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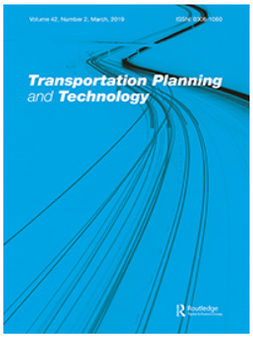

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Future advanced long-haul Evacuated Tube Transport (EET) system operated by TransRapid Maglev (TRM): a multidimensional examination of performance

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ABSTRACT
This paper presents a multidimensional examination of the infrastructural, technical/technological, operational, economic, environmental, social, and policy performance of the future advanced Evacuated Tube Transport (ETT) system operated by TransRapid Maglev (TRM) (the ETT-TRM system). The examination implies analyzing, modeling, and estimating selected performance criteria using the case of the Trans-Atlantic passenger transport market currently served exclusively by the Air Passenger Transport (APT) system. The purpose is to assess the ETT-TRM system's competitive capabilities compared to those of the current and future APT system and consequently its potential contribution to mitigating impacts of both systems on society and the environment – the sustainability of the transport sector - under given conditions.

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Advanced transport systems; performance; Evacuated Tube Transport (ETT); TransRapid Maglev (TRM); ETT-TRM system; Trans-Atlantic passenger transport market

1. Introduction

The future of the world 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 9–10 billion;
(ii) *growing developing economies* contributing to strengthening the 'middle' class and consequently increasing demand for mobility in 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 cities and mega-cities (CIA 2012).

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Consequently, 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* with respect to highly differentiated passenger needs;
(iii) *further diminish the impacts on the environment and society* thanks to deploying innovative and new technologies and operational procedures; and
(iv) *contribute to national and global welfare* by further increasing direct and indirect employment and expansion, i.e. synergies, with the new technologies from other fields/areas.

The advanced Evacuated Tube Transport (ETT) and TransRapid Magelv (TRM) system seems to be one of the prospective future systems able to contribute to fulfilling the above-mentioned requirements through competition mainly with the long-haul Air Passenger Transport (APT) system (http://www.popsci.com/scitech/article/2004-04/trans-atlantic-maglevhttp://www.popsci.com/scitech/article/2004-04/trans-atlantic-maglev). By taking over a part of APT demand, as a presumably environmentally friendlier system/mode, the ETT-TRM system can contribute to mitigating the overall transport sector-related negative impacts on the environment and society, and consequently contribute to the sector's more sustainable development.

This paper consists of four sections. The next section, Section 2, describes the main components and concept of performance of an ETT-TRM system. Section 3 deals with a multi-dimensional examination and modeling of the selected indicators of this performance. Section 4 presents an application of the proposed approach to the long-haul passenger transport market where an ETT-TRM system competes with the APT system according to 'what-if?' (hypothetical) scenarios. The last section presents some conclusions.

2. The components and concept of performance of an ETT-TRM system

The ETT-TRM, defined as a very high-speed long-haul transportation system, has been elaborated for a long time (Janić 2014). Its main components are vacuum tubes, TRM trains, and supporting facilities and equipment for the energy supply, maintaining a vacuum in the tunnels, train/traffic control/management systems, and fire protection system. They all determine and influence the ETT-TRM system's infrastructural, technical/technological, operational, economic, environmental, social and policy performance, and vice versa, as shown in Figure 1.

As indicated by arrows, particular performances may influence each other in both top-down (heavy lines) and bottom-up (dotted lines) respects. In such cases:

- *infrastructural and technical/technological performances* generally relate to the physical, constructive, and technical and technological features of the infrastructure: individual tubes, stations/terminals at their ends, and their network(s); the rolling stock-TRM trains; and supporting facilities and equipment;
- *operational performances* relate to demand, capacity, their relationship, i.e. quality of services, fleet size, and technical productivity;
- *economic performances* include 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 an alternative;

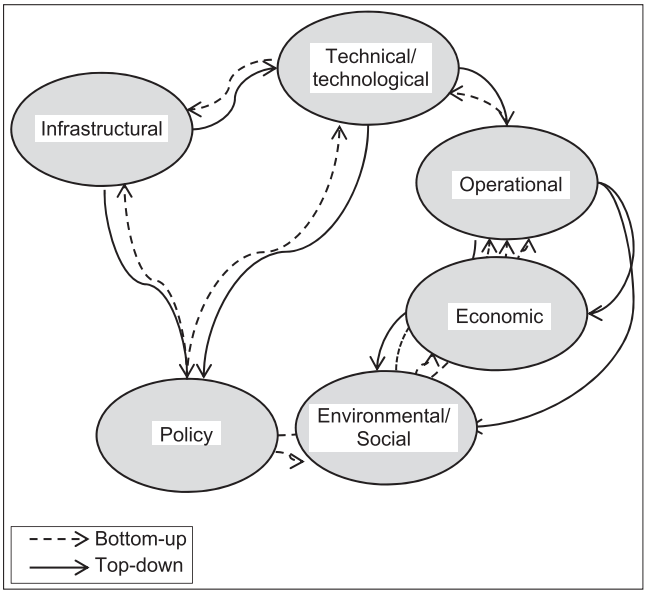

Figure 1. Simplified scheme of performances of an ETT-TRM system and their possible interrelationships (Source: Janić 2014).

- *environmental and social performances* generally embrace impacts on the environment and society in terms of the energy/fuel consumption derived from the non-renewable primary sources and related emissions of Green House Gases (GHG), 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, these impacts represent externalities, which could also be considered in the scope of economic performances; and
- *policy performances* reflect compliance of the given ETT-TRM system with the future medium- to long-term transport policy regulations and specified targets related mainly to the particular environmental and social impacts mentioned above.

3. Examination of performances of the ETT-TRM system

3.1. Infrastructural performance

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

3.1.1. Tubes/tunnels and stations/terminals

In cases of connecting between two continents, the infrastructure of an ETT-TRM system would be designed generally as underground tunnels under the seabed or as underwater floating tubes anchored by steel cables to the seabed. The latter concept can be designed as: (i) two transport and one separate service/maintenance tubes, the latter shared with pipelines for oil, water, gas, electric power transmission, and/or communication lines, etc.; or (ii) a single tube divided vertically into a main section with the train lines, the

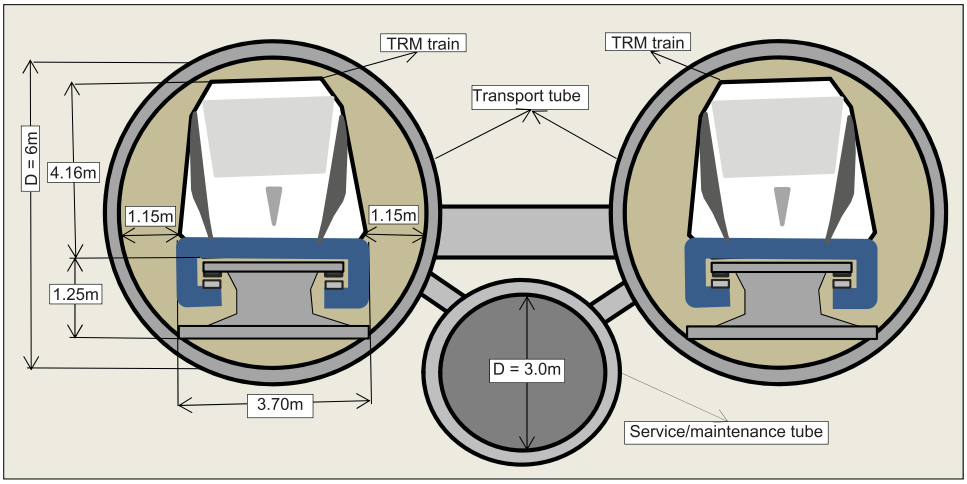

Figure 2. Simplified scheme of two-tube design for an underwater ETT-TRM system (Source: Janić 2014).

maintenance section above, and the emergency section below. Figure 2 shows a simplified scheme of the two-tube design using TRM trains (Janić 2014; Salter 1972; Sirohiwala, Tandon, and Vysetty 2007).

