostate, kidneys and we can conclude that proliferative processes are not changed because the values of AI_E statistically not significant different from AI_C. While SMF depressed cell proliferation of immune spleen tissue and brain cells.

Table. The average values of AI for the explants organotypic tissues culture in control (AI_C) and experiment (AI_E)

	cerebral cortex	**spleen**	**liver**	**renal**	**prostate**	**heart**
AI_C, п.и.	1.6±0.26	1.98±0.62	1.67±0.67	2.11±0.78	1.37±0.2	1.79±0.37
AI_E, п.и.	1.29±0.12	1.6±0.34	1.66±0.3	1.76±0.32	1.36±0.2	1.78±0.19
P-value	0.03	0.03	0.83	0.26	0.85	0.65

There is decreasing AI for explants in the experiment compared to the control statistically significantly (P=0.03) for the tissues of the cerebral cortex (ΔPI = –19.7 %) and spleen (ΔPI = –18.9 %).

Despite the above results impact of SMF on living organisms and cells, the long-term practice of SMF application in medical procedures, for example MRI, allowed to publish the works, confirming the safety of SMF application [19, 20]. Although using relatively strong magnetic fields, such procedures can really be safe for patients due to the short duration of magnetic exposure. For the staff, the chronic action of SMF and other harmful factors, allows to neutralize compliance with Sanitary and epidemiological requirements that are non-specific to neutralize the action of SMF [18]. The presented data do not exclude the remote manifestations of SMF by induction 1T exposure for human health [21, 22], although no such effects have been found in other studies [23].

In according to above, there is important to search protection means to reduce the biological effect of SMF on passengers and service men using the transport

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system "RM". Therefore, in our work we have tried to present the testing model for various neutralization or decrease means of SMF biological effects with the organotypic tissue culture. For this in the 2nd series of experiments, the polypeptides with tissue-specific and stimulating proliferative effect were selected [23, 24] and were introduced into the culture medium for SMF undergone explants. The drug Cortexin® was added to medium of explants the cerebral cortex and Timalin® was added to medium of explants the spleen. These drugs were added at effective concentration 50 nG/ml. Figure 1 shows to decrease statistically not significant the number of AI (ΔAI= –12.3 %) under the action of Cortexin® in explants of the cerebral cortex (thus, the effect of SMF decreased overall by 9 %). The increase of AI statistically not significant was observed in the experimental compared to control the Petry dishes with explants of the spleen undergone combined effect of Thymalin® and SMF (ΔAI =+13.4 %).

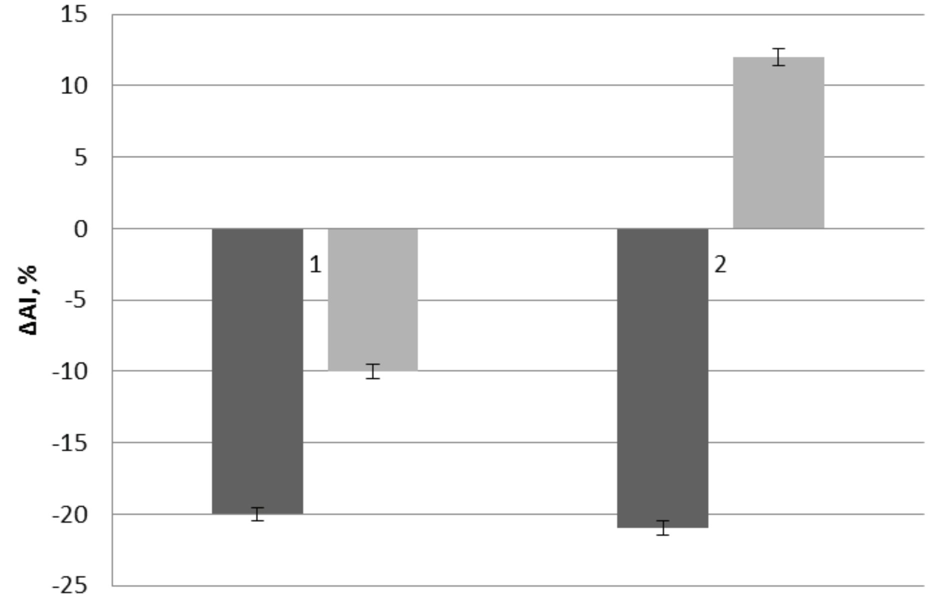

Fig. The SMF influence on the cortex (1) and spleen (2) in isolation (dark bars) and in combination with Cortexin® and Timalin® respectively (light bars)

The data confirm the functional inhibition of proliferative activity explants of spleen and cerebral cortex under the influence of SMF and the normalization proliferative potential under the influence contained growth factors in the used drugs.

