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A MULTIDIMENSIONAL EXAMINATION OF PERFORMANCES OF THE FUTURE ADVANCED TRANSPORT SYSTEMS: THE ETT (EVACUATED TUBE TRANSPORT) TRM (TRANSRAPID MAGLEV) SYSTEM

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Keywords

Advanced transport systems, ETT (Evacuated Tube Transport) TRM (Trans Rapid Maglev) system, performances, multidimensional examination, sustainability

ABSTRACT

This paper presents a multidimensional examination of infrastructural, technical/technological, operational, economic, environmental, social, and policy performances of the future advanced ETT (Evacuated Tube Transport) TRM (TransRapid Maglev) system. These performances are examined, analytically modelled, and then estimated using the case of Trans-Atlantic passenger transport market currently exclusively served by the APT (Air Passenger Transport) system. The aim is to assess the ETT TRM system's competitive capabilities compared to those of the current and future APT system and potential contribution to mitigating impacts of both systems on the society and environment, i.e., sustainability of the transport sector, under given conditions.

1. Introduction

The future economy and society until and beyond the year 2050 will very likely be characterized by: i) *Continuous growth* but also *aging* of the world's population expected to reach $9\text{-}10 \cdot 10^9$; ii) *Growing developing economies* contributing to strengthening the "middle" class and consequently increasing demand for mobility in the countries like China, India, Russia and Brazil; and iii) *Urbanization* implying that by the year 2025 about two-thirds of the world's population will live in (also mega-) cities. Consequently, the future transport systems will very likely be exposed to challenges to: i) *Connect* large urban agglomerations and markets thus further fostering globalization of economic, trade, and other social/policy relationships; ii) *Provide transport services of refined quality at reasonable cost/price* regarding the very differentiated passenger needs; iii) *Further diminishing impacts on the environment and society*; and iv) *Contribution to the national and global welfare* by further increasing employment and expansion, i.e., synergies with the new technologies from other fields/areas.

The future advanced ETT (Evacuated Tube Transport) TRM (TransRapid Magelv) system seems to be one able to contribute to fulfilling the above-mentioned requirements through competition mainly with the long-haul APT (Air Passenger Transport) system. In addition, by taking over a part of the APT demand, as presumably environmentally friendlier system/mode, it would contribute to mitigating the overall transport sector-related negative impacts on the environment and society, and consequently to its - sector's more sustainable development.

In addition to this introductory, this paper consists of four other sections. Section 2 describes the main components and concept of performances of an ETT TRM system. Section 3 deals with multidimensional examination and modelling of these performances. Section 4 presents an application of the proposed approach to the given long-haul passenger transport where an ETT TRM competes with the APT system according to the "what-if" (hypothetical) scenarios. The last section summarizes some conclusions.

2. The Components and Concept of Performances of an ETT TRM System

The concept of ETT TRM defined as a very high speed long-haul transportation system had been elaborated for a long time [1]. Its main components are vacuumed tubes, TRM trains, and supporting facilities and equipment for the energy supply, maintaining vacuum in the tunnels, train/traffic control/management systems, and fire protection system. They all influence the ETT TRM system's infrastructural, technical/technological, operational, economic, environmental, social and policy performances, and vice versa, shown in Fig. 1.

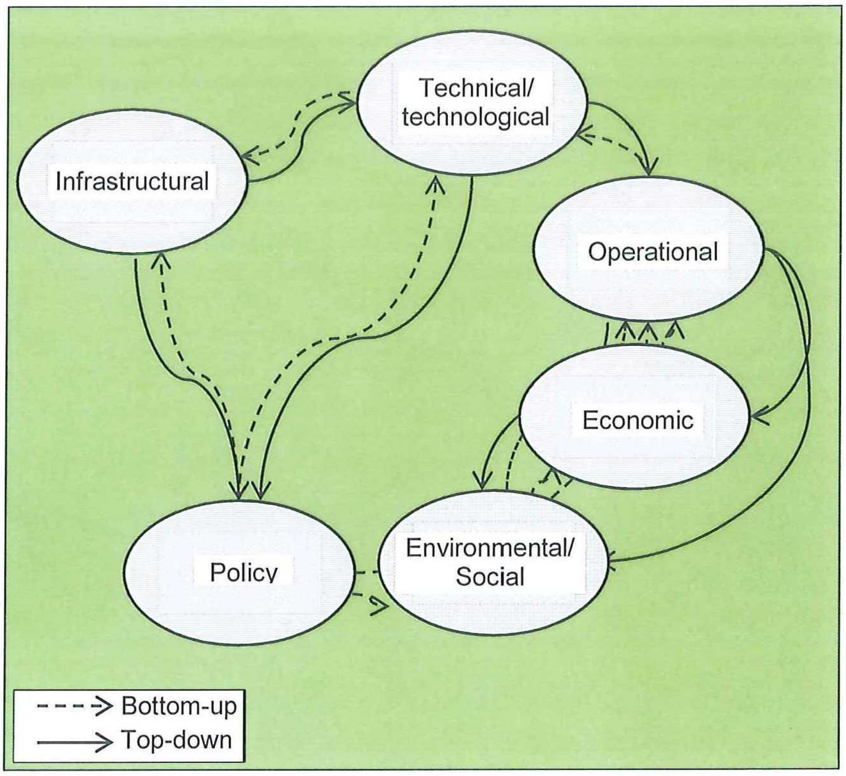

Figure 1 A simplified scheme of performances of an ETT TRM system and their possible interrelationships [1]

As shown by arrows, the particular performances may influence each other top-down (heavy lines) and bottom-up (dotted lines). In such case:

- *Infrastructural and technical/technological performances* generally relate to the physical, constructive, and technical and technological features of the infrastructure - tubes, rolling stock-TRM trains, and supporting facilities and equipment;
- *Operational performances* relate demand, capacity, their relationship, i.e., quality of services, fleet size, and technical productivity;
- *Economic performances* are represented by costs, revenues, and their differences (profits/loses). In some cases these can include savings in the cost of passenger travel time just due to using this instead of some other transport system as alternative;
- *Environmental and social performances* include scale of impacts on the environment and society such as energy/fuel consumption and related emissions of GHG (Green House Gases), land use, noise, congestion, and traffic incidents/accidents (i.e., safety). In some cases, congestion could be considered as an operational performance influencing the overall quality of service. If monetized, hese impacts represent externalities, which could also be considered as economic performance.

- *Policy performances* reflect compliance with the future medium- to long-term transport policy regulations and specified targets mainly related to particular (above-mentioned) environmental and social impacts.

3. A Multidimensional Examination of Performances of an ETT TRM System

3.1. Infrastructural performances

The infrastructural performances of an ETT TRM system include the characteristics of tubes/tunnels, stations/terminals, and corresponding network(s).

3.1.1. Tubes/tunnels and stations/terminals

In cases of spreading between two continents, the infrastructure of an ETT TRM system would be designed generally as underground tunnels under the seabed or as the under-water floating tubes anchored by steel cables to the seabed. The latter concept would be as: i) two transport and one separate service/maintenance tube, the latest shared with pipelines for oil, water, gas, electric power transmission, and communication lines, etc.; or ii) a single tube divided vertically into the main section with the train lines, the maintenance section above, and the emergency section below. Fig. 2 shows a simplified scheme of two-tube design using the TRM trains, [1], [2], [3].

