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Electromagnetic Fields of High-Speed Transportation Systems

Maglev Technologies in Comparison with Steel-Wheel-Rail

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Outline

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Executive Summary

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The potential health risks on passengers and the environment related to electromagnetic fields (EMF) caused by the operation of electrically driven high-speed transportation systems have been recognized as a significant issue for many years, since magnetic properties can potentially generate physiological effects in body tissues.

In this study, the calculated and experimental values of electromagnetic fields in high-speed steel-wheel-rail systems such as ICE, TGV and Shinkansen are compared with the two high-speed maglev systems, Germany's Transrapid and Japan's superconducting maglev (SC Maglev) system, based on available data. To estimate the impact on passengers, the field values generated by the power supply system as well as by the drive and suspension systems are taken into account. For the comparison, the peak values of the electromagnetic fields have been considered.

The results show that there are little to no health risks from the electric fields to be expected, based on current knowledge. Regarding the magnetic induction, the calculated peak values remain well below the limits given by internationally accepted regulations. In the case of the Transrapid and the SC Maglev systems, the measured peak values in the environment and inside the vehicle depend on the levitation and the guidance technology and the geometrical parameters. The SC Maglev system requires and employs effective magnetic shielding measures which relate to heavy materials. Since such materials may have a negative influence on the energy balance and the economics of operation, research and development efforts are focusing on the optimization of materials and the structure of shields.

In all considered high-speed transportation systems, no higher potential risks from electrical fields were found. Regarding magnetic fields, the induction generated by the power supply and the drive system remain well below the frequency-dependent limits. The situation is equally safe for magnetic levitation systems, but still varies depending on the chosen suspension and guidance technology. For example, the SC Maglev requires effective shielding measures which may have a negative impact on the overall energy consumption in operation. Nevertheless, EMF values remain well below the human health protection guidelines.

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<u>Keywords</u>*:* Maglev, wheel-rail systems, high-speed transportation systems, Transrapid, Chuo Shinkansen, electromagnetic fields, physiological effects, health risks, rail-wheel systems, ICE, Transrapid.

Introduction

Biological effects of electromagnetic fields are among the most serious environmental issues in the public regarding health risks and quality of life.

The physiological effects of electrical, magnetic and electromagnetic fields on the human body are dependent on the frequency. The effects of static electric fields are limited to the surface of the human body and can cause motion of body hair and corona discharges.

Static magnetic fields exert forces on ferro- and diamagnetic materials as well as charged moving particles. This may lead to acceleration, torque effects and the induction of electric fields in the tissue.

In the low-frequency range up to some 100 kHz the main physiological effect is the electrical stimulation of excitable body tissues like muscles, nerves and sensory organs. Biological effects on nerves and other tissue of the body caused by induced currents are dominating. In the high-frequency (HF) range thermal effects are increasingly important [1].

Because all EMF-related biological effects in the low-frequency range are linked to peak values in the internal electrical field strength and magnetic flux density in body tissues, all exposure limit values of the fields must be taken into account. To reduce risks for health, such limits are imposed on the emission of electromagnetic fields (EMF). Table 1 shows the limits for the electric field strength and the magnetic induction for the different frequency ranges, as imposed by the German regulation BImSchV 26 (German Law on Protection against Harmful Environmental Effects due to Air Pollution, Noise, Vibrations and Similar Processes (Federal Emission Control Act)). In the case of high-speed transportation systems, the low-frequency range must be considered, ranging from static fields to frequencies up to a few kHz.

Table 1. Limits for the emission of electromagnetic fields, valid in Germany provided by the regulation BImSchV 26. The magnitude f is the frequency.

Frequency (Hz)	**Electric field strength (kV per meter)**	**Magnetic induction (µTesla)**
0	-	500
1 - 8	5	40,000/f
8 - 25	5	5,000/f
25 - 50	5	200
50 - 400	250/f	200
400 – 3,000	250/f	80,000/f
3,000 – 10,000,000	0.083	27

The study compares the electromagnetic fields generated by high-speed transportation systems by a typical railway system and maglev systems, based on available data. As examples for the comparison, the German high-speed InterCity Express (ICE) train, the German magnetic levitation system Transrapid (TR), and the Japanese superconducting maglev (SC Maglev) systems have been selected. The present comparison is focusing on the electromagnetic field distribution and its influence on the passengers and on the environment outside. In the comparison, the maximum values of the electrical and magnetic fields are calculated.

In other European countries and around the world similar upper limits exist, depending on the corresponding regulations.

In electrically powered high-speed transportation systems, several contributions to the electromagnetic field distribution must be considered:

1) Fields generated by the power supply system (external and internal);

2) Fields generated by the drive / motor system.

Other contributions, e.g., from air condition and lighting, are neglected in this comparison.

Basic physical relations

Electrical field

The maximum electrical field strength E_{max} is defined as

$$E_{max} = U_0/d \ [V/m]$$

where U_0 is the peak voltage and d the distance from the origin of the source of the field.

Magnetic field

The maximum magnetic field strength or magnetic induction B_{max} is given by

$$B_{max} = \mu_0 I_0/(2\pi r) \ [T]$$

where μ_0 is the air permeability with a value of $4\pi*10^{-7}$ Vs/(Am), I_0 the peak current value, and r the distance from the wire or the current conductor.

The shielding of electrical fields can be realized in a simpler way than the shielding of magnetic fields since the metallic body of a train acts as a Faraday cage, shielding the internal space from low-frequency electrical fields.

The efficient shielding of magnetic fields requires the application of special materials (ferromagnetic or superconducting). Therefore, much more attention must be paid to emission of the magnetic fields generated by currents of the power supply and the drive system. These currents are determined by the power and the voltage level. The focus of the current investigation concerns the peak values of the power-related magnetic fields.

Assumptions, calculations and results

1. Railway system

The power is supplied by substations fed by public or railway-owned high-voltage power grid to the transportation system via high-voltage overhead wires. In general, the voltage level of alternating-current (AC) systems is 15 kilovolts (kV) or 25 kV with a frequency of 16.7 or 50 Hz, respectively. The maximum driving power is applied during acceleration of the train. The electrical peak power may achieve a value of several megawatts (MW). The corresponding current value is in the range between several hundreds and a few kiloamps (kA) along the pathway.

