SOLAR-POWERED VACTRAIN – A PRELIMINARY ANALYSIS

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ABSTRACT

This paper analyzes a high-speed electric train running inside an evacuated tunnel that is powered by solar panels mounted above the tunnel that continuously produce 137 kW of average power per km of track. This train will be totally weather-proof and consume much less power than today's high speed trains, so that surplus solar electricity from the solar panels can be profitably sold to the grid. A preliminary economic analysis indicates that this 500 km/h solar-powered vactrain can be profitable at a ticket price of 0.29 to 0.40 U.S dollars per km per passenger so that it will be cheaper than air travel.

INTRODUCTION

High Speed Trains such as the Japanese Shinkansen bullet train and the French Train a Grande Vitesse (TGV) are technological success stories as well as economically profitable with an excellent safety record [Gow, 2008]. These electric trains routinely travel at speeds of over 300 km/h (180 mph) though the TGV holds the world record by reaching a top speed of 574.8 km/h in April 2007. However, such record-breaking runs require special track preparation and overhead electric catenary tensioning and are not practically achievable on a day-to-day basis. Trials with the Fastech 360 bullet trains show that a peak speed of 360 km/h may not be achievable under Japanese conditions because of noise concerns, excessive overhead wire wear and braking distances. In France too, there have been a few protests against the noise from the TGV [Davey ,2001]. Special noise barriers have been erected around these high speed railroad tracks in Japan and France [Takagi, 2005]

In spite of their high speeds, these trains actually are more energy efficient than automobiles or airplanes. An analysis by Strickland [Janardhan and Fesmire, 2011] shows that 300 km/h trains attain a fuel consumption of 380 passenger-miles per gallon. In contrast, a Toyota Prius achieves only 96 passenger mpg while an airplane can fly 50 miles per gallon of fuel per passenger. It does take more energy to build a railroad track than to build a road, i.e., the embodied energy associated with trains is greater. Yet, even accounting for the higher embodied energy of railroads shows that a trip from Frankfort to Munich (190 km) results in CO_2 emissions of only 17.8 kg per passenger or 94 grams per passenger-kilometer [Becken and Hay, 2007]. Only the most efficient passenger cars are able to match this figure and that only when the CO_2 emissions from road construction are neglected, according to web-based calculators like the UmweltMobilCheck by Deutsche Bahn [Becken and Hay, 2007]. Since 80% of the electricity in France is generated by nuclear power plants, the CO_2 emissions, during operation, from a TGV are essentially zero.

Under European and Asian conditions, the economics of such high speed trains are fairly good, as stated earlier. A study by Levinson et al. [1997], concludes that a high speed rail system in California will be more expensive than expanding air service and marginally more costly than automobile travel. The authors recommend that high speed rail be restricted to shorter distances. However, this study was done in the mid-1990s when the prices of gasoline and jet fuel were only a third of what they are today. Therefore, its conclusions may no longer be valid.

Thus, it is clear that high speed trains are not only energy efficient, but also contribute less to Global Warming than any other mode of transportation. Hence, in an energy-starved future where climate change will be a major challenge, high speed rail is a must. Therefore, this paper proposes a new concept in high speed rail that will be even more energy efficient, less carbon intensive and faster than today's high speed trains.

NOMENCLATURE

A_f = train's frontal area, m^2
C_d = drag coefficient based on frontal area
F_r = frictional rolling resistance of train, kN
F_d = drag force on train, kN
g = gravitational acceleration, m/s^2
G = track gradient, %
M = train mass, metric tons (tonne)
P_{ex} = power for acceleration or hill-climbing, kW
P_{cr} = power consumption during cruising, kW
v = train speed, m/s
V = train speed, km/h

THE PROPOSED CONCEPT

The proposed concept, briefly, is as follows: the solar vactrain will run on a railroad track inside a partially evacuated tunnel whose sloping roof supports solar panels; d.c. power from the solar panels is fed to the 2 rails of the track. The following will be its advantages over today's high speed trains:

i) Because there is no overhead catenary, this solar-powered vactrain is potentially capable of higher speeds than the TGV or bullet trains whose speeds are limited by pantographs and overhead wires. Instead, the solar vactrain's wheels will act as current collectors.
ii) Because the tunnel will contain only low density air, the solar vactrain will not suffer much aerodynamic drag, so will consume much less power than similarly fast conventional trains.
iii) The enclosed track will possibly also result in less noise pollution – which is a concern raised by today's high speed trains [Takagi, 2005].
iv) The solar panels will produce far more power than the trains will need. The excess power will be sold to the grid, to improve the economics of the solar vactrain.
v) The solar vactrain will be totally weather-proof, unlike regular trains or airplanes, so its maintenance cost may actually be less than that of today's trains.