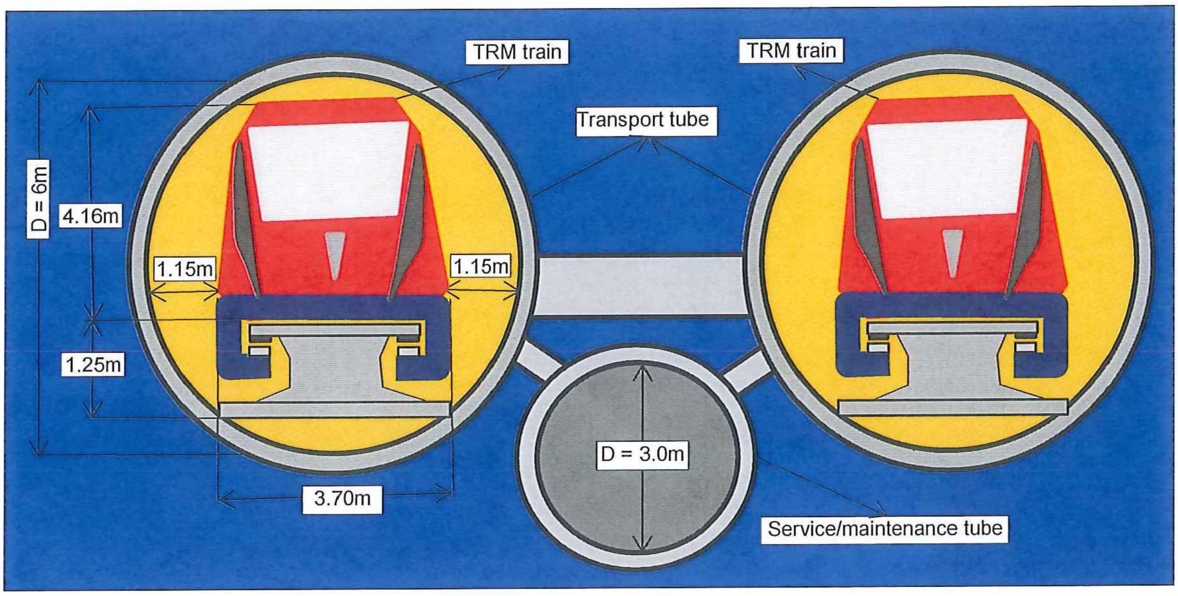

Figure 2 A simplified scheme of the two-tube design for an underwater ETT TRM system [1]

The floating tubes could be made of either the thermal conductive pure steel guaranteeing air-proof at a rather moderate cost or of the composite materials including steel and concrete layer at the inner and outside wall of the tube, respectively [4]. The thickness of the tubes' walls would be sufficient to sustain the water pressure at a given depth from the outside and almost zero pressure from the inside (at the depth of 300m the outside pressure is about 30atm, i.e., the pressure increases by 1atm for each 10m of depth (atm -atmosphere)). The tubes would be composed of prefabricated sections joined together in order to compose an airtight tube. Alternatively, an interlocking mechanism would be incorporated into the sections in order to keep them assembled. The vacuum-lock isolation gates at the specified distance would be constructed in order to evacuate air from particular sections of the tubes more efficiently and thus prevent the spreading of potentially large scale air leakages throughout the entire tubes. These gates would consist of vertically up and down moving doors, which could also function as part of the fire protection system. These doors would be closed during the initial evacuation of air from the tubes and in the cases of large scale leakages, and opened otherwise [2]. The floating of such tubes at the given depth with the TRM guideway(s) inside would depend as follows [1]:

$$W_b = M - \rho_0 \cdot V = \pi \cdot L \cdot \left[(R_2^2 - R_1^2) \cdot s_w \cdot f - \rho_0 \cdot R_2^2 \right] \tag{1}$$

where

W_b	is the resultant buoyant force (ton);
V	is the volume of displaced water by tube(s) (m^3);
M	is the mass (weight) of the tube(s) (ton, kg);
ρ_0	is density of sea water (ton/m^3);
V	is the volume of displaced water equal to the volume of tube(s) (m^3);
R_1, R_2	is the inside and outside radius of the tube, respectively, (m) ($R_1 < R_2$); and
L	is the length of the tube (m);
s_w	is the specific gravity of tube's material (ton/m^3);
f	is the factor of increasing the total mass (weight) of the tube due to its internal and external content ($\pi = 3.14$).

If $W_b = 0$, the tube(s) will float at the surface; if $W_b < 0$, the tube(s) will be pushed upwards implying that they would need to be anchored to the ocean floor by a cable system in order to stay at the given depth; if $W_b > 0$, the tube(s) will sink to the sea floor [1], [2] [3], [4].

3.1.2. Network

The tubes lying mainly under the sea level with a short portion at the surface just near the coast and dedicated passenger stations/terminals at their ends would compose the EET TRM system network. These terminals would be located at the coast preferably incorporated into larger intermodal passenger terminals (i.e., under the "same roof") also accommodating the short- and medium-distance rail- and road-based passenger transport systems/'feeding' networks driving passengers between the ETT system and their final origins/destinations. Fig. 3 shows the simplified scheme of an intercontinental ETT TRM system with a single line/route and the lines/routes of its 'feeding' networks. In this case, the relevant infrastructure performance of end terminals is the number of tracks to handle the TRM trains, which can be estimated as follows:

$$n_t = f_{ETT}(T, d) \cdot t_{ETT/s} \tag{2}$$

where

$f_{ETT}(d, T)$	is the transport service frequency on the line/route *(d)* during time *(T)* (dep/*T*); and
$t_{ETT/s}$	is the time a TRM train occupies a track (min, h).

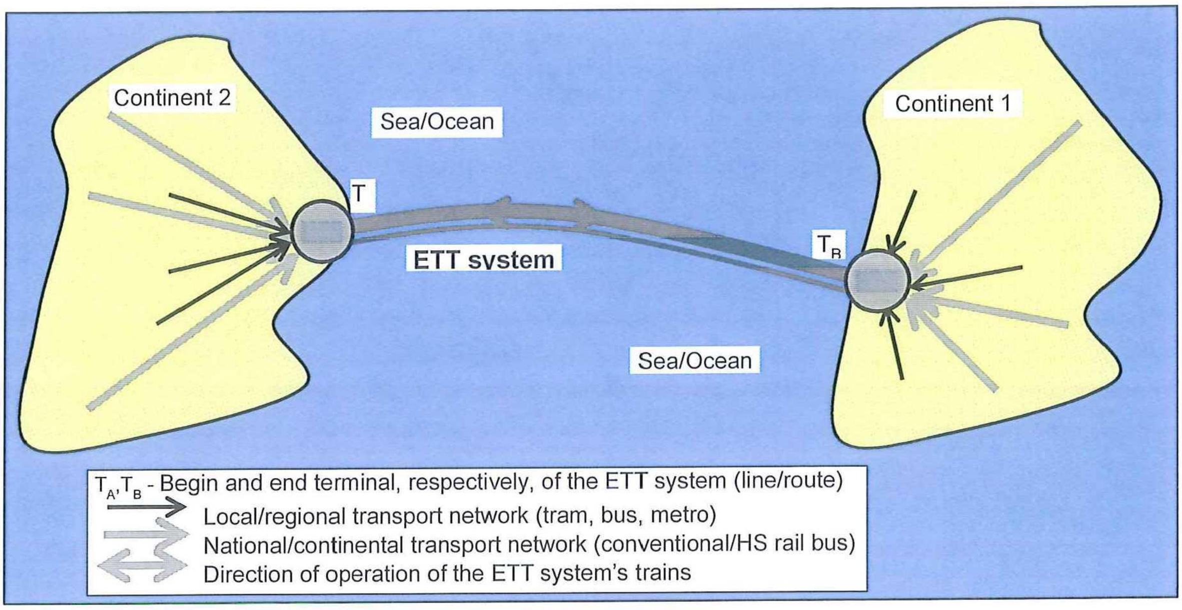

Figure 3 A simplified scheme of an intercontinental ETT TRM system/network with a single line/route [1]

In Eq. 2, time ($t_{ETT/s}$) includes the time for passengers' disembarking/embarking, cleaning, energy/fuel supply, inspection and other activities for making ready the TRM train(s) next safe trip.

3.2. Technical/technological performances

Technical/technological performances of an ETT TRM system relate to the vacuum pumps, TRM trains, and traffic control/management system.

3.2.1. Vacuum pumps

The vacuum pumps would be applied to initially evacuate and later maintain the required level of vacuum inside the tubes. In particular, creating an initial vacuum consists of large scale evacuation and later on removal of smaller molecules near tube walls using heating techniques. These would require powerful vacuum pumps consuming a substantive amount of energy. How would the pumps work? At the initial stage, they would be operating until achieving the required tube evacuation level, then, automatically stopped, and the vacuum-lock isolation gates opened. In cases of air leakage in some section(s), the corresponding gates would be closed and the pumps activated again. The pumps would be located along the tube(s) in the required number depending on the volumes of air to be evacuated, available time, and their evacuation capacity.

