Dynamically Supported Launcher[1]

JOHN KNAPMAN
Daicon Ltd., Cambridge, CB1 2BH, U.K.

A launching system for space vehicles is proposed that is supported by fast-moving projectiles in an evacuated tube. In a worked example, payloads are propelled to a height of 50 km, comparable to the performance of a first-stage rocket. Recent progress in magnetic levitation makes such a system feasible with existing materials. An outline of the economics shows that it can be cost effective, although there are considerable engineering challenges.
Keywords: magnetic levitation, space launch, evacuated tube

1. Introduction

The *skyway* is a proposal