Both magnetically levitated vactrains and wheeled vactrains were explored in the 1970s by Robert Salter [Salter, 1972] of the Rand Corporation, an American think-tank. Typical vactrain concepts envisage a magnetically levitated (maglev) train gliding inside an evacuated tunnel. Though an actual vactrain has never been put in operation, it is, by no means, an impractical idea. In the late 1990s, Swissmetro seriously considered building a vactrain, though by 2009 the project was shelved.

A possible disadvantage of any vactrain could be large air leaks through the tunnel wall caused deliberately by sabotage or worse. This could be overcome by having doors inside the tunnel which would automatically isolate the leaky area so that no shock waves are formed within the tunnel. A vactrain also may have to run at somewhat non-uniform, time-varying speeds so that its exact location cannot be easily estimated by a saboteur outside the tunnel.

At a cost of over 42.6 million US dollars per km [Trans Rapid International, 2007], the Shanghai maglev is twice as expensive as conventional high speed trains. Its ridership is at 20% capacity.

Therefore, this paper confines itself to wheeled vactrains, specifically a wheeled vactrain that will be powered by solar energy. It may be mentioned that a conventional solar-powered train running across

Arizona has been proposed by Raymond Wright [Chapa, 2009]. Its promoters are still waiting for a research grant to further investigate their idea. Their proposed Solar Bullet express will not run inside an evacuated tunnel, so would reportedly require 110 MW of electric power to run at 220 miles/hour (350 km/h), presumably because of the enormous aerodynamic drag at such speeds. However, the wheeled vactrain proposed in this paper will consume only a fraction of that power, at a much higher speed, as will be shown in the next section.

TECHNICAL ANALYSIS OF THE SOLAR-POWERED VACTRAIN

Based on Skojvist's data, Kelley et al. [1994], derived an equation which computes the sum F_r of frictional rolling resistance of the wheels of a TGV. The equation is:

$$F_r = 3.82 + 0.039V \text{ or } F_r = 3.82 + 0.01083v \qquad [1]$$

where F_r is in kilonewtons.

As for the drag force, Skojvist [Kelley et al., 1994] estimated the form+friction drag coefficient C_d of high speed trains to be 1.5 with 20% of the drag coefficient being due to the pantographs. For the solar vactrain which has no pantographs, the total drag coefficient will be 80% x 1.5 = 1.2. The drag force, in kilonewtons, can then be computed from the formula:

$$F_d = 0.001 \times C_d A_f \rho v^2 / 2 \qquad [2]$$

where F_d will be in kilonewtons if v is in meters/second and the constant 0.001 is in kN per N.

The 'cruising' power P_{cr} , in kilowatts, consumed by the solar vactrain at a steady speed v on a level track will be:

$$P_{cr} = (F_r + F_d)\, v \qquad [3]$$

Power is also needed to accelerate a train with a steady acceleration 'a' and/or to maintain speed over a gradient of G%. This 'extra' power P_{ex} kilowatts is given by:

$$P_{ex} = Mav + (MgG/100)v \qquad [4]$$

The TGV and bullet train speeds are limited by the sliding contact between the pantographs and overhead wires which sets standing wave patterns in the wires. Increasing the wire tension allows higher speeds and is done during record-breaking runs. Since the solar vactrain will not have pantographs and overhead wires, it may be capable of 500 km/h average speed. That is less than the maximum speed that today's wheeled TGV has achieved during record runs. Hence, in this study, the design speed of the solar vactrain is set to V = 500 km/h or v = 138.9 m/s, based on the fact that the TGV, a wheeled train, was able to achieve a top speed of 574.8 km/h.

