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Analysis and Modelling Performance of the SC (Super Conducting) Maglev Line/System

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Abstract

The Maglev systems are characterised by their infrastructural, technical/technological, operational, economic, social, environmental, and policy performances. These can be represented by the indicators reflecting the main stakeholders' preferences under given conditions. The objectives of this paper are to develop analytical models for indicators of these performances and apply them to the case of the SC (Superconducting) Maglev line/system, assumed to operate according to the still hypothetical "what-if" scenarios. Regarding the fact that the line/system is not yet implemented and operational, the models use inputs compiled from the secondary sources implying considering the corresponding results, rather illustrative, a basis for further research, and useful for comparing with the available official ones when they are available. The SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis based on the results from the application of the models of indicators to the given case is applied for the qualitative evaluation of the potential advantages and disadvantages of the given Maglev line/system for their comparison to the wheel-rail HSR (High-Speed Rail) system.

Keywords: SC (Super Conducting) Maglev line/system, Performances, Analysis, Modelling, Indicators, SWOT (Strengths, Weaknesses, Opportunities, Threats) Analysis, Evaluation.

Introduction

The Maglev (Magnetic Levitation) system is an advanced technology transport system in which magnetic forces lift, propel, and guide a vehicle/train over specially designed guideways. The system uses two sets of magnets, one to repel and push the train off the track as levitation, and the other to move the floating train ahead [1]. The high-speed Maglev systems (> 400 km/h) are designed to operate in interregional (long-distance) routes. As such they have generally been expected to provide savings in the passenger's time, higher comfort, and lower impacts on the environment and society compared to the potential competitors - road cars, High-Speed Rail (HSR), and Air Passenger Transport (APT).

The development of Maglev transport lines/systems has a relatively long history spanning over a century. Most efforts have been made in Germany and Japan [2]. At present, six Maglev systems around the world carry out commercial transport and three are under construction by the year 2021/24. The total length of lines of the existing Maglev systems is 75.3 km and that under construction is 302.8 km, which gives their total length of 378.1 km from the year 2034/35 when the SC Shinkansen Chuo Maglev line/system between Tokyo and Nagoya (Japan) is expected to start commercial services [3, 4].

In addition to this introductory section, the paper consists of five other sections. Section 2 briefly describes the Maglev line's/system's main components and performances. Section 3 deals with analytical modelling indicators of the performance of the given Maglev line/system. Section 4 presents an application of the models of indicators of performance to the given SC Maglev line/system, assumed to operate according to a hypothetical "what-if" scenario. Section 5 presents a qualitative evaluation of the advantages and disadvantages of the given Maglev compared to the competitive HSR line based on the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis [5]. The last Section presents some conclusions, including existing achievements, constraints, and prospective research.

Components and Performances of Maglev Line/System

Components

The Maglev line(s)/system(s) comprise the physical supply and demand components. The supply component embraces the sub-components such as infrastructure, supporting facilities and equipment, rolling stock/trains, and directly, and indirectly operating staff. The demand component embraces the users/passengers to be transported between their origins and destinations under given conditions, i.e., those attracted/shifted from the existing transport modes/systems, and the system's self-generated.

The non-physical/virtual components are the messages with different information circulating through the systems enabling decision-making by the stakeholders directly involved - the system's operators and users/passengers [6].

Performances

The Maglev line/system in the given context is generally characterized by its infrastructural and technical/technological, operational, economic, social, environmental, and policy performance [7, 8].

- Infrastructural and technical/technological performance is specified by the design of infrastructure - lines/guideways and stations/terminals, vehicles/trains, and supporting facilities and equipment.
- Operational performance relates to the user/passenger demand, transport serving it, and their relationship, materialized as the quality of services.
- Economic performances relate to the capital/investment costs in the Maglev infrastructure/guideways and rolling stock/trains, their operating costs, revenues, profits/losses, and socioeconomic effects/benefits as direct and indirect contributions to local and national Gross Domestic Product (GDP).
- Environmental and social performance relates to the physical impacts of the Maglev lines on the environment and society, and related costs as externalities.
- Policy performances mainly relate to the general acceptance of the Maglev lines by the potential main stakeholders involved.

Although they are inherently dependent and influential on each other the above-mentioned performances of the Maglev line(s)/system(s) are frequently considered individually. In general, these performances and their indicators are of relevance generally users/passengers, investors, infrastructure and rolling stock/trains providers, transport service operators, local, regional, and national communities, and policymakers. Except for users/passengers, the other stakeholders can use them for planning and operational, and policy purposes.

Modelling Performance of Maglev Line/System

Literature Review

From the academic/professional perspectives, the Maglev systems have been under investigation for a long time; their performances have been modelled and estimated, but presented mostly fragmentarily [9]. Some research related to the scope of dealing with the set of performances in this paper have been for example i) general and infrastructural; ii) technical/technological; iii) operational; iv) economic; v) environmental and social; and vi) policy [10-15].

Objectives of the Research

The research objectives in this paper are to analyse and develop analytical models of performance indicators for a given SC (Superconducting) Maglev line/system, implicitly reflecting the assumed preferences of the main stakeholders involved. In particular, the generic but modified analytical models generally applicable to most rail-based systems have been chosen and elaborated from the transport and traffic engineering and planning perspective [16-20]. The scope of dealing with the performances and models of indicators, in addition to their estimation, aims at enabling qualitative evaluation of the given yet non-implemented SC Maglev line/system when compared with its HSR alternative counterpart. The appropriate evaluation tool, in this case, is the SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis. Therefore, the proposed approach extends beyond the scope of the existing research by applying a well-established but necessary modified methodology to a novel (wider) scope and to the case of the yet non-implemented and non-operational SC Maglev line/system operating according to the specified "what-if" scenarios [21-23].

Assumptions

The analytical models of indicators of the performance of the given Maglev line are based on the following assumptions

- The Maglev line/system as an alternative competes with the existing ones (primarily wheel-based High-Speed Rail (HSR)) operating between common origins and destinations during the specified period under given conditions.
- The indicators of infrastructural and technical/technological performances of the Maglev line are specified by design.
- The indicators of operational performance are based on the "what-if" scenarios of operating the Maglev line/system, given the indicators of infrastructure and technical/technological performance.
- The indicators of economic, environmental, and social performances of the Maglev ine/system are mainly driven by the indicators of operational performance.
- The indicators of policy performances reflect the eventual barriers to the implementation and operation of the given Maglev line/system, which are not elaborated.

Models of Indicators of Performance

Infrastructural Performance

Design

The indicators of infrastructural performance are represented by the design of the Maglev lines - guideways and terminals/stations. The specific parts of the Maglev line are tunnels and their design [24-27]. In addition to the indicators by design, the operation-related indicators can be the traffic capacity of the Maglev line(s), their segments, end terminals and stations along the line(s).

Line capacity

The capacity of a given Maglev line is defined as the maximum number of trains, which can safely pass in the same direction through the selected "reference location" under given conditions, i.e., usually constant demand for service. This rather theoretical capacity is:

$$\mu(\tau) = \frac{\tau}{\tau_{ij/min}} \qquad \text{(trains/h)} \qquad (1a)$$

were

$$\tau_{ij/min} = \tau_{b/j} + \frac{v_j}{2 \cdot a_j^-} + \frac{S_{b/j} + l_i}{v_j} \quad \text{(min)} \quad (1b)$$

were

i, j is leading and trailing train, respectively, in the sequence of two successive trains (ij) passing through the "reference location";

$\tau_{i\,j/min}$ the minimum time interval between the successive trains (i) and (j) moving in the same direction, passing through the "reference location" (min); and

τ is the period for calculating the route/line capacity (h, day);

$\tau_{b/j}$ is the time of activating the brakes of tr ailing train (j) (s);

v_j is the maximum operating speed of the trailing train (j) (km/h);

a^- is the average deceleration rate of the trailing train (j) at the maximal braking rate (m/s²);

$S_{b/j}$ is the "buffer" distance between trains (i) and (j) at the time when trailing train (j) stops behind train (i); and

l_i is the length of the leading train (i) (m).