Our data have been compared with the other studied data, as the SMF with induction in the range from hundredth to hundreds of mT in the laboratory is created relatively easy. Currently, there is two main areas for scientist's attention of research: the actioned mechanisms of SMF on living organisms are searched and

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the biological effects of weak SMF usually with adverse effects on the body are observed. We will discuss the latter direction in more detail. In a number of studies with MF with similar characteristics were obtained cellular effects. In all studies the inhibition of cell proliferation due to an increase in DNA damage when exposed to SMF induction 970 mT [9] or MF with a frequency of 50 Hz and induction 400 mT [10], stimulation of apoptosis MF with a frequency of 50 Hz and induction of 150 mT [11] and SMF with induction 1T [13], increased transcription of genes in SMF with induction 100 mT [15] and damaging effect on the cell membrane with induction of SMF 100–300 mT [17] were described.

However, simple decrease as the induction level of SMF 10–1 000 times then the maximum permissible level (according to 2.2.4.3359-16 “Sanitary and epidemiological requirements to physical factors in working places”) does not neutralize the negative effects of SMF at the cells. According to the literature, enhancing proliferation due to inhibition of apoptosis in SMF with induction of 0.6 mT [12], decreasing the adhesive ability of white blood cells in SMF with induction of 0.05–10 mT [14], increasing the intracellular concentration of heat shock proteins in MF with a frequency of 50 Hz and induction of 10–140 µT [16] are observed. In this regard, there is our direction of research studying the damaging effects of MF with the value of induction and measured characteristics around the “RM”.

CONCLUSION

It was shown, the people need for protection from MF of “RM” system. On the basis of the research listed in this article, the prospect of using the presented biological model in the development and testing of methods and measures to protect against the adverse effects of MF arising from the operation of the magnetic levitation transport system is created. After substantiation of medical and biological safety at the cellular level of technogenic MF system “RM”, it is possible to conduct monitoring studies on real models [26].

The above data allowed us to draw the following conclusions:

1. At the level of the calculated values of the induction of the static magnetic field of the project “Russian Maglev” there is a negative effect on the proliferative activity of the organotypic tissue culture of the cerebral cortex and spleen.
2. The presented biological model of evaluation of the influence of static magnetic fields in the organotypic tissue culture allows to carry out preliminary testing of physical protection means intended for use in the project “Russian Maglev”.

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NEW TECHNOLOGY FOR MANUFACTURING INDUCTORS OF LINEAR INDUCTION MOTORS FOR MAGNETIC-LEVITATION TRANSPORT

Background: Significant economic growth in many countries of the world can contribute to an increase in the speed of movement of modern and fundamentally new vehicles. This will increase the turnover of goods during the transportation of goods, revive international trade, increase the comfort of passengers and reduce their travel time.

Aim: The solution of this problem is the development and wide application of high-speed magnetic-levitation transport (HSMLT) with linear traction engines. It is promising to use linear induction motors (LIM) for the HSMLT drive, which can have various design versions. Linear induction motors come with a longitudinal, transverse and longitudinal-transverse closure of the magnetic flux. LIM inductors can be installed on both high-speed transport crews and in the HSMLT track structure, as it was done in the People's Republic of China, where express trains on magnetic suspension connect Shanghai with the airport and reliably operate for more than 10 years. The main elements of the inductor of a linear induction motor are a magnetic core (ferromagnetic core) a multiphase (usually three-phase) winding. With the development of high-speed magnetic-levitation transport, the issues of improving the manufacturing technology of various HSMLT devices, including the methods for producing inductors of linear induction motors, will become increasingly relevant. Traditionally, LIM inductors are assembled from pre-manufactured individual parts.

Methods: An integral technology for manufacturing inductors of linear induction motors for high-speed magnetic-levitation transport is proposed and considered by the method of spraying materials onto a substrate through replaceable stencils. The new technology eliminates the alternate manufacture of individual assemblies and parts and their subsequent assembly to obtain a finished product. A method for determining the size of stencils for manufacturing one of the inductor variants of a linear induction motor is proposed as an example.

Conclusion: Integral manufacturing technology is promising for the creation of high-speed magnetic-levitation transport.