3.2.2. Vehicles and propulsion

The vehicles of an EET TRM system would be modified (redesigned) German TRM07 trains [1], [5], [6], [7]. The modifications would be needed due the very high operating speed of about $v_{ETT} = 6.4 - 8.0 \cdot 10^3$km/h and the horizontal acceleration/deceleration rate(s) of about a=1.5-3.0m/s^2 to be used thanks to operating in vacuum tubes. These TRM trains would use electric energy for their levitation, guidance, air conditioning, heating, lighting and powering other facilities and equipment, and LH_2 (Liquid Hydrogen) propelling some kind of the rocket engine for propulsion [3], [8]. In particular, due accelerating/decelerating of TRM train(s) to/from the very high speed ($8.0 \cdot 10^3$km/h), respectively, a substantive energy would be consumed, which can be estimated as follows:

$$E_{ETT/a/d} = 1/2 \cdot m_{ETT} \cdot v_{ETT}^2 \qquad (3a)$$

where

m_{ETT} is the mass (weight) of TRM train (kg, ton);
V_{ETT} is the cruising speed of TRM train (m/s; km/h).

The acceleration/deceleration phase of a trip would require much stronger than basic TRM trains' engines, with minimum required power/thrust estimated as follows:

$$P/T_{ETT/e} = m_{ETT} \cdot a_{ETT}^{+/-} \cdot v_{ETT} \tag{3b}$$

where

$a_{ETT}^{+/-}$ is the acceleration/deceleration rate, respectively, of ETT TRM train to/from the average cruising speed (v_{ETT}) (m/s^2).

The other symbols are analogous to those in the previous Eqs.
During cruising phase of a trip, the TRM trains pressurized similarly as modern commercial aircraft (about 1atm) would move thanks to the inertial force gained after acceleration without aerodynamic (due to vacuum) and rolling (due to levitation) resistance.
Using low density LH_2 stored at low temperature, the ultimately larger insulated fuel-storage tanks would be needed, which would together with engine(s) very likely increase their mass/weight. In addition, operating in the vacuum tube(s) at the very high speeds would eliminate the shock waves when breaking the sound barrier (important for passing trains in a single tunnel/tube concept), and make negligible air friction and consequent heating of trains. Nevertheless, heat shields would be installed at TRM trains as protection from from overheating caused by unpredictable air leakages [4].

3.2.3. Traffic control/management system

The traffic control/management system at TRM trains would be fully automated, i.e., controlled (guided) very likely analogously to the modern UAV (Unmanned Flying Vehicles - designed pilotless aircraft), and managed (separated) along the line/route according to the TRM operating principles.
This is because the drivers simply would not have time to react to unpredicted events due to train's very high operating speed.

3.4. Operational performances

The operational performances of an ETT TRM system relate to demand, capacity, and quality of service, the vehicle fleet size, and technical productivity [1].

3.4.1. Demand

i) <u>General</u>

The demand for an ETT TRM system operating in the long-haul markets (i.e., at the higher level) such as those between large urban agglomerations located in the same or different countries and/or at the same and/or different continents, can be estimated by assuming its competition with the APT (Air Passenger Transport) system using the conventional subsonic, super-, and/or hypersonic (forthcoming) aircraft. In these cases the ETT TRM system is assumed to take over part of the APT demand, collected and distributed to/from it by the short- and medium-haul rail and road passenger transport systems. This prospectively attracted demand can be estimated by logit model.

ii) <u>Logit model</u>

The logit model estimates the probability of choice of a given among several alternatives, in this case ETT TRM and APT system /mode as follows [1]:

$$p[U_{ETT}(d,T)] = \frac{e^{-U_{ETT}(d,T)}}{e^{-U_{ETT}(d,T)} + e^{-U_{APT}(d,T)}} \tag{4a}$$

where

$U_{ETT}(d, T)$	is dis-utility function of the ETT system operating on the line/route *(d)* during time *(T)*;
$U_{APT}(d, T)$	is dis-utility function of the APT system operating on the line/route *(d)*.

The dis-(utility) functions $U_{ETT}(d, T)$ and $U_{APT}(d, T)$ in Eq. 4a consists of the generalized costs of perceived door-to-door travel time and the price/fare paid for a trip by the ETT TRM system and its APT counterpart, respectively. The dis-(utility) function $U_{ETT}(d, T)$ in Eq. 4a for a given category of users/passengers can be estimated as follows:

$$U_{ETT}(d,T) = \alpha \cdot \tau_{ETT/a} + \beta \cdot t_{ETT/iv}(d) + \alpha \cdot \tau_{ETT/a} + p_{ETT}(d,T) = \alpha \cdot \left[\tau_{ETT/a} + 1/2 \left(\frac{T}{f_{ETT}(d,T)} \right) \right] +$$

$$+ \beta \cdot \left[\frac{v_{ETT}(d)}{a_{ETT}^{+}} + \frac{d}{v_{ETT}(d)} + \frac{v_{ETT}}{a_{ETT}^{-}} \right] + \alpha \cdot \tau_{ETT/l} + p_{ETT}(d,T) \tag{4b}$$

where

$\tau_{ETT/a}$, $\tau_{ETT/l}$	is the time of accessing/leaving the system, respectively (min, h);
α	is the unit cost of passenger time during assessing, waiting for departure, and leaving the ETT TRM system ($US/min/pass);
$t_{ETT/iv}(d)$	is the in-vehicle transit time on the line/route *(d)* (h, min)
β	is the unit cost of passenger in-vehicle transit time ($US/min/pass);
$p_{ETT}(d, T)$	is the price/fare for a trip by the system on the line/route *(d)* during time *(T)* ($US/pass).

The other symbols are analogous to those in the previous Eqs. The dis-(utility) function $U_{APT}(d, T)$ can be estimated analogously.

iii) The number of passengers

The number of passengers choosing the newly implemented ETT TRM system/mode, i.e., taken over from the existing APT system/mode, on the line/route *(d)* during time *(T)* can be estimated by Eq. 4a-b as follows [1]:

$$Q_{ETT}(d,T) = p[U_{ETT}(d,T)] \cdot Q_{APT}(d,T) \tag{4c}$$

where

$Q_{APT}(d, T)$	is the number of passengers on the given line/route *(d)* during time *(T)* exclusively carried by the APT system/mode at the time of implementing the ETT TRM system/mode.

Equation 4c implies that only the passenger demand taken over by the EET TRM from the APT system is considered and not the ETT TRM system's self-generated demand.

3.4.2. Capacity

The service frequency ($f_{ETT}(d, T)$) of the ETT TRM system satisfying the expected passenger demand on the line/route *(d)* during time *(T)* can be derived from Eq. 4c as follows:

$$f_{ETT}(d,T) = \frac{Q_{ETT}(d,T)}{\lambda_{ETT}(d,T) \cdot S_{ETT}(d,T)} \tag{4d}$$

where

$\lambda_{ETT}(d, T)$	is the average load factor of an ETT TRM train operating on the line/route *(d)* during time *(T)*;
$S_{ETT}(d, T)$	is the seating capacity of an ETT TRM train operating on the line/route *(d)* during time *(T)* (seats).

3.4.3. Quality of service

The quality of services of an ETT TRM system, in addition to attributes such as frequency, reliability, and punctuality, could be particularly influenced by the in-vehicle comfort during a trip. This comfort highly depends on the horizontal, vertical, an lateral forces acting on passengers while accelerating/decelerating the TRM train(s) to/from the very high speed ($8.0 \cdot 10^3$km/h), respectively. The lateral force could be mitigated through design of the ETT tubes (preferably as straight as possible in both horizontal and vertical plane) and the appropriate arrangements of seats within the TRM trains. The design would be rather complex to achieve in the vertical plane since, for example, the long intercontinental tubes would have to align with the Earth's curvature; in the horizontal plane the straight line shortest (Great Circle) distances would likely be followed. Consequently, the other two -horizontal and vertical- forces would remain. If the TRM trains were accelerating/decelerating at the rate of a = 1.5-3.0 m/s^2, thus achieving the maximum cruising speed in about 12.3 - 24.7 min, the horizontal G-force as a proportion of the nominal gravitational force (g = 9.81m/s^2) would be: 0.152-0.306g - not particularly compromising riding comfort of passengers.

