A NEW GENERATION SURFACE PROPULSION SYSTEM: CRITICAL STUDY

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Abstract - *This paper presents a MATLAB model of a 42 km hyperloop line, with a 30-passenger pod running in a 4.0 m steel tube held at 100 Pa. The pod follows a trapezoidal speed profile at peak speeds of 300, 320 and 340 km/h. It accelerates over 60 percent of the route, cruises over 20 percent and brakes over 20 percent. From one set of inputs, we sized propulsion, levitation, tube, vacuum system and cost. Raising the peak speed from 300 to 340 km/h cuts the journey from 907.20 s to 800.47 s and lifts the average speed from 166.7 to 188.9 km/h. Energy per trip changes little, from 26.56 to 26.91 kWh, because the extra traction energy is almost offset by a lower onboard hotel load. At 340 km/h the peak electrical power is 410.6 kW and the energy cost is about Rs 6 per passenger. Braking peaks at 0.054 g against a comfort limit of 0.10 g. The blockage ratio of 0.4225 stays below the Kantrowitz limit of 0.5419, and the tube buckling safety factor is 12.8. Magnetic drag (994 N) far exceeds aerodynamic drag (11.4 N), and in a one-at-a-time sensitivity test the assumed lift-to-drag ratio changes trip energy by 23.9 percent. We estimate the project cost at about Rs 6355 crore, or Rs 151 crore per km. These values are a first design basis until vendor or test data are available.*

Key Words: Hyperloop, Linear synchronous motor, Speed profile, Regenerative braking, Tube aerodynamics, Kantrowitz limit, Energy per trip, Cost estimate.

1. INTRODUCTION

A hyperloop carries passengers in a levitated pod through a steel tube held at low pressure, so the pod meets very little air drag [1]. Feasibility analyses [2], [3] and technology reviews [4] describe the concept, its subsystems and its open problems. The Kantrowitz limit sets the largest pod-to-tube blockage ratio that the air can pass without choking at a given Mach number [5]. Aerodynamic studies of the pod in the tube use analytical models and numerical flow simulation [6], [7], [8], [9].

Open-source sizing models and conceptual feasibility studies give first estimates of pod mass, power and battery size [10], [11]. Linear synchronous motors (LSMs) [12] and magnetic levitation [13], [14] supply thrust and lift, and a full tube system adds the dynamics of vehicles and infrastructure [15]. Each of these works answers one part of the design question. A short route needs all parts to agree. The speed profile fixes the thrust, the thrust fixes the stator and the power, and the tube and the pumps fix most of the cost. An integrated design case [16] and an energy and emissions analysis [17] address this system level.

We build one MATLAB model for a 42 km line between two terminals, Node A and Node B. A 30-passenger pod runs in a 4.0 m steel tube at 100 Pa at peak speeds of 300, 320 and 340 km/h. The model gives the journey time and average speed, the power and energy per trip, the aerodynamic, comfort, structural and battery checks, and the project cost. Section 2 describes the method, Section 3 gives and discusses the results, and Section 4 concludes.

2. METHODOLOGY

Fig. 1 shows the design flow. We start from the project requirements, then size the pod, set the speed profile and check the tube aerodynamics. Next we size propulsion and levitation, design the tube, civil works and vacuum system, and estimate energy and cost. A decision block tests the comfort, blockage, headroom, buckling and battery limits. If a check fails, we revise the design inputs and repeat the loop.

2.1 Given and Assumed Values

Table -1 lists the inputs. We take the route length, peak speeds, profile shares, passenger load, pod and tube sizes and tube pressure as given values. We assume the remaining values because we have no vendor or test data for them. These include the magnetic lift-to-drag ratio (150), the propulsion and regeneration efficiencies (0.85 each) and the pod drag coefficient (0.40). Section 3.7 tests how much each one matters. We take the air density in the tube as 0.0012 kg/m^3 at 100 Pa and 288 K.