The drive system within the transportation equipment consists of inverters and three-phase motors with a voltage level up to 2 kV. The frequency is in the range between 0 and 200 Hz [2]. The nominal operational speed considered for the ICE 3 is 300 km/h with a maximum allowable speed up to 330 km/h.

In general, two different situations for the exposure to electromagnetic fields need to be considered: (1) the emission of electromagnetic fields to the external environment, i.e. the impact on the neighboring environment of the railway line, and
(2) the exposure of passengers inside the train.

Calculation of the electrical field

1) The electrical field strength — measured at a distance of 25 meters (m) from the overhead wire with a voltage of 25 kV —is E = 1000 V/m, which is well below the limit of 5 kV/m given in Table 1. Field strengths of 1 kV/m will cause only a small electrical field in body tissue of about 1 mV/m [1].

2) The estimation of the electrical field within the train is more complicated. The distance from the overhead wire is smaller but, on the other hand, the metallic roof of the wagon represents an effective electrical shielding.

Therefore, the impact of the electrical fields from power supply of railway systems on the neighboring environment and on passengers can be neglected.

Calculation of the magnetic field (induction)

Outside the train

To estimate the magnetic field, or induction, generated by the overhead power line, we should consider the number of trains running within one section between two substations where the power is fed-in. In Germany, at the newly constructed ICE line between Nuremberg and Berlin, a typical distance between two substations is approximately 25 kilometers (km). With two-to-three trains per hour in both directions, we can restrict the analysis to consider only the power for two trains within the same section. In other words, the peak current in the overhead power line for at least two trains within this section could reach the value of 2 x 850 A (1,700 A) in the case of 15 kV. At 25 kV the current is correspondingly lower. The magnetic induction generated by the peak current of 1,700 A at a distance of 25 m from the overhead power line is 13.6 microtesla (µT), which lies well below the limit of 300 µT for the frequency of 16.7 Hz. Therefore, the impact of the magnetic field from the outside power supply to the neighboring environment along the railway line can be neglected.

Inside the train

The determination of the magnetic field or induction inside the train is more complicated. In the rail-wheel example of the ICE 3, the power is supplied via the inverter stages to the motors. In this case, the mechanical power reaches 8,000 kW at the maximum speed of 330 km/h, delivered to 16 motors, each motor having a power of 500 kW. The driving concept consists of 16 motors, divided into four sections with four motors in each section [2]. We therefore focus on one section which supplies a power of 2,000 kW. The power is delivered to the motors via a three-stage transformation/conversion system in which, initially, a single-phase transformer transforms the voltage of 25 kV or 15 kV from the overhead line at the frequency of 50 Hz or 16.7 Hz to 2 x 1,100 V. At the second stage, the AC voltage of 1,100 V is converted into a direct-current (DC) voltage of 2,800 V by two converters.

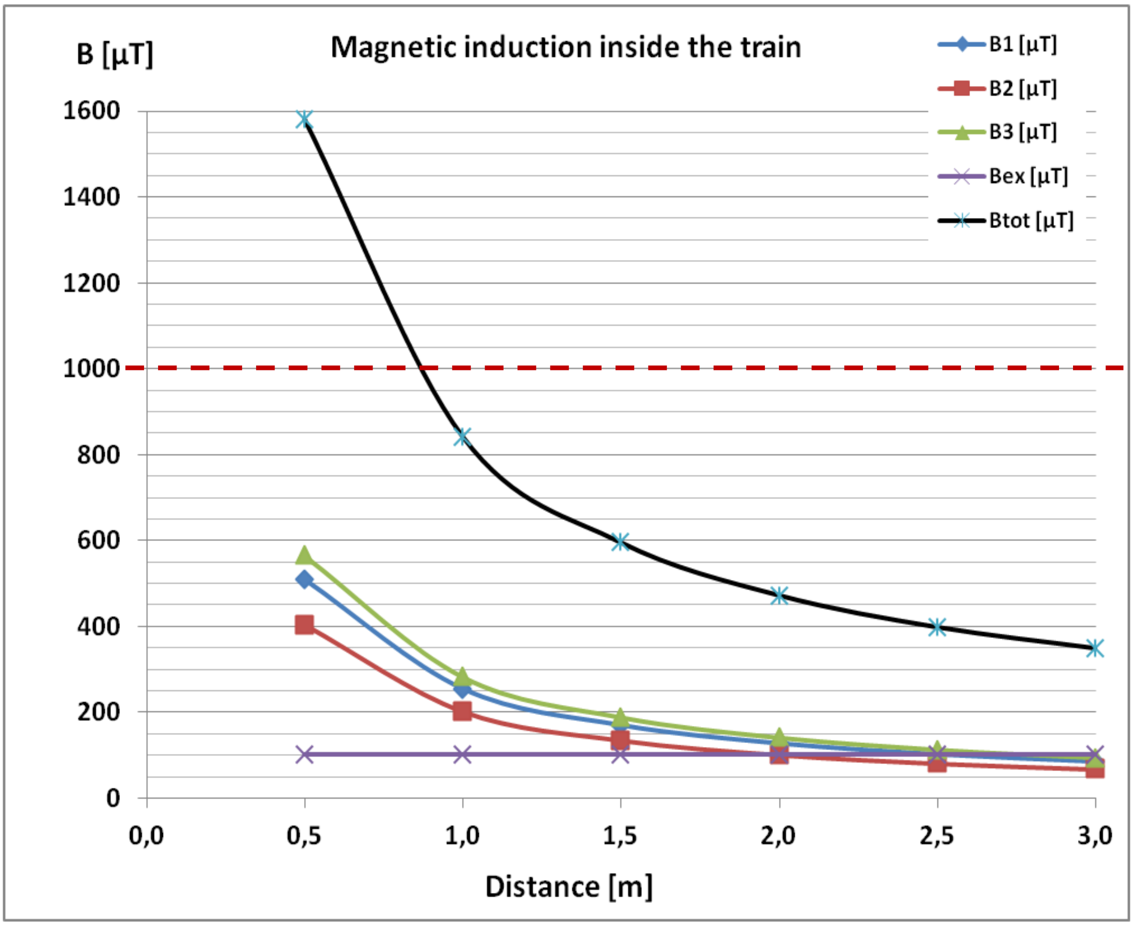

Fig. 1. The maximum magnetic induction generated by: the transformer (B_1), the converter (B_2) and the inverter currents to the motors (B_3) as function of the distance from the source of the magnetic field (system component). B_{ex} is the field generated by the external overhead wires in both directions. B_{tot} is the sum of all magnetic field contributions.