The floating tubes could be made of either thermal conductive pure steel guaranteeing air-proof at a rather moderate cost or of composite materials including steel and concrete layers at the inner and outside wall of the tube, respectively (Zhang et al. 2011). The thickness of the tube walls has to be sufficient to sustain the water pressure at given depths from the outside and almost zero pressure from the inside (at a depth of 300 m the outside pressure is about 30 atmospheres (atm)), that is, the pressure increases by one atm for each 10 m of depth. The tubes could be composed of prefabricated sections joined together in order to create an airtight tube. Alternatively, an interlocking mechanism could be incorporated into the sections in order to keep them assembled. Vacuum-lock isolation gates at specified distances would be constructed in order to evacuate air from particular sections of the tubes more efficiently, on the one hand, and prevent spreading of potentially large-scale air leakages throughout the entire tube(s), on the other. These gates would consist of vertically up- and down-moving doors, which can 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 (Salter 1972). The floating of such designed tubes at a given depth with the TRM guideway inside depends on the following relationships (Janić 2014):

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

where W_b: is the resultant buoyant force (ton); V: is the volume of water displaced by the tubes (m^3); M: is the mass (weight) of the tubes (ton, kg); ρ_0: is density of sea water (ton/m^3); V: is the volume of displaced water equal to the volume of the tubes (m^3); R_1, R_2: is the inside and outside radius of the tube, respectively, (m) ($R_1 < R_2$); 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; and π: is the constant 3.142.

If $W_b = 0$, the tubes would float at the surface; if $W_b < 0$, the tubes would be pushed upwards, implying that they 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 tubes would sink to the sea floor (Janić 2014; Salter 1972; Sirohiwala, Tandon, and Vysetty 2007; Zhang et al. 2011).

3.1.2. Network

The tubes lying mainly under the sea with a short portion at the surface near the coast with dedicated passenger stations/terminals at their ends compose the EET-TRM system network. These stations/terminals would be located at the coast and preferably incorporated into larger intermodal passenger stations/terminals (i.e. under the 'same roof'). This would enable facilitation and an efficient exchange of passengers between the ETT-TRM and other ground-based short- and medium-distance rail- and road-based passenger transport systems acting as its demand collection and distribution networks. Figure 3 shows the simplified layout of an intercontinental ETT-TRM system with a single line/route and the lines/routes of its passenger demand collection/distribution networks.

In this case, the relevant infrastructure performance of the end stations/terminals is the number of tracks to handle the TRM trains, which can be estimated as follows:

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

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

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

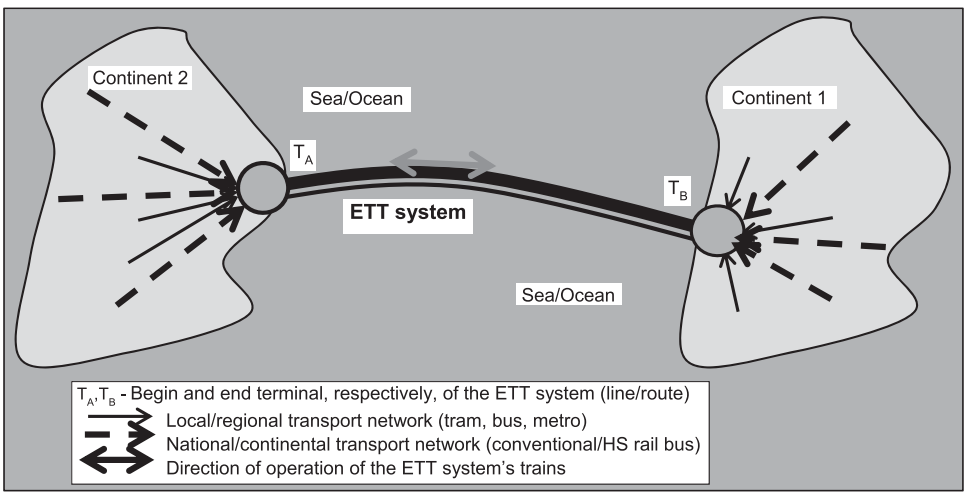

Figure 3. Simplified scheme of intercontinental ETT-TRM system/network with a single line/route (Source: Janić 2014).

3.2. Technical/technological performance

The technical/technological performance of an ETT-TRM system relate to its vacuum pumps, TRM trains, and traffic control/management system.

3.2.1. Vacuum pumps

Vacuum pumps are applied to initially evacuate and later maintain the required level of vacuum inside the tubes. In particular, creating a vacuum consists of an initially large-scale evacuation of air and later on of removal of the smaller molecules near the tube walls using heating techniques. These require the powerful vacuum pumps to consume a substantial amount of energy. At the initial stage, these pumps would operate until achieving the required level of tube evacuation, then be stopped automatically, and the vacuum-lock isolation gates opened. In cases of air leakage in some sections, the corresponding gates would be closed and the pumps activated again. The pumps would be located along the tubes in the required number depending on the volume 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 most likely be modified (redesigned) TRM07 trains (Janić 2014; Lee, Kim, and Lee 2006; Naumann, Schach, and Jehle 2006; Yaghoubi 2008). The modifications are needed due to the very high operating speeds of about: $v_{\mathrm{ETT}} = 6.4–8.0{\cdot}10^3$ km/h and the horizontal acceleration/deceleration rate(s) of about: $a = 1.5–3.0$ m/s^2, to be used thanks to operating in the vacuum tubes. These TRM trains would use electric energy for their levitation, guidance, air conditioning, heating, and lighting. They would be propelled by liquid hydrogen (LH_2) powering some kind of rocket engine The electrical energy would also be used for powering other facilities and equipment (Dewar and Bussard 2009; Sirohiwala, Tandon, and Vysetty 2007). In particular, due to the acceleration/deceleration of TRM trains to/from the very high speeds ($8.0{\cdot}10^3$ km/h), respectively, a substantial amount of energy would be consumed, as follows:

$$E_{\mathrm{ETT}/a/d} = 1/2 \cdot m_{\mathrm{ETT}} \cdot v_{\mathrm{ETT}}^2 \tag{3a}$$

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

The acceleration/deceleration phase of a trip would require engines considerably more powerful than the basic TRM train power plant, with the minimum required power/thrust as follows:

$$P/T_{\mathrm{ETT}/e} = \frac{1}{2} \cdot (m_{\mathrm{ETT}} \cdot a_{\mathrm{ETT}}^{\pm} \cdot v_{\mathrm{ETT}}) \tag{3b}$$

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

The other symbols are the same as those in previous equations.

During the cruising phase of a trip, the TRM train cabins would be pressurized similar to contemporary commercial aircraft (about one atm) and would travel thanks to the

inertial force gained after acceleration, and without aerodynamic and rolling resistance. due to the vacuum and levitation, respectively.