Capacity of the stations on the line

The time of the Maglev train's passing through the station:

$$\tau_{ij/s/min} = \tau_{i/s} + \frac{v_i}{2 \cdot a_i^+} \quad \text{(min)} \quad (2a)$$

$$\tau_{ij/s/min} = \tau_{i/s} + \frac{v_i}{2 \cdot a_i^+} + \tau_{d/j} + \frac{v_j}{2 \cdot a_j^-} \quad \text{(min)} \quad (2b)$$

In Eq. 2a) the leading train (i) stops at the station and the trailing train (j) passes through. In Eq. 2b the leading train (i) and the trailing train (j) stop at the station,

The theoretical capacity of a station on the line where Maglev trains pass through in the same direction is [8]:

$$\mu_S(\tau) = \frac{\tau}{\tau_{ij/s/min}} \quad \text{(trains/h)} \quad (2c)$$

where

$\tau_{i\,j/s/min}$ is the minimum time interval between passing successive trains (i) and (j) in the same direction through the station (s);

a^+_j is the acceleration rate of the leading train (i) (m/s²);

a^-_j is the deceleration rate of the trailing train (j) (m/s²);

$\tau_{i/s}$ is the dwell time of the leading train (i) at the station (min);

$\tau_{d/j}$ is the time of activating the brakes of the trailing train (j) (s); and

v_j is the cruising speed of the trailing train (j) (km/h);

Capacity of the terminal(s)

The capacity of a single track $\mu_{tr}(\tau)$ in Eq.3a, the terminal with the available tracks $\mu_T(\tau)$ in Eq. 3b, and the required number of tracks $N_T(\tau)$ in Eq.3c in the terminal are:

$$\mu_{tr}(\tau) = (\tau/\tau_{tr}) \quad \text{(trains/h)} \quad (3a)$$

$$\mu_T(\tau) = \sum_{k=1}^{N_T(\tau)} \mu_{k/tr}(\tau) \quad \text{(trains/h)} \quad (3b)$$

$$N_T(\tau) = \left\{ \sum_{m=1}^{M} \min\left[\mu_m(\tau); \min \mu_{m/s}(\tau)\right] \right\} \cdot \tau_{tr/m/max} \quad \text{(tracks)} \quad (3c)$$

where

$\mu_m(\tau)$ is the traffic capacity of the Maglev line (*m*) during the period (τ) (trains/h);

$\mu_{m/s}(\tau)$ is the capacity of the station of the Maglev line (m) during the period (τ) (trains/h); and

$\tau_{tr/m/max}$ is the maximum turnaround time of the Maglev trains from the line (m) in the assigned tracks in the terminal (min; h).

The turnaround time of the Maglev train in the terminal in Eq. 3a is:

$$\tau_{tr} = \tau_{ss} + \frac{l}{v_1} + \tau_b + \frac{v_1}{2 \cdot a^-} + \tau_{dwt} + \tau_{ss} + \frac{v_2}{2 \cdot a^+} + \frac{l}{v_2} \quad \text{(min)} \quad (3d)$$

where

τ_{ss} is the time to set up a route to/from the terminal including locking switches and setting signals for the train's arrival, and unlocking switches and setting signals for the train's departure (min; s);

l is the average length of a Maglev train (m);

τ_b is the time of activating the brakes of Maglev train (s);

v_1, v_2 is the entry and exit train's speed, respectively, of the terminal (km/h);

a^-, a^+ is the train's deceleration and acceleration rate at the entry and exit terminal, respectively (m/s²); and

τ_{dwt} is the dwell time of a Maglev train on a track in the terminal (s; min).

τ_{un} is the time of unlocking the track to enter another train (s).

Total capacity

The total capacity of the given Maglev line/system is:

$$\mu^*(\tau) = min[\mu(\tau); \mu_S(\tau); \mu_T(\tau)] \quad \text{(trains/h)} \quad (3e)$$

Technical/Technological Performances

The indicators of technical/technological performances of the given Maglev line/system relate to the design of Maglev train(s), the Operation Control System (OSC), and the power supply system. They are used as input for estimating the indicators of operational, economic, environmental, and social performance of the given Maglev line/system.

Operational Performances

The main indicators of the operational performance are a) the maximum and operating speed; b) user/passenger demand; c) transport capacity; d) transport work, technical productivity, productive capacity, and size of rolling stock; and e) quality of services provided to users/passengers (schedule delay, travel time (non-stop), punctuality and reliability of services).

Maximum and Operating Speed

The maximum design speed of the Maglev train in Table 1 is specified by the system's design. This maximum designed speed influences the maximum operating speed along the given line. For example, the relationship between the maximum, average operating speed, and the number of stops of the forthcoming SC Maglev Chuo Shinkansen train(s) operating according to the specified "what-if" scenarios on the line between Tokyo and Nagoya (Japan) (Travel distance: L = 285.6 km) is $v(n) = -45.686 \cdot n + 491.95$; $R^2 = 0.938$ (1 min stop per station) and $v(n) = -49.732 \cdot n + 491.98$; $R^2 = 0.924$ (2 min stop per station) (n is the number of stations; $n = 4$).

User/Passenger Demand

The user/passenger demand on the Maglev line(s) can be modelled by the commonly exclusively or in combinations used models in transportation planning such as i) regression model, ii) logistic saturation model, iii) logit model, iv) passenger demand of the category (k) using the mode/system (i) - Maglev under given conditions; and v) passenger generalized travel cost at the mode/system (i) as:

$$q_L(t) = a + b \cdot t \quad \text{(p)} \quad (4a)$$

$$q_L(t) = q_{max/L}/(1 + a \cdot e^{-b \cdot t}) \quad \text{(p)} \quad (4b)$$

$$p_{i/k/L} = e^{-c_{i/k/L}} \Big/ \sum_{i=1}^{N_L} e^{-c_{i/k/L}} \quad \text{(-)} \quad (4c)$$

$$q_{i/k/L} = p_{i/k/L} \cdot q_L \quad \text{(p)} \quad (4d)$$

$$c_{i/k/L} = vot_{k/L} \cdot \tau_{i/L} + F_{i/k/L} \quad \text{(USD/p)} \quad (4e)$$

where

L is the length of a given line/route/corridor (km);

q_L is the expected user/passenger demand on the line/route/corridor (L) during the period (τ) (p) (p - passenger(s));

a, b are the coefficients to be estimated by calibration of the model; and

$q_{max/L}$ is the saturation level of user/passenger demand on the line/route/corridor (L) (number/period);

t is the period (year of the few years of the observed period);

$c_{i/k/L}$ are the generalized travel costs of the users/passengers of the category (k) choosing the transport mode/system (i) - Maglev, in the line/route/corridor L) (USD/p);

$q_{i/k/L}$ is the user/passenger demand of the category (k) choosing the transport mode/system (i) - Maglev, in the line/route/corridor L) (p/year);

K_L is the number of categories of users/passengers travelling in the given line/route/corridor (L) (-);

N_L is the number of available transport modes/systems operating in the given line/route/corridor (L) (-);

$vot_{k/L}$ is the value/cost of time of users/passengers of the category (k) while travelling along the given line/route/corridor (L) (USD/h-p);

$\tau_{i/L}$ is the user/passenger travel time by the transport mode/system (i), Maglev, along the line (L) (single direction) (h); and

$F_{i/k/L}$ is the average fare charged by the system (i), Maglev, to the user/passenger of the category (k) for the trip along the line/route/corridor (L) (USD/p); and

p passenger(s).

By forecasting the users/passengers' demand driving variables-forces in Eq. 4a or estimating them by Eq. 4b, the total demand can be estimated for the future period. Equation 4 (c, d, e) can be used to estimate the market share and the corresponding user/passenger demand for the Maglev line/system.

Transport Capacity

The transport capacity in terms of the required service frequency to serve a given passenger demand can be estimated as:

$$f_L(\tau) = min[\mu(\tau);\ \mu_S(\tau);\ \mu_T(\tau);\ q_L(\tau)]/(\lambda_L(\tau) \cdot s_L(\tau)) \quad \text{(dep/h)} \quad (5a)$$

where

$\mu(\tau)$ is the traffic capacity of the line/route per period (τ) (trains/h or trains/day);

$\mu_S(\tau)$ is the traffic capacity of stations along the line/route (L) per period (τ) (trains/h or trains/day);

$\mu_T(\tau)$ is the traffic capacity of both end terminals of the line/route(L) per period (τ) (trains/h or trains/day);

$q_L(\tau)$ is the expected user/passenger demand on the line/route (L) during the period (τ) (p/h or p/day per dir.) (p - passenger(s); dir - direction);

$\lambda_L(\tau)$ is the average load factor of the trains scheduled on the line/route (L) during the period (τ) ($\lambda(\tau) \le 1.0$); and

$s_L(\tau)$ is the seating capacity of a train scheduled on the line/route (L) during the period (τ) (seats/ train).