Keywords: magnetic-levitation transport, linear induction motor, inductor, materials spraying, replaceable stencils.

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НОВАЯ ТЕХНОЛОГИЯ ИЗГОТОВЛЕНИЯ ИНДУКТОРОВ ЛИНЕЙНЫХ АСИНХРОННЫХ ДВИГАТЕЛЕЙ ДЛЯ МАГНИТНОЛЕВИТАЦИОННОГО ТРАНСПОРТА

Обоснование: Существенному экономическому росту во многих странах мира может способствовать увеличение скорости движения современных и принципиально новых транспортных средств. Это позволит увеличить грузооборот при перевозке товаров, оживит международную торговлю, повысит комфорт пассажиров и сократит их время пребывания в пути.

Цель: Решение этой задачи – развитие и широкое применение высокоскоростного магнитнолевитационного транспорта (ВМЛТ) с линейными тяговыми двигателями. Перспективно использование для привода ВМЛТ линейных асинхронных двигателей (ЛАД), которые могут иметь различные конструктивные исполнения. Линейные асинхронные двигатели бывают с продольным, поперечным и продольно-поперечным замыканием магнитного потока. Индукторы ЛАД могут устанавливаться и на высокоскоростных транспортных экипажах, и в путевой структуре ВМЛТ, как это было сделано в Китайской Народной Республике, где экспрессы на магнитном подвесе связывают г. Шанхай с аэропортом и надежно работают более 10 лет. Основными элементами индуктора линейного асинхронного двигателя являются магнитопровод (ферромагнитный сердечник) и многофазная (как правило, трехфазная) обмотка. С развитием высокоскоростного магнитнолевитационного транспорта все более актуальными будут становиться вопросы совершенствования технологии изготовления различных устройств ВМЛТ, в том числе и методы производства индукторов линейных асинхронных двигателей. Традиционно индукторы ЛАД собираются из заранее изготовленных отдельных деталей.

Методы: Предлагается и рассматривается интегральная технология изготовления индукторов линейных асинхронных двигателей для высокоскоростного магнитно-левитационного транспорта методом напыления материалов на подложку через сменяемые трафареты. Новая технология исключает поочередное изготовление отдельных узлов и деталей и последующую их сборку для получения готового изделия. Предложена в качестве примера методика определения размеров трафаретов для изготовления одного из вариантов индуктора линейного асинхронного двигателя.

Вывод: Интегральная технология изготовления перспективна для создания высокоскоростного магнитнолевитационного транспорта.

Ключевые слова: магнитнолевитационный транспорт, линейный асинхронный двигатель, индуктор, напыление материалов, сменяемые трафареты.

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INTRODUCTION

In the seventies and eighties of the last century, in many countries of the world, including in the Soviet Union, scientists and engineers were engaged in the development of high-speed magnetic-levitation transport. Numerous scientific researches and experimental design developments in the field of magnetic-levitation and linear traction drive of high-speed transport have been carried out, many technical solutions, protected by patents for inventions, have been created, experimental polygons have been constructed for carrying out experiments. These studies for various reasons were either minimized or significantly reduced.

At the beginning of the two thousand years, the development of the world economy required the creation of radically new high-speed vehicles for the organization of freight and passenger transportation. Great interest arose for the high-speed MLT after the successful implementation of the development of scientists and engineers from the FRG in the People's Republic of China. This was the first successfully implemented commercial project: a high-speed magnetic-levitation train provided fast and comfortable travel of air passengers between Shanghai and the airport. All this contributed to the beginning of a new stage in the creation, research and development of high-speed magnetic-levitation transport at a new, higher level. Work has been intensified in the field of MLT and in the Russian Federation, as evidenced by the modern publications of PSTU staff (St. Petersburg), presented in serious publications [1–7]. OJSC «Russian Railways» is interested in new developments [8–11]. Periodically, at the enlarged meetings of the scientific and technical council OJSC «Russian Railways» issues are considered on the development of new modes of transport.

One of the most important elements in high-speed MLT systems is a linear induction motor, that converts electricity directly into the translational movement of the transport crew, therefore, the issues of improving the technology for manufacturing inductors of traction LIM are important and urgent.

AIM

Analysis of literature sources on the technology of electrical machines showed that there is no special literature on the technology of manufacturing linear electric motors. Although in the Russian Federation linear motors are not produced in large series, a number of specialized enterprises organized their production.