Using the low density LH_2 stored at low temperature, larger insulated fuel-storage tanks would ultimately be needed, which would – together with the more powerful engines – very likely increase their mass/weight. In addition, operating in the vacuum tubes at very high speeds would eliminate the shock waves at the moment of breaking the sound barrier (this is important for trains passing in the single tunnel/tube concept), and make air friction and consequent heating of trains negligible. Nevertheless, heat shields would have to be installed on the TRM trains for protection from overheating caused by unpredictable air leakages (Zhang et al. 2011).

3.2.3. Traffic control/management system

The traffic control/management system for TRM trains would have to be fully automated, that is, controlled (guided) analogously to modern Unmanned Flying Vehicles (UAV), and managed (separated) along the line/route according to the TRM operating principles. The reason for this is because train drivers simply would not have time to react to any unpredicted events due to the train's very high operating speed.

3.4. Operational performance

The operational performance of an ETT-TRM system relate to demand, capacity, quality of services, vehicle fleet size, and technical productivity (Janić 2014).

3.4.1. Demand

(i) General

The demand for an ETT-TRM system operating in long-haul markets 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 Air Passenger Transport (APT) system using conventional subsonic, super-, and/or hypersonic aircraft. In these cases, the ETT-TRM system is assumed to take over part of APT demand, which can be estimated by logit model.

(ii) Logit model

The logit model estimates the probability of choice of a given among several transport alternatives, in this case between an ETT-TRM and APT system, as follows (Janić 2014):

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

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

The dis-utility functions $U_{\mathrm{ETT}}(d,\ T)$ and $U_{\mathrm{APT}}(d,\ T)$ in Equation (4a) consist 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 $U_{\mathrm{ETT}}(d, T)$ for a given category of user/passenger can be estimated as follows:

$$\begin{aligned} U_{\mathrm{ETT}}(d, T) =& \alpha \cdot \tau_{\mathrm{ETT}/a} + \beta \cdot t_{\mathrm{ETT}/iv}(d) + \alpha \cdot \tau_{\mathrm{ETT}/l} + p_{\mathrm{ETT}}(d, T) \\ &= \alpha \cdot \left[\tau_{\mathrm{ETT}/a} + 1/2\left(\frac{T}{f_{\mathrm{ETT}}(d, T)} \right) \right] \\ &+ \beta \cdot \left[\frac{v_{\mathrm{ETT}}(d)}{a^{+}_{\mathrm{ETT}}} + \frac{d}{v_{\mathrm{ETT}}(d)} + \frac{v_{\mathrm{ETT}}}{a^{-}_{\mathrm{ETT}}} \right] + \alpha \cdot \tau_{\mathrm{ETT}/l} + p_{\mathrm{ETT}}(d, T) \end{aligned} \quad (4b)$$

where $\tau_{\mathrm{ETT}/a}$, $\tau_{\mathrm{ETT}/l}$: is the time of accessing (a)/leaving (l) the system, respectively (min, h); α: is the unit cost (i.e. value) of passenger time during accessing, waiting for departure, and leaving the ETT-TRM system (cost/min/pass);

$t_{\mathrm{ETT}/iv}(d)$: is the in-vehicle transit time on line/route *(d)* (h, min); β: is the unit cost (i.e. value) of passenger in-vehicle transit time (cost/min/pass); and $p_{\mathrm{ETT}}(d, T)$: is the price/fare for a trip on line/route *(d)* during time *(T)* (cost/pass).

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

(iii) Number of passengers

The number of passengers choosing the newly implemented ETT-TRM system, that is, taken from the existing APT system, both operating along route *(d)* during time *(T)* can be estimated by Equation (4a-b) as follows (Janić 2014):

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

where $Q_{\mathrm{APT}}(d, T)$: is the number of passengers on the given route *(d)* during time *(T)* exclusively carried by the APT system, which can be attracted by the ETT-TRM system at time of its implementation. 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 and transport service frequency

(i) Capacity

Similarly as with other transport systems, the capacity of given line, in this case of the ETT evacuated tube, can be expressed by the maximum number of TRM trains which can be served during a given period of time (usually one hour) under conditions of constant demand for service. This capacity can be estimated as follows (Janić 2014):

$$\mu(T) = T/\tau_{\min} \quad (4d)$$

where τ: is the minimum time interval between dispatching successive TRM trains in the tube in a single direction (min).

The minimum time interval *(τ)* in Equation (4d) can be determined as the minimum TRM train's deceleration/breaking time, as follows:

$$\tau_{\min} = v_{\max/\mathrm{ETT}} / a^{-}_{\max/\mathrm{ETT}} \tag{4e}$$

where $v_{\max/\mathrm{ETT}}$: is the maximum operating speed of the TRM trains in the evacuated tube (km/h); and $a^{-}_{\max/ETT}$: is the maximum safe deceleration rate of the TRM train while operating in the tube (m/s^2).

(ii) Transport service frequency

The transport service frequency $(f_{\mathrm{ETT}}(d,T))$ of the ETT-TRM system satisfying the expected/attracted passenger demand on route *(d)* during time *(T)* derived from Equation (4c) is as follows:

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

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

3.4.3. Quality of service

The quality of service of an ETT-TRM system, in addition to the attributes such as transport service frequency, reliability, and punctuality, can be particularly influenced by in-vehicle comfort during a trip. This comfort primarily depends on the horizontal, vertical, and lateral forces acting on passengers during accelerating/decelerating phases of the TRM train to/from the very high speed ($v_{\mathrm{ETT}} = 8.0{\cdot}10^3$ km/h), respectively. The lateral force can be mitigated by design of the ETT tubes (preferably as straight as possible in both horizontal and vertical planes) and the appropriate arrangement of seats on the TRM trains. It is rather complex to achieve such a design 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 are likely to be followed. Consequently, the other two – horizontal and vertical – forces would remain. For example, if the TRM trains accelerate/decelerate at the rate of $a^{\pm}_{\max/\mathrm{ETT}} = 1.5 - 3.0\,\mathrm{m/s^2}$, thus achieving maximum cruising speed in about ($v_{\mathrm{ETT}}/a^{\pm}_{\max/\mathrm{ETT}} = 12.3 - 24.7$ min), the horizontal G-force as a proportion of the nominal gravitational force ($g = 9.81$ m/s^2) would be: $G = 0.152$–$0.306\,g$, which does not particularly compromise the riding comfort of passengers.

3.4.4. Fleet size

Given the service frequency $(f_{\mathrm{ETT}}(d,\,T))$ in Equation (4f), the size of the TRM train fleet of an ETT-TRM system can be estimated as follows:

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

where $t_{\mathrm{ETT}/tr}(d)$: is an ETT-TRM train's average turnaround time along route *(d)* (min, h).

Under an assumption that the TRM train always operates at maximum speed, the minimum time ($t_{ETT/tr}$ (d)) in Equation (5a) can be estimated as follows:

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

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

The other symbols are analogous to those used in previous equations.

3.4.5. Technical productivity

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

(i) Single train/vehicle:

$$TP_{ETT/v}(d, T) = s_{ETT}(d, T) \cdot v_{ETT}(d) \quad (\text{seat} - \text{km/h}) \tag{6a}$$

(ii) Fleet of trains/vehicles:

$$TP_{ETT/f}(d, T) = f_{ETT}(d, T) \cdot s_{ETT}(d, T) \cdot v_{ETT}(d) \quad (\text{seat} - \text{km/h}^2) \tag{6b}$$

where $v_{ETT}(d)$: is the average operating speed of TRM train(s) (km/h).