Transport Work, Technical Productivity, Productive Capacity, and Required Rolling Stock/Trains

Based on Eq. 4a, the additional indicators of operational performances relevant to the SC Maglev transport service provider are:

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Transport work

$$TW_{1/L}(\tau) = f_L(\tau) \cdot s_L \cdot L \quad \text{(s-km)} \quad (5b\text{-}1)$$

$$TW_{2/L}(\tau) = f_L(\tau) \cdot \lambda_L \cdot s_L \cdot L \quad \text{(p-km)} \quad (5b\text{-}2)$$

Technical productivity

$$TP_{1/L}(\tau) = s_L \cdot \bar{v}_L \quad \text{(s-km/h)} \quad (5c\text{-}1)$$

$$TP_{2/L}(\tau) = s_L \cdot \lambda_L \cdot \bar{v}_L \quad \text{(p-km/h)} \quad (5c\text{-}2)$$

Productive capacity

$$PC_{1/L}(\tau) = f_L(\tau) \cdot s_L \cdot \bar{v}_L \quad \text{(s-km/h}^2\text{)} \quad (5d\text{-}1)$$

$$PC_{2/L}(\tau) = f_L(\tau) \cdot s_L \cdot \lambda_L \cdot \bar{v}_L \quad \text{(p-km/h}^2\text{)} \quad (5d\text{-}2)$$

Required rolling stock/trains

$$n_{RS/L}(\tau) = f_L(\tau) \cdot (\tau_{0/tr} + 2 \cdot \tau_L + \tau_{d/tr}) \quad \text{(-)} \quad (5e)$$

where

$\tau_{o/tr}$, $\tau_{d/tr}$ is the average turnaround time of a train at the beginning and the end terminal of the line (*L*), respectively (min); and

τ_L is the train's operating time along the line (*L*) in a single direction (min; h).

v) Travel time (non-stop

$$\tau_L = v_L/2a^{+} + L/v_L + v_L/2a^{-} \quad \text{(min; h)} \quad (5f)$$

where

v_L is the average cruising time along the line (*L*) (km/h);

$a^{\mp}$ is the average acceleration and deceleration rate, respectively, of the Maglev train (m/s²);

Quality of Services Provided to Users/Passengers

The main indicators of the quality of services provided on the Maglev line/route in this context are:

Schedule delay

$$sd_L(\tau) = (1/2) \cdot (\tau/f_L(\tau)) \quad \text{(min)} \quad (6a\text{-}1)$$

Punctuality of services

$$PUN_L(\tau) = f_{L/d}(\tau)/f_{L/s}(\tau) \quad (-) \quad (6b\text{-}2)$$

Reliability of services

$$REL_L(\tau) = f_{L/r}(\tau)/f_{L/s}(\tau) \quad (-) \quad (6b\text{-}3)$$

where

$f_{L/r}(\tau)$, $f_{L/s}(\tau)$ are the realized and scheduled/planned transport service frequencies on the line/route (L), respectively, during the period (τ); and

$f_{L/d}(\tau)$ are the delayed transport service frequencies on the line/route (L) during the period (τ).

Modelling of the indicators of quality of services, such as spatial accessibility of terminals/stations, convenience of booking tickets/seats, and comfort on board Maglev trains, is not considered.

Economic Performances

Total costs

The total costs of the infrastructure and transport services of the Maglev line/system (L) during the given period (i.e., usually 1 year) are expressed as:

$$C_L(t) = C_{F/L}(t) + C_{V/L}(t) \quad \text{(USD/year)} \quad (7a)$$

where

$C_{F/L}(t)$ is the fixed cost of depreciation, capital maintenance, and administration of the infrastructure and rolling stock/trains of the Maglev line (*L*) during the given period (year) (USD/year);

$C_{V/L}(t)$ is the operating costs of infrastructure (regular maintenance) and rolling stock/trains (energy, maintenance, staff, infrastructure charges) of the Maglev line (L) during the given period (USD/year); and

t is the period (1 year).

The average annuities on loans for building and capital maintenance of the Maglev line (L) and acquiring and maintaining the rolling stock/trains are:

$$\bar{C}_{F/L}(t) = \frac{C_{1L} \cdot i_1}{1-(1+i_1)^{-N1}} + \frac{C_{2L} \cdot i_2}{1-(1+i_2)^{-N2}} + \frac{C_{1RS} \cdot i_3}{1-(1+i_3)^{-N3}} + \frac{C_{2RS} \cdot i_4}{1-(1+i_4)^{-N4}} \quad \text{(USD/year)} \quad (7b)$$

where

C_{1L} are the investments for building the Maglev line/system (*L*) (USD);

i_1 is the interest rate on the bonds for investments for building the Maglev line/system (L) (decimal per cent);

N_1 is the service time, i.e., the age of the Maglev line/system (L) (years);

C_{2L} are the investments for the capital maintenance (renewal) of the Maglev line/system (L) (USD);

i_2 is the interest rate on the bonds for investments in the capital maintenance of the Maglev line/system (L) (decimal per cent);

N_2 is the time, i.e., the age of the capital maintenance of the Maglev line/system (L) (years);

C_{1RS} are the investments for acquiring the Maglev rolling stock/trains (USD);

i_3 is the interest rate on the bonds for investments for acquiring the Maglev rolling stock/trains (decimal per cent);

N_3 is the time, i.e., the age of the Maglev rolling stock/trains (years);

C_{2RS} are the investments for the capital maintenance (renewal) of the Maglev rolling stock/trains (USD);

i_4 is the interest rate on the bonds for investments for capital maintenance of the Maglev rolling stock/trains (decimal per cent);

N_4 is the time, i.e., the age of the capital maintenance of the Maglev rolling stock/trains); and

t is the year of the periods *(N1), (N2), (N3)*, or *(N4)*.

The acquiring and capital maintenance costs of the rolling stock/trains depend on the number needed to operate on the given line (*L*). The total annual variable/operating cost of the rolling stock/trains operating on the Maglev line/route (*L*) in the year *(t) (t= 365 days)* of the observed period of (N_4) years generally embraces the fixed (commercial, stations, management) and the variable (mainly operating staff and energy consumption) costs as:

$$\bar{C}_{V/L}(t) = t \cdot c_{L/t} \cdot f_{L/t}(\tau_t) \quad \text{(USD/year)} \quad (7c)$$

where

t is the period in which the costs are counted (year);

$c_{L/t}$ is the average operating cost per departure of a Maglev train on the line (*L*) in the year *(t)* of the observed period.

Average cost

The total average cost of the Maglev line (*L*) per unit of transport work carried out, respectively, is:

$$\bar{c}_{1/L}(t) = \frac{C_{T/L}(t)}{t \cdot \tau \cdot f_L(,\tau) \cdot s \cdot 2L} \quad \text{(USD/s-km)} \quad (7d)$$

$$\bar{c}_{0/L}(t) = \frac{C_{T/L}(t)}{t \cdot \tau \cdot f_L(\tau) \cdot \lambda \cdot s \cdot 2L} \quad \text{(USD/s-km)} \quad (7e)$$

Revenues

The total annual revenue obtained by charging users/passengers travelling along the Maglev line/route/corridor *(L)* during the period *(t)* (USD/year) (*t* = 365 days/year) is:

$$R_L(t) = t \cdot q_L(\tau) \cdot F_L(\tau) \quad \text{(USD/year)} \quad (7f)$$

where

$q_L(\tau)$ is the average number of users/passengers travelling on the Maglev line/system (*L*) during the period (*τ*) (both directions) (passengers/day); and

$F_L(\tau)$ is the average fare charged to users/passengers travelling on the Maglev line/system *(L)* during the period *(τ)* (single direction) (USD/p).

Users/passengers "welfare"

The users/passengers' "welfare" expressed in savings of their generalized travel costs thanks to switching from the existing HSR lower to the new Maglev higher speed system introduced along the given line/route/corridor, can be estimated as [6]:

$$SC_{i/j/L}(\tau) = q_{i/j/L}G(\tau) \cdot \{vot_{i/j/L}(\tau) \cdot [(sd_{i/L} + \Delta\tau_{i/L}) - (sd_{j/L} + \Delta\tau_{j/L}] + (F_{i/L} - F_{j/L})\} \quad \text{(USD/p)} \quad (7g)$$

where

i, j is the existing lower-speed HSR and the new higher-speed Maglev system, respectively;

$q_{i/j/L}$ is the user/passenger demand switching from the exist-

ing lower-speed HSR system *(i)* to the new higher-speed Maglev system *(j)* on the line/route/corridor *(L)* during the time (τ) (p/h, day, year); and
$vot_{i/j/L}(\tau)$ is the average value of time of user/passenger switching from the existing lower-speed HSR system (i) to the new higher-speed Maglev system *(j)* on the line/route/corridor *(L)* during the time *(τ)* (USD/min-p).

