DOI 10.17816/transsyst201843s1134-155

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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

Received: 03.09.2018. Revised: 03.09.2018. Accepted: 17.11.2018.

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

Received: 03.09.2018. Revised: 03.09.2018. Accepted: 17.11.2018.

Transportation Systems and Technology. 2018;4(3 suppl. 1):134-155
doi: 10.17816/transsyst201843s1134-155

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

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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

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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.

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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).

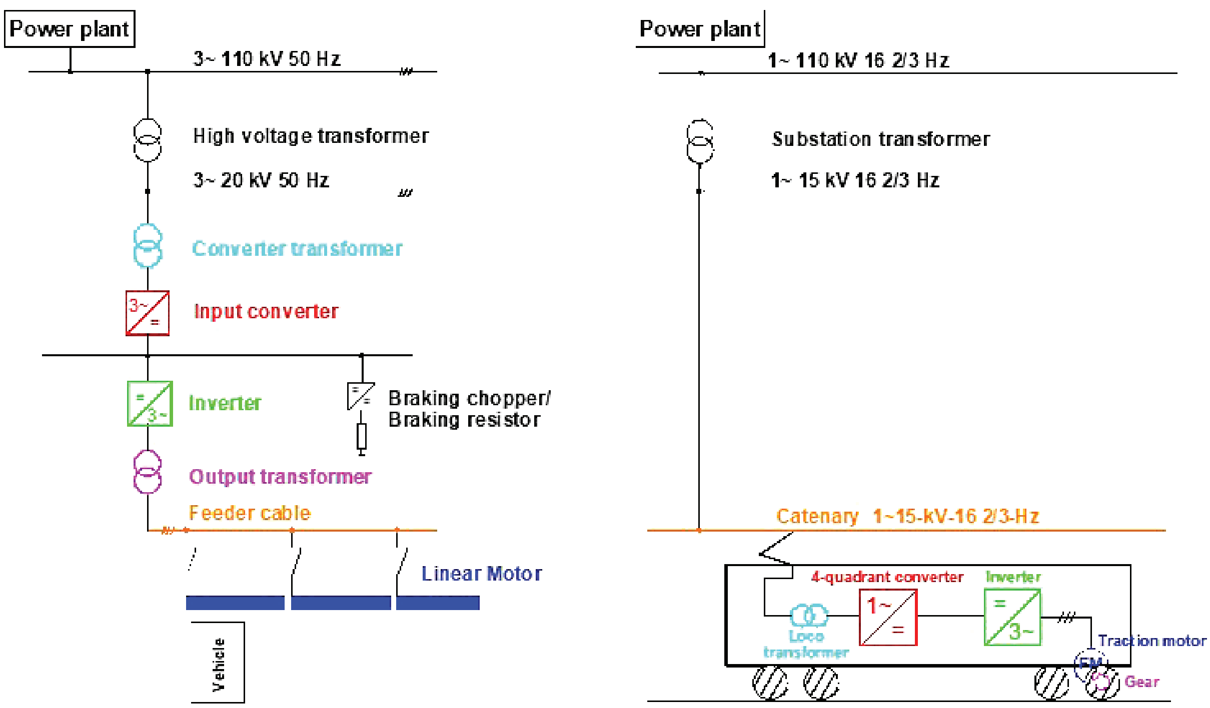

Fig. 1. Basic setup of the energy supply structure for the Maglev system (long stator) and for the wheel-on-rail system with the respective interfaces

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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.

Received: 03.09.2018. Revised: 03.09.2018. Accepted: 17.11.2018.
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doi: 10.17816/transsyst201843s1134-155