All other symbols are as used in previous equations.

3.5. Economic performance

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

3.5.1. Costs

(i) Infrastructure

The total infrastructure cost of an ETT-TRM system consists of capital investments in buildings and expenses for capital maintenance of the infrastructure and supporting facilities and equipment, on the one hand, and their operating costs on the other. The investment generally includes the expenses for building the tubes (2 + 1), TRM train guideways, and stations/terminals at both ends of the given 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 expenses for their capital maintenance. The operational costs mainly include the expenses for regular maintenance, labor, and energy for maintaining the tube vacuum (http://tunnelbuilder.comhttp://tunnelbuilder.com).

(ii) Rolling stock – TRM trains

The cost of rolling stock consists of both capital investment and operational costs. The former relate to acquiring and capital maintenance of the TRM train fleet, whereas the latter includes expenses for regular maintenance, material, labor, and energy/fuel consumed for operating the TRM fleet under given conditions.

3.5.2. Revenues

The revenues of an ETT-TRM system can be both direct and indirect. The direct revenues are mainly obtained from charging its users/passengers. The indirect revenues 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 latter revenues/savings occur by reducing the scale of operations of the competing APT system due to losing passenger demand taken over by the ETT-TRM system.

3.6. Environmental and social performance

The environmental and social performance of an EET-TRM system generally relates to its impacts on the environment (energy/fuel consumption and related emissions of GHG and land use/take) and society (noise, congestion, and safety, i.e. traffic incidents and accidents), all estimated according to the scenarios of competing with other transport systems, in this case with the APT system. The cost of these impacts (i.e. externalities) can be considered in the scope of these instead of, as mentioned above, including them in economic performance.

3.6.1. Energy/fuel consumption and GHG emissions

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 obtained from the renewable primary sources (water, sun, nuclear) for levitation and guidance, the TRM trains operating in the vacuum tubes would have negligible GHG emissions and consequent impacts on the environment, particularly compared to those from burning of kerosene fuel (JP-1) by conventional APT aircraft emitted directly into the atmosphere (Janić 2014).

3.6.2. Land use

An ETT-TRM system would occupy additional land only for building coast terminals if they are not already included as parts of the larger intermodal passenger stations/terminals incorporated into existing urban structures.

3.6.3. Noise

An ETT-TRM system would not generate any noise, which disturbs population near and around the route's start and end stations/terminals. The main reason is that the TRM trains would operate at low speeds within their isolated 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 routes. Regarding the intensity of operations, the automated traffic management systems would have to provide a precise guidance of TRM trains in order to achieve almost perfect (in terms of seconds) matching of their 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 start and end terminals simply due to the increased intensity of mobility there.

3.6.5. Traffic incidents/accidents (safety)

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

3.7. Policy performance

An ETT-TRM system would demonstrate its policy performance both at the national scale as contributing to the creation of an integrated transport system and at the international (global) scale in terms of creating an integrated global, very high speed, non-APT-based passenger transport system/network, which would be able to contribute to furthering the globalization of the already highly global economy and society at that time. At such, the ETT-TRM system would certainly contribute to increasing the sustainability of the transport sector through contributing to its social economic welfare and reducing overall impacts on the environment and society.

4. An Estimation of the performance of the ETT-TRM system

4.1. The case of the Trans-Atlantic APT market

One among prospective long-haul (intercontinental) passenger transport markets for implementation of the ETT-TRM system is between Europe and North America (i.e. Trans-Atlantic). At present, this is the world's largest intercontinental air passenger market served by the Air Passenger Transport (APT) system. Some estimates indicate that the average share of this market in the total global APT market of about 8.3% in 2011 would decrease to about 6.5% or 5.4% in 2031. This indicates expectations for its increasing maturity over time implying the lower growth rates. Figure 4 shows the past and forecast/prospective development of the APT demand in this market for the period 2004–2060 (Airbus 2012; Boeing 2014; FAA 2013).

As can be seen, the assumed average annual growth rates indicate a gradual maturation of the market and weakening of 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} =

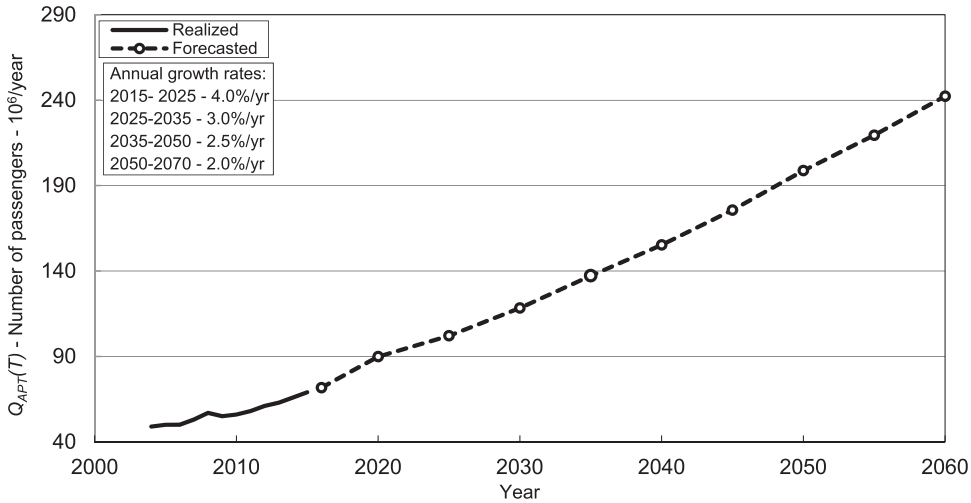

Figure 4. Possible long-term development of APT demand in Trans-Atlantic market (both directions) (Sources: Airbus 2012; Boeing 2014; FAA 2013; Janić 2014; http://centreforaviation.com/analysis/the-north-atlantic-the-state-of-the-market-fiveyears-on-from-eu-us-open-skies-100315).

$199 \cdot 10^6$ in the year 2050, and $240 \cdot 10^6$ in the year 2060. In the year 2050/51, the implemented EET-TRM system could immediately attract a part of this expected APT demand consisting mainly of business (premium class) passengers. These passengers consider transport/travel time as one of the most important attributes for choice of the transport system. They would access the ETT-TRM system at its start and end station/terminal at both ends of the route by integrated transport services provided by the above-mentioned collection/distribution ground transport systems. Later over time, the ETT-TRM system could become increasingly convenient for more extensive use by non-business and leisure passengers, used to traveling economy class.

4.2. Infrastructural scenario

The length of the ETT-TRM line/route in the above-mentioned Trans-Atlantic ATP market to be built over a 20-year period (2031–2050) would be: $d = 5664$ km (similar to the length of the air route between London and New York). As shown in Figure 2, the ETT-TRM system design with two transport and single service/maintenance tubes, the inside and outside diameter of each transport tube would be about: $D_2 = 2R_2 = 6.2$ m and $D_1 = 2R_1 = 6.0$ m, and that of the service tube: $D_{s2} = 2R_{s2} = 3.2$ m and $D_{s1} = 2R_{s1} = 3.0$ m, respectively. This implies that the thickness of all tubes is 200 mm (Antaki 2003). They can accommodate TRM trains with a height of 4.16 m and width of 4.16 m, and guideways of the height of 1.25 m (Figure 2; Table 1) (Janić 2014). For example, let the density of the ocean's water be: $\rho_0 = 1.027$ ton/m^3, the dimension of the tubes as above, the factor for installing guideways and other systems inside: $f = 2$, and the average specific gravity of the tube 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 Equation (1) the buoyant force of the tube of length of 1 m would be: $W_b = 21.72–29.02 = -7.3$ kg < 0, which implies that the tube would float and

Table 1. Technical/technological and operational performances of the basic and modified ETT-TRM 07 train.