Since the solar vactrain will run inside a partially evacuated tunnel, the value of the air density ρ in equation 2 will be small. The Swissmetro will use a tunnel where the air pressure will be one-tenth that of atmospheric pressure [Mossi and Rossel, 2001], so that the air density ρ will be 0.1182 kg/m^3. Similarly, the solar vactrain of frontal area A_f = 10 m^2 , i.e., 3 m wide x 3.33 m tall, will run inside a tunnel where the air density ρ will be 0.1182 kg/m^3 , so the drag force will be nearly 10 times less than with atmospheric air. Therefore, according to equations 1-3, the rolling resistance will be 23.32 kN, the drag force 13.68 kN and the 'cruising' power P_{cr} needed to propel this train on a level track will be 5140 kW. Thus, running the train inside a low pressure tunnel reduces the power to overcome the drag force by a factor of 10.

A fully evacuated tunnel is neither practical nor desirable, because air is needed to cool the traction motors which are mounted between the wheels and are exposed to a moving airstream. Also, having air in the tunnel allows the possibility of having air scoops in the train which supply air for ventilation and breathing. At high speeds, ram air induction can conceivably increase the supply air pressure to breathable levels inside the train.

Trains, automobiles and airplanes weigh around 1 ton per passenger. Thus, a 350 passenger TGV weighs about 350 tons and is propelled by motors producing a total power of around 9000 kW. If the cruising power absorbed by the solar vactrain is 5140 kW, then the total power rating of its traction motors should be 25000 kW. It can be shown from the above equations and calculus that 25000 kilowatts are enough to propel a 350 ton train up a 4% gradient at 500 km/h or accelerate it from rest at an acceptable rate to a speed of 500 km/h. The train's traction motors can be d.c motors so that the d.c power from the solar panels does not have to be inverted to a.c.

All the power required by the solar vactrain will be supplied by solar panels mounted on top of the tunnel. During winter, snow will be removed from these solar panels by automatic scrapers. Several panels will be wired in series so as to form power sources producing 3000 Volts d.c (which was a standard electric locomotive voltage in Belgium, for instance) to be supplied to the 2 rails (positive and negative) of the track and then to the traction motors. Being much thicker than overhead wires, the rails should be able to transmit a current of 8333 Amperes at 25 MW, with much less transmission loss (resistive I^2R loss) than an overhead catenary. Based on usual steel rail dimensions, the current density in the steel rails is computed to be under 70 A/cm^2. According to the electrical code's ampacity charts, the current density in copper wires used in power transmission is 280 A/cm^2. Since steel has an electrical resistivity that is 4 times higher than copper, acceptable current densities in steel rails should be only 70 A/cm^2 to minimize transmission losses. If current densities are kept below this limit, then transmission losses will not be significant.

If the solar vactrain has a frontal area of 10 m^2, then the tunnel should have a cross-sectional area of 30 m^2 (6 m wide x 5 m average height), so that it will have the same 'blockage ratio', i.e., 10/30 = 0.333, as the proposed Swissmetro vactrain [Mossi and Rossel, 2005]. The tunnel needs to have a high pitch roof so that the snow will not settle easily on the solar panels. If a pitch angle of 45 degrees is used, the roof will be 6/cos(45^0) meters wide, i.e., 6.85 m wide. Assuming that the track length is 500 km (which is the distance between New York and Washington, DC or between Toronto and Montreal), the total solar panel area will be 500 km x 6.85 m = 3.425 million square meters, i.e., 3.425 square kilometers.

The annual average sunlight intensity falling on New York or Montreal is around 200 Watts per square meter, after accounting for clouds and the absence of sunlight at night. Fixed solar panels mounted at non-optimum angles can be assumed to have an energy conversion efficiency of 10%. Therefore, 500 km of track length can continuously generate 3.425×10^6 m^2 x 200 W/m^2 x 10% = 68.5 continuous megawatts, on average, i.e., 137 kW per km.

The peak electric power generated will be greater than 68.5 MW (continuous). A rule-of-thumb states that it will be 5 times higher on a bright summer day, when the rays of the sun are exactly perpendicular to the surface of the solar cells. In other words, the maximum power that can be generated will equal 5 x 137 kW/km, or 685 kW/km.

Since the cruising power of a solar vactrain was computed to be 5140 kW, it follows that 68.5 MWe of power can easily propel 10 trains. Or in other words, 50 km track length can power 1 solar vactrain and

500 km of track can power 10 solar vactrains. Since a distance of 500 km will be covered in 1 hour by a 500 km/h train, it is unrealistic to expect 10 trains to be leaving a station during a 1 hour time interval, i.e., one every 6 minutes. This means that there will be surplus power from the solar panels that can be sold to the electrical grid. This point is discussed further in the next section.