At the third stage, the DC voltage is again converted to a three-phase AC voltage ranging from 0 to 2,000 V and a variable frequency in the range from 0 to 200 Hz which is applied to the four motors. As a result, a maximum efficient current value of 250 A is flowing to each motor at a constant maximum speed of 330 km/h on a flat track.

For the calculation of the magnetic field inside the train, the current values at each stage need to be considered in addition to the field induced by the external overhead wire. Since these values are taken from the efficient power, the maximum or peak values must be used for the estimation of the peak magnetic field by

$$I_p = I_0 = I_{eff} * \sqrt{2}$$

The effective current value at the secondary side of the transformer is about 900 A, the peak value 1,273 A, at each of the two output lines with an output voltage of 1,100 V. The maximum current value at the output of the two AC-DC converters is 1,010 A, and the 3-phase DC-AC inverter delivers currents to the four motors up to 4 times 353 A to the four motors. However, we have to consider that the four motors are distributed along the section.

The resulting magnetic induction generated by the components of the power supply system in one section, the transformer, the converter and the inverter feeding the motors is shown as a function of the distance from the system component in Fig. 1. However, we should keep in mind that there is some shielding of the stray fields by the material of the component containment. Especially for the stray field of the transformer, much lower values than in Fig. 1 can be assumed due to the shielding of the containment.

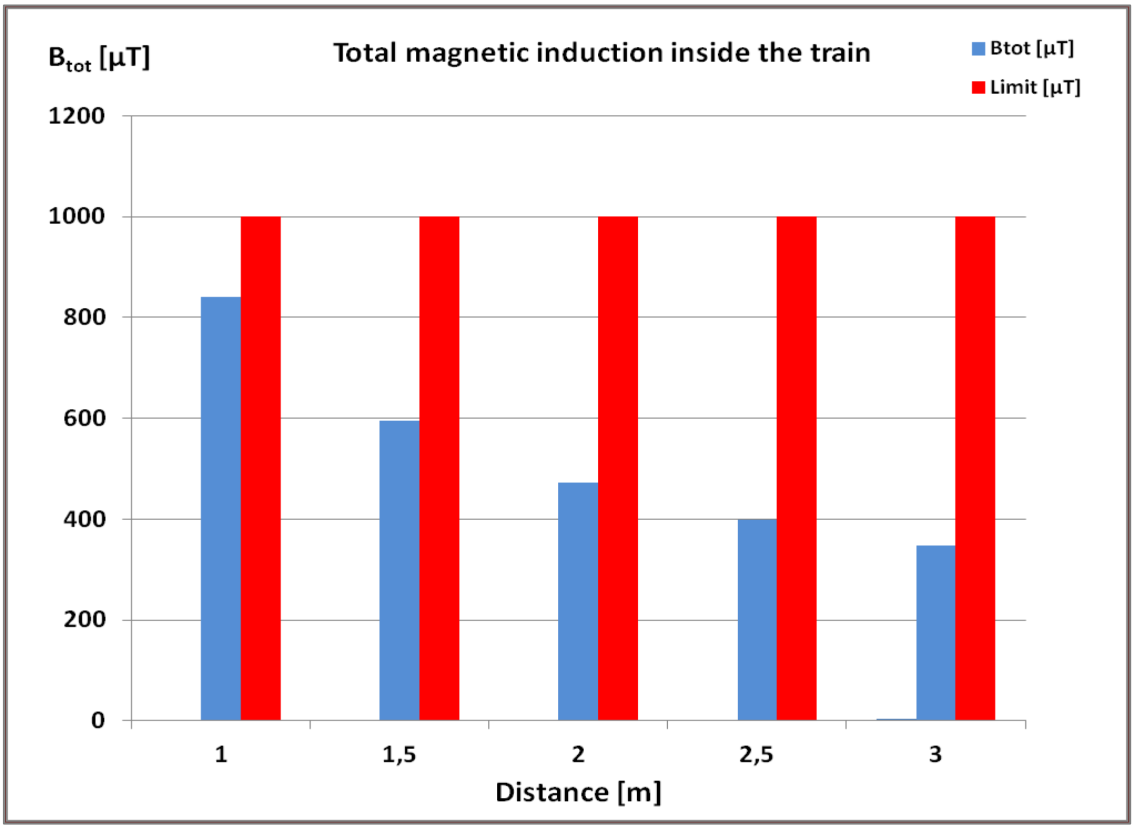

Fig. 2. The maximum total magnetic induction as a function of the distance from the location of the field generation.

It is clearly seen that most of the contribution to the magnetic induction is caused by the large currents from the inverter to the motors (B_3). However, the four motors are distributed over the driven train section. The external field from the two overhead power lines is of only minor influence. By adding the maximum values of all four contributions at a distance of 1 m, the total induction B_{tot} would peak around 800 µT. However, this is a theoretical and not a realistic value. Comparing with the frequency-dependent limits of 300 µT (16.7 Hz), 500 µT (DC) and 200 µT (200 Hz) in Table 1, all field contributions remain well below the limits inside the train. In addition, the body of the wagon will further reduce the concentration of the magnetic field inside the train. The total magnetic induction inside the train, depending on the distance from the location of the generated field, is shown in Fig. 2.

2. Maglev systems

Maglev systems, unlike conventional trains, have no wheels, axles, transmissions or pantographs. Maglevs are typically propelled by linear motors. The power for the levitation, guidance and propulsion systems is supplied via coils integrated into the guideway, or track. As a consequence, electrical fields can be neglected and only magnetic fields need to be taken into account.
In this paper, we compare the German system Transrapid and the Japanese SC Maglev system, also called the Linear Chuo Shinkansen. The Transrapid system is based on normal-conductor magnet technology using a magnetically attractive approach (called electromagnetic suspension (EMS)), whereas the Japanese system is based on superconducting maglev technology in a magnetically repulsive approach (called electrodynamic suspension (EDS)) that uses onboard superconducting magnets and normal-conducting reaction coils for levitation, guidance and propulsion integrated along the guideway [6].