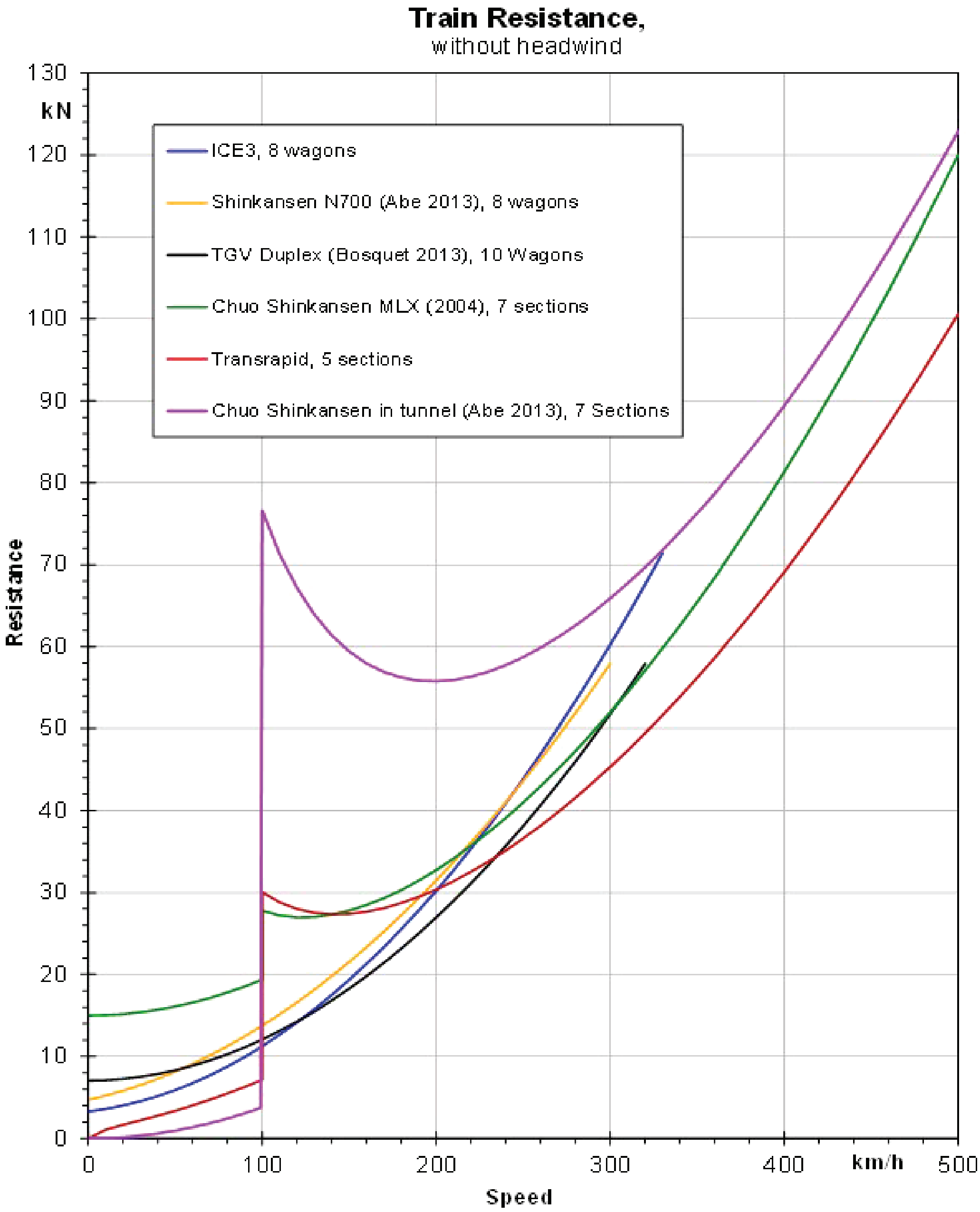

Fig. 2. Driving resistance curves of the considered Wheel-Rail and Maglev systems on an open-air section