The development of high-speed magnetic-levitation transport, as well as flexible production systems, robotics, advanced types of in-plant transport, automation systems and simple (in kinematics) electric drives will facilitate the

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production of an increasing number of electric linear machines. At the same time, the production of linear motors in small series at different plants leads to the fact that everywhere one develops its own technologies based on the traditional methods of manufacturing electric machines, including the sequential manufacture of individual elements of the structure and their subsequent assembly into a finished product, which reduces labor productivity and increases the cost products.

For stamping the inductor plates of a linear motor, special matrices are made. When manufacturing a small batch of linear motors, the magnetic cores are made by milling the grooves for laying the winding.

Windings of inductors of linear electric machines are carried out by traditional technologies, including winding and laying of sections, as well as impregnation and drying.

The assembly of electric machines is the final technological process, in which the nodes and individual parts are combined into a finished product. The energy and operational parameters of the electric machine largely depend on this technological process: efficiency, power factor, reliability and durability.

The inventions in the field of improving the technology of electric machine building are relatively small, if we bear in mind technical solutions that are fundamentally different from traditional ones. A number of inventions are devoted to non-waste technologies for making cores of electric machines, containing twisted yokes and corrugated tooth zones. Many developments on the manufacture of magnetic cores from ferromagnetic powders of cermets-based. This method is also suitable for the production of cores of linear electric machines.

All this indicates that there are practically no new, high technologies in the production of electric machines, including linear ones. We have proposed a new, integral technology for manufacturing inductors of traction linear induction motors.

FUNDAMENTALS OF A NEW TECHNOLOGY FOR MANUFACTURING INDUCTORS LIM

In the production of electrical machines to this day, technologies that make extensive use of manual labor prevail. New technologies for manufacturing inductors of linear induction motors allow to reduce the number of stages of manufacturing the machine and significantly reduce the share of human participation in the technological process, and in some cases – fully automate the production of inductors of linear motors.

The technology is based on the methods known in the art for the manufacture of parts by methods of powder metallurgy and the deposition of materials [12, 13].

This technology can be used to manufacture inductors, chokes, transformers and other electrical devices.

One of the promising technological methods related to high technology is the deposition of materials [12, 13]. This method is increasingly used in various fields of technology. The method of sputtering of materials is used in the production of condenser tapes, for the production of anticorrosion coatings, for the restoration and hardening of worn parts, for the application of case insulation of coils of electrical apparatuses and for the making of slot insulation of some electric machines.

The technology of sputtering materials is divided into three main types:

1. Gas-flame or gas-thermal spraying, which uses the heat, generated by the combustion of a mixture of combustible gas with oxygen. Depending on the state of the sprayed material, it can be of three types: wire, rod and powder.

2. Gas-plasma spraying, based on the use of heat released during the combustion of electric dust. In this method, the gas is heated to the temperature at which the dissociation process takes place. The temperature of this process is determined by the type of gas and pressure.

3. Vacuum deposition is widely used in space technology and electronics. With this type of spraying, electron guns are used.

The new technology excludes the preliminary manufacture of individual elements of the inductor structure and their subsequent assembly into the finished product [14, 15]. The inductor is proposed to be manufactured by alternately spraying a ferromagnetic material (the core of a magnetic core), an insulating material (applying slot, interturn and intercoil insulation) and an electrically conductive material (winding) to the substrate. As a result, immediately obtained product – inductor LIM, ready for use on MLT. In other words, the new technology, combining, summing up the individual stages of inductor production of a linear induction motor, is integral.

The process for manufacturing the inductor core of a linear induction motor (LIM) is shown in Fig. 1. The core can be completely sprayed with a gas-flame or gas-plasma method, or a tooth layer is applied to the pre-prepared yoke (laminated or solid) through the stencil.

A yoke 2 and a tooth layer 3 are deposited on the substrate 1, prepared for deposition. For the spraying of the teeth, a stencil 4, having apertures 5, through which ferromagnetic material 6 is sprayed through the desired places with the help of a burner 7 which is movable in the direction of the arrows A and B, is used. The stencil 4 is fixed relative to the substrate and yoke by means of guides 8 passing through the stencil holes 9. In Fig. 1 for reasons of clarity, the stencil is shown elevated above the core, in fact, the stencil lies on the core, closing the slots of the inductor with its jumpers.