Contribution to GRP and national GDP
The contribution of the Maglev line *(L)* to the regional GRP and national GDP is approximated as (USD/year):

$$R_{GDP/L}(t) = \frac{TW_{m/L}(t) \cdot GDP_r(t)}{TTW_r(t)} \quad (7g)$$

where
$TW_{m/L}(t)$ is the transport work carried out on the Maglev line (L) during the time (t) (p-km/year).
$GDP(t)$ is the GDP generated by the rail passenger transport system in the given region during time (t) (USD/year); and
$TTW_r(t)$ is the total transport work carried out by the rail passenger transport system in the given region during the time (t) (p-km/year).

Environmental Performances
The indicators of environmental performance of the Maglev line/system relate to its impact on the environment, including a) energy consumption and related Greenhouse Gases (GHG) emissions; b) land use; and c) waste [28, 29].

Energy Consumption and Greenhouse Gas (GHG) Emissions
Energy consumption
The energy consumed by the SC Shinkansen Maglev train carrying out the non-stop transport service along a given flat and straight line (L) in a single direction is:

$$E_{L/TOT}(L) = (1/\eta) \cdot [E(L_a) + E(L - L_a - L_d) + E(L_d)] \quad (J) \quad (8a)$$

and

- Acceleration

$$E_a(L_a) = 0.5mV^2 + \left\{\left[\left(\frac{V_l}{V}\right)C_R + \left(1 - \frac{V_l}{V}\right)mg\right] + F_g + F_d(V) + 0.5\rho V^2 A\, C_A\right\} \cdot L_a \quad (J) \quad (8b\text{-}1)$$

- Cruising

$$E_c(L - L_a - L_d) = [F_g + F_d(V) + mg + 0.5\rho V^2 AC_A] \cdot (L - L_a - L_d) \quad (J) \quad (8b\text{-}2)$$

- Deceleration

$$E_d(L_d) = (1 - p_{reg}) \cdot 0.5mV^2 + \left\{\left[\left(\frac{V_l}{V}\right)C_R + \left(1 - \frac{V_l}{V}\right)mg\right] + F_g - F_d(V) - 0.5\rho V^2 AC_A\right\} \cdot L_d \quad (8b\text{-}3)$$

and

$$L_a = V^2/2 \cdot a^+ \text{ and } L_d = V^2/2 \cdot a^- \quad (8b\text{-}4)$$

where
η is the overall (traction) system efficiency of a Maglev system (η ≤ 1.0);
L, L_a, L_d is the length of the line/route, acceleration, and deceleration distance of the Maglev train(s) (m);
m is the total mass of a train (kg);
g is the gravitational constant (m/s²);
V is the cruising speed of a Maglev train (m/s);
V_l is the speed at which the levitation force is fully established (m/s);
C_R, C_D is the coefficient of rolling and aerodynamic resistance, respectively, of the Maglev train;
ρ is the air density (kg/m³);
A is the frontal area of a Maglev train (m²);
p_{reg} is the proportion of returned energy during the regenerative braking (-).
a^+, a^- is the constant acceleration and deceleration rate, respectively, of the Maglev train (m/s²); and
F_g, $F_d(V)$ are the onboard generating and magnetic resistance force, respectively; and
J, kJ is Joule (kgm²/s²), kilo Joule (103 J) (1 J = 2.77778 · 10-7 kWh).

During the acceleration phase, the SC Shinkansen Maglev train uses the wheels until the levitation force is established at the speed (V_l). After that, the rolling resistance force disappears, and the levitation force continues to act [30]. A similar process occurs during the deceleration phase, but in the reverse order. If the train operated at a speed lower than the speed (V_l) during the entire trip, a sufficient levitation force does not exist, but the rolling resistance force acts instead. From Eq. 8a, the verge energy consumption (J/s-km is:

$$e_{L/OT} = E_{L/TOT}(L)/(s \cdot L) \quad (J/s\text{-}km) \quad (8b\text{-}5)$$

GHG Emissions
The total and average per trip (tonCO_{2e}/departure) and per unit of transport work (gCO_{2e}/s-km), respectively, along the given line (L) in a single direction from Eq. 8a are:

$$EM_{L/GHG} = E_{L/TOT} \cdot r_{GHG} \quad (gCO_{2e}/s\text{-}km) \quad (8c\text{-}2)$$

$$\overline{em}_L(\tau, s) = EM_{L/GHG}/(s \cdot L) \quad (kgCO_{2e}) \quad (8c\text{-}1)$$

where
r_{GHG} is the GHG emission rate from the national/regional power grid (kgCO²e/J); and
s is the average seating capacity per scheduled departure of Maglev train(s) along the given line/route/corridor (L) (seats/dep).

Land use
The Maglev system's infrastructure occupies the land taken for building the lines/guideways and terminals/stations. The largest proportion of land is generally taken for building the lines/guideways, and can be approximately estimated as (ha or km²):

$$LU_L = L \cdot D \quad (km^2) \quad (8d)$$

where
D is the width of the cross-section of the line/guideway/corridor (m); and
L is the length of a line/guideway (m).

Waste
The waste generated by operating the Maglev line/system can be expressed by the average quantity of generated waste per unit of transport work (kg or tons/p-km) carried out during a given period *(t)* (year) under given conditions as:

$$\bar{w}_L(t) = \frac{W_L(t)}{TW_{1/L}(t)} \quad (kg/s\text{-}km) \quad (8e)$$

where
$W_L(t)$ is the total quantity of waste generated by the Maglev

line/system *(L)* during the period *(t)* (year)

Social Performances

The indicators of social performance generally relate to the Maglev line/system relate to impacts on the general society, including a) noise; b) congestion and delays; and c) traffic incidents/accidents (safety).

Noise

The noise of the Maglev trains can primarily be materialized as aerodynamic noise. This implies that the experienced noise mainly depends on the level generated by the source, i.e., passing by train(s) and their distance from an exposed population/observer(s). Thus, the noise, depending on the distance between a passing train and the potentially affected observer(s), is estimated as:

$$L_{AE}[r(t)] = L_{AE}(\gamma) - 20log_{10}[r(t)/\gamma] \quad \text{(dBA)} \quad (9a)$$

where

t is the time of passing by trains at the distance $(r(t))$ and (γ) (s; min);

$L_{AE}[r(t)]$, $L_{AE}(\gamma)$ is the noise from the source at the distances r(t) and (γ), respectively (dBA);

γ is the reference right-angle distance between the measurement location and the passing train (usually $\gamma = 25$ m); and

$r(t)$ is the time-dependent distance during approaching, passing, and moving away Maglev train and an observer $(\gamma \leq r(t))$ (m).

Congestion and Delays

Thanks to the controlling successive Maglev trains operating simultaneously along the line in the same direction, the system is assumed to be free of congestion and consequent delays under regular operating conditions.

Traffic Incidents/Accidents (safety)

Similarly, as with the road-based system, the number of perceived incidents/accidents of the rail-based systems, including the Maglev line/system operating during a given period is:

$$n_{L/ac}(t) = ac_{L/r} \cdot t \cdot f_L(\tau) \cdot s \cdot L \quad \text{(events)} \quad (9b)$$

where

acr *(L)* is the train incident/accident rate along the line/route/corridor *(L)* (events, fatalities, injuries/p-km).

Applications of Models of Indicators of Performance

The Case

The above-mentioned models of the indicators of performance are applied using the data from the case, the forthcoming SC Shinkansen Chuo Maglev line/system (Japan). It was initially planned to start commercial services in 2027 but was recently postponed to the year 2034/35 [31]. Figure 1 shows the simplified horizontal layout of the line/system.