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

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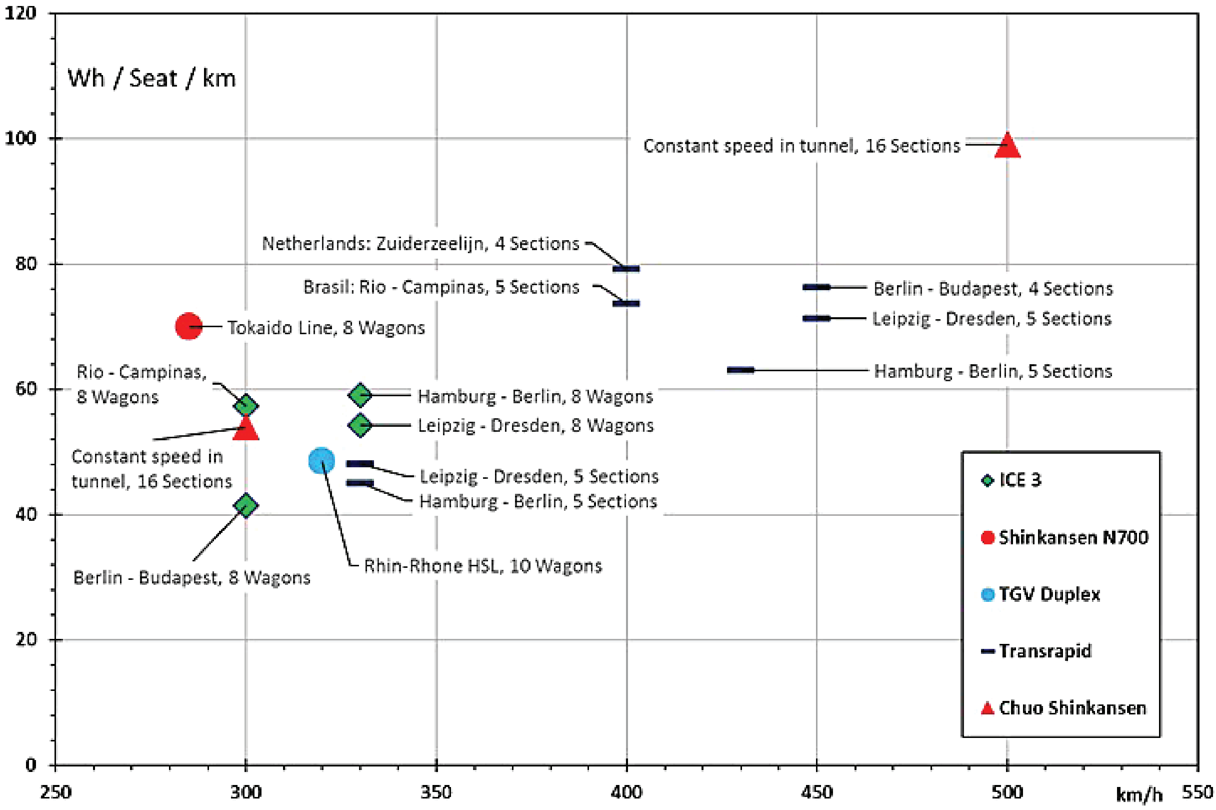

Fig. 3. Conventional representation:
Specific energy consumption of the HRS systems being considered per seat-km (Wh/Pl/km) based on the projects under study. Note on distortion: Different vehicle sizes and seat numbers are being compared. The speed range below 250 km/h is not shown