3.4.4. Fleet size

Given the service frequency ($f_{ETT}(d, T)$) in Eq. 4d, the TRM train fleet size of a given ETT system can be estimated as follows:

$$N_{ETT}(d,T) = f_{ETT}(d,T) \cdot t_{ETT/tr}(d) \tag{5a}$$

where

$t_{ETT/tr}(d)$ is an ETT TRM train's average turnaround time along the line/route *(d)* (min, h).

The time ($t_{ETT/tr}(d)$) in Eq. 5a can be estimated as follows:

$$t_{ETT/tr}(d) = 2 \cdot \left(\frac{v_{ETT}(d)}{a_{ETT}^{+}} + \frac{d}{v_{ETT}(d)} + \frac{v_{ETT}(d)}{a_{ETT}^{-}} + t_{ETT/s} \right) \tag{5b}$$

where

$t_{ETT/s}$ is the average stop time of an ETT TRM train at the end terminal (h, min).

The other symbols are analogous to those in the previous Eqs.

3.4.5. Technical productivity

Technical productivity of an ETT TRM system (s-km/h) can be estimated for a single and the fleet of TRM trains.

i) Single train/vehicle:

$$TP_{ETT/v}(d,T) = s_{ETT}(d,T) \cdot v_{ETT}(d) \tag{6a}$$

ii) Fleet of trains/vehicles:

$$TP_{ETT/f}(d,T) = f_{ETT}(d,T) \cdot s_{ETT}(d,T) \cdot v_{ETT}(d) \tag{6b}$$

All other symbols are as in the previous Eqs.

3.5. Economic performances

The economic performances of an EET TRM system include the cost of infrastructure, rolling stock - TRM trains, and supportive facilities and equipment, direct revenues from charging passengers, and indirect revenues as savings in the costs of passenger time and environmental and social impacts (i.e., externalities) though competition with other transport systems/modes, in this case ATP system.

3.5.1. Costs

i) Infrastructure

The infrastructure costs of an ETT TRM system include expenses for building infrastructure and supporting facilities and equipment. These costs would include investments, maintenance and operating costs. The investments generally include the expenses for building tubes (2+1), TRM train guideways, and terminals at both ends of the given line/route, and facilities and equipment such as vacuum pumps, the power supply system, traffic control system, communications, and fire protection system. The maintenance costs include the expenses of regular and capital maintenance of infrastructure and supporting facilities and equipment. The operational costs mainly include the expenses of labor and energy for maintaining vacuum in the tubes [9].

ii) Rolling stock - TRM trains

The cost of rolling stock would consist of the investments and operational cost. The former relate to acquiring the TRM train fleet. The later includes the expenses for maintenance, material, labor, and energy/fuel to operate the TRM fleet under given conditions.

3.5.2. Revenues

The revenues of an ETT TRM system can be direct and indirect. The former are mainly obtained from charging its passengers. The later can be savings in the cost of passenger time and the cost of environmental and social impacts (i.e., externalities) such as energy consumption and related emissions of GHG, noise, congestion, and traffic incidents/accidents. These later savings occur by reducing the scale of operations of competing APT system/mode due to losing passenger demand taken over by the ETT TRM system.

3.6. Environmental and social performances

The environmental and social performances of an EET TRM system relate to its impacts on the environment (energy/fuel consumption and related emissions of GHG (Green House Gases) and land use/take) and society (noise, congestion, safety, i.e., traffic incidents and accidents), all estimated according to the scenarios of competing with other transport modes. The costs of these impacts (i.e., externalities) can be considered in the scope of these instead of, as mentioned above, economic performances.

3.6.1. Energy/fuel consumption and emissions of GHG (Green House Gases)

The energy/fuel consumption of an ETT TRM system includes the energy for setting up and then maintaining vacuum in the tubes, operating TRM trains (levitation, propulsion, guidance), and powering the other supporting systems, facilities, and equipment. Due to using LH_2 for propulsion and electric energy from the renewable primary sources (water, sun, nuclear) for levitation and guidance, the TRM trains operating in the vacuumed tubes would have negligible emissions of GHG and consequent impact on the environment, particularly compared to those from burning of JP-1 fuel (kerosene) by the conventional APT aircraft emitted directly in the atmosphere [1].

3.6.2. Land use

An ETT TRM system would occupy additional land only for building its coast terminals should they not already be a part of the larger intermodal passenger terminals incorporated within existing urban structures.

3.6.3. Noise

An ETT TRM system would not generate any noise disturbing population around the line's/route's begin and end terminal mainly because its TRM trains would operate at low speeds within the tubes in their vicinity.

3.6.4. Congestion

Due to the nature of operations, an ETT TRM system would be free from congestion along the lines/routes. Regarding the intensity of operations, the automated traffic management systems would have to provide a precise guidance in order to achieve almost perfect (in terms of seconds) matching of the TRM train's actual and scheduled departure and arrival times. However, while relieving airports from congestion by taking over some APT demand, the ETT TRM system could contribute to increasing congestion in the areas around its begin and end terminals simply due to the increased intensity of mobility there, as described above.

3.6.5. Traffic incidents/accidents (safety)

An ETT TRM system is expected to be safe at least as its APT counterpart. This implies that incidents/accidents should not occur due to the known reasons. However, the particular attention will have to be devoted to the safety and security of infrastructure (tubes), for example, preventing eventual terrorist threats/attacks, maintaining vacuum, and intervening in cases of losing it due to disturbing and disruptive events. Consequently, the TRM trains operating at the very high speed would be immediately automatically stopped.

3.7. Policy performances

An ETT TRM system would demonstrate its policy performances both at the national scale as contribution to creating an integrated transport system and international (global) in terms of creating an integrated global the very high speed non-APT system/network, which would even stronger contribute to further globalization of the already highly global economy and society. At such, the system would contribute to sustainability of transport sector through contributing to the social economic welfare and reducing its overall impacts on the environment and society.

4. An Estimation of Performances of the ETT TRM System

4.1. The case: Trans-Atlantic APT market

As mentioned above, one among prospective long-haul (intercontinental) passenger transport markets for implementation of the ETT TRM system could be the one between Europe and North America (i.e., Trans-Atlantic). At present, this is the world's largest intercontinental air passenger market served by APT (Air Passenger Transport) system. Some estimates indicate that the average share of this market in the total global APT[1] market of about 8.3% in 2011 would decrease to about 6.5% or 5.4% in 2031, thus indicating its increasing maturity over time implying lower growth rates(s). Consequently, Fig. 4 shows the past and forecasted/prospective development of the APT demand in this market for the period 2004-2060 [10], [11], [12].