A) The Transrapid system

The Transrapid maglev system does not roll; it hovers. Electronic systems guarantee that the magnetic clearances for levitation and guidance subsystems remain constant (nominally 10 mm) during travel. To hover, Transrapid advertises that it requires less power than its air conditioning equipment. The levitation system and all onboard electronics are supplied by the power recovered from harmonic oscillations of the magnetic field of the track's linear motor (stator) — those oscillations being parasitic cannot be used for propulsion anyway — at speeds above 100 km/h, while at lower speeds power is obtained through a physical connection to the track. In case of a power failure of the track's propulsion system, the Transrapid vehicle uses on-board backup batteries that can supply power to the levitation system, which is therefore independent of the propulsion system.

Electronically controlled support magnets located on both sides along the entire length of the vehicle pull the vehicle up toward the ferromagnetic stator packs mounted to the underside of the guide way. Guidance magnets located on both sides along the entire length of the vehicle keep the vehicle laterally on the track. The vehicle is capable of hovering up to one hour without external energy. While travelling, the on-board batteries are recharged by linear generators integrated into the support magnets.

The Transrapid maglev system uses a long-stator linear synchronous motor (LSM) both for propulsion and braking. The linear motor functions like a rotating electric motor whose stator is cut open and stretched along under the guide way. The LSM is divided in sections (typical stator length ranges between 500 and 2,000 m) due to economic reasons (reduce losses) and reasons of propulsion.

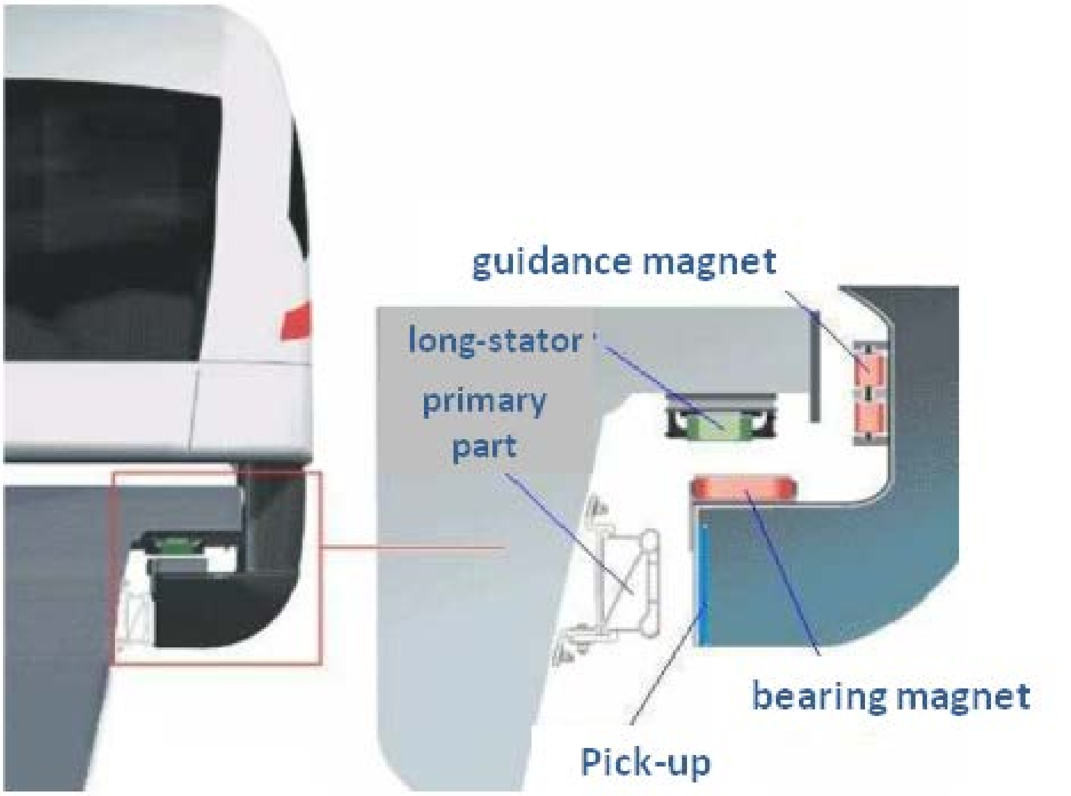

Fig. 3. Structure of the bearing and propulsion system of TR08 [4].

Inside the motor windings, alternating current generates a magnetic traveling field which moves the vehicle without contact. The support magnets in the vehicle function as the excitation portion (rotor). The respective magnetic traveling field works in only one direction, and therefore makes moving train collisions extremely unlikely, as more than one train in the same track section would theoretically travel in the same direction.

Recent developments in converter technology with reactive power compensation features suggest a reduction of the high-voltage level in the propulsion system from previously 2-10 kV to a voltage level between 400-900 V along the line, with a frequency of 50 Hz [3]. The power is transmitted along propulsion sections of the guide way by wayside substations that switch the power only in that section in which a vehicle is moving. Other sections are switched off and free of power. Fields are generated by the levitation system, the lateral guidance and the linear-motor drive system.

The physical structure of the TR08 system is illustrated in Fig. 3.

The nominal operational speed chosen for the comparison is 430 km/h. For the Transrapid TR08 system there exists a wide basis of available information and experimental data by direct measurement.

We consider the magnetic field or induction in the neighborhood of the guideway as well as inside the vehicle.