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

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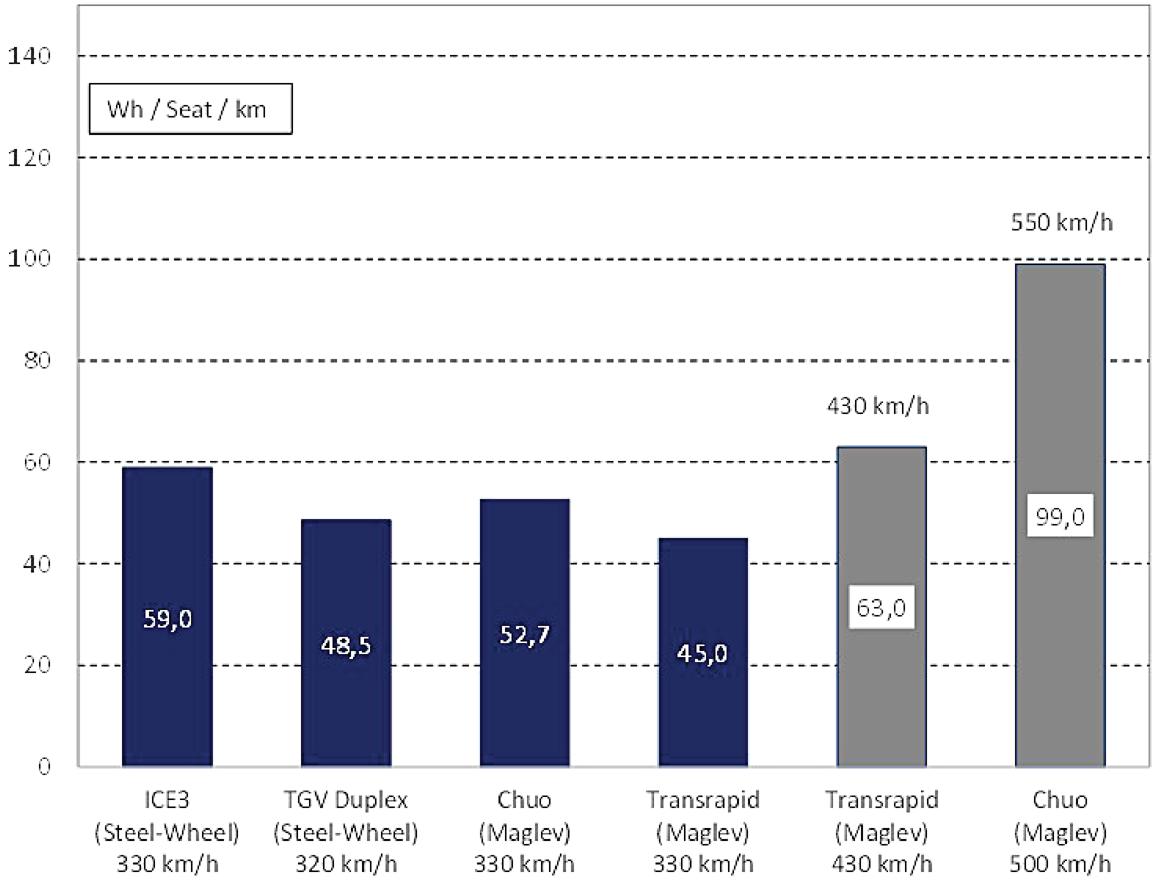

Fig. 4. Specific energy consumption in Wh per seat-km (Wh/Pl/km) at 330, 430 and 500 km/h (conventional representation)

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

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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.