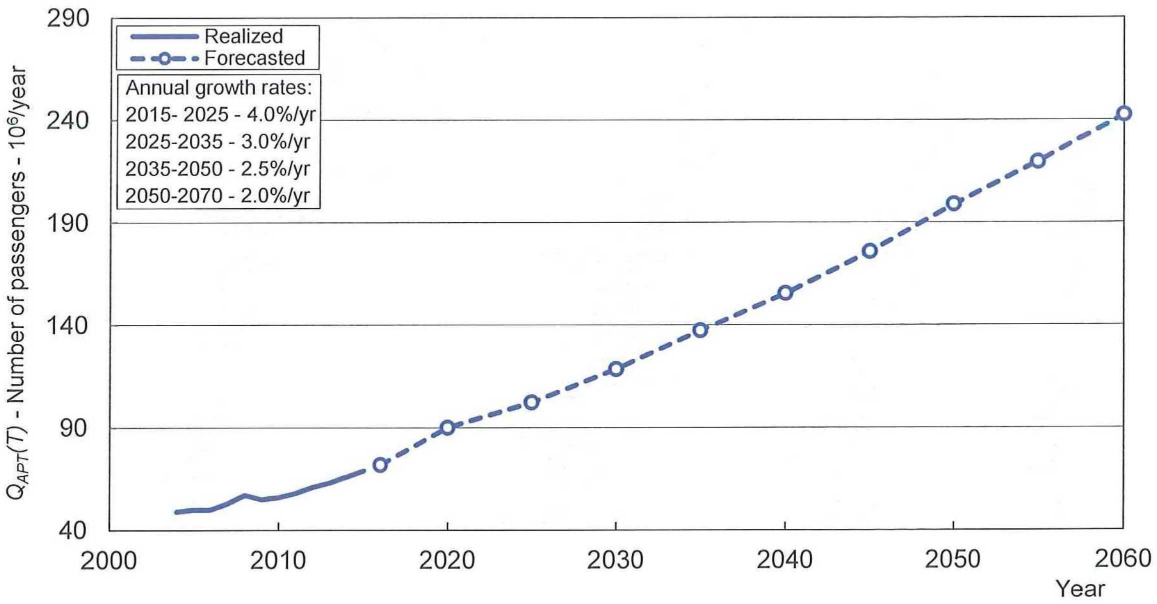

Figure 4 Possible long-term development of APT (Air Passenger Transport) demand in Trans-Atlantic market (both directions) [1], [10], [11], [12], [16] (Airbus, 2012; Boeing, 2014; FAA, 2013; Janić, 2014; http://centreforaviation.com/analysis/the-north-atlantic-the-state-of-the-market-five-years-on-from-eu-us-open-skies-100315)

As can be seen, under the assumed average annual growth rates during particular sub-periods of the given long-term period indicating gradual maturation of the market and weakening its main demand-driving forces on both sides of Atlantic, the annual number of passengers (both directions) is expected to increase to about $Q_{APT} = 199 \cdot 10^6$ in the year 2050, and $240 \cdot 10^6$ in the year 2060. At the year 2050/51, the implemented EET TRM system is supposed to immediately attract a part of this expected APT demand consisting mainly of business (premium class) passengers considering the transport time as one of the most important attributes for choice of the transport system/mode. These passengers would access the ETT TRM system at begin/end terminal at both ends of the route/line by (integrated) feeder services provided by the above-mentioned transport systems/modes. Later over time, the ETT TRM system could also become increasingly convenient for more massive use also by the economic class-passengers.

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[1] Generally, for the period (2011-2030/31), both Boeing and Airbus predict the annual APT growth in terms of RPK (Revenue Passenger Kilometers) of about 5% [10], [11].

4.2. Infrastructural scenario

The length of the ETT TRM line/route in the above-mentioned Trans-Atlantic ATP market to be built over the period of 20 years (2031-2050) would be d = 5664km (similarly as the length of route between London and New York). As shown in Fig. 2, at the ETT TRM system design with two transport and single service/maintenance tube, the inside and outside diameter of each transport tube would be about: $D_2 = 2R_2$ = 6.2m and $D_1 = 2R_1$ = 6.0m, and that of the service tube: $D_{s2} = 2R_{s2}$ = 3.2m and $D_{s1} = 2R_{s1}$ = 3.0m, respectively. This implies thickness of all tubes of 200mm [13]. They would accommodate the TRM train's height and width of 4.16m and 3.70m, respectively, and height of guideway(s) of 1.25m (Fig. 2; Table 1) [1]. For example, let the density of ocean water be: ρ_0 = 1.027ton/m^3, the dimension of the tubes as above; the factor: f = 2 for installing guideway(s) and other systems inside, and the average specific gravity of the tubes' material: s_w = 5.67 ton/m^3 (i.e., 60/40% mix of steel (specific gravity: s_s = 7.85 ton/m^3) and concrete (specific gravity: s_{ct} = 2400 ton/m^3)). Then, based on Eq. 1 the buoyant force of tube of length of 1m would be: W_b = 21.72 - 29.02 = -7.3kg < 0, which implies that the tube would float and thus must be anchored to the seabed. In addition, the buoyant force would be used to specify the need for anchoring cables. The quantity of material used to build two transport and one service/maintenance tube with 200mm thick walls and the specific gravity of the mixture of material (5.67ton/m^3) would amount to about 152·10^{6}ton. In addition, about 200 vacuum pumps (units), each with capacity of 100m^3/min and energy consumption of 260KWh would be located at a distance of about 28km along the line. The volume of air to be evacuated from two tubes would be: $V_{ar} = 2 \cdot 3.14 \cdot 5564 \cdot 10^3 \cdot 3^2 \approx 320 \cdot 10^6$m^3, initially during about 11.1 days [1], [2], [3], [4].

4.3. Technical/technological scenario

The ETT TRM system would consume most energy/fuel for propulsion, i.e., accelerating/decelerating of TRM train(s) to/from their maximum cruising speed of: $v_{ETT} = 8.0 \cdot 10^3$ km/h. If, for example, the gross weight of five-car TRM train was 320ton, the energy needed to accelerate it to/from the above-mentioned maximum cruising speed would be estimated by Eq. 3a as: $E_{ETT/a/d} = 1/2 \cdot 320 \cdot 10^3 \cdot (8.0 \cdot 10^6/3.6 \cdot 10^3)^2 = 790.2 \cdot 10^9$J = 219.5MWh. This acceleration phase would take about: $\Delta t_{ETT/a/d} = v_{ETTT}/a_{ETT} = [(8.0 \cdot 10^6/3.6 \cdot 10^3)/3.0]/60$ = 12.3min (the average acceleration/deceleration rate is a_{ETT} = ±3m/s^2). After that, the TRM train would continue to be driven by inertial force without consuming additional energy for propulsion. At the end of route, the TRM train(s) would spend again the same as above amount of energy and the time for deceleration and stop. Consequently, the minimum required power of the rocket engine estimated by Eq. 3b would be: $P/T_{ETT/e} = 1/2 \cdot [320 \cdot 10^3 \cdot (8.0 \cdot 10^6/3.6 \cdot 10^3) \cdot 3.0] = 1066.7 \cdot 10^6$kg·m^2/s^3 = 1066.7MW. The mass/weight of this engine would be: m_{re} = 1.7-6.3ton [1], [14]. If LH$_2$ (Liquid Hydrogen) with the energy content of 142MJ/kg was used, its consumption during acceleration/deceleration phase of a trip would be about $F_{C/a/d} = E_{ETT/a/d}/142$ = 790123.5/142 = 5.6ton each, and the total consumption 11.2ton implying the capacity of reservoirs onboard the TRM of C_r = 12ton. Giving the density of LH$_2$ of: D = 70.86kg/m^3, the volume of these reservoirs would be: $V_r = C_r/D$ = 12000/70.85 ≈ 170m^3 [15]. These all above-mentioned modifications including the weight of insulated reservoirs would increase the gross weight of the TRM train to about: m_{ETT} = 340ton. Then, the energy consumption during acceleration/deceleration would be: $E_{ETT/a/d}$ = 233.2MWh ($F_{C/a/d}$ = (2·839520.5)/142 = 11.9ton), and the minimum required power of the rocket engine: $P/T_{ETT/e}$ = 1133.3MW. The resulting differences between the main technical/technological and operational performances of the basic and modified TRM train, the later to be operated by the ETT system is given in Table 1.

Table 1 Technical/technological and operational performances of the basic and modified ETT TRM (TransRapid MAGLEV) 07 train [1], [5], [6], [7]

Characteristic	**Value1)**	**Value2)**
Carriages/sections per train	5	5
Length of train (m)	128.3	128.3
Width of carriage (m)	3.70	3.70
Height of carriage (m)	4.16	4.16
Weight of empty train ton)	247	247
Gross weight of a train3) (ton)	318-320	340
Seating capacity (max) (seats)	446	400
Gross weight/seat ratio (average)	0.71	0.85
Axle load - gross weight (ton/m)	2.47-2.479	2.65
Technical curve radius (m)	2825-3580	2825-3580
Maximum engine power (MW)	25	1133.3
Lateral tilting angle (^{0})	12-16	12-16
Maximum operating speed (km/h)	400-450	8000
Maximum acceleration/deceleration (m/s^2)	0.8-1.5	3.0

1) Non-vacuum; 2)Vacuum; 3)Approximately 64ton/carriage including the weight of passengers and their baggage

4.4. Operating scenario

4.4.1. General

The "what-if" operating scenario is developed for the year 2050/51 when the EET TRM system is supposed to be implemented between Europe and North America (over North-Atlantic) and as such start competing with the well-established APT system.