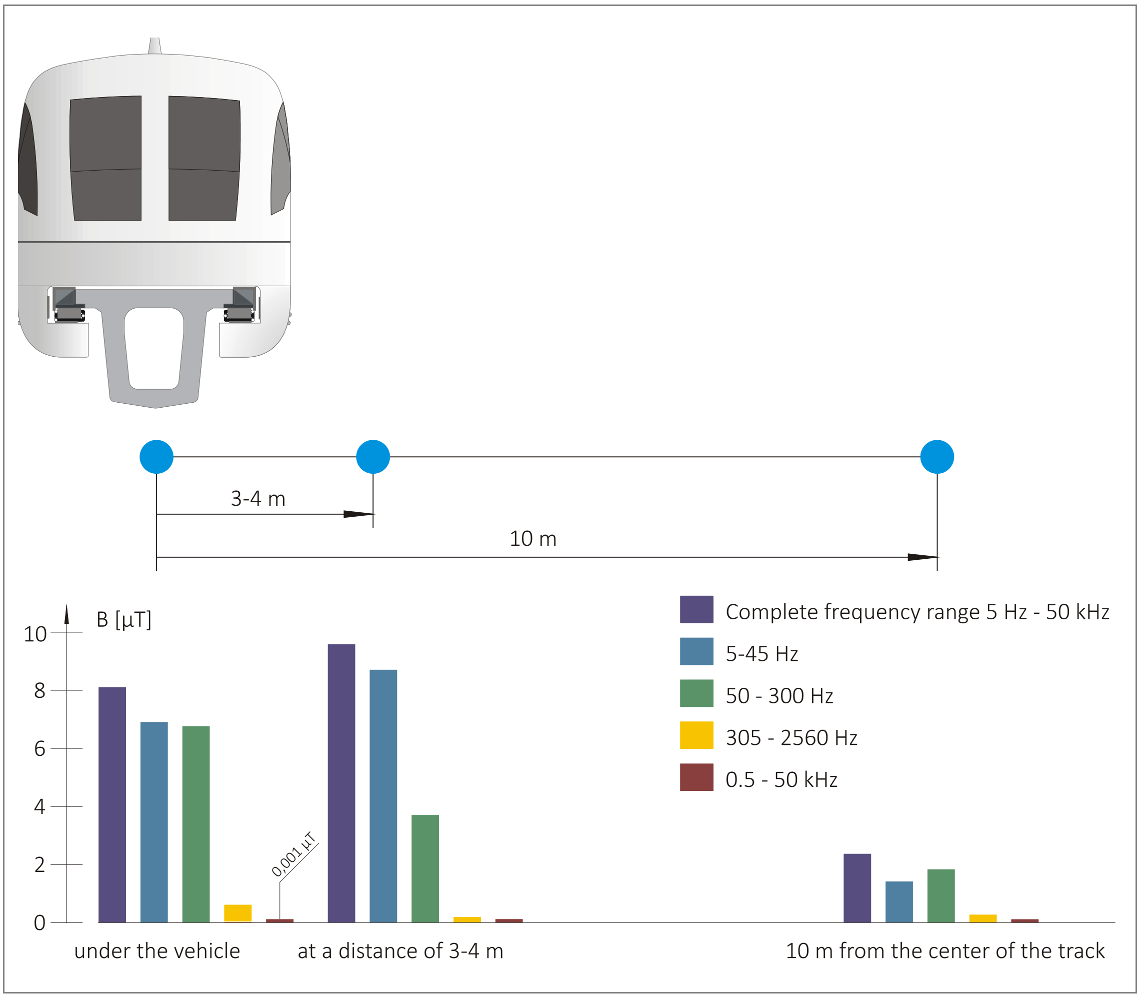

Fig. 4a. Magnetic induction along the track [5].

The magnetic field or induction and its frequency dependence along the track is shown in Fig. 4a. The induction is lower than 10 µT, even very close to the guideway; there is therefore little impact to be expected for residential areas. The reason for the low induction values is the small air gaps between the bearing/support and the guidance magnets and the stator coils in the vehicle that come with an attractive (vs. repulsive) magnetic arrangement. This drastically reduces the stray fields outside the guideway.

The situation is different inside the vehicle. Since the linear-motor coils are located in the vicinity of the floor of the vehicle, they generate higher induction values inside, as illustrated in Fig. 3b. The maximum value is, as expected, just on the floor with a maximum value up to more than 25 µT, depending on the frequency. With increasing distance to the floor, the induction values decrease. All values are below the limits of the BImSchV 26, and even much lower than those of the ICE 3 rail-wheel system. For comparison, the earth's magnetic field is in the range of 30 -50 µT, depending on geographical location.

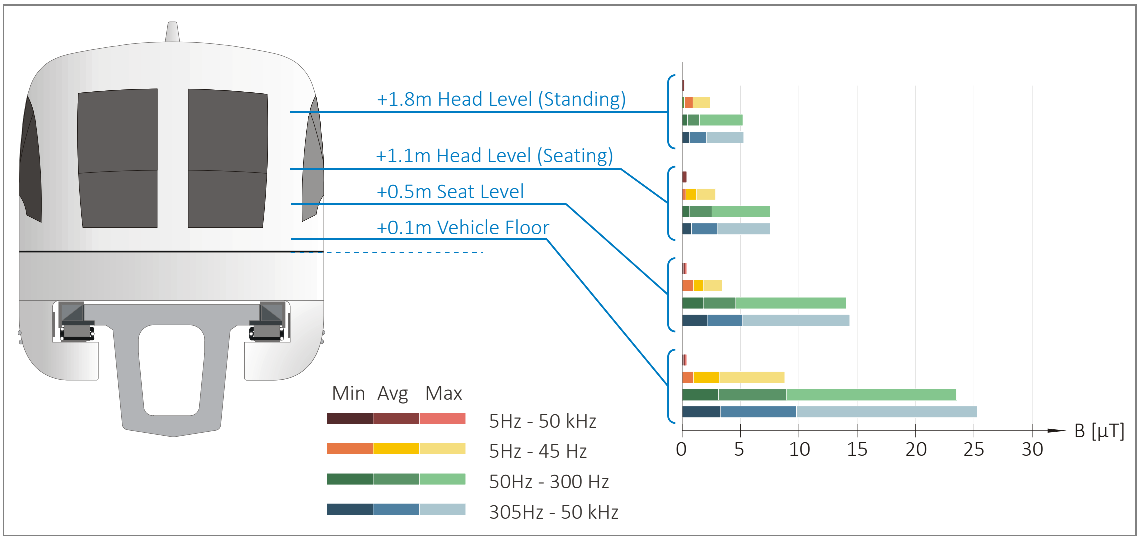

Fig. 4b. Magnetic induction inside the TR08 vehicle [5].

B) The SC Maglev system

Regarding the Japanese superconducting maglev system, only limited public information and data are available. The data used in the present comparison are therefore taken mainly from Japanese literature.

The Japanese SC Maglev system makes use of modern superconducting magnets which allow for a larger magnetic air gap in a repulsive EDS levitation. Moving magnetic fields create a reactive force in a conductor because of the magnetic field effect. This force holds up the train. The maglev train has onboard superconducting magnetic coils and the guideway sidewalls contain the propulsion, levitation and guidance coils. The maglev concept of the SC Maglev is illustrated in Figs. 5a, 5b and 5c [6].