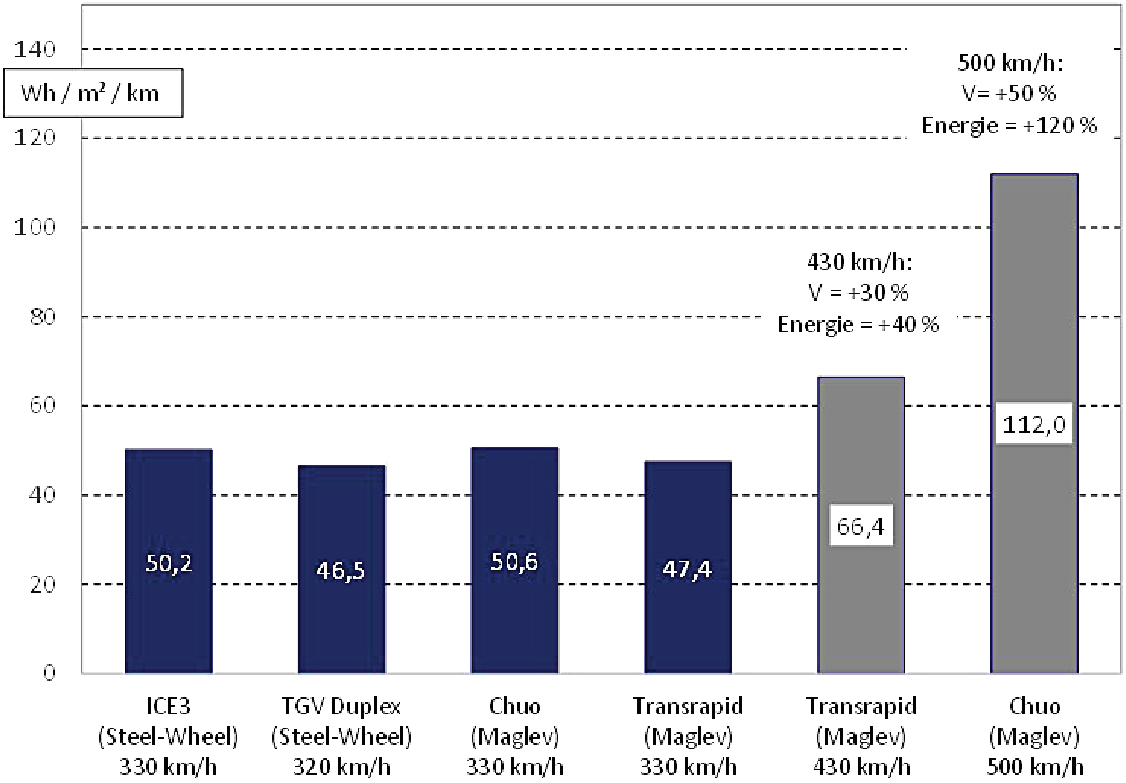

Fig. 5. Specific energy consumption per m²-km of system-typical effective area at 330 km/h and 500 km/h

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*

Received: 03.09.2018. Revised: 03.09.2018. Accepted: 17.11.2018.
Transportation Systems and Technology. 2018;4(3 suppl. 1):134-155