Three operational competing scenarios are considered regarding the APT system exclusively operating:

i) Conventional sub-sonic aircraft fleet with the cruising speed of about 0.85M at the altitudes of about $33\cdot10^3$ft (1M = 1078km/h at the altitude of $33\cdot10^3$ft (M - Mach number) (ETT-APT/C);
ii) Fleet of STA NASA (Supersonic Transport Aircraft-NASA High-Speed Civil Transport) beyond the year 2030 with the cruising speed of 2.0-2.4M at the altitudes of $60\cdot10^3$ft (1M = 1062 km/h at the altitude of $60\cdot10^3$ft; 1ft = 0.305m) (EET-APT/STA NASA); and
iii) Fleet of ECH M5C (EC Hydrogen Mach 5 Cruiser A2) beyond the year 2030 with the cruising speed of M 5.0 at the altitudes of $60\cdot10^3$ft (1M = 1062 km/h at the altitude of $60\cdot10^3$ft; 1ft = 0.305m) (EET-APT/ECH M5C) [1].

4.4.2. Estimation of passenger demand

According to the forecasted passenger demand in Fig. 4, the above-mentioned APT system is expected to carry out about $199\cdot10^6$ in the year 2051 and about $240\cdot10^6$ passengers in the year 2060. Based on the past experience and assuming that it will continue in the future, about 16-18%, i.e., 32-$33\cdot10^6$ of these mainly business (premium class) passengers would be expected to choose between the APT system operated by different above-mentioned aircraft categories and the newly implemented EET TRM system [16].

Under an assumption that the cost of access time and prices are going to be approximately equal for both systems, the travel time between origin and destination airport(s) of the ATP and between begin/end terminus of ETT TRM appears to be the main attribute of system/mode choice. Some relevant operational characteristics (altitude, cruising speed) and consequent average route travel time relevant for the modal choice are estimated and given in Table 2.

Table 2 Some operating characteristics of the EET TRM and the APT system in the given case - Trans-Atlantic market [1], [27], [28] , [29] (Coen, 2011; EC, 2006, 2008; Janić, 2014; NAS, 2001)

Transport mode	**Length of route** $\underline{d}$ (km)	**Operating altitude**$^{1)}$ $\underline{H}$ (10^3ft)	**Average block speed**$^{2)}$ v (M; km/h)	**Average door-to-door travel time**$^{2)}$ $\underline{(\tau_o + \tau_l) + t_{iv}(d)}$ (h)
ETT	5564	- 1.0	5.5; 6700	3.5 + 0.83 = 4.33
APT/C	5564	+ 33	0.7; 740	1.5 + 7.5 = 9.0
APT/STA NASA	5564	+ 60	2.0-2.4; 2124-2549	1.5 + 2.66 = 3.16
APT/ECH M5C	5564	+ 60	5.0; 5310	1.5+ 1.09 = 2.59

ETT- Evacuated Tube Transport; APT/C-Air Passenger Transport/Conventional; APT/STA NASA - Air Passenger Transport/NASA High-Speed Civil Transport; APT/ECH M5C-Air Passenger Transport/EC Hydrogen Mach 5 Cruiser A2; M - Mach number; $^{1)}$ Above MLS (Middle Sea Level); 1ft = 0.305m; $^{2)}$ Including acceleration and deceleration rate of: $a^{+/-} = \pm 3$ m/s, respectively, to/from the maximum corresponding cruising speed of $8.0*10^3$ km/h in the vacuum tube.

As can be seen, the ETT is supposed to have the shorter door-to-door time than its APT/C counterpart, thus presumably demonstrating capability for attracting the above-mentioned passenger demand. However, it would not be superior compared to its APT/STA NASA and APT/ECH M5C counterpart, mainly due to the much longer accessing/leaving time.

Based on this door-to-door travel time, the market share and the corresponding volumes of passenger demand expected to be attracted by the ETT system under given conditions are estimated means by Eq. 4a-c and given in Table 3.

Table 3 Market share and demand of the EET TRM in the competing scenarios with the APT system in the given case - Trans-Atlantic market

Competing modes (Scenario)		**Market share of ETT** $\underline{p_{ETT}}$ (%)	**Demand for ETT (Year 2050/51)** $\underline{Q_{ETT}}$ (10^6pass/yr)	**Demand for ETT (Year 2050/51)** $\underline{q_{ETT}}$ (10^3pass/day/dir)$^{1)}$
ETT-APT/C	32 - 36	0.990	31.70 - 35.96	43.4 - 48.8
EET-APT/STA NASA	32 - 36	0.458	14.66 - 16.49	20.0 - 22.6
EET-APT/ECH M5C	32 - 36	0.149	4.77 - 5.36	6.5 - 7.3

ETT- Evacuated Tube Transport; APT/C- Air Passenger Transport/Conventional; APT/STA NASA - Air Passenger Transport/ NASA High-Speed Civil Transport; APT/ECH M5C - Air Passenger Transport / EC Hydrogen Mach 5 Cruiser A2; dir - direction; yr – year; $^{1)}$ Average during the day per direction (1year = 365 days)

As can be seen, if competing exclusively with the ATP/C, the ETT would attract almost its entire (premium class) passenger demand. If competing with the APT/STA NASA and APT/ECH M5C, it would attract about 46% and 15%, respectively, of the total ATP/C (premium class) passenger demand.

If an ETT TRM train have the seating capacity S_{ETT} = 400seats and the average load factor of λ_{ETT} = 0.90, the service frequency estimated by Eq. 4d based on the passenger demand in Table 3 is given in Table 4.

Table 4 Service frequency of the ETT TRM system in the competing scenarios with the APT system in the given case - Trans -Atlantic market

Competing modes (Scenario)	**Demand by ETT (Year 2050/51)** $\underline{q_{ETT}}$ (10^3pass/day/dir)1)	**Daily service frequency** $\underline{F_{ETT}}$ (dep/day/dir)	**Hourly service frequency** $\underline{f_{ETT}}$ (dep/h/dir)1)
ETT-APT/C	43.4 - 48.8	60 - 68	3-4
EET-APT/STA NASA	22.0 - 22.6	28 - 31	2-2
EET-APT/ECH M5C	6.5 - 7.3	9 - 10	1-1

1) Operating time during the day: 18h; S_{ETT} = 400seats; λ_{ETT} = 0.90 (dir –direction)

As can be seen, in the case of competition between the ETT and APT/C, the departures on the given line/route would take place every 15-20min giving the average passenger schedule delay of 1/2·(15-20) = 7.5-10.0 min. In the case of competition between the EET and APT/STA NASA, the departures would take place every 30min with an average schedule delay of 15min. In the case of competition between the EET and APT/ECH M5C, the departures would be carried once per hour (60min) and the schedule delay would be 30min.

The required TRM fleet competing with the EET- APT/C scenario based on Eq. 5a would be: N_{EET} = (3-4) ·5.66 ≈ 17-23trains, and 19-25 trains, if a 10% reserve was included. Respecting that the stop time of each EET train at both end terminals was: $t_{ETT/s}$ = 2h (120min) (mainly due to safe refueling with LH_2), the turnaround time based on Eq. 5b would be: $t_{ETT/rd}$ = 2· (0.83+2) = 5.66h. As well, by Eq. 2, the required number of tracks at each terminal to handle departing and arriving TRM trains in the scenario EET-APT/C when each of them stops for an average time of: $t_{ETT/s}$ = 2h (120min) would be: n_{ot}= (3-4)·(2)≈6-8 tracks. The length of each track would be minimum 150-200m to enable accommodation of the TRM trains and their comfortable embarking and disembarking. The additional tracks (1-2) need also to be provided at each terminal for TRM trains temporary not in service.