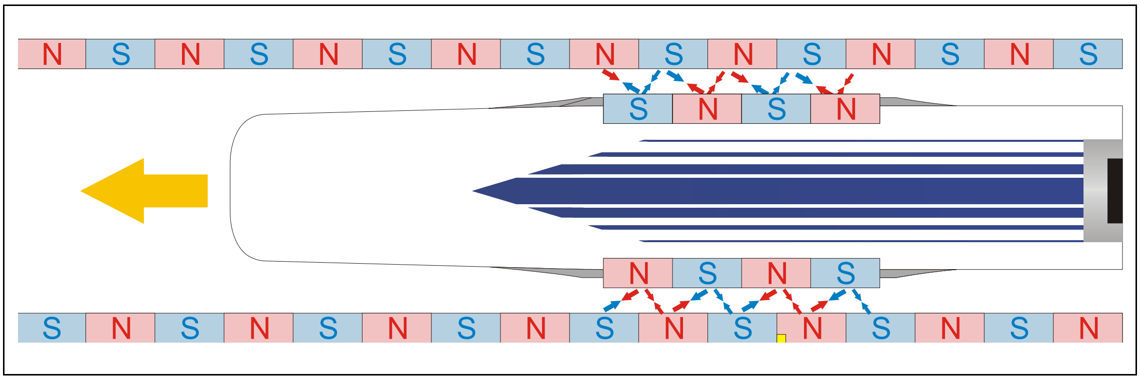

Fig. 5a. Propulsion concept of the superconducting maglev [6].

The SC Maglev train, like the Transrapid, is driven by a LSM propulsion system. This system is needed to supply power to the coils in the guideway sidewalls.

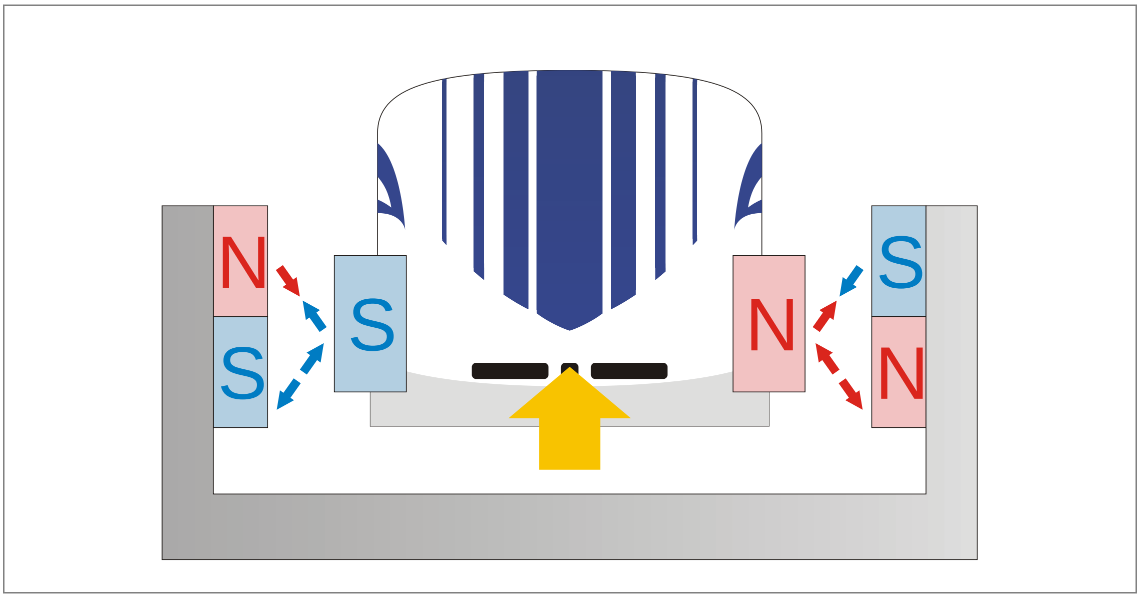

Fig. 5b. Levitation concept of the superconducting maglev [6].

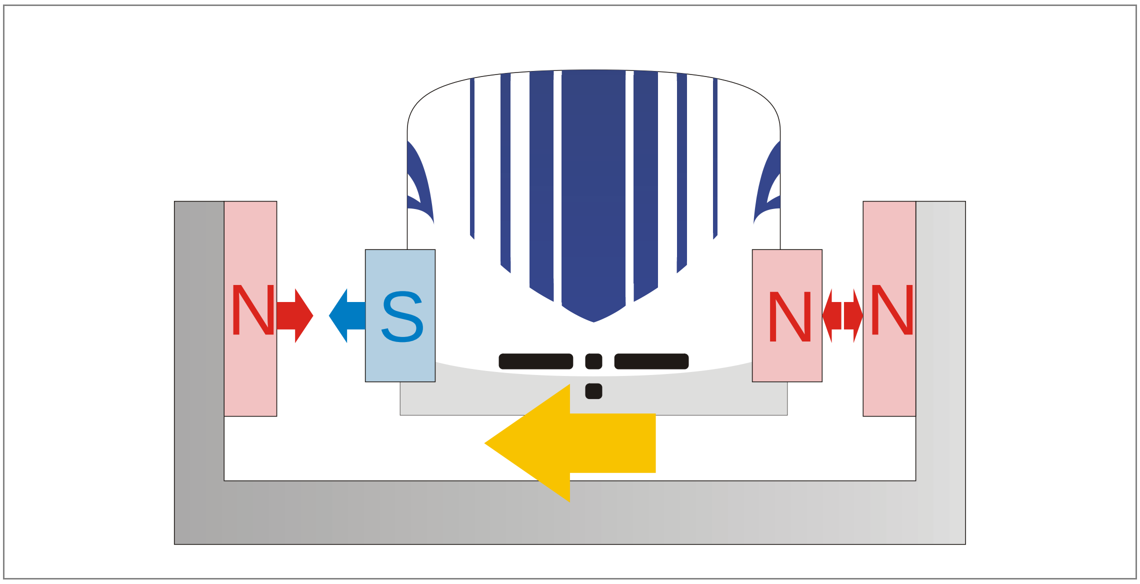

Fig. 5c. Guidance concept of the superconducting maglev [6].

When the train is running at high speed, levitation coils mounted in the guideway sidewalls produce reactive forces in response to the approach of the superconducting magnetic coils onboard the trains. The EDS system has the advantage of larger gaps than the EMS system, but the EDS system needs support wheels which are required in low-speed running because the EDS system cannot produce a large-enough levitation force at speeds below approximately 160 km/h to support the vehicle weight. However, once the train reaches that speed, the wheels will retract so that the train is floating.