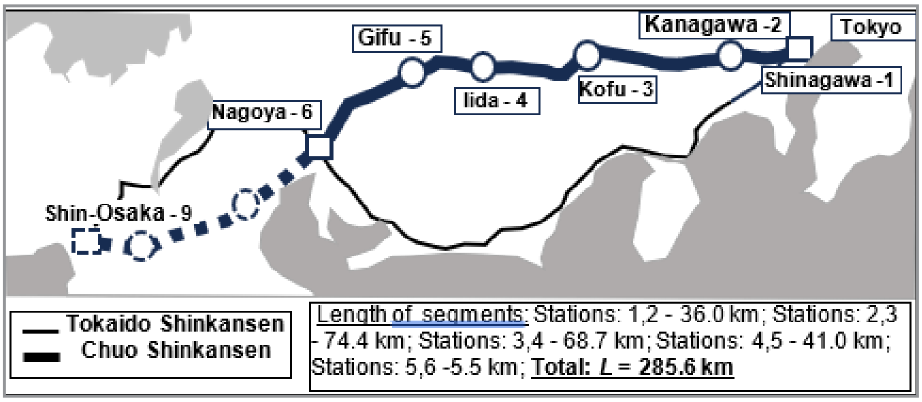


Figure 1: Horizontal layout of SC Shinkansen Chuo Maglev line/system

Because of the scarcity and inherent unreliability of these data and the lack of rather realistic operating scenarios, the assumptions on using these data and the "what-if" operating scenarios of the line/system are as follows:

- The SC Shinkansen Chuo Maglev line/system spreads between Tokyo and Nagoya (Japan) where the commercial services expected are to compete exclusively with the current Tokaido Nozomi Shinkansen services for the period 2034/37-2050 (the competition with the road-based passenger cars and APT system is not considered).
- The infrastructural and technical/technological indicators of the SC Shinkansen Chuo Maglev line/system are given by its design [32, 33].
- The transport services of both systems operate along the corresponding lines/routes between the end terminals without intermediate stops.
- The passenger demand for the SC Shinkansen Chuo Maglev is assumed to consist of i) the shifted demand from the existing and forecasted Tokaido Nozomi user/passenger demand analysed and forecasted by the logistic saturation model; the shift of this demand to the SC Shinkansen Chuo Maglev is carried out through a competition based on the generalized travel costs where the average fare per travel is assumed to be approximately comparable at both systems; and ii) the self-generated user/passenger demand by the SC Shinkansen Chuo Maglev estimated from the regression models.
- The market share of the SC Shinkansen Chuo Maglev line/system based on the generalised travel costs is assumed to remain constant during the observed period (2027/34 - 2050).
- The SC Shinkansen Chuo Maglev line/system operates the homogenous rolling stock/trains in terms of the seating capacity and constant average load factor during the observed

period (2027/34 - 2050); and

- The costs of the SC Shinkansen Chuo Maglev line/system are known during the observed period (2027/34-2050).

Inputs

Infrastructure Performances

The main inputs for estimating the indicators of infrastructure performance of the SC Shinkansen Chuo Maglev line/system - capacity of line, terminal(s), and station(s) along the line are given in Table 1.

Table 1: Inputs for estimating indicators of infrastructural performance of the SC Shinkansen Chuo Maglev line (Japan)

Line/route/corridor	Tokyo-Nagoya
System	SC Maglev Chuo Shinkansen
Length of route - L (km)	285.6
Length of train - l (m)	299
Time of activating brakes of the train - τ_b (s)	6
The “buffer” distance between the stopping trains - S_b (m)	150
Maximum train operating speed - v_L (km/h)	505
Train acceleration/deceleration rate - $a^{\pm}$ (m/s^2)	0.7
Entry and exiting train’s speed at end terminals - v_1, v_2 (km/h)	160
Time for entry/exit route setup - τ_{ss} (min) Terminal dwell time - τ_{twd} (min)	0.5-1.0 12

Technical/Technological Performance

The indicators of the technical/technological performance of the SC Shinkansen Chuo Maglev line/system by design as inputs for estimating operational, economic, environmental, and social performance are given in Table 2.

Table 2: Inputs as indicators of the technical/technological performances by the design of SC Shinkansen Chuo Maglev train(s) (Case of the line/system Tokyo and Nagoya (Japan)

Component/specification	SC Shinkansen Chuo Maglev
	
Train length/composition (m)	299 (12 cars)
Car length (m)	28 (end cars); 24.3 (intermediate cars)
- Width (m); Height (m)	2.9; 3.1
Seats/train (average)	728
Empty weight/train (tons)	30/end car; 25/intermediate car;
2·30 + 10·25 = 310	30/end car; 25/intermediate car; 2·30 + 10·25 = 310
Levitation/Suspension	
Type; Primary; Secondary; Princip; Gap (mm)	EDS (Repulsive force). Electrodynamic; Mechanical.
Superconducting magnets on trains and coils on track;100 -150	
Propulsion	
Motor type; Power (MW)	Linear synchronous; ≈ 18/19 [1)]
Power Supply/Transfer	
Electricity	33 kV AC ~50 Hz induction
Operations	
Maximum design speed (km/h)	505
Acceleration/deceleration (m/s^2)	0.7/1.0

[1)] Based on the acceleration of a^{+} = 0.7 m/s; 80 kg/passenger

Operational Performance

User/passenger demand

The user/passenger demand is analysed and forecasted for the Tokaido Shinkansen HSR line for the period 2000-2019 and 2027-2050, respectively, as shown in Fig. 2. This is considered to remain as the exclusively competing alternative to the SC Shinkansen Chuo Maglev line Tokyo-Nagoya, which, once implemented, is expected to take over some of this demand under given conditions.

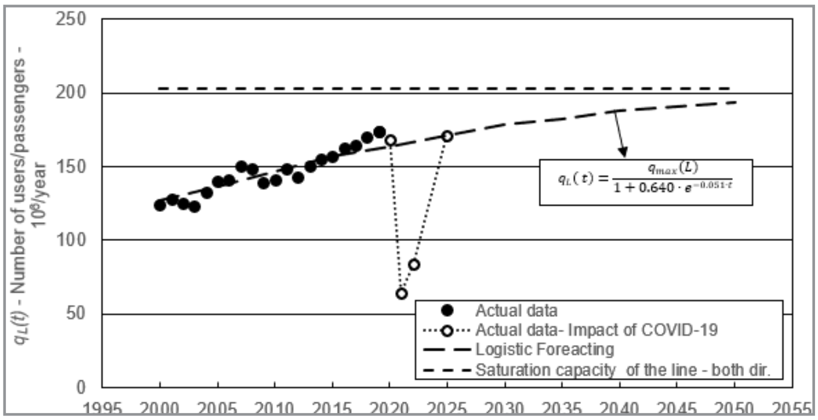


Figure 2: Development of the user/passenger demand on the Shinkansen Tokaido line Tokyo - Nagoya - Shin Osaka (Japan - Period: 2000-2050) [34-37].

During the period 2000-2019, this demand continuously grew before being severely affected by the impact of the COVID-19 pandemic during the years 2020-2022. Assumed to fully recover by the year 2025/26 to the level close to that in 2019, this demand is forecasted to continue to increase but at a decreasing rate during the period 2025-2050, and to approach the level of saturation of the capacity of the line, estimated to be about qmax (2050) = 203.5 million passengers/year. The average share of user/passenger demand of the Shinkansen Tokaido Nozomi services in the total number of users/passengers on this line has been about 14% and is assumed to remain constant during the observed future period (2027/34-2050) [38].

Transport Capacity

The inputs for estimating indicators of the operational performance of the Tokaido Nozomi and SC Shinkansen Chuo Maglev line/system for the period 2027/34-2050 are given in Table 3.

Table 3: Inputs for estimating as indicators of the operational performance of Shinkansen Tokaido Nozomi and SC Shinkansen Chuo Maglev line/route (Japan)

Line/Route/Corridor	Tokyo-Nagoya	
System	Tokaido Nozomi Shinkansen	SC Maglev Chuo Shinkansen
Line operating time - Δτ (h/day)	18	18
Frequency - $f_L(\tau)$ (dep/h)	4	1
Average travel time - τ_L (min/dir.) 1)	100	40

1) Without stops at the intermediate stations

Economic Performances

The CJRC (Central Japan Railway Company) has initially estimated the total investment costs of constructing the SC Shinkansen Chuo Maglev line of L = 285.6 km between Tokyo and Nagoya of about $C_{IL} = 64 \cdot 10^9$ USD [32]. The service and maintenance ages are specified to be $N_1 = N_2 = 40$ years. The acquisition costs of rolling stock/trains would be $C_{2RS} = 65.3 \cdot 10^6$ USD/train (maintenance costs/year = 10% of the acquisition costs), and the service and maintenance age $N_3 = N_4 = 30$. The bond interest rate is assumed to be i = 5% for infrastructure and rolling stock. The average train operating cost is assumed to be c_0 = 0.15894 USD/s-km [39-42]. Also, the average value of user/passenger time for both systems - Tokaido Nozomi and SC Maglev Chuo Shinkansen, based on the average salary in Japan (2022), is estimated to be vot = 0.278 USD/min-p [43]. The price of the Nozomi services has been F_L = 120-140 USD/p. That of the SC Maglev Chuo is assumed to be approximately the same [44].