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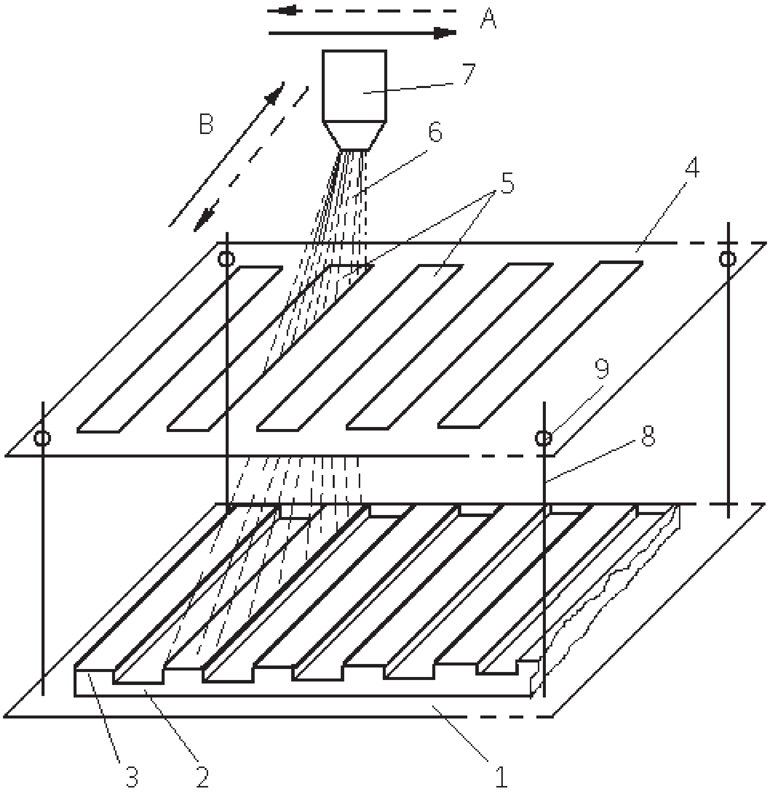

Fig. 1. The process of manufacturing the core of the inductor LIM

In Fig. 2, a sprayed solid yoke 2 is shown on the substrate 1. This is the simplest method for manufacturing a magnetic inductor system of a linear motor, but this manufacturing method will result in significant core losses during machine operation. The structure of the core, similar to the laminated from individual electrical steel plates, can be obtained using another stencil, with which the core is not sprayed on top, as shown in Fig. 1, but on the side. In this case, the ferromagnetic and insulating material is applied alternately in layers, and as a result, a core 1 is obtained (Fig. 3), in which the ferromagnetic zones 2 are separated by layers of insulation 3, in which can be used as alumina. We would like to draw your attention to the fact that the thickness of the film of the insulating material can be equal to the fractions of the micron, and consequently, the core filling factor of steel can reach 99% and even higher values, which is completely unattainable with the use of traditional technologies for manufacturing magnetic core of electric machines.

One of the stages of the new technology is the production of the first coil layer. For this purpose, use the stencil (mask) shown in Fig. 4. The stencil 1 comprises apertures 2 that repeat the shape of the first coil winding layer, through which a layer of electrically conductive material, usually copper or aluminum, is sprayed. The jumpers, in the form of flags, cover the teeth of the core and do not allow the coil to become short-circuited. To increase the electrical conductivity of

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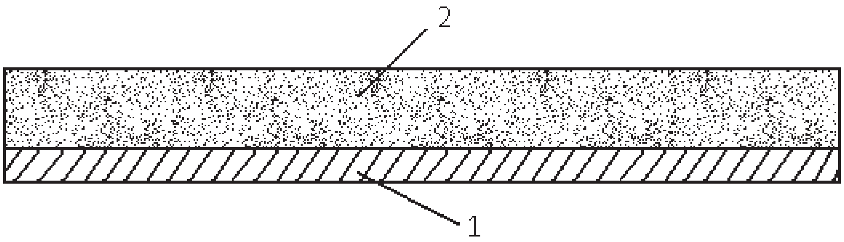