The SC Maglev 's repulsive levitation system has a "self-stable" air gap of about 10 cm, whereas Transrapid's attractive approach, with its EMS system, has an air gap of 1 cm, which is magnetically unstable and must be constantly controlled. The SC Maglev levitation coils, which are located along the guideway sidewalls, generate lateral guiding and stabilizing forces. The following figure and tables are official data published in [7].

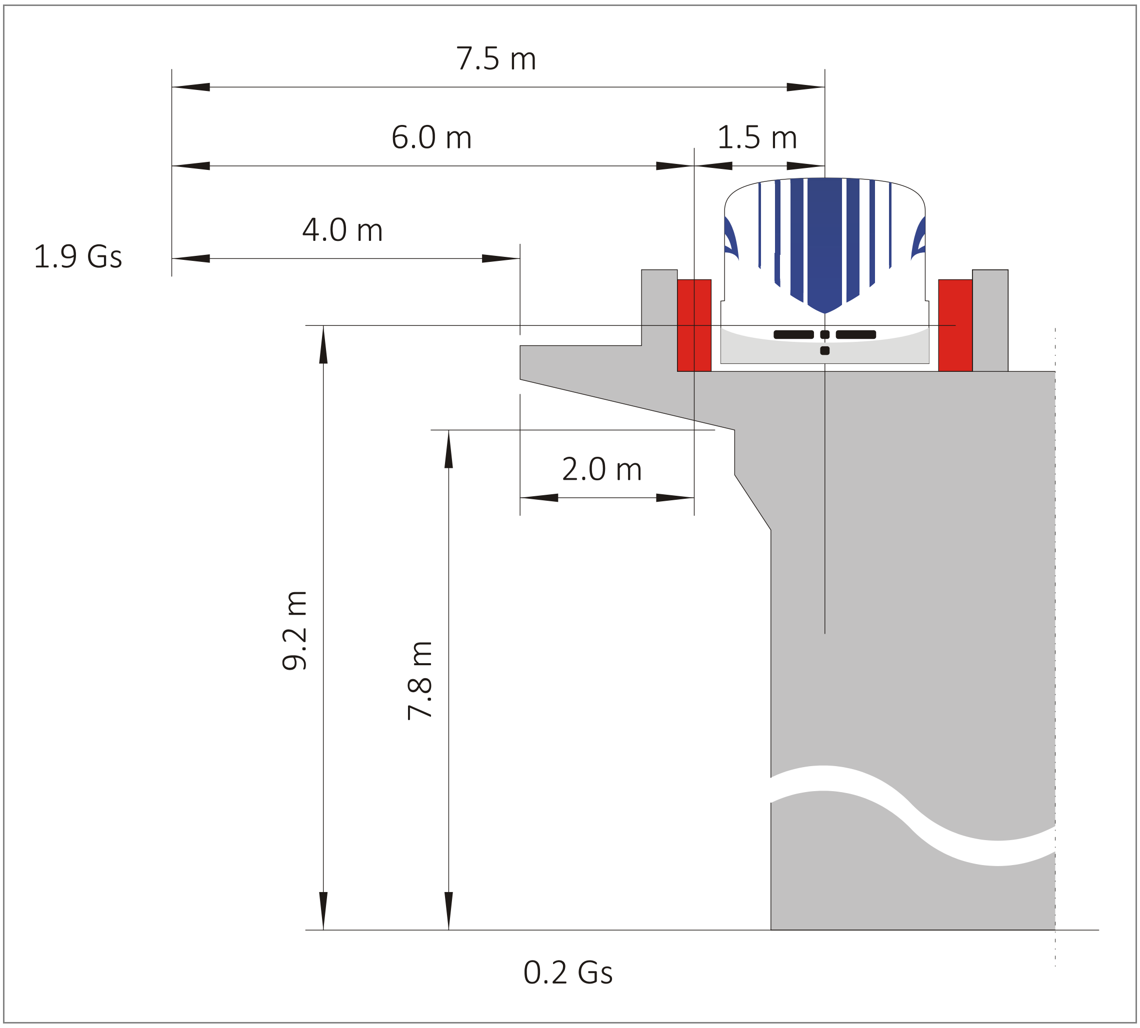

Fig. 6. Locations of the measurement points of the induction values.

Table 2. Maximum induction values inside the vehicle (at different locations).

Height	Position / Condition	Gangway	Inside of the vehicle: Passenger compartmt. 1	Inside of the vehicle: Passenger compartmt. 2	ICNIRP guideline
1.5 m	Vehicle stop	440 µT	X	310 µT	400 mT
1.0 m	Static field	810 µT	50 µT	370 µT	
0.3 m	Meas. equipmt. 1	920 µT	40 µT	371 µT	
	Vehicle running Meas. equipmt. 1	900 µT	X	430 µT	

Table 3. Induction values inside the SC Maglev vehicle (data taken from Miyzaki test facility)

Measurement location		w/o shielding	w shielding
Center of seating row	1 m above floor	116 µT	88 µT
	seat level	96 µT	64 µT
	10 cm above floor	112 µT	58 µT
Center of gangway/aisle	1.5 m above floor	90 µT	89 µT
	10 cm above floor	105 µT	83 µT
Bogie position	1.0 m above floor	1,656 µT	429 µT
	seat level	2,697 µT	382 µT
	10 cm above floor	1,764 µT	1,061 µT
Gangway			
1.4 m from connection	1.5 m above floor	134 µT	206 µT
	10 cm above floor	1,841 µT	366 µT
2.4 m from connection	1.5 m above floor	153 µT	63 µT
	10 cm above floor	12,720 µT	1,331 µT

Table 4. Static and alternating induction values outside along the "Chuo Shinkansen" line at various locations

		Measurement location	Magnetic induction
Static field		area 8 m² under bridge	20 µT
		area 4 m² from guideway	190 µT
		along the guideway	200 µT
		loading platform	800 µT
		max. inside vehicle	1,330 µT
Alternating field		along the guideway	200 µT
	Propulsion	generated max. by coil	200 µT (at 100 km/h)
	Oncoming traffic	max. inside vehicle	700 µT (at 20 km/h)

Table 5. Regulations given by the National Environmental Research Center of Japan