Characteristic	Value[a]	Value[b]
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 train[c] (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)	2.47–2.48	*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*

[a]Non-vacuum.
[b]Vacuum.
[c]Approximately 64 ton per carriage including the weight of passengers and their baggage.
Sources: Janić 2014; Lee, Kim, and Lee 2006; Naumann, Schach, and Jehle 2006; Yaghoubi 2008.

thus must be anchored to the seabed. In addition, the buoyant force can be used to specify the need for the anchoring cables. The quantity of material used to build the two transport and one service/maintenance tubes with 200 mm thick walls and the specific gravity of the mixture of materials (5.67 ton/m^3) would amount to about $152{\cdot}10^6$ ton. In addition, about 200 vacuum pumps (units), each with the capacity of 100m^3/min and the energy consumption of 260 KWh, would be located at a distance of about 28 km along the line. The volume of air to be evacuated from the 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 (Antaki 2003; Janić 2014; Salter 1972; Sirohiwala, Tandon, and Vysetty 2007; Zhang et al. 2011).

4.3. Technical/technological scenario

The ETT-TRM system would consume most energy/fuel for propulsion, that is, for accelerating/decelerating of a TRM train to/from its maximum cruising speed of: $v_{\mathrm{ETT}} = 8.0{\cdot}10^3$ km/h. If, for example, the gross weight of a five-car TRM train was 320ton, the energy needed to accelerate it to/from the above-mentioned maximum cruising speed would be, estimated by Equation (3a), as follows: $E_{\mathrm{ETT}/a/d} = 1/2{\cdot}320{\cdot}10^3{\cdot}(8.0{\cdot}10^6/3.6{\cdot}10^3)^2 = 790.2{\cdot}10^9 J = 219.5$ MWh. The acceleration/deceleration phase of a trip would take about: $\tau_{\mathrm{ETT}/a/d} = v_{\mathrm{max/ETTT}}/a_{\mathrm{ETT}} = [(8.0{\cdot}10^6/3.6{\cdot}10^3)/3.0]/60 = 12.3$ min (the average acceleration/deceleration rate is: $a^{\pm}_{\mathrm{max}/\mathrm{ETT}} = \pm 3$ m/s^2). After that, the TRM train can continue to be driven by the inertial force without consuming additional energy for propulsion. At the end of the route, the TRM train would then spend the same as the above-mentioned amount of energy and time for deceleration and stopping. Consequently, the minimum required power of the rocket engine, estimated by Equation (3b), would be: $P/T_{\mathrm{ETT}/e} = 1/2{\cdot}[320{\cdot}10^3{\cdot}(8.0{\cdot}10^6/3.6{\cdot}10^3){\cdot}3.0] = 1066.7{\cdot}10^6$ kg·m^2/s^3 = 1066.7 MW. The mass/weight of this engine would be: $m_{re} = 1.7$–6.3 ton (IBRD 2012; Janić 2014). If LH_2 with the energy content of 142MJ/kg is used, its consumption during acceleration and deceleration phases of a trip would be about: $F_{C/a/d} = E_{\mathrm{ETT}/a/d}/142 = 790123.5/142 = 5.6$ ton each, and the total consumption 11.2 ton. This requires the capacity of fuel

reservoirs onboard the TRM of: $C_r = 12$ ton. Given the density of LH_2 of: $D = 70.86$ kg/m^3, the volume of these reservoirs would be: $V_r = C_r/D = 12000/70.85 \approx 170$ m^3 (http://www.projectrho.com/public_html/rocket/enginelist.php).

These all above-mentioned modifications, including the weight of insulated reservoirs, would increase the gross weight of the TRM train to about: $m_{ETT} = 340$ tons. Then, the energy consumption during acceleration/deceleration would be: $E_{ETT/a/d} = 233.2$ MWh ($F_{C/a/d} = (2{\cdot}839520.5)/142 = 11.9$ tons), and the minimum power required of the rocket engine: $P/T_{ETT/e} = 1133.3$ MW. The resulting differences between the main technical/technological and operational performance of the basic and modified TRM train, the latter to be operated by the ETT-TRM system, is given in Table 1.

4.4. Operating scenarios

4.4.1. General

The 'what-if?' operating scenarios are developed for the year 2050/51 when the EET-TRM system is supposed to be implemented between Europe and North America (over the North-Atlantic) and as such to start competing with the well-established APT system. The start/end stations/terminals could be in Southampton/London (UK) and New York (USA), which is a distance of: $d = 5564$ km. Three operational and competing scenarios are defined by considering the APT system as follows:

(i) ETT-APT/C: Conventional sub-sonic aircraft fleet operating at a cruising speed of about 0.85M at altitudes of about 33,000 ft (1M = 1078 km/h at this altitude and M is the Mach number);
(ii) EET-APT/STA-NASA: Fleet of Supersonic Transport Aircraft-NASA High-Speed Civil Transport (STA-NASA) beyond the year 2030 operating at a cruising speed of 2.0–2.4M at altitudes of 60,000 ft (1M = 1062 km/h at this altitude); and
(iii) EET-APT/ECH-M5C: Fleet of EC Hydrogen-Mach 5 Cruiser (A2ECH-M5C) beyond the year 2030 with a cruising speed of 5.0M at altitudes of 60,000 ft (1M = 1062 km/h at this altitude) (Coen 2011; EC 2008; NAS 2001).

4.4.2. Passenger demand

According to the passenger demand forecast in Figure 4, this APT system is expected to carry out about $199{\cdot}10^6$ passengers in 2051 and $240{\cdot}10^6$ passengers in 2060. Based on past experience and assuming that it would continue in the future, about 16–18%, i.e. 32–$36{\cdot}10^6$ of these mainly business (premium class) passengers are expected to be able to choose between these three APT systems and the newly implemented EET-TRM system in the year 2050/51 (http://www.projectrho.com/public_html/rocket/enginelist.php).

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

Table 2. Some operating characteristics of EET-TRM and APT systems in the Trans-Atlantic market.

Competing system (Scenarios)	Length of route d (km)	Operating altitude[a] H (10^3ft)	Average block speed[b] v (M; km/h)	Average door-to-door travel time[b)] $(\tau_a \pm \tau_l) \pm t_{iv}(d)$ (h)
ETT	5564	−1.0	5.5; 6700	3.50 + 0.83 = 4.33
APT/C	5564	+33	0.7; 740	1.50 + 7.50 = 9.00
APT/STA-NASA	5564	+60	2.0–2.4; 2124–2549	1.50 + 2.66 = 3.16
APT/ECH-M5C	5564	+60	5.0; 5310	1.50 + 1.09 = 2.59

Note: 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.

[a]Above MLS (Middle Sea Level); 1 ft = 0.305 m.

[b]Including acceleration and deceleration rate of: $a^{+/-} = \pm 3$ m/s, respectively, to/from the maximum corresponding cruising speed of $v_{max/ETT} = 8.0 \cdot 10^3$ km/h in the vacuum tube.