Table -1: Design inputs and assumed values

Parameter	Value
Given (design inputs)	
Route length	42 km
Peak speeds	300, 320, 340 km/h
Profile (share of distance)	60 / 20 / 20 % (accel. / cruise / brake)
Passengers	30 × 90 kg
Pod tare mass	12 500 kg
Pod diameter	2.6 m
Tube diameter, wall	4.0 m, 25 mm
Tube pressure	100 Pa
Air temperature	288 K

Assumed (replace with vendor or test data)	
Magnetic lift-to-drag ratio	150 (constant with speed)
Pod drag coefficient	0.40 (free stream)
Air density in tube	0.0012 kg/m^3
Propulsion, regeneration efficiency	0.85, 0.85
Parameter	**Value**
Levitation power	1.5 kW per tonne
Hotel load, ECS load	35 kW, 12 kW
Magnetic flux density, gap	1.0 T, 10 mm
Battery energy density	136 Wh/kg
Emergency load, duration, DoD	45 kW, 2 h, 80 %
Terminal dwell time	300 s per end
Pump-down factor, leak pumping	4, 2.0 MW
Tube dead load (rails etc.)	600 kg/m
Cost unit rates	Engineering estimate

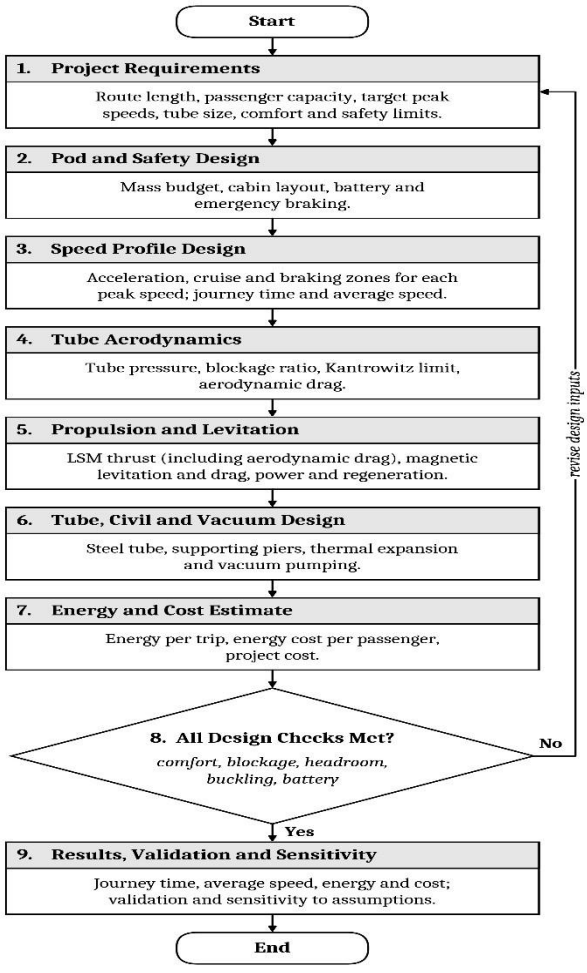


Fig -1: Design flow of the hyperloop model.

2.2 Speed Profile

The pod accelerates at a constant rate over the first 60 % of the route. It cruises at the peak speed v over the next 20 % and brakes at a constant rate over the last 20 %. With the route length L and the distance shares f_a, f_c and f_b, the acceleration a and the braking rate b follow from Eq. (1).

$$a = v^2/(2\, f_a\, L), \quad b = v^2/(2\, f_b\, L) \qquad (1)$$

The pod averages half the peak speed while it accelerates or brakes, so the three zones take $2f_aL/v$, f_cL/v and $2f_bL/v$.

Eq. (2) gives the journey time T, and the average speed is therefore 5/9 of the peak speed.

$$T = L(2f_a + f_c + 2f_b)/v = 1.8\ L/v \qquad (2)$$

2.3 Force, Power and Energy

We integrate force, power and energy in time steps of 0.1 s for a gross pod mass m of 15 200 kg. The force F in Eq. (3) adds inertia, aerodynamic drag and magnetic drag. The signed acceleration a_t is positive in acceleration, zero in cruise and negative in braking. Here ρ is the air density, C_d the drag coefficient, A_p the pod cross-section area, g the gravitational acceleration and L/D the magnetic lift-to-drag ratio.

$$F = m\, a_t + \tfrac{1}{2}\, \rho\, v^2\, C_d\, A_p + m\, g/(L/D) \qquad (3)$$

Eq. (4) gives the electrical power P_e, where η is the propulsion efficiency and η_r is the regeneration efficiency.

$$P_e = F\, v/\eta \ \ (F \geq 0), \quad P_e = F\, v\, \eta_r \ \ (F < 0) \qquad (4)$$

Energy drawn is the integral of the positive power, energy regenerated is the integral of the negative power, and net traction energy is the difference. We add a hotel load of 35 kW over the whole journey time: 23 kW for levitation and 12 kW for the environmental control system. We price the total energy at Rs 6.70 per kWh.