Environmental and Social Performances

Table 2 provides the part of inputs for estimating environmental performance indicators such as energy consumption and related GHG emissions. An additional input is the rate of GHG emissions from the power grid in Japan during the period 2027/34-2050, which will be dependent on the share of renewable primary sources for producing electric energy [45, 46].

Since the SC Shinkansen Chuo Maglev line, stations, and terminals are mainly (about 87%) underground constructions, the inputs for land use are not particularly considered. The same relates to the impacts of noise and waste, the latter expected to be handled and managed similarly to the existing HSR system.

The completely automated system would enable the operation of trains safely, effectively, and efficiently under regular operating conditions without congestion and delays. Like its Shinkansen Tokaido Nozomi counterpart, the SC Maglev line/system would be free of traffic incidents and accidents caused by the system's internal causes.

Results

Infrastructural Performance

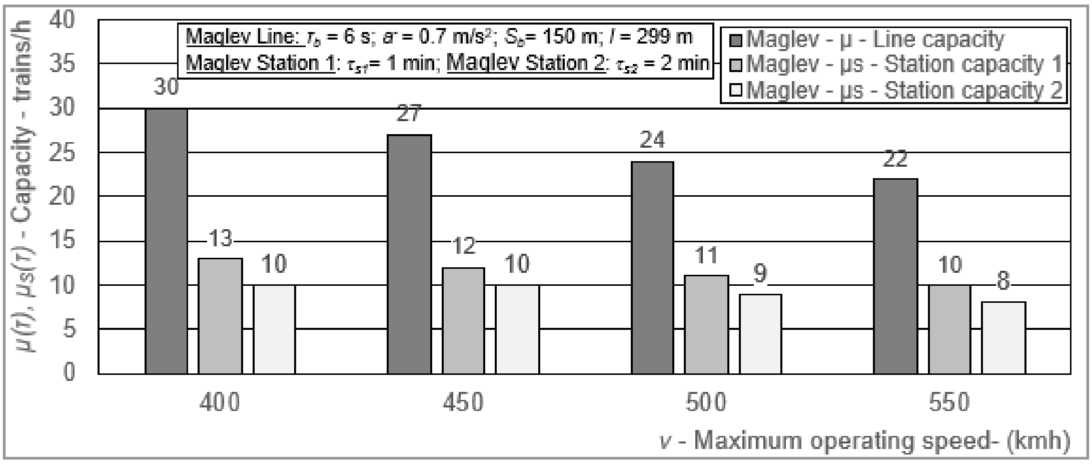


Figure 3: Relationship between the capacity of the SC Shinkansen Maglev line/route and stations, and the maximum operating on the line/route Tokyo-Nagoya (Japan - Period: 2027/34-2050)

The line capacity decreases with the increase of the maximum operating speed due to the increase in the minimum required separation between successive trains operating under the specified conditions. The station capacity decreases with the trains' dwell time at the station. Consequently, the smaller of the line capacity and the station capacity represents the capacity of the given line.

Terminal(s)

The capacity of the terminal(s9 of the SC Shinkansen Chuo Maglev line//system is calculated by Eq. 3 (a-d). The trains of the length of l = 299 m enter and leave the terminus at a speed of $v_1 = v_2$ = 200 km/h and deceleration/acceleration rate of $a^- = a^+$ = 0.7 m/s², respectively. Given the terminal's average dwell time of τ_{dwt} = 12 min and the time for the entry/exit routes set-up of τ_{sst} = 1 min, the total time of occupying the track is $\tau_{tr} \approx$ 15 min. The corresponding track capacity is $\mu_{tr}(\tau) = (\tau/\tau_{tr}) = 60/15 = 4$ trains/h. The required number of tracks will be: $N(\tau) \geq \mu(\tau) \cdot \tau_{tr} = 11 \cdot (15/60) \approx 3$ and $N(\tau) \geq \mu(\tau) \cdot \tau_{tr} = 8 \cdot (15/60) = 2$. The planned number of tracks in the SC Maglev Chuo terminals is N = 4. Given the capacity of the single track and the number of tracks, the terminal capacity is $\mu_T(\tau) = N \cdot \mu_{tr}(\tau) = 4 \cdot 4 = 16$ trains/h [31].

Total Line/System Capacity

The resulting capacity of the given Maglev line/system is calculated by Eq. 3e as the minimum of the line, stations, and terminal capacities : $\mu^*(\tau) = min[\mu(\tau), \mu_S(\tau), \mu_T(\tau)] = min(24, 11, 16) = 11$ trains/h/dir., or $\mu^*(\tau) = min[\mu(\tau), \mu_S(\tau), \mu_T(\tau)] = min(24, 9, 16) = 9$ trains/h/dir.

Line and stations

The capacity of the SC Shinkansen Chuo Maglev line, and stations along it calculated by Eqs. 3 (a-e), depending on the maximum operating speed, are shown in Fig. 3.

Operational Performance

User/passenger demand

The Tokaido Nozomi Shinkansen services shared about 14% of the total demand served by the Shinkansen Tokaido on the line/route Tokyo-Shin-Osaka, shown in Fig. 2. This share from the period 2000-2019/2023 is assumed to remain constant during the future period until 2050. The SC Shinkansen Chuo Maglev is assumed to compete to take over part of this share on the route from Tokyo and Nagoya, and later on the route Shin-Osaka during the period 2027-2050 [47].

The access/egress time to the end terminals is not considered because the stations of both systems are at identical locations (those of SC Shinkansen Chuo Maglev are underground constructions just below the existing HSR Shinkansen stations. Given the initial departure frequency and travel time in Table 3, these costs are estimated as.

Tokaido Shinkansen Nozomi: $c_{L/TSN} = 29.9$ (USD/p)
SC Shinkansen Chuo Maglev: $c_{L/SCM} = 19.2$ (USD/p)

The relative market shares of both systems are:

Tokaido Shinkansen Nozomi : $p_{L/TSN}$=0.473 (-)
SC Shinkansen Chuo Maglev: $p_{L/SCM}$= 0.527 (-)

The SC Shinkansen Chuo Maglev could count on two categories of user/passenger demand during the observed period. The first is the gradual increase of the annual user/passenger demand, shifted from the existing Tokaido Nozomi services from about 13 to 14.3 million users/passengers/year. The potentially shifted demand from competing with the road passenger cars and APT is not considered. The other category is the self-generated user/passenger demand, consisting of also gradually increasing business and tourism trips from about 16 to 21 million/year, as shown in Fig. 4.

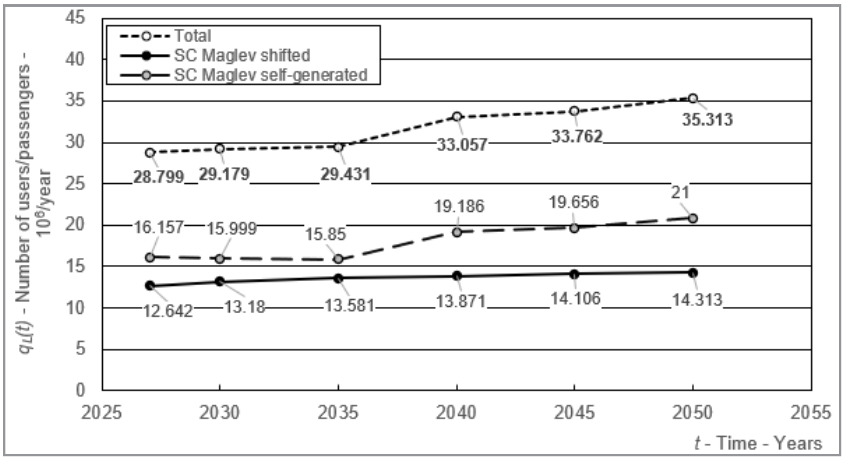


Figure 4: Indicator of the operational performances - development of the user/passenger demand of the SC Shinkansen Chuo Maglev line/route Tokyo-Nagoya (Japan - Period: 2027-2050)

The potentially attracted demand is not considered when competing with the road passenger cars and APT.