Location	Max. Value of induction
Directly above motor	max. 600 µT
Inside vehicle above reactor at floor	max. 4,000 µT
5 cm under the motor	max. 70,000 µT
15 cm under the motor	max. 20,000 µT

A system has been proposed to reduce the magnetic field inside superconducting maglev vehicles by shielding measures [8]. Grain-oriented electrical (silicon) steel (GOES) has a high saturated magnetic flux density and higher permeability than pure iron, which makes it suitable as the shielding material at the target level of less than 500 µT. The challenge consists in handling the magnetic anisotropy (the quality of exhibiting properties with different values when measured along different axes) of this material. To avoid the problem of anisotropy a bilamellar shielding (composed of two layers) has been proposed to the coach. The outer shielding material is pure iron and the inner one is permalloy B, a nickel–iron magnetic alloy that has a relatively high saturated magnetic flux density, and has magnetic isotropy (the quality of exhibiting properties with the same values when measured along any axis). The magnetic field in this double-shielding system reaches a maximum value of 300 µT locally, but its value is less than 100 µT in almost all regions inside the vehicle. This maximum value corresponds to an open space without shielding, through which passengers can move from coach to corridor. The disadvantage of the bilamellar shielding is an increase of 80 percent in the weight of the magnetic shield system. There still might be some room for further optimizing the shielding configuration to reduce the weight.

To evaluate the environmental concerns related to electromagnetic fields of high-speed transportation systems we must compare the maximum magnetic induction inside the vehicles at the location of passenger seats. Fig. 7 shows the maximum induction values to which passengers are exposed during their trips in the various high-speed transportation systems being compared, together with the corresponding limits.

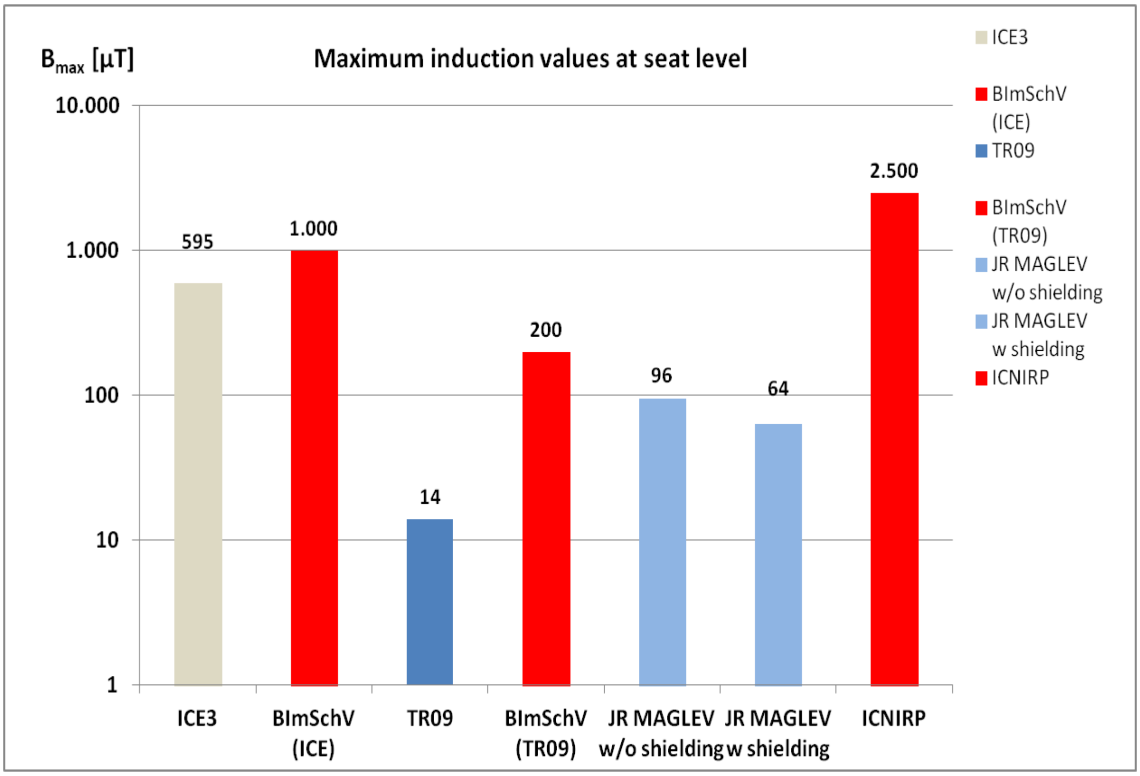

Fig. 7. Comparison of the maximum induction values inside the vehicle at a passenger's position. The red columns are the corresponding limits given by BImSchV and ICNIRP, respectively.

The values are represented on a logarithmic scale due to the high limit specified by the independent organization of scientific experts comprising the International Commission on Non-Ionizing Radiation Protection (ICNIRP).

All induction values remain under the limits.

Conclusion

In this study, the electromagnetic fields generated by the power supply subsystems of high-speed transportation systems have been calculated and compared. Since the biological effect of the peak electrical field strength of 1 kV/m is considered as negligible, the focus of the comparison was especially on the magnetic field which is more critical than the electrical field.

The worst-case calculation for the ICE railway system results in induction values of about 600 µT, which is well below the limit given by the BImSchV regulation. Therefore, the power supply system of conventional railway systems seems to have little to no negative impacts on passengers or on the environment.

In the case of high-speed magnetic-levitation transportation systems developed in Germany and Japan, the situation is different. The magnetic field strength strongly depends on the magnetic technology used for levitation, propulsion and guidance.

In the case of Transrapid, which uses normal-conducting magnets and small air gaps, past investigations based on experimental measurements show that there are little to no negative impacts of the magnetic induction on passengers and the environment to be expected. For comparison, the value of the magnetic field of earth at central Europe is 48 µT, which is more than 3 times the measured value in the Transrapid.

In case of the Japanese SC Maglev system, which uses superconducting magnets and wide air gaps, considerable efforts are necessary — and have been undertaken for decades — to shield passengers from the high magnetic field strength. However, with present shielding measures the induction values inside the SC Maglev vehicles — admittedly, four to six times higher than those inside the Transrapid vehicle — remain well below the human health protection guidelines. In addition, the material for shielding high magnetic fields has the drawback of heavy weight, which has a negative influence on the energy balance. Research in Japan is focusing on new and innovative materials to reduce weight without loss of shielding properties [6; 7; 8; 9].

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