The technical productivity of a single TRM train for the scenario EET-APT/C is estimated by Eq. 6a as: $TP_{ETT/v}$= $400 \cdot 6.8 \cdot 10^3 \approx 2.720 \cdot 10^6$s-km/h. In addition, the technical productivity of the TRM train fleet during one hour estimated by Eq. 6b would be: $TP_{ETT/f}$ = $(3\text{-}4) \cdot 400 \cdot 6.8 \cdot 10^3$(km/h) ≈ 8.16-10.90s-km/h/h. Table 5 summarizes some of the above mentioned the ETT system's operational performances in particular competing scenarios.

Table 5 Some infrastructural and operational performances of the ETT TRM system in the competing scenarios with the APT system in the given case - Trans-Atlantic market

Competing modes (Scenario)	**Service frequency** $\underline{f_{ETT}}$ (dep/h/dir)1)	**Tracks at end terminals** $\underline{n_t}$ (tracks/terminal)	**Required TRM fleet** $\underline{N_{ETT}}$ (trains)	**Technical productivity** $\underline{TP_{ETT/f}}$3) (10^6 s-km/h/h)
EET-APT/C	3 - 4	6 - 8	17 - 23 1)/19 - 25 2)	8.15 – 10.9
EET-APT/STA NASA	2 - 2	4/5	11/13	5.5
EET- APT/ECH M5C	1 - 1	2/3	6/6	2.7

1) Operating; 2) Including reserve of 10%; 3) The fleet of TRM trains

4.4. Economic scenario

According to the "what-if" economic scenario, the ETT system in the given case is assumed to provide a return on investment, i.e., positive or zero cost-benefit ratio over a period of 40 years after being implemented.

4.4.1. Costs

The investment costs for building tubes appear to be very uncertain but some estimates indicate that they could be about 14.6-20.2·10^{6}\$US/km (i.e., 81-115·10^{9}\$USfor the entire link/line of length of 5564km including the passenger terminals at both ends) [17]. The cost of the TRM guideways in the tubes in a single direction would be similar as at the today's TRM-about 16.8·10^{6}\$US/km (i.e., for two tracks this gives the total investment cost of $5564\cdot 2\cdot 16.8\cdot 10^{6} = 187\cdot 10^{9}$\$US). Thus, if the system was built over the 20-year period between 2030 and 2050, the total infrastructure (tubes, TRM guideways, terminals) and the cost of facilities and equipment (vacuum pumps, power supply system, traffic control system, and fire protection system) would be about 268-302·10^{9}\$US, or without taking into account the interest rate(s), 13.4-15.1·10^{9}\$US/yr. As an illustration, the share of the investment costs in the cumulative GDP of Europe (EU) (690.34·10^{12} \$US) and North America (USA, Canada) (771.4·10^{12} \$US) during that period would be about 0.018 - 0.026%, respectively [1], [18].

The costs of operating infrastructure would amount to about 10% of the investment costs, which would give total infrastructure costs of about: C_I = 14.74-16.61·10^{9}\$US/yr. Assuming that the passenger demand in each year of the investment-returning 40-year period would be at least the same as in 2050/51, and the operational cost of a TRM train c_o = 0.095\$US/p-km, the total unit costs (c_t) of an EET TRM system for different competing scenarios in Table 3 are estimated and given in Table 6.

Table 6 Some economic performances of the ETT TRM system for the competing scenarios with the APT system in the given case - Trans-Atlantic market

Competing modes (Scenario)	**Passenger demand**[1)] $\underline{Q_{ETT}^{*}}$ (10^{9}p-km/yr)	**Infrastructure (unit) cost**[2)] $\underline{c_I}$ (\$US/p-km)	**Operational (unit) cost** $\underline{c_o}$ (\$US/p-km)	**Total (unit) cost** $\underline{c_t}$ (\$US/p-km)
EET-APT/C	179.5 - 207.5	0.087-0.076	0.095	0.182 - 0.171
EET-APT/STA NASA	83.0 - 93.2	0.189-0.168	0.095	0.284 - 0.263
EET- APT/ECH M5C	27.0 - 30.4	0.580-0.516	0.095	0.675 - 0.610

[1)] $Q_{ETT}^{*}=Q_{ETT}\cdot d$; [2)] The average annual total costs of infrastructure are estimated to be: $C_I = [(14.74+16.61)*10^{9}]/2 = 15.68\cdot 10^{9}$ \$US/yr; p-km-passenger-kilometer; yr-year

4.4.2. Revenues

The revenues gained from operating the EET system under given conditions can be considered to be direct, i.e., those from charging users/passengers, and indirect, i.e., savings in the cost of passenger in-vehicle time under given competing scenarios with APT.

The ETT system direct revenues are illustrated by the relationship between the EET average cost-covering fare per passenger and the annual volume of passenger demand diverted from the APT in the above-mentioned competing scenarios in the given case as shown on Fig. 5.

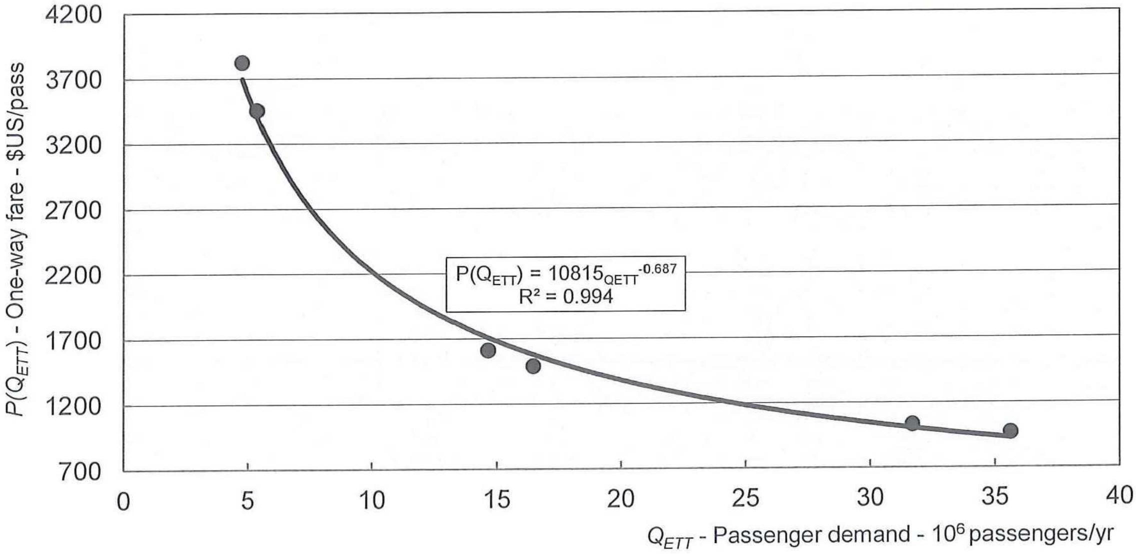

Figure 5 Relationship between the average fare and the annual (premium) passenger demand at the ETT TRM system in the given case - Trans-Atlantic market

As can be seen, the one-way fare covering the cost varies between about $P(Q_{ETT})$ = 970 and 3500$US/pass, and decreases more than proportionally with increasing of the annual (premium class) passenger demand. As based on the average total cost, this fare also reflects existence of economies of demand density at the EET TRM system under given conditions. The ETT TRM system indirect revenues, i.e., saving in the passenger cost door-to-door time, in dependence of the annual (premium class) passenger demand are shown on Fig. 6.