2.4 Design Checks and Cost

We compare the blockage ratio β, the pod-to-tube area ratio, with the one-dimensional isentropic Kantrowitz limit [5] at each peak speed. We check the buckling pressure of the stiffened tube against the atmosphere with the externalpressure formula for thin cylinders [18], [19]. We check the bending stress and deflection of a 30 m simply supported span with beam formulas [19]. Eq. (5) gives the ideal pumpdown work W [20], where p_0 is atmospheric pressure, V is the tube volume and p is the tube pressure. We multiply W by 4 to estimate the real work. We cost 14 items from the design quantities and engineering-estimate unit rates (Section 3.6).

$$W = p_0 V \ln(p_0/p) \quad (5)$$

3. RESULTS AND DISCUSSION

3.1 Journey Time and Speed Profile

Table -2 gives the zone times for each peak speed. At 340 km/h the pod accelerates for 533.65 s, cruises for 88.94 s and brakes for 177.88 s, so the journey takes 800.47 s (13 min 20 s). The 300 km/h case takes 907.20 s (15 min 07 s). A 13.3 % higher peak speed therefore saves 106.73 s, or 11.8 % of the journey time. The average speed is 5/9 of the peak speed in every case: 166.7, 177.8 and 188.9 km/h. It stays well below the peak speed because the pod accelerates or brakes over 80 % of the route.

Table -2: Journey time and average speed for each peak speed

Peak speed [km/h]	Accel. [s]	Cruise [s]	Brake [s]	Total [s]	Avg. speed [km/h]
300	604.80	100.80	201.60	907.20	166.7
320	567.00	94.50	189.00	850.50	177.8
340	533.65	88.94	177.88	800.47	188.9

Fig. 2(a) plots speed against time. Fig. 2(b) plots speed against distance, and its dashed lines mark 25.2 km, where acceleration ends, and 33.6 km, where braking starts. The braking zone is one third as long as the acceleration zone, so the braking rate is three times the acceleration rate: 0.5309 against 0.1770 m/s^2 at 340 km/h.

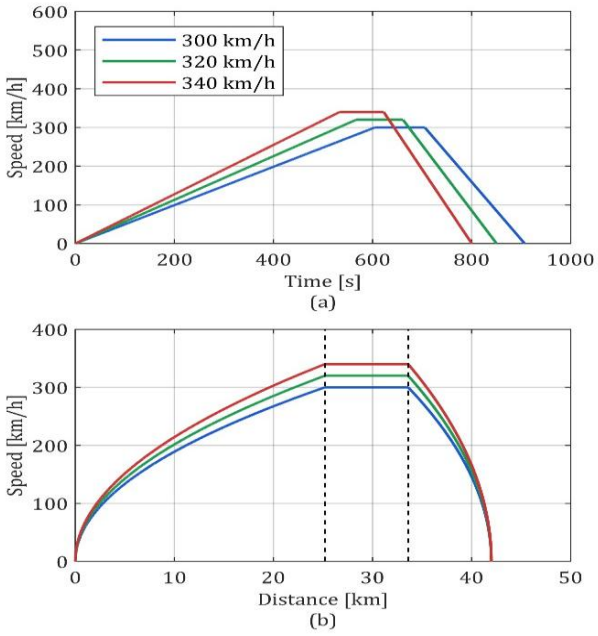


Fig -2: Speed profiles: (a) speed against time; (b) speed against distance.

3.2 Forces, Power and Energy

Table -3 and Fig. 3 give the power and energy. At 340 km/h the stators deliver a peak thrust of 3695.5 N and 410.6 kW of electrical power at the end of acceleration (Fig. 3(a)). Power then drops to 111.7 kW in the cruise zone, and braking regenerates up to 566.9 kW.

Table-3: Forces, power and energy per one-way trip

Parameter	300 km/h	320 km/h	340 km/h
Peak thrust with drag [N]	3097.3	3387.1	3695.5
Peak electrical power [kW]	303.6	354.2	410.6
Cruise-zone stator power [kW]	98.3	105.0	111.7
Regeneration peak [kW]	374.0	464.0	566.9
Kinetic energy [kWh]	14.66	16.68	18.83
Energy drawn [kWh]	28.22	30.61	33.15
Energy regenerated [kWh]	10.48	12.19	14.02
Net traction energy [kWh]	17.74	18.42	19.13
Hotel load energy [kWh]	8.82	8.27	7.78
Total energy per trip [kWh]	26.56	26.69	26.91
Energy per passenger [kWh]	0.885	0.890	0.897
Specific energy [Wh/pax-km]	21.08	21.18	21.36
Energy cost per trip [Rs]	177.9	178.8	180.3
Energy cost per passenger [Rs]	5.9	6.0	6.0