ECONOMIC ANALYSIS

Campos, de Rus and Barron [Campos et al., 2009a, 2009b] show that high speed railroad track construction costs 8.9 and 17.5 million Euros per km in Spain (1 Euro = 1.38 US$). In 2001, the TGV Mediterranee line had a construction cost of 12.9 million Euros per km. Japan's high speed railroad tracks cost about the same as Spain's. In this work, the high speed track cost per km under North American conditions is assumed to be $20 million per km or 14.5 million Euros/km, i.e., about the same as Japanese, French (TGV) or Spanish high speed rail.

Compared to today's high speed trains, the solar vactrain system will have 2 extra components – the tunnel and the solar panels. The tunnel walls have to be made from ¼ inch (0.00635 m) thick steel, to withstand the bursting stress due to the pressure differential between the tunnel and the atmosphere. The outside of the steel tunnel will have to be lined with a rust-proof material to prevent corrosion. As stated earlier, the tunnel will have a 6 meter wide base, two 5 meter tall sides and a sloping roof panel having a width of 6.85 meters. Therefore, the tunnel mass per kilometer will be = (6+5+5+6.85) x 0.00635 m x 1000 m x 7800 kg/m^3 steel density = 1132 tonnes.

Actually the tunnel mass per km should be more than 1132 tonnes when the masses of the support steel and rust-proof lining are included. Therefore a tunnel mass of 2000 tonnes per km is conservatively assumed in this paper, for estimation purposes. The material cost of mild steel is around $2000 per tonne. Many cost-estimating books state that large welded steel structures can be fabricated at a total cost of $2.75 per lb including the material cost. Therefore, the estimated tunnel construction cost per km will equal 2000 tonnes x 2200 lb/tonne x $2.75 per lb = $12 million per km (or 12000 dollars per meter of tunnel length). It can be shown that if the tunnel is made of concrete pipes, instead of steel, the cost per km will not be much different.

Solar panels cost around $6000 per peak kilowatt. Since 1 km of tunnel length will produce a computed 137 kW of continuous power or an assumed 685 kW peak power, the solar panel cost will be $6000/kW x 685 kW = $4.11 million per km.

The track cost, tunnel cost and solar panel cost add up to (20 + 12 + 4.11) x 10^6 = 36.11 million dollars per km. Therefore, it is assumed that the solar vactrain track can be built at a cost of $40 million a kilometer.

The success of any high speed rail will depend on passenger patronage. Based on the Travelocity website's flight data, an estimated 15000 people fly from New York to Washington every day, on 106 flights. The load factor, i.e., the percentage of occupied seats, on these flights is around 86%.

When the TGV started running in France between Marseilles and Paris, many airlines stopped flying that route because it became unprofitable [Gow, 2008].

Therefore, it is reasonable to assume that 15000 passengers may take the solar vactrain instead of flying or driving from New York to Washington, DC. The minimum number of solar vactrain journeys needed to transport them will be 15000 / 350 = 43 trips. Assuming that these trains are only 86% full (load factor), then 50 trips will be required, spread over an assumed 17 hour period every day. Thus, 3 trainsets will have to depart from New York every hour, or one every 20 minutes. Therefore, 8 trainsets will be needed if it is assumed that each one of them stops for 20 minutes at its destination before starting its trip in the opposite direction, on another track. Thus, at any instant, there will be 4 trains (= 3 moving trains + 1 stationary train in the platform) on the track between New York and Washington and another 4 on the return track from Washington.

It is enough to analyze the economics of a one-way trip, as is done below.

According to [Campos et al., 2009b], a TGV trainset costs up to 65000 Euros or $91000 per seat. Therefore, this paper assumes that 1 solar vactrain will cost 350 x $91 000 = $31.85 million and 4 of them will cost $127.5 million. Thus, the combined capital cost of the 500 km rail line between the above 2 cities and 4 trainsets is: 500 km x $40 million/km + $127.5 million = 20.1275 billion dollars.

According to Campos et al., [2009b], a 35 year life for a high speed train is reasonable. Assuming that the capital cost is available free of interest and an amortization period of 35 years, the capital will have to be paid off at the rate $1.575 million per day.