Sources: EC 2006; 2008; Janić 2014; NAS 2001.

As can be seen, the ETT-TRM system is supposed to have a shorter door-to-door travel time than its APT/C counterpart, thus presumably demonstrating capability for attracting the above-noted passenger demand. However, it would not be superior compared to its APT/STA-NASA and APT/ECH-M5C counterparts, mainly due to its 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-TRM system under given conditions are estimated by Equation (4a-c) and shown in Table 3.

As can be seen, if competing exclusively with the ATP/C, the ETT-TRM system would be able to attract almost the entire premium class passenger demand. If competing with the APT/STA-NASA and APT/ECH-M5C, it would attract about 46% and 15%, respectively.

4.4.3. Capacity and transport service frequency

If the maximum speed of TRM trains is: $v_{max/ETT} = 8.0 \cdot 10^3$km/h and the acceleration/deceleration rate is: $a_{max} = 3.0$ m/s^2, the minimum time interval between successive dispatching of these trains in a single direction is estimated from Equation (4e) as: $\tau_{min} =$ 12.34 min, and the capacity from Equation (4d) as: $\mu = 60/12.34 \approx 5$ dep/h/dir. In addition, the seating capacity of an ETT-TRM train is: $S_{ETT} = 400$ seats and the average load factor is: $\lambda_{ETT} = 0.90$, the transport service frequency estimated by Equation (4f), based on the passenger demand in Table 3, is given in Table 4.

As can be seen, in the case of competition with APT/C, the ETT-TRM, departures would take place every 15–20 min, thus giving an average passenger schedule delay of: 1/2·(15–20) = 7.5–10.0 min. In the case of competition with APT/STA-NASA, the ETT-TRM departures would be every 30 min with an average schedule delay of: 1/2 · (30) = 15 min. Finally, in the case of competition with APT/ECH-M5C, ETT-TRM departures would be every hour (60 min) and the average schedule delay would be: 1/2·(60) = 30 min.

4.4.4. Required fleet

Recognizing that the stop time of each EET-TRM train at both start stations/terminals is: $t_{ETT/s} = 2$ h (120 min) (mainly due to the need for safe refueling with LH_2), the turnaround time based on Equation (5b) would be: $t_{ETT/rd} = 2 \cdot (0.83 + 2) = 5.66$ h. Then, based on Equation (5a), the required TRM fleet competing in the EET-APT/C scenario would be: $N_{ETT} = (3–4) \cdot 5.66 \approx 17–23$ trains, and 19–25 trains if a 10% reserve is included. In

Table 3. Market share and volume of demand of EET-TRM in the competing scenarios with the APT system – Trans-Atlantic market (Year 2050/51).

Competing system (Scenarios)	Annual demand for competition Q_{APT} 10^6 (pass/yr)	Market share of ETT p_{ETT} (%)	Annual demand for ETT Q_{ETT} (10^6pass/yr)	Daily demand for ETT q_{ETT} (10^3pass/day/dir)[a]
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

Note: 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;
[a]Average during the day per direction (1year = 365 days).

addition, by Equation (2), the required number of tracks at each end station/terminal to handle departing and arriving TRM trains in the scenario EET-APT/C when each of them stops for an average time of: $t_{ETT/s} = 2$ h (120 min) would be: $n_{ot} = (3–4)\cdot(2) = 6–8$ tracks. The length of each track would be a minimum of 150–200 m to enable the accommodation of TRM trains and the comfortable embarking and disembarking of passengers. One or two additional tracks would also need to be provided at each end station/terminal for TRM trains temporarily out of service.

4.4.5. Technical productivity

The technical productivity of a single ETT-TRM train operating according to the EET-APT/C scenario is estimated by Equation (6a) as: $TP_{ETT/v} = 400\cdot6.8\cdot10^3 \approx 2.720\cdot10^6$ s-km/h. In addition, the technical productivity of the ETT-TRM train fleet during one hour estimated by Equation (6b) is: $TP_{ETT/f} = (3–4)\cdot400\cdot6.8\cdot10^3$ (km/h) $\approx 8.16–10.90$ s-km/h^2.

Table 5 summarizes some of the significant infrastructural and operational performances of the ETT-TRM system under the competing scenarios.

4.5. Economic scenario

According to the 'what-if?' economic scenarios, the ETT-TRM system in the case under consideration is assumed to provide a return on investment, that is, positive or zero cost–benefit ratios over the 40 year period following implementation in 2050/51.

4.5.1. Costs

The investment cost for building tubes appears to be very uncertain but some estimates indicate that they can be about: $c_{It} = 14.6–20.2\cdot10^6$ US$/km (i.e. $C_{It} = 81–115\cdot10^9$ US$

Table 4. Transport service frequency of ETT-TRM system in the competing scenarios with the APT system – Trans-Atlantic market (Year 2050/51).

Competing system (Scenarios)	Daily demand for ETT q_{ETT} (10^3pass/day/dir)[1)]	Daily service frequency F_{ETT} (dep/day/dir)	Hourly service frequencyf_{ETT} (dep/h/dir)[a]
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

[a]Operating time during the day: 18 h; $S_{ETT} = 400$seats; $\lambda_{ETT} = 0.90$ (dir –direction).

Table 5. Some infrastructural and operational performances of the ETT TRM system in the competing scenarios with the APT system – Trans-Atlantic market (Year 2050/51).

Competing systems (Scenario)	Hourly service frequency f_{ETT} (dep/h/dir)[a]	Tracks at end terminals n_t (tracks/terminal)	Required TRM fleet N_{ETT} (trains)	Technical productivity $TP^c_{ETT/f}$ (10^6 s-km/h/h)
EET-APT/C	3–4	6–8	17–23[a]/19–25[b]	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

[a]Operating.
[b]Including reserve of 10%.
[c]Fleet of TRM trains.

for the entire 5564 km length of the line, including the passenger stations/terminals at both ends) (http://www.projectrho.com/public_html/rocket/enginelist.php).

The cost of the TRM guideways in the tubes in a single direction would be similar to that of today's TRM – about: $c_{Im} = 16.8 \cdot 10^6$ \$US/km (i.e. for two tracks this gives total investment cost of: $C_{Im} = 5564 \cdot 2 \cdot 16.8 \cdot 10^6 = 187 \cdot 10^9$ US\$). Thus, if the system is built over a 20-year period between 2030 and 2050, the total infrastructure costs (tubes, TRM guideways, terminals) and the cost of facilities and equipment (vacuum pumps, power supply system, traffic control system, and fire protection system) would amount to: $C_T = 268–302 \cdot 10^9$ US\$. Without taking into account interest rates, these costs would be: $c_T = 13.4–15.1 \cdot 10^9$ US\$/yr. As an illustration, the share of these investment costs in the cumulative Gross Domestic Product (GDP) of Europe (EU) ($690.34 \cdot 10^{12}$ US\$) and North America (USA, Canada) ($771.4 \cdot 10^{12}$ US\$) during that period would be about 0.018–0.026%, respectively (CIA 2012; Janić 2014).

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

4.5.2. Revenues

The revenues gained from operating the EET-TRM system proposed here can be considered to be direct, i.e. those from charging users/passengers, and indirect, i.e. as savings in the cost of passenger in-vehicle time under the competing APT system scenarios. The direct revenues are illustrated by the relationship between the EET-TRM average cost-covering fare per passenger and the annual volume of passenger demand diverted from the APT and shown on Figure 5.