doi: 10.17816/transsyst201843s1134-155

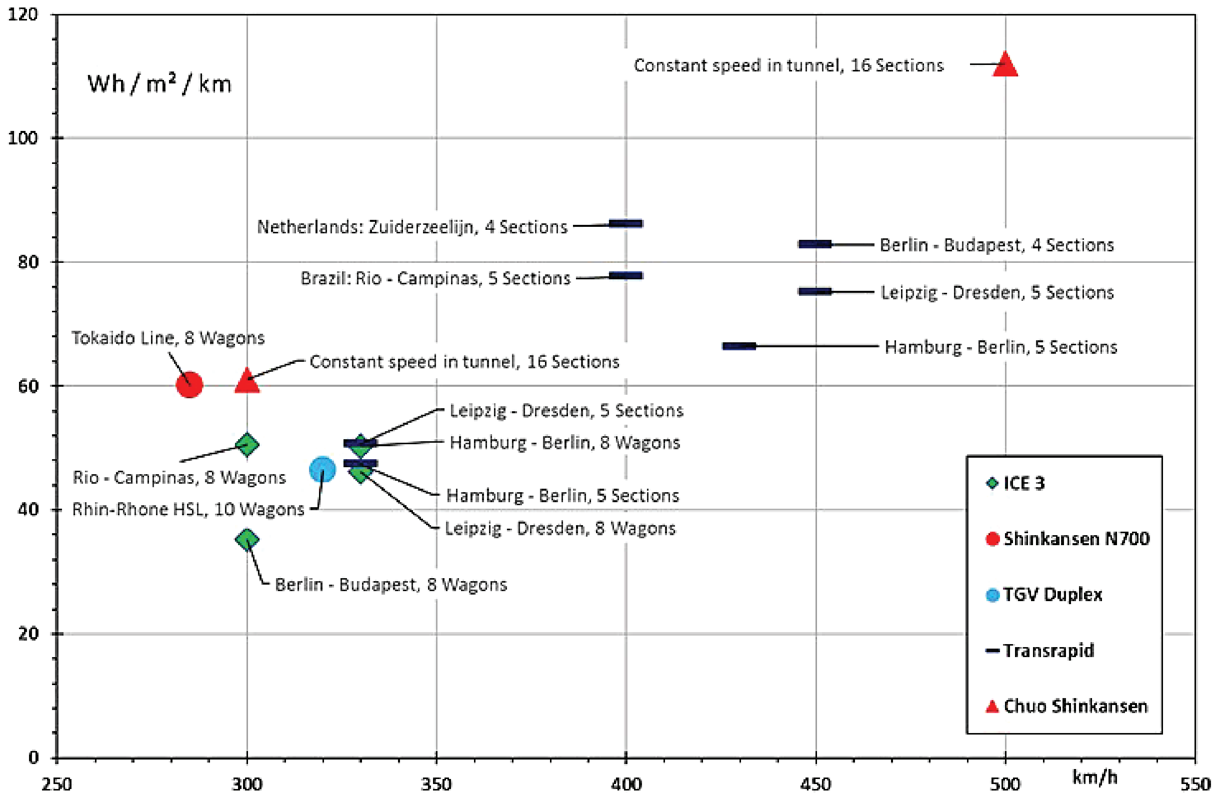

Fig. 6. Specific energy consumption of the HSR systems being considered in Wh per m²-km (system typical effective area) for various applications (projects). Comment: The speed range under 250 km/h is not shown here for purposes of better readability

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

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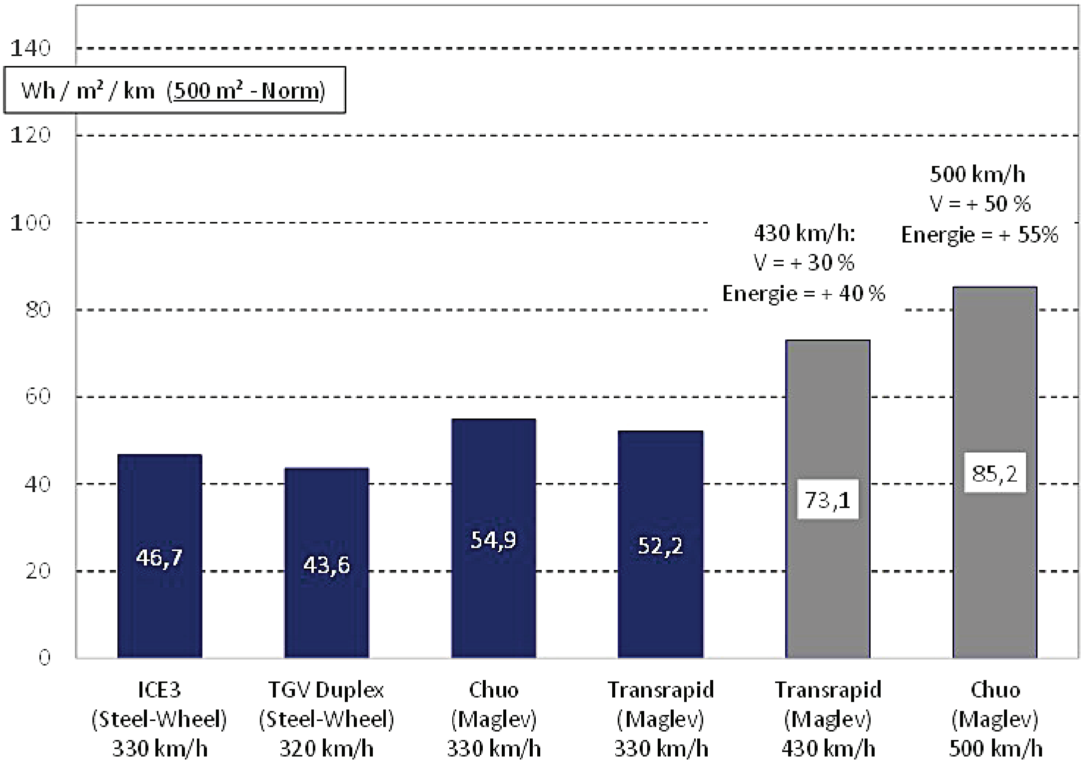

Fig. 7. Specific energy consumption per m²-km at 330 km/h to 500 km/h, calculated for a typical system effective area of 500 m² per system

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

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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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To cite this article:
Blow L, Fritz E, Kircher R, Klühspies J, Witt M. Energy Consumption of Track-Based High-Speed Trains: Maglev Systems in Comparison with Wheel-Rail Systems. *Transportation Systems and Technology.* 2018;4(3 suppl. 1):134-155. doi: 10.17816/transsyst201843s1134-155