Since only 3 trains will be in motion on the track during any 1 hour period, the average power drawn by these trains from the solar panels may only be 25 MW. This will leave an estimated 43.5 MW of continuous power available for sale to the electrical grid. Today, along the Washington-New York route, at least one state, i.e., Maryland, purchases solar electricity at 20 cents per kWhr. Thus, the daily average hourly income stream from the surplus power generated by the solar vactrain system will be 43500 kW x 1 hour x 0.2 $/kWhr x 24 hr/day = $208 800 per day. Note that even though the solar panels do not produce power at night, this calculation is correct, because the 43.5 MW figure refers to continuous average power. In other words, if 1044 megawatt-hours is the amount of surplus electricity generated during 12 hours of sunlight, the average power generated is taken to be 1044 MWhr / 24 hr = 43.5 MW continuous.

This daily income stream of 208 800 dollars should be subtracted from the daily capital cost payment of $1.575 million per day. Dividing the result by 15000 passengers per day and then dividing by 500 km tells us that the amortization cost will be equivalent to $0.18 per passenger-km.

Besides the amortization cost, there will be operating and maintenance (O&M) costs which include driver and crew salaries, track and train repairs. Table 1.3 in reference 12 presents such data for European high speed trains. The operating cost ranges from 0.0776 to 0.1766 Euros per seat per kilometer. The highest maintenance cost given in Table 1.3 in reference 12 is only 0.014 Euros per seat per kilometer. Therefore, the O&M cost in this study was taken to be 0.08 Euros or $0.11 per seat-kilometer.

Therefore, in order to avoid operating losses, the minimum ticket price should equal the sum of the amortization cost ($0.18 per passenger-km) and the O&M cost ($0.11 per passenger-km), i.e., $0.29 per passenger-km. Thus, a minimum per passenger ticket price of $147 needs to be charged for the 500 km one-way trip, in order to break even. This is not a high ticket price for such a swift 500 km journey and is less than the today's nation-wide average ticket price of a short-haul airline flight at the same average speed.

The return ticket too has to cost $147 so that it can finance the second vactrain track that will serve as the return line from Washington to New York. Thus, there have to be 2 tracks between the 2 cities, one for the 'down' journey and the other for the 'up' journey.

A search on the Travelocity website reveals that a one-way plane ticket from New York to Washington can be bought for 70 dollars if bought 1 month in advance or 370 dollars if bought 5 days before the trip. The travel time is given as 1 hour and 15 minutes – about the same as that assumed for the vactrain.

Therefore, one can conclude that solar-power high speed rail between New York and Washington will be competitive with air travel.

The above economic analysis was based on 2 key assumptions: 20 million $/km track cost and 0.11 $/km/passenger O&M cost. Both these figures were at the low end of the published range of costs in references 12 and 14. The same references state that high-speed track cost could be as high as 17.5 million Euros per km, or 24.15 million $/km and that the O&M cost can be up to 0.1906 Euros per km per passenger, i.e., 0.263 $/km/passenger. Using both these figures, the break-even ticket price is computed to be 0.40 $/km/passenger, instead of 0.29 $/km/passenger. Thus, a one-way vactrain ticket for a 500 km journey has to be sold for $200 whereas an air ticket may cost anywhere between 70 and 370 dollars.

CONCLUSIONS

The following are the conclusions of this paper:

1) Several high-speed trains with wheels running at 500 km/h on a railroad track inside an evacuated tube can be powered solely by stationary solar panels mounted above the tube or tunnel.
2) These 'vacuum trains' or vactrains will be totally weather-proof and will consume less power than today's high speed trains, and will be faster and less noisy.
3) The tunnel-mounted solar panels will produce, on average, an estimated 137 kW of electricity per every 1 km of track or tunnel length or 68.5 MW over a 500 km long railroad track.
4) Only 25 MW of electricity will be needed to power 3 high speed trains inside a 500 km long tunnel, leaving a surplus of 43.5 MW of solar power which can be profitably sold.
5) Cost calculations show that a ticket price of 0.29 to 0.40 dollars per km per passenger will be the break-even ticket price for this solar-powered vactrain to be economically feasible and that such a ticket price will often be cheaper than short-haul air travel which has the same average speed.

Therefore, based on a preliminary analysis, a solar-powered vactrain seems to be a technically and economically feasible idea. This is the main conclusion of this paper.

ACKNOWLEDGEMENTS
This paper is dedicated to my late father Dr. M. Subrahmanyam, who was a lifelong railfan and model railroader.

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ENDNOTE: This paper is of the 'regular' type.