Table 6. Some economic performances of the ETT-TRM system for the competing scenarios with the APT system – Trans-Atlantic market (Year 2050/51).

Competing systems (Scenario)	Passenger demand[a] Q_{ETT}*(10^9p-km/yr)	Infrastructure (unit) cost[b] c_{TI} (US\$/*p*-km)	Operational (unit) cost c_o (US\$/*p*-km)	Total (unit) cost 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

[a]Q_{ETT}* = $Q_{ETT} \cdot$ d.
[b]Average annual total costs of infrastructure estimated to be: $c_{TI} = [(14.74 + 16.61)*10^9]/2 = 15.68 \cdot 10^9$ US\$/yr; *p*-km-passenger-kilometer (the number of passengers . distance traveled); yr-year.

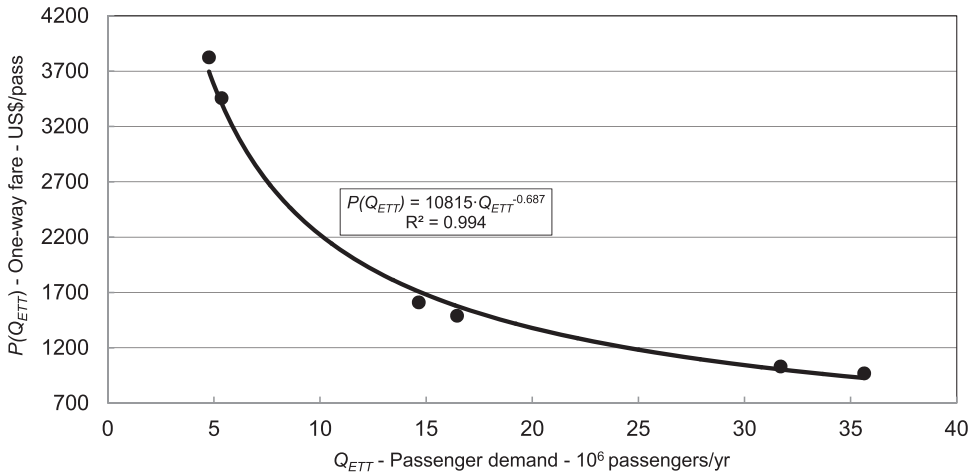

Figure 5. Relationship between average fare and annual premium passenger demand for the ETT-TRM system – Trans-Atlantic market (Year 2050/51).

As can be seen, the one-way fare covering the total ETT-TRM system's cost varies between: $P(Q_{ETT}) = 970$ and 3500 US$/passenger, and decreases more than proportionally with increasing annual (premium class) passenger demand. Based on average total cost, this fare also reflects the existence of economies of demand density of the EET-TRM system. In addition the ETT-TRM system's indirect revenues, that is, the saving in passenger cost door-to-door time, dependent on annual (premium class) passenger demand, are shown on Figure 6.

As can be seen, the really significant savings in the costs of passenger door-to-door travel time can be achieved with the EET-APT/C competing scenario. However, these savings would be negative and not in favor of the ETT-TRM system in the other two scenarios (particularly with ETT-APT/ECH-M5C) mainly due to the relatively low level of attracted passenger demand (Table 3) (Janić 2014; Landau et al. 2015; USDT 2011).

4.6. Environmental/social/policy scenario

The ETT-TRM system operating in the case outlined above is assumed to be free of environmental impacts associated with fuel/energy consumption from non-renewable sources, related emissions of GHG, and land use/take. It would also be free from social impacts such as noise, congestion, and traffic incidents/accidents (safety). As such, it would possess substantive performances contributing to policies aimed at reducing the overall impacts of the transport sector on society and the environment. Nevertheless, the 'what-if?' environmental scenario relates mainly 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.

The rocket-engine propellants used by the ETT-TRM trains and burning out within the tubes would not produce emissions of GHG impacting on the outside environment (NASA 2002). The electrical energy for operating the ETT-TRM system's supporting facilities and equipment would be obtained completely from non-renewable (nuclear) and renewable (solar, wind, water) sources, thus implying that the emissions of GHG

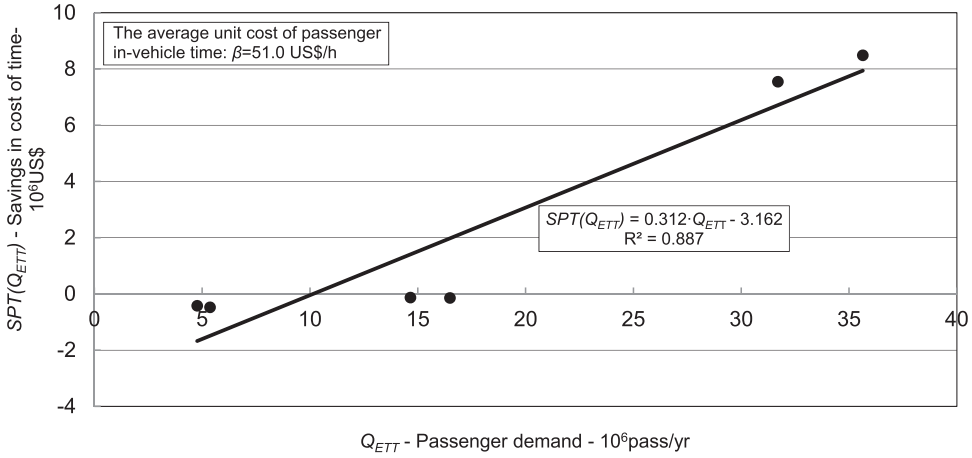

Figure 6. Relationship between savings in cost of passenger door-to-door time and volume of annual premium passenger demand for the ETT-TRM system – Trans-Atlantic market (Year 2050/51).

from its operation would be negligible compared to that of burning crude oil-based kerosene (JP-1 fuel). Under such conditions, taking passenger demand away from the APT system could reduce the scale of its operations and consequently the corresponding impacts on the environment and society. This would be particularly so in the ETT-TRM -APT/C competing scenario, when the APT system is assumed to operate exclusively aircraft similar to today's Boeing B787-8/9 and Airbus A350-800/900, with average fuel consumption of about: $fc_{\mathrm{APT}/1} = 0.0257$ kg/s-km and $fc_{\mathrm{APT}/2} = 0.0206$ kg/p-km, respectively (the load factor is assumed to be $\lambda_{\mathrm{APT}} = 0.80$) (http://www.airbus.com/; http://www.boeing.com/commercial/).

The emission rate of JP-1 fuel is: $e_m = 5.25$ $kgCO_{2e}$/kg (GAO 2009; IPCC 1999), which gives the average GHG emission rates of about: $e_{\mathrm{APT}/1} = 0.108$ $kgCO_{2e}$/s-km or $e_{\mathrm{APT}/2} = 0.135$ $kgCO_{2e}$/p-km. Then, the cost of CO_{2e} emissions as externalities of the APT system saved by the ETT-TRM system can be estimated for the competing scenarios and are shown in Table 7.

As can be seen, savings in CO_{2e} emission externalities can be substantial and dependent mainly on the volumes of demand switched away from APT as well as on the aircraft technologies operated by the ATP system. Particularly, in the scenario using a fleet of ECH-M5C beyond 2030 powered by LH_2 (Liquid Hydrogen), the savings of the above-mentioned externalities would be considerably less.