Transport capacity, transport work, technical productivity, productive capacity, and required rolling stock/trains

Based on the above-mentioned user/passenger demand, the indicators of operational performance of the SC Shinkansen Chuo Maglev system are estimated in Table 4.

Table 4: Indicators of the operational performance of the SC Shinkansen Chuo Maglev line/route Tokyo-Nagoya (Japan - Period: 2027-2050)

Indicator	Period (years)					
	2027	2030	2035	2040	2045	2050
User/passenger demand Attracted: $q_{1/L}(t)$ (10^6/yr) 1)	12.642	13.180	13.581	13.871	14.106	14.313
Self-generated: $q_{2/L}(t)$(10^6/yr) 2)	16.157	15.999	15.850	19.186	19.656	20.842
Total: $q_L(t)$ (10^6/yr) 1)	28.619	29.179	29.431	33.057	33.274	35.015
Service frequency $f_L(\Delta\tau)$ (dep/day) 3)	135	137	142	156	157	165
Schedule delay $sd_L(\tau)$ (min) 3)	8	8	7.6	7.0	7.0	6.5
Transport work $TW_L(t)$ (10^9 p-km/year)	8.171	8.334	8.405	9.441	9.503	10.001
Technical productivity $TP_L(\tau)$ (10^3 p-km/h/dir.)	319.87	319.87	319.87	319.87	319.87	319.87
Productive capacity $PC_L(\tau)$ (10^6 p-km/h^2/dir.)	1.279	1.279	1.279	1.279	1.599	1.599
Required rolling stock/trains $n_{RS/L}(\tau)$ 4)	4	4	4	5	5	5

1) Both directions shifted from Tokaido Nozomi; 2) Newly generated business and tourism trips [47]; 3) Operating time: 365 days/year; $\Delta\tau$ =18 h/day; Length of line: L = 285.6 km; Turnaround time along the line: τ_L = 1.07 h (non-stop travel time); Train composition: 12 cars/train; Seat capacity: s = 728 seats/train; Load factor: λ = 0.8 [21], [47]; 4) Rounded to integers-exclusively for operations not including reserves (All values rounded to integers where necessary).

Economic Performances

Costs and revenues

The indicators of the economic performance of the SC Shinkansen Chuo Maglev system under given conditions are given in Table 5.

Table 5: Indicators of the economic performances of the SC Chuo Shinkansen Maglev line/route Tokyo-Nagoya (Japan - Period: 2027-2050)

Indicator	Period (years)					
	2027	2030	2035	2040	2045	2050
Costs						
Infrastructure $C_{F/L}(t)$ (10^9 USD/yr) 1)	3.730	3.730	3.730	3.730	3.730	3.730
Rolling stock $C_{F/RS/L}(t)$ (10^6 USD/yr)1)	16.991	16.991	16.991	21.239	21.239	21.239
Operating $C_{V/L}(t)$ (10^9/USD/yr)2)	1.633	1.655	1.670	1.886	1.899	1.998
Total costs $C_{F/L}(t)+C_{V/L}(t)$ (10^{9} USD/yr)	5.380	5.412	5.427	5.638	5.650	5.749
Average cost $c_L(t)$ (USD/p-km)	0.658	0.649	0.646	0.597	0.595	0.575
Revenues						
Operational $R_L(t)$ (10^x USD/yr)3)	-	-	-	-	-	-
Passenger "welfare" $SGC(\tau)$ (USD/p-km) 4)	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375
Contribution to GRP $R_L(t)$ (USD/p-km)5)	0.109	0.116	0.108	0.120	0.123	0.125

1)Investment costs in the infrastructure: C_{1L} = 64 · 10^9 USD; $N_1 = N_2$ = 40 years; Acquisition price of rolling stock: C_{2RS} = 65.3 ·10^6 USD/train (maintenance costs/year = 10% of the acquisition costs); $N_3 = N_4$= 30; Interest rate: i = 5% for both infrastructure and rolling stock; 2) Average train operating cost: c_0 = 0.159 USD/s-km ; 3) Should be set up to cover the costs and provide competitiveness to Nozomi Shinkansen; 4) Based on the generalized cost function as the difference in the cost of travel time of 10.7 USD/p; 5) Based on the estimated GRP (Gross Regional Product) [48].

The total costs embrace building and maintenance of infrastructure (87% of line length would be tunnels), terminals/stations, and supporting facilities and equipment), rolling stock/trains (acquisition and maintenance), and operations (energy, supporting staff, sales, administration, etc. The total average cost (USD/p-km) is estimated based on these total costs. As can be seen, it would decrease more than proportionally during the observed period. Such a decrease would be mainly influenced by the constant annual annuities for infrastructure, increasing annuities on rolling stock/trains, and slightly increasing operational costs on the one hand, and a stronger increase in the user/passenger demand on the other. In addition, the relationship between the total average cost and the volume of SC Shinkansen Chuo Maglev transport work carried out under given conditions is shown in Fig.5.

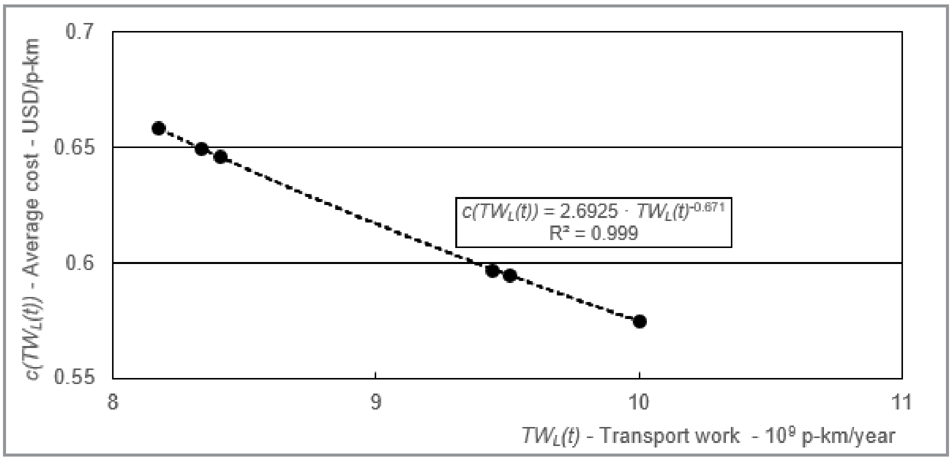


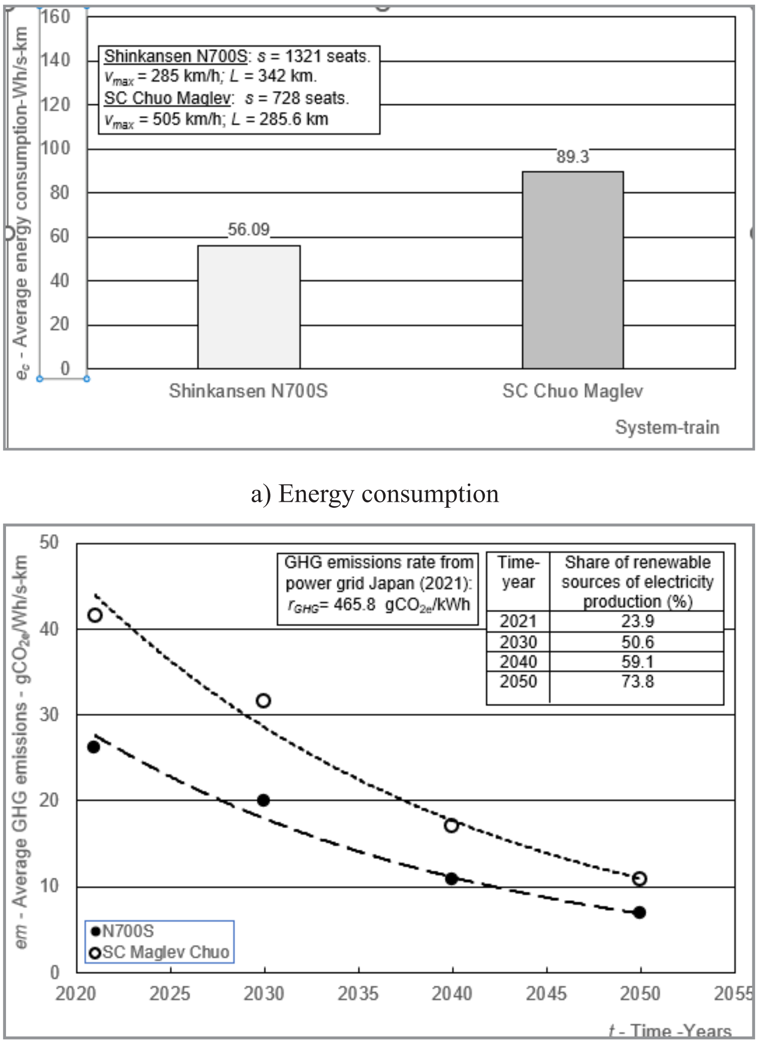
Figure 5: Relationships between the average cost and the transport work according to the "what-if" operating scenario of the SC Shinkansen Chuo Maglev line/route Tokyo-Nagoya (Japan - Period: 2027-2050).