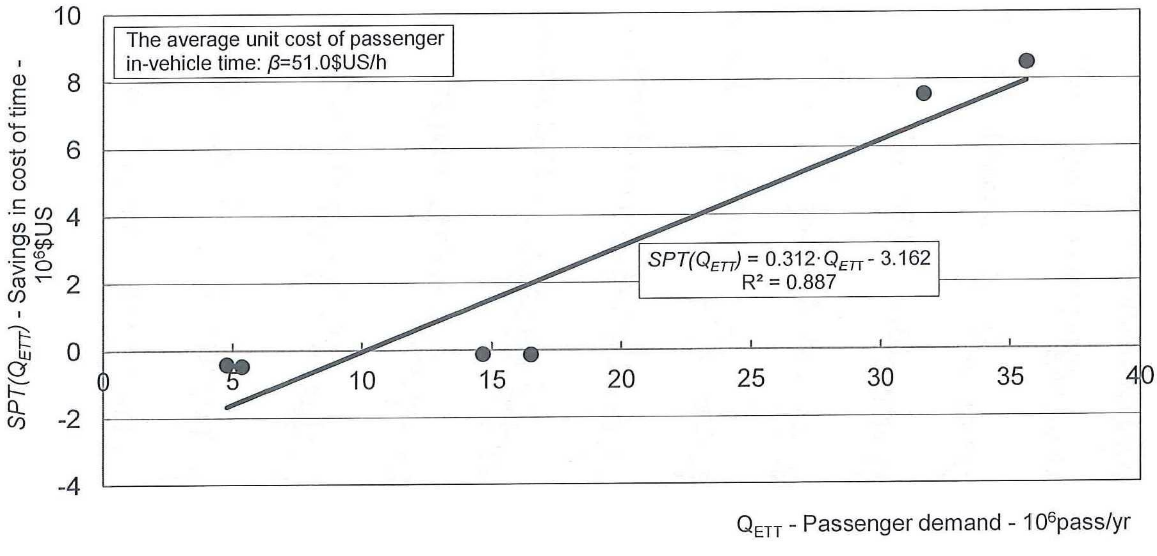

Figure 6 Relationship between the savings in cost of passenger door-to-door time and the volume of annual (premium) passenger demand at the ETT TRM system in the given case - Trans-Atlantic market [1], [19], [20] (Janić, 2014; Landau et al., 2015; USDT, 2011)

As can be seen, the rather enormous savings in the costs of passenger door-to-door travel time would be achieved at the EET-APT/C competing scenario. These savings would be negative and not in favor of the ETT system in the other two scenarios (particularly at ETT-APT/ECH M5C) mainly due to the relatively low attracted passenger demand under given conditions (Table 3) [1], [19], [20].

4.5. Environmental/social/policy scenario

The ETT TRM system operating in the given case is assumed to be free of the environmental impacts such fuel/energy consumption from the non-renewable sources, related emissions of GHG (Green House Gases), and land use/take. It is also free from the social impacts such as noise, congestion, and traffic incidents/accidents (safety), the latest not to happen due to known reasons. As such, it would possess substantive performances contributing to policies aiming at reducing the overall impacts of transport sector on the society and environment. Nevertheless, its "what-if" environmental scenario mainly relate to savings in the above-mentioned impacts due to reducing the scale of operations of the APT system thanks to attracting passenger demand from it under given conditions.

The rocket-engine propellants used by the ETT TRM trains and burning out within the tubes would not produce emissions of GHG impacting the outside environment [30]. The (electric) energy for operating the ETT TRM system's supporting facilities and equipment would be completely obtained from the non-renewable (nuclear) and renewable (solar, wind, water) sources thus implying that the emissions of GHG from operating the ETT TRM system would be negligible compared to that from burning crude oil-based JP-1 fuel-kerosene. Under such conditions, taking over the passenger demand from the APT system would reduce the volumes of its operations and consequently the corresponding impacts on the environment and society. This would be particularly in the ETT TRM - APT/C competing scenario, when the APT system was assumed to exclusively operate the aircraft similar to today's B787-8/9 and A350-800/900 aircraft with the average fuel consumption of about: $f_{APT/1} = 0.0206$ kg/s-km or $f_{APT/2} = 0.0257$ kg/p-km (the load factor was supposed to be $\lambda_{APT} = 0.80$) [21], [22]. The emission rate of JP-1 fuel is: $e_m = 5.25$ kgCO$_{2e}$/kg, which gives the average GHG emission rates of about: $e_{APT/1} = 0.108$ kgCO$_{2e}$/s-km or $e_{APT/2} = 0.135$ kgCO$_{2e}$/p-km. Then, the costs of CO$_{2e}$ emissions as the saved externalities by the ETT TRM from the APT system are estimated for the above-mentioned competing scenarios and given in Table 7.

Table 7 Some environmental performances - savings in externalities - of the ETT TRM system for the competing scenarios with the APT system in the given case - Trans-Atlantic market [1], [14], [24], [25]

Competing modes (Scenario)	**Passenger demand**$^{1)}$ $\underline{Q_{ETT}^{*}}$ (10^9p-km/yr)	**Savings in cost of CO$_{2e}$** $\underline{SC_e}$ (10^9 \$US/yr)	**Savings in total costs - externalities**$^{4)}$ $\underline{SC_{te}}$ (10^9 \$US/yr)
EET-APT/C	179.5 - 207.5	9.0 - 10.4$^{2)}$	16.4 - 18.5
EET-APT/STA NASA	83.0 - 93.2	0.5 - 0.84$^{3)}$	6.5 - 7.3
EET- APT/ECH M5C	27.0 - 30.4	0.24 - 0.27$^{3)}$	2.1 - 2.4

$^{1)}$ $Q_{ETT}^{*} = Q_{ETT} \cdot d$; $^{2)}$ $c_e = 0.050$\$US/p-km (BAU - Business As Usual scenario); $^{3)}$ $c_e = 0.009$\$US/p-km (Unit cost of CO$_{2e}$ externalities); $^{4)}$ $c_{te} = 0.078$\$US/p-km (Total cost of the social and environmental impacts-externalities); p-km-passenger-kilometer; yr-year

As can be seen, the savings in externalities would be substantive and dependent mainly on volume of switched APT demand and the aircraft technologies operated by the ATP system under given conditions.

5. Conclusions

This paper has dealt with the multidimensional examination of infrastructural, technical/technological, operational, economic, environmental, social, and policy performances of the advanced futuristic ETT TRM system operated by the TRM (TransRapid Maglev) trains. These all have been modeled and then estimated according to the "what-if" scenario approach of competition of the ETT TRM with APT (Air passenger Transport) system in the given long-haul (intercontinental) passenger market. The results have shown the following:

i) The ETT TRM system operating appropriately redesigned TRM (TransRapid Maglev) trains could successfully compete in the given (North-Atlantic) and presumably other long-haul markets with the APT system exclusively operating the conventional (kerosene-fueled) aircraft. This implies its contribution to savings in the APT system's impacts on the society (cost of passenger time, local noise, congestion, and traffic incidents/accidents (safety)) and environment (energy/fuel consumption and related emissions of GHG (Green House Gases)), and land use; and
ii) The ETT TRM system competing with the APT system exclusively operating the super- and hypersonic aircraft in the given (North-Atlantic) and other long-haul markets would be less successful due to attracting much lower passenger demand and consequently contributing much lower if at all to savings in the above-mentioned social and environmental impacts.

In addition, this examination has indicated some advantages and disadvantages of the ETT TRM system itself and its potential contribution to the overall sustainability of transport sector.

The ETT TRM system's main advantages would be as follows:
i) The very high speed of transport services by the TRM trains;
ii) Substantive fuel (LH_2) consumption for propulsion of TRM trains during acceleration and deceleration phase of a trip;
iii) Free from impacts on the environment and society such as emissions of GHG (Green House Gases), land use, noise, and congestion; and
iv) Inherent complexity challenging international cooperation in planning, design, implementation, and operation.

The ETT TRM system's main disadvantages could be as follows:
i) Redesign of basic configuration of TRM train(s);
ii) High vulnerability (exposure) to different (external) disturbing/disruptive events;
iii) Continuous need for maintaining vacuum in the above-mentioned vulnerable (exposed) tubes; and
iv) High infrastructure building and operating (maintenance) costs including the cost of maintaining permanent vacuum in the tubes.

Summary

Multidimensional examination of performances of the future advanced ETT (Evacuated Tube Transport) system operated by TRM (TransRapidMaglev); assessment of the ETT TRM system contribution to sustainability of the future transport sector through its completion with APT (Air Passenger Transport) system in the given case - long-haul (North-Atlantic) passenger transport market.

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