Table 7. Some environmental performances of the ETT-TRM system for the competing scenarios with the APT system – Trans-Atlantic market (Year 2050/51).

Competing systems (Scenario)	Passenger demand[a] Q_{ETT}*(10^9p-km/yr)	Savings in cost of CO_{2e} SC_e (10^9 US$/yr)	Savings in total costs/ externalities[d] SC_{te} (10^9 US$/yr)
EET-APT/C	179.5–207.5	9.0–10.4[b]	16.4–18.5
EET-APT/STA-NASA	83.0–93.2	0.5–0.84[c]	6.5–7.3
EET- APT/ECH-M5C	27.0–30.4	0.24–0.27[c]	2.1–2.4

[a] $Q_{\mathrm{ETT}}^* = Q_{\mathrm{ETT}} \cdot d$.
[b] $c_e = 0.050$ US$/$p$-km (BAU – Business As Usual scenario).
[c] $c_e = 0.009$ US$/$p$-km (Unit cost of CO_{2e} externalities).
[d] $c_{te} = 0.078$ US$/$p$-km (Total cost of social and environmental impacts-externalities); p-km-passenger-kilometer; yr-year.

5. Conclusions

This paper has demonstrated a multidimensional examination of infrastructural, technical/technological, operational, economic, environmental, social, and policy performance of the advanced Evacuated Tube Transport (ETT) system operated by TransRapid Maglev (TRM) – the ETT-TRM system. These have been modeled and then estimated according to a 'what-if?' scenario approach of competition between the ETT-TRM and Air Passenger Transport (APT) systems in a given long-haul (intercontinental) passenger market.

The results have shown that an ETT-TRM system operating appropriately redesigned TRM (TransRapid Maglev) trains could compete successfully with an APT system exclusively operating conventional kerosene-fueled aircraft in the North Atlantic market and, presumably, in other long-haul markets. This could bring contributions to savings in the APT system's impacts on society (including cost of passenger time, local noise, congestion, and traffic incidents/accidents (safety)) and the environment (energy/fuel consumption and related emissions of GHG, and land use take). It has also been shown that an ETT-TRM system competing with an APT system exclusively operating super- and hyper-sonic aircraft across the North Atlantic and other long-haul markets would be less successful, due to attracting a much lower level of passenger demand, and consequently contributing considerably lower if at all to the savings in the above-mentioned social and environmental externalities.

In addition, this examination has indicated some of the potential inherent ultimate advantages and disadvantages of the ETT-TRM system itself and its potential contribution to the overall sustainability of the transport sector. The ETT-TRM system's main advantages can be identified, firstly, as the very high speed of transport services provided by TRM trains and, secondly, freedom from creating impacts on both the environment by the emission of GHGs and land use take, and society by noise and congestion. However, the system's main disadvantages can be summed up as follows: (i) a need to redesign the basic configuration of TRM trains; (ii) substantial fuel (LH_2) consumption for propulsion of the TRM trains during the acceleration and deceleration phases; (iii) high infrastructure building and maintenance costs, including the costs of maintaining a permanent vacuum in the tubes; (iv) high inherent vulnerability and exposure to a range of external disturbing/disruptive events; and (v) its inherent complexity, challenging and requiring international cooperation in the planning, design, implementation, and operation of the system.

Disclosure statement

No potential conflict of interest was reported by the author.

References

Airbus. 2012. *Delivering the Future: Global Market Forecast 2012-2030*. Blagnac: AIRBUS S.A.S.
Antaki, A. G. 2003. *Piping and Pipeline Engineering: Design, Construction, Maintenance, Integrity, and Repair*. Amsterdam, The Netherlands: CRC Press.
Boeing. 2014. *Current Market Outlook 2015-2034*. Seattle, WA: Boeing Commercial Airplanes.
CIA. 2012. *The World Fact-Book*. Washington, DC: Central Intelligence Agency.

Coen, P. 2011. "Fundamental Aeronautic Program: Supersonic Projects", 2011 Technical Conference, National Aeronautic and Aerospace Administration, Cleveland, Ohio, p. 34.

Dewar, J., and R. Bussard. 2009. *The Nuclear Rocket: Making Our Planet Green, Peaceful and Prosperous*. Burlington: Apogee Books.

EC. 2006. *ATLLAS (Aerodynamic and Thermal Load Interactions with Lightweight Advanced Materials for High Speed Flight), Sixth Framework Program, Final Public Report, Thematic Priority 1.4 Aeronautics and Space*. Brussels: European Commission.

EC. 2008. *LAPCAT (Long/Term Advanced Propulsion Concepts and Technologies), Sixth Framework Program, Final Public Report, Thematic Priority 1.4 Aeronautics and Space*. Brussels: European Commission.

FAA. 2013. *FAA Aerospace Forecast Fiscal Years 2013-2033*. Washington, DC: Federal Aviation Administration.

GAO. 2009. *Aviation and Climate Change: Aircraft Emissions Expected to Grow, but Technological and Operational Improvements and Government Policies Can Help Control Emissions, Report to Congressional Committees, GAO-09-554*. Washington, DC: US Government Accountability Office.

IBRD. 2012. *Air Travel and Energy Efficiency, Transport Papers TP-38*. Washington, DC: International Bank for Reconstruction and Development/The World Bank.

IPCC. 1999. *Aviation and the Global Atmosphere, Intergovernmental Panel on Climate Change*. Cambridge: Cambridge University Press.

Janić, M. 2014. *Advanced Transport Systems: Analysis, Modelling, and Evaluation of Performances*. London: Springer.

Landau, S., G. Weisbrod, G. Gosling, C. Williges, M. Pumphrey, and M. Fowler. 2015. *Passenger Value of Time, Benefit-Cost Analysis, and Airport Capital Investment Decisions, Volume 1: Guidebook for Valuing User Time Savings in Airport Capital Investment Decision Analysis, ACRP (Airport Cooperative Research Program)*. Washington, DC: Transportation Research Board.

Lee, W., K. Kim, and J. Lee. 2006. "Review of Maglev Train Technologies." *IEEE Transactions on Magnetics* 42 (7): 1917–1925.

NAS. 2001. *Commercial Supersonic Technology: The Way Ahead, National Academy of Science*. Washington, DC: National Academy Press.

NASA. 2002. *Propellants - NASA Facts*. Virginia: National Aeronautics and Space Administration.

Naumann, R., R. Schach, and P. Jehle. 2006. "An Entire Comparison of Maglev and High-Speed Railway Systems", 19th International Conference on Magnetically Levitated Systems and Linear Drives, Dresden.

Salter, R. M. 1972. "The Very High Speed Transit System", *Rand Corporation*, p. 4874, Santa Monica, CA, p. 18.

Sirohiwala, Y. A., A. Tandon, and R. Vysetty. 2007. *Feasibility and Economic Aspects of Vactrains: An Interactive Qualifying Project*. Worcester, MA: Worcester Polytechnic Institute.

USDT. 2011. *Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis, Office of the Secretary of Transportation*. Washington, DC: US Department of Transportation.

Yaghoubi, H. 2008. "Magnetically Levitated Trains", *Maglev*, Vol. 1, Pooyan Farnegar Publisher, Tehran.

Zhang, Y., D. Oster, M. Kumada, J. Yu, and S. Li. 2011. "Key Vacuum Technology Issues to be Solved in Evacuated Tube Transportation." *Journal of Modern Transportation* 19 (2): 110–113.