The average costs would decrease almost more than proportionally with the increase in the annual transport work carried out (p-km). This could reflect the existence of economies of scale in the given context. If the fares were set up to just cover these costs, they would be about FL ≈ 185 USD/p in the year 2035 and FL ≈ 164 USD/p in the year 2050. These fares are higher than the existing fares of the Tokaido Nozomi services (100, 120, 140 USD/p), which could compromise the abovementioned market share of the SC Shinkansen Chuo Maglev line/system. Therefore, some subsidising of the services would be needed, also based on the "welfare" of users/passengers shifted from the Tokaido Nozomi transport services and the contribution to the GRP (Gross Regional Product) of the Tokyo Metropolitan Area (4 Prefectures), Yamanashi Prefecture, and Nagoya Metropolitan Area (3 Prefectures) [48]. In addition, according to Japan's "National Land Policy Simulation Model", the SC Shinkansen Chuo Maglev line between Tokyo and Nagoya would contribute to the improvement of the productivity of about 3.5 trillion yen/year (about 19.022 billion USD/year), which gives about 1.56 USD/p-km in the year 2050. The extension of the line to Shin-Osaka would increase this contribution to about 6.5 trillion yen/year (35.326 billion USD/year), which gives about 2.84 USD/p-km (1 USD = 184 Yen - the year 2027) [49].

Environmental Performance

Energy Consumption and GHG Emissions

The estimated energy consumption and related GHG emissions under given conditions are shown in Fig. 6 (a, b)



a) Energy consumption

b) GHG emissions

Figure 6: Average energy consumption and GHG emissions of the Tokaido Nozomi and SC Chuo Maglev line/system) [50].

The average energy consumption per unit of transport work of the SC Shinkansen Chuo Maglev train would be higher by about 59% than that of the Tokaido Nozomi counterpart under the given conditions. The average GHG (CO_{2e}) emissions also differ for the same percentage due to differences in the average energy consumption, given the rates of GHG emissions from the power grid in Japan during the period 2021-2050. Thanks to the increasing share of renewable primary sources for electricity production, the average GHG emissions of both systems would decrease more than proportionally. The costs of GHG emissions as externalities will be dependent on the carbon tax of the electricity power grid.

Land use and waste

These indicators are already explained in the description of the corresponding inputs. The SC Shinkansen Chuo Maglev line/system does not take up the substantive surface land, as it is mostly underground construction. The quantity and intensity of waste generation during the line/system operations will be even less than at its Nozomi counterpart, simply due to the shorter time users/passengers spend inside. The substantive tunnelled soil is to be mostly recycled, and the rest deposited to minimise the impacts as waste.

Social Performance

These are already explained in the description of the corresponding inputs. The SC Maglev Chuo Shinkansen line will be free of external noise, congestion and delays, and traffic incidents/ accidents under regular operating conditions.

Evaluation

Based on the estimated indicators of performance, the SC Maglev line's/system's potential advantages and disadvantages compared to the existing wheel-based HSR line, based on the SWOT analysis, are given in Table 6.

Table 6: SWOT analysis evaluation of the SC Shinkansen Chuo Maglev compared to Tokaido Nozomi line/route Tokyo-Nagoya (Japan - Period: 2050)

Indicators of performance	Advantage/Disadvantage
Infrastructural	Inferior - Mostly underground construction
Technical/technological	Superior - Innovative after being fully developed and implemented
Operational	
User/passenger demand	Comparable - Self-generated and attracted mostly from the wheel-based HSR and
Required rolling stock (vehicle units)	Superior - Shorter turnaround time along the line/route/corridor.
Transport work	Comparable/superior - Depending on the demand, train seating capacity, service frequency, and load factor
Technical productivity and productive capacity	Superior - Higher maximum and operating speed.
Load factor	Comparable - At a reasonably high level, depending on the self-generated and attracted user/passenger demand.
Quality of services	Comparable/superior - Schedule delays, reliability, and punctuality of services thanks to the fully automated operations.
Economic	
Investment costs	Inferior - Mostly underground construction of infrastructure.
Operating costs	Comparable - Transporting sufficient demand, lower maintenance and staff costs.
Users/passengers' "welfare" (generalized travel costs)	Comparable/inferior - Comparable passenger generalised travel costs if the higher fares covering higher total costs do not eliminate the effects of the shorter travel time.
Contribution to GRP and GDP	Comparable/superior - At the regional and interregional scale.
Environmental	
Energy consumption	Inferior - Generally higher operating speed.
Emissions of GHG	Inferior - Influenced by the higher energy consumption.
Land use	Superior - Mostly underground construction of infrastructure.
Social	
Noise	Superior - Mostly operating in the tunnels.
Congestion	Superior - free due to fully automated operations.
Traffic incidents/ accidents (safety)	Comparable/superior - Fully automated operations and continued experience of wheel-based HSR.
Actors/stakeholders involved	**Contribution/preference**
Users/passengers	Superior - Higher "welfare" through shorter travel time, and potentially comparable total generalized travel costs.
Investors, providers of infrastructure and rolling stock/trains	Inferior - High investment costs in both infrastructure and rolling stock.
Transport service operators	Superior - Smaller rolling stock due to the shorter turnaround time along the line/route, given the required transport service frequency and seating capacity per train's departure.
Local, regional, and national communities	Superior - Free of noise, congestion and delays, incidents and accidents, and land use, and with comparable if not higher contribution to regional GRP and national GDP.
Policymakers	Inferior - Concerned about the overall social-economic feasibility still not proven by the comparable real-life cases elsewhere.

The SC Shinkansen Chuo Maglev line/system, assumed to operate according to the given "what-if" scenario, would be "superior" according to 7, "inferior" according to 4, "comparable" according to 4, and comparable/superior according to 3 indicators of performance. Three of five categories of stakeholders would consider the SC Shinkansen Chuo Maglev line/system as "superior" and two of five as "inferior".

Conclusions

The paper presents an analysis and analytical modelling of indicators for infrastructural, technical/technological, operational, economic, environmental, social, and policy performances of the SC Maglev line/system operating under specified "what-if" scenarios. The analysis and models have been applied to the forthcoming SC Shinkansen Chuo Maglev line/system (Japan) expected to start commercial operations between Tokyo and Nagoya (Japan) in the year 2034/35. The results and qualitative evaluation by SWOT analysis indicated its potential advantages and disadvantages compared to the wheel-based HSR system competing with it from the perspective of the main stakeholders involved.

This paper is written under the circumstances which need to be considered in the further elaboration of the topic by both academics and professionals:

The considered SC Maglev line/system is under implementation, thus offering very limited information from the secondary sources, particularly on the operational scenarios. This has required developing the "what-if" operating scenarios and adapting the available input data to them for estimating the indicators of performance.

The analytical models of the indicators of performance have been developed from transport and traffic engineering scope, case-driven and modified for the hypothetical "what-if" operating scenarios of the SC Maglev system.

Evaluation of the total performance of the given SC Maglev line/system by the SWOT analysis has been qualitative rather than quantitative and, as such, left to the author's subjective judgement about the roles and preferences of the stakeholders involved.

The above circumstances have opened the space for further research, including innovative modelling of indicators, designing additional "what-if" operating scenarios, also including the SC Maglev competition with other transport modes - road-based and APT, further collecting the forthcoming, more reliable data when available, and applying the quantitative MCDM and other evaluation methods.

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Conflict of interest

The authors declare no conflict of interest.

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