Fig. 2. Solid yoke, produced by spraying

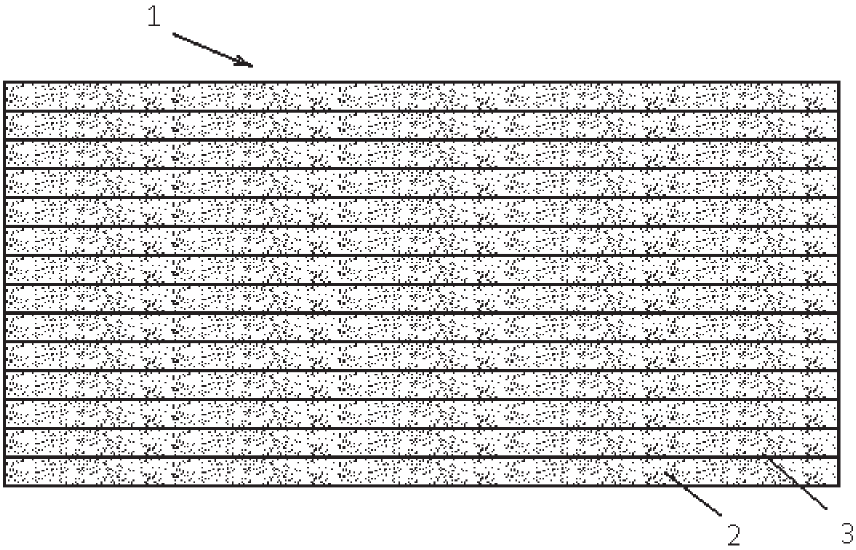

Fig. 3. Yoke, produced by spraying, in which layers of a ferromagnetic alternate with layers of insulation

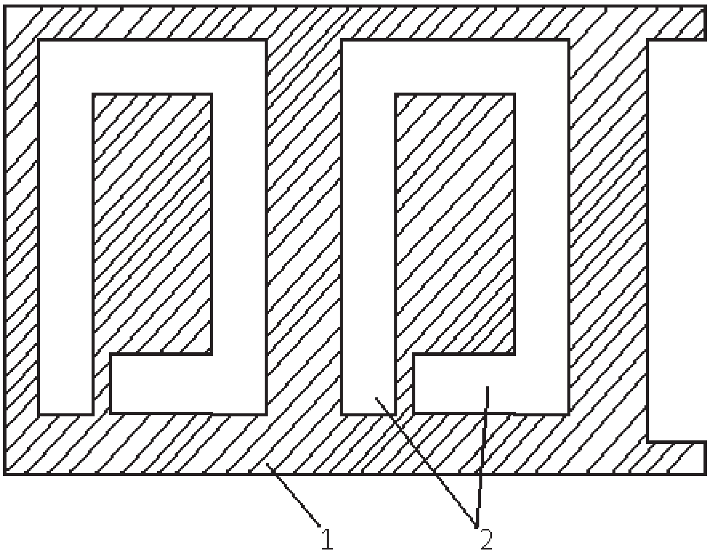

Fig. 4. Stencil for the manufacture of the first layer of coil winding coils of an inductor winding of a linear induction motor

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the coil, the deposited conductive layer is subjected to the flame-burning operation of the burner. The stencil is suitable for the manufacture of only one first layer of coil windings of the inductor winding. It should be noted that the stencil for spraying the windings should be made of a material whose melting point exceeds the melting point of the electrically conductive material. But this is necessary if the technological process involves the operation of melting the sprayed layers of electrically conductive material.

DETERMINATION THE SIZES OF STENCILS FOR MANUFACTURING OF INDUCTOR LIM

Let's consider an example of calculation of the sizes of stencils for manufacturing of inductor LIM with a winding consisting of the concentrated coils.

To produce a series of similar inductors of linear induction motors, it is necessary in advance to produce a set of stencils for spraying the core and winding the machine. The set includes a substrate (base), on which the yoke of the inductor is applied. Depending on the method of applying the material, a substrate is prepared. Its surface is cleaned and roughened for gas-flame and plasma yoke sputtering, or the surface of the substrate is polished by vacuum deposition of materials.

To determine the sizes of the stencils, the length and width of the inductor of the linear machine, the number and dimensions of the inductor teeth, the number and dimensions of the coils of the winding, the number of turns in each coil should be specified.

When calculating the stencils, the following conventions are adopted:

L_u – length of inductor;
b_u – width of inductor;
L_{mp} – length of stencil;
$2p$ – number of poles of inductor of linear motor;
τ – pole division;
b_z – width of inductor tooth;
l_z – length of tooth;
b_k – turn width of coil of winding of inductor;
δ – insulation thickness of coil turns;
b_{mp} – width of stencil;
A – width of inter-turn connection;
n – turn number (by coil height);
W_1 – longitudinal dimension, showing the distance from the left inner corner of the turn to the beginning of the inter-turn connection;

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W_2 – longitudinal dimension, showing the distance from the right inner corner of the turn to the beginning of the inter-turn connection;

b_n – distance between inner sides of two turns of adjacent coils;

b_1, b_2, b_3 – distance between the protrusions of the stencils for the deposition of insulation;

c – height of the base of the stencil for applying insulation.