The LSM has two parts. The main stator covers the acceleration and braking zones, 33.6 km in all, and carries the peak thrust and the regenerative braking. The cruise stator is a light stator over the 8.4 km cruise zone. In cruise the pod needs only 1005 N, which is 994 N of magnetic drag and 11.4 N of aerodynamic drag, or 27 % of the peak thrust. A light winding rated for 111.7 kW is therefore enough. Without the cruise stator the pod coasts. Its speed falls by 21.9 km/h to 318.1 km/h by the end of the zone, and the journey takes 815.7 s instead of 800.47 s. We keep the cruise stator and include its cost in Section 3.6.

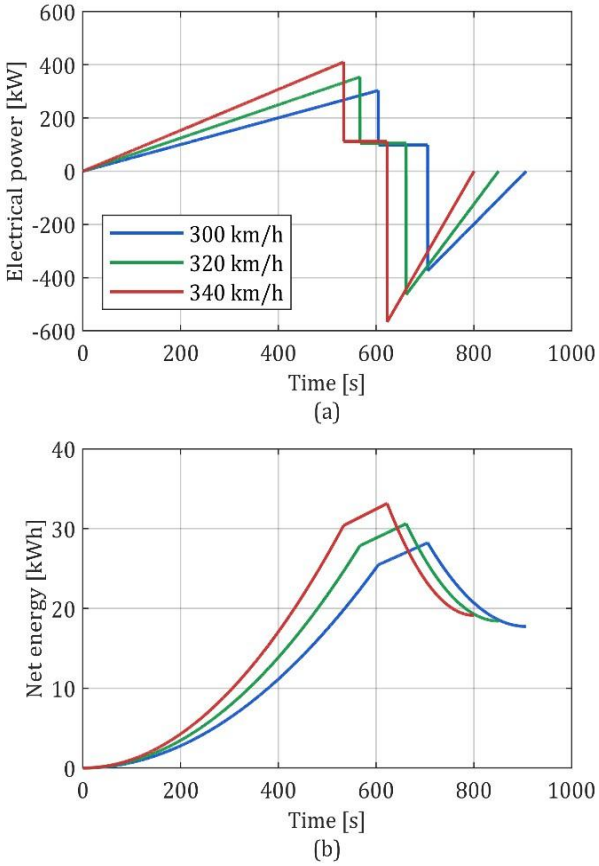


Fig -3: Electrical power and net energy: (a) LSM electrical power; (b) net energy.

Fig. 3(b) shows the net energy rising to 33.15 kWh at the end of cruise and falling to 19.13 kWh as regeneration returns 14.02 kWh. Energy per trip changes little with speed. The total rises only from 26.56 kWh at 300 km/h to 26.91 kWh at 340 km/h, which is 1.3 %. Kinetic energy grows 28.4 %, from 14.66 to 18.83 kWh. Net traction energy grows only 7.8 %, from 17.74 to 19.13 kWh, because regeneration recovers part of the kinetic energy. The hotel load energy falls from 8.82 to 7.78 kWh because the trip is shorter. The 340 km/h trip uses 0.897 kWh per passenger (21.36 Wh per passenger-km) and costs Rs 180.3, or Rs 6.0 per passenger.

3.3 Aerodynamics, Comfort and Braking

Table -4 lists the aerodynamic and comfort checks. The Mach number is 0.2775 at 340 km/h. The blockage ratio β is 0.4225 for the 2.6 m pod in the 4.0 m tube. The Kantrowitz limit falls from 0.5917 at 300 km/h to 0.5419 at 340 km/h, and the margin shrinks from 0.1692 to 0.1194. Even so, β stays below the limit in all three cases. Aerodynamic drag at top speed is only 11.37 N at 340 km/h because the dynamic pressure is 5.35 Pa. Magnetic drag (994 N) is about 87 times larger.