In Fig 5 shows a stencil for applying a tooth layer of the inductor core. To determine the width of the winding coil, the values are given: b_u, b_z, l_z, τ, and the dimensions of this stencil are determined by the size and number of teeth of the inductor, and also by the width of the latter.

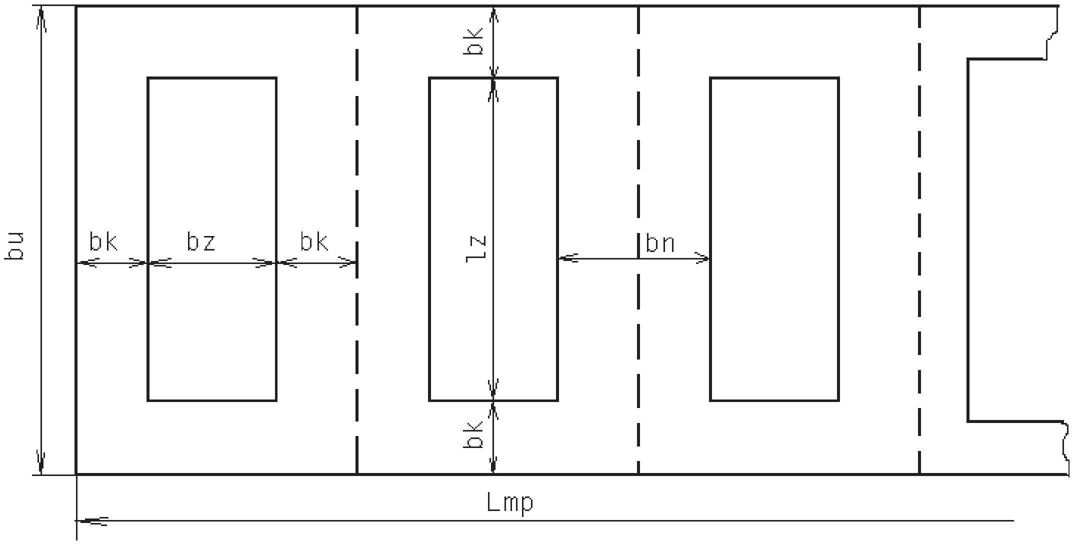

Fig. 5. Stencil for sputtering the tooth layer of the inductor core of a linear induction motor

Width of coil of winding without allowance for thickness of inter-coil insulation:

$$b_k = (\tau / 3 - b_z) / 2. \quad (1)$$

Distance between inner sides of two turns of adjacent coils:

$$b_n = 2b_k = \tau / 3 - b_z. \quad (2)$$

Length of inductor of linear electric motor:

$$L_u = 2p\tau + 2b_k = 6p(2b_k + b_z) + 2b_k. \quad (3)$$

The stencil for the production of the «n-th» turn layer is shown in Fig. 6.

Width of turn:

$$b_{k1} = b_k - 2\delta. \quad (4)$$

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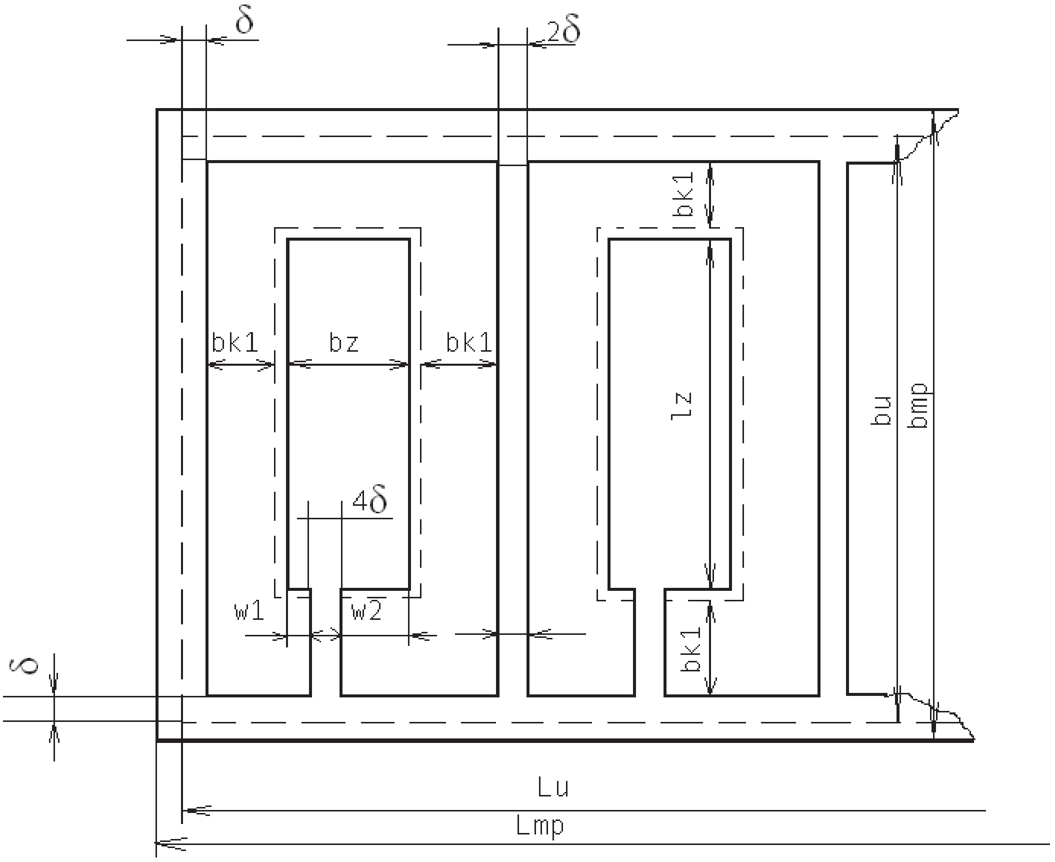

Fig. 6. The stencil for sputtering of the «*n*-th» turn layer of the coil of winding of the inductor LIM

Length of stencil, m:

$$L_{mp} = L_u + 0{,}04. \tag{5}$$

Distance from the left inner corner of the turn to the beginning of the interturn connection:

$$W_1 = (n - 1)(A + 4\delta). \tag{6}$$

Distance from the right inner corner of the turn to the beginning of the interturn connection:

$$W_2 = b_z - W_1 - 4\delta. \tag{7}$$

A stencil for applying an insulation layer on the turns of the winding, that closes the interturn connection, is shown in Fig. 7.

Longitudinal dimensions:

$$b_1 = b_k - \delta_1 + W_1 + 0{,}02 + 4\delta; \tag{8}$$

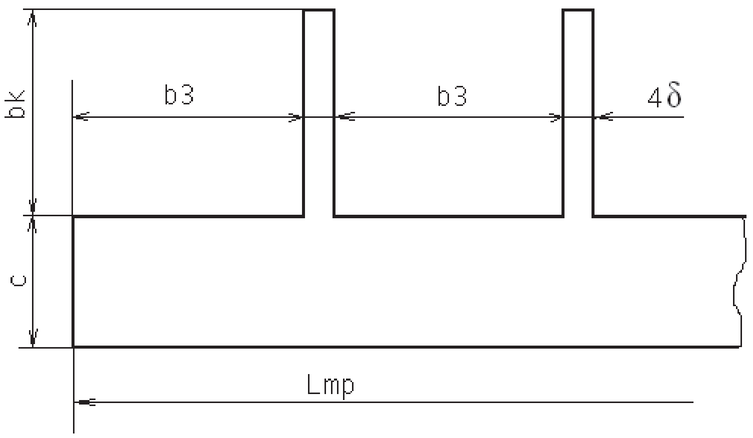

Fig. 7. A stencil for applying an insulation layer on the turns of the winding

$$b_2 = W_2 + 2b_k + W_1 - A + 4\delta; \tag{9}$$

$$b_3 = b_1 + A. \tag{10}$$

Thus, the dimensions of the stencils for manufacturing inductors of linear induction motors are determined on the basis of calculation data and design documentation.

CONCLUSIONS

1. The new integral technology for manufacturing inductors of linear induction motors by the method of deposition of materials is high and will allow to increase the quality of traction LIM for magnetic-levitation transport.
2. Manufacture of traction LIM inductors by the method of deposition of materials will allow to automate the process of production of linear machines for such promising modes of transport as high-speed magnetic-levitation, including vacuum.
3. The proposed technology can be used in the production of transformers and electric motors.

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