Table-4: Aerodynamics, comfort and braking

Parameter	300 km/h	320 km/h	340 km/h
Mach number	0.2449	0.2612	0.2775
Blockage ratio β	0.4225	0.4225	0.4225
Kantrowitz limit	0.5917	0.5666	0.5419
Margin to limit	0.1692	0.1441	0.1194
Dynamic pressure [Pa]	4.17	4.74	5.35
Aero drag at top speed [N]	8.85	10.07	11.37
Acceleration [m/s^2]	0.1378	0.1568	0.1770
Acceleration [g]	0.0140	0.0160	0.0180
Braking [m/s^2]	0.4134	0.4703	0.5309
Braking [g]	0.0421	0.0479	0.0541
Comfort check (≤ 0.10 g)	Pass	Pass	Pass
Emergency stop at 0.2 g [m]	1770	2014	2273
Emergency stop time [s]	42.5	45.3	48.1

The pod can carry an onboard compressor. It takes in part of the air ahead of the pod and discharges it behind, which lowers the effective blockage. We treat it as optional because β stays below the Kantrowitz limit at every speed, so the flow does not choke without it. We still keep the compressor mass of 650 kg in the 12 500 kg tare budget and estimate its power. We assume the compressor passes half of the swept air flow, 0.607 kg/s at 340 km/h, through a pressure ratio of 1.3 at an isentropic efficiency of 0.80. Its shaft power is then 8.54 kW. The 26.91 kWh in Table -3 does not include this power. If the compressor ran for the whole trip, it would add 1.90 kWh, or 7.1 %. We keep it as a fallback in case CFD shows a smaller margin than the onedimensional limit.

Acceleration is 0.0180 g and braking is 0.0541 g at 340 km/h, both below the comfort limit of 0.10 g. An emergency stop at 0.2 g takes 48.1 s and 2273 m at 340 km/h.

3.4 Pod, Tube and Vacuum Design

Table -5 gives the pod design. The gross mass of 15 200 kg is a tare mass of 12 500 kg plus 30 passengers of 90 kg each. The 23.0 m pod has 30 seats in a 2+1 layout, and its aisle headroom of 1.959 m exceeds the 1.9 m we require. Its weight is 149.1 kN. A flux density of 1.0 T gives a magnetic pressure of 398 kPa, so the levitation magnets need 0.375 m^2 of pole area, and we design for 0.468 m^2. Levitation takes 22.8 kW and causes 994 N of magnetic drag at a lift-to-drag ratio of 150. The 150 kWh battery exceeds the 112.5 kWh minimum for a 45 kW emergency load over 2 h at 80 % depth of discharge, and it weighs

1100 kg.

Table -5: Pod, levitation and battery design (340 km/h design case)

Parameter	Value	Unit
Gross mass	15 200	kg
Tare mass	12 500	kg
Passenger mass (30 × 90 kg)	2700	kg
Pod length	23.0	m
Pod diameter	2.6	m
Seats (2+1, 10 rows)	30	–
Aisle headroom (required 1.9)	1.959	m
Pod weight	149.1	kN
Magnetic pressure at 1.0 T	398	kPa
Pole area, required	0.375	m^2
Pole area, design	0.468	m^2
Levitation power	22.8	kW
Magnetic drag (L/D = 150)	994	N
Battery, design	150	kWh
Battery, minimum	112.5	kWh
Battery mass	1100	kg

Table -6 gives the tube. The 25 mm wall gives 2482 kg of steel per metre and 119 860 t for the 42 km tube with stiffening rings. The tube buckles at 13.0 bar of external pressure, a safety factor of 12.8 against one atmosphere. We carry it on 1400 piers at a 30 m span, where the bending stress is 12.1 MPa and the deflection is 2.8 mm. A 35 K temperature swing expands the tube by 17.64 m, so we place 420 expansion joints that each take 42.0 mm.

Table-6: Tube and civil design

Parameter	Value	Unit
Tube diameter	4.0	m
Wall thickness	25	mm
Steel mass per metre	2482	kg/m
Tube mass with rings	119 860	t
Buckling pressure Pcr	13.0	bar
Buckling factor of safety	12.8	–
Pier span	30	m
Number of piers	1400	–
Bending stress	12.1	MPa
Deflection	2.8	mm
Thermal expansion (35 K)	17.64	m
Expansion joints	420	–
Gap per joint	42.0	mm

The vacuum system pumps 646 357 kg of air out of the 527 788 m^3 tube. The ideal pump-down work to 100 Pa is 103 MWh, and we take 411 MWh, four times the ideal value, as the real work. Twenty sections of 2.10 km each hold the vacuum, and leak pumping of 2.0 MW costs Rs 11.7 crore per year.

Tube Pressure Options

We repeat the 340 km/h trip at six tube pressures from 100 to 10 000 Pa. Aerodynamic drag at top speed rises in proportion to pressure, from 11.4 N at 100 Pa to 1137 N at 10 000 Pa (Fig. 4(a)). The aerodynamic energy per trip rises from 0.09 to 9.36 kWh (Fig. 4(b)). The ideal pump-down work falls from 103 to 34 MWh (Fig. 4(c)). Pump-down is a one-time cost, while aerodynamic energy recurs on every trip. At 1000 Pa the ideal pump-down work is 69 MWh, and Table -7 shows that this pressure adds only 3.0

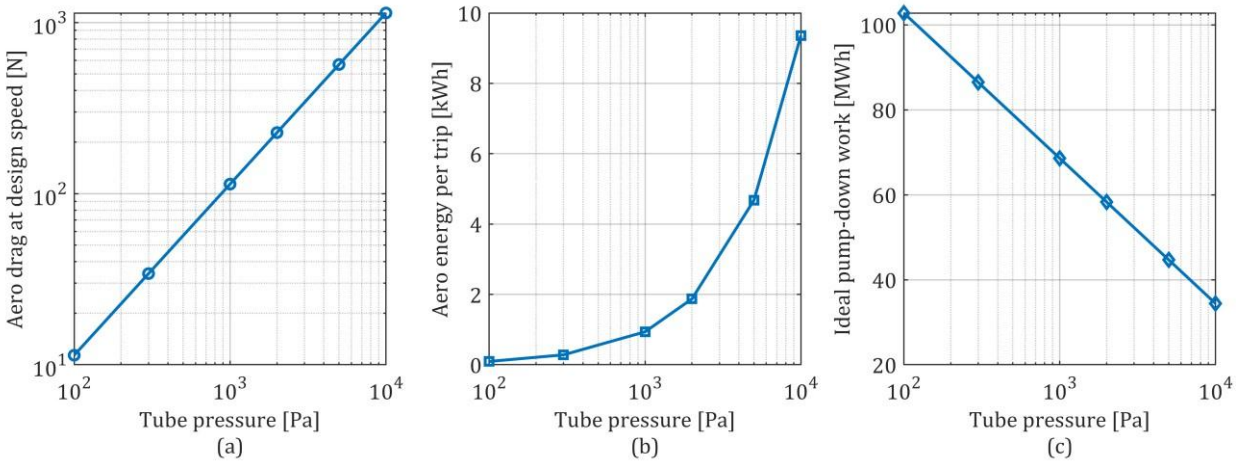


Fig -4: Effect of tube pressure: (a) aerodynamic drag at design speed; (b) aerodynamic energy per trip; (c) ideal pumpdown work.

% to the trip energy because magnetic drag dominates. We keep 100 Pa as the base case and mark 1000 Pa for a later trade-off study.

3.5 Cost

Fig. 5 shows the 14 cost items. The two largest items are piers and foundations (Rs 1540 crore for 1400 piers) and tube steel (Rs 1378 crore for 119 860 t). Together they make up 57 % of the hard cost. The main stator costs Rs 470 crore and the cruise stator Rs 118 crore. We price both at Rs 14 crore per km, so the light cruise stator carries the full stator rate, which is a conservative choice.

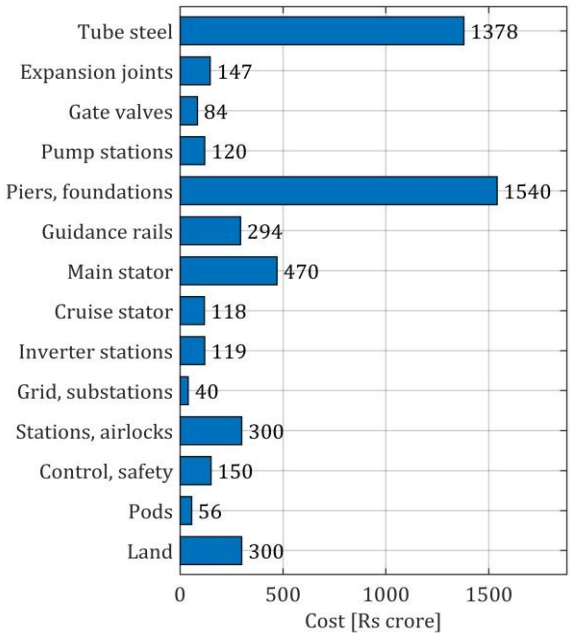


Fig -5: Cost breakdown of the 14 hard-cost items.

The 14 items add up to a hard cost of Rs 5116 crore. Two more costs follow the hard cost. Project management, design, testing and commissioning cost 8 % of the hard cost, Rs 409 crore. Contingency covers quantities and unit rates that change after a first estimate. We set it at 15 % of hard cost plus project management, Rs 829 crore. The total is Rs 6355 crore, or Rs 151 crore per km (we round each part separately). We quote the total, not the hard cost, because the owner funds all three parts. Every unit rate is an engineering estimate, so we give the total a range of ±30 %, from Rs 4448 to 8261 crore. An assumed benchmark of Rs 100 to 170 crore per km gives Rs 4200 to 7140 crore for 42 km, and our total lies inside this range.

3.6 Sensitivity to Assumed Values

Table -7 changes one assumed value at a time at 340 km/h. The journey time is the same in every row because we prescribe the profile. The magnetic lift-to-drag ratio matters most. A ratio of 100 raises the trip energy by 23.9 % to 33.36 kWh and the peak power to 466 kW. A ratio of 300 lowers the energy by 23.9 % to 20.47 kWh. A propulsion efficiency of 0.80 or 0.90 changes the energy by +7.7 % or −6.8 %. A tare mass of 11 250 or 13 750 kg changes it by −5.8 % or +5.8 %. The drag coefficient has little effect: values of 0.3, 0.8 and 1.6 change the energy by −0.1 %, +0.3 % and +1.0 %. We include 1.6 to cover the extra drag of a pod that blocks 42 % of the tube, because the free-stream value of 0.40 is optimistic. We therefore need vendor data on magnetic drag and propulsion efficiency first.

Table -7: Sensitivity of peak power and trip energy to assumed values (340 km/h, one value changed at a time)

Parameter changed	Value	Peak elec. power [kW]	Energy per trip [kWh]	Energy change [%]
Base case	Table 1	411	26.91	0.0
Magnetic L/D	100	466	33.36	+23.9
Magnetic L/D	300	355	20.47	−23.9
Pod Cd	0.3	410	26.89	−0.1
Pod Cd	0.8	412	27.00	+0.3
Pod Cd	1.6	414	27.18	+1.0
Efficiency	0.80	436	28.98	+7.7
Efficiency	0.90	388	25.07	−6.8
Tare mass [kg]	11 250	377	25.35	−5.8
Tare mass [kg]	13 750	444	28.48	+5.8
Tube pressure [Pa]	300	413	27.09	+0.7
Tube pressure [Pa]	1000	422	27.72	+3.0

3.7 Limitations of the Model

The results are a first design basis, and six limits apply. The assumed values in Table -1 are not vendor data, and the magnetic lift-to-drag ratio alone moves the trip energy by 23.9 %. The Kantrowitz limit is a one-dimensional isentropic estimate, so we need CFD to confirm the blockage margin at 340 km/h. We design the tube for self-weight and vacuum only and leave out wind, seismic, settlement and pod loads. We do not model the heat balance of the pod in vacuum. The speed profile has no jerk limit, and a jerk limit would lengthen the journey slightly. All cost rates and the cost benchmark are estimates and need quotations.

4. CONCLUSIONS AND FUTURE SCOPE

We built one model for a 42 km, 30-passenger hyperloop line and ran it at 300, 320 and 340 km/h. Raising the peak speed from 300 to 340 km/h cuts the journey from 907.20 s to 800.47 s and lifts the average

speed from 166.7 to 188.9 km/h. Energy per trip stays between 26.56 and 26.91 kWh. At 340 km/h the peak electrical power is 410.6 kW and the energy cost is Rs 6.0 per passenger.

The design passes its checks at all three speeds. Braking reaches 0.0541 g against a limit of 0.10 g, the blockage ratio of 0.4225 stays below the Kantrowitz limit of 0.5419, and the buckling safety factor is 12.8. The optional compressor is therefore not needed in the base case. A light cruise stator over 8.4 km holds the speed with 111.7 kW. Without it the pod would lose 21.9 km/h and add about 15.2 s to the journey.

The hard cost is Rs 5116 crore. With project management and contingency, the total is Rs 6355 crore, or Rs 151 crore per km. Tube steel and piers make up 57 % of the hard cost. The magnetic lift-to-drag ratio is the most influential assumed value, with ±23.9 % in trip energy.

In future work we will replace the assumed values with vendor or test data and confirm the 340 km/h blockage margin with CFD. We will also add a jerk limit to the speed profile and a thermal balance of the pod in vacuum. We will include wind, seismic and pod loads in the tube design.

REFERENCES

1) E. Musk, “Hyperloop Alpha,” SpaceX, Aug. 12, 2013.

2) C. Taylor, D. Hyde, and L. Barr, “Hyperloop commercial feasibility analysis: High level overview,” Volpe Nat. Transp. Syst. Center, Cambridge, MA, USA, Rep. DOT-VNTSC-NASA16-01, Jul. 2016.

3) I. A. Hansen, “Hyperloop transport technology assessment and system analysis,” Transp. Plan. Technol., vol. 43, no. 8, pp. 803-820, Nov. 2020, doi: 10.1080/03081060.2020.1828935.

4) J. K. Nøland, “Prospects and challenges of the Hyperloop transportation system: A systematic technology review,” IEEE Access, vol. 9, pp. 28439-28458, 2021, doi: 10.1109/ACCESS.2021.3057788.

5) A. Kantrowitz and C. du P. Donaldson, “Preliminary investigation of supersonic diffusers,” NACA Wartime Rep. L713 (ACR L5D20), May 1945.

6) J. Braun, J. Sousa, and C. Pekardan, “Aerodynamic design and analysis of the Hyperloop,” AIAA J., vol. 55, no. 12, pp. 40534060, Dec. 2017, doi: 10.2514/1.J055634.

7) M. M. J. Opgenoord and P. C. Caplan, “Aerodynamic design of the Hyperloop concept,” AIAA J., vol. 56, no. 11, pp. 42614270, Nov. 2018, doi: 10.2514/1.J057103.

8) J.-S. Oh, T. Kang, S. Ham, K.-S. Lee, Y.-J. Jang, H.-S. Ryou, and J. Ryu, “Numerical analysis of aerodynamic characteristics of Hyperloop system,” Energies, vol. 12, no. 3, Art. no. 518, Feb. 2019, doi: 10.3390/en12030518.

9) S. Alzhrani, M. M. Abdulla, K. Juhany, and I. AlQadi, “Numerical investigation of jet-propelled multiple-vehicle Hyperloop system considering the suspension gap,” Sustainability, vol. 16, no. 21, Art. no. 9465, Oct. 2024, doi: 10.3390/su16219465.

10) J. C. Chin, J. S. Gray, S. M. Jones, and J. J. Berton, “Open-source conceptual sizing models for the Hyperloop passenger pod,” presented at the AIAA SciTech Forum, Kissimmee, FL, USA, Jan. 2015, NASA Tech. Rep. GRC-E-DAA-TN14666.

11) K. Decker et al., “Conceptual feasibility study of the Hyperloop vehicle for next-generation transport,” presented at the AIAA SciTech Forum, Grapevine, TX, USA, Jan. 2017, NASA Tech. Rep. GRC-E-DAA-TN37945.

12) J. F. Gieras, Z. J. Piech, and B. Z. Tomczuk, Linear Synchronous Motors: Transportation and Automation Systems, 2nd ed. Boca Raton, FL, USA: CRC Press, 2011.

13) H.-W. Lee, K.-C. Kim, and J. Lee, “Review of maglev train technologies,” IEEE Trans. Magn., vol. 42, no. 7, pp. 19171925, Jul. 2006, doi: 10.1109/TMAG.2006.875842.

14) J. K. Nøland, “A reality check on maglev technology for the Hyperloop transportation system: Status update after a decade of development,” IEEE Access, vol. 12, pp. 162918162928, 2024, doi: 10.1109/ACCESS.2024.3491904.

15) R. Janzen, “TransPod ultra-high-speed tube transportation: Dynamics of vehicles and infrastructure,” Procedia Eng., vol. 199, pp. 8-17, 2017, doi: 10.1016/j.proeng.2017.09.142.

16) D. Radeck et al., “Case study of an integrated design and technical concept for a scalable Hyperloop system,” Appl. Syst. Innov., vol. 7, no. 6, Art. no. 113, Nov. 2024, doi: 10.3390/asi7060113.

17) A. Hirde, A. Khardenavis, R. Banerjee, M. Bose, and V. S. S. P. K. Hari, “Energy and emissions analysis of the hyperloop transportation system,” Environ. Dev. Sustain., vol. 25, pp. 8165-8196, 2023, doi: 10.1007/s10668-022-02393-5

18) S. P. Timoshenko and J. M. Gere, Theory of Elastic Stability, 2nd ed. New York, NY, USA: McGraw-Hill, 1961.

19) W. C. Young and R. G. Budynas, and Strain, 7th ed. New York, NY, USA: McGraw-Hill, 2002.

20) K. Jousten, Ed., Handbook of Vacuum Technology, 2nd ed. Weinheim, Germany: Wiley-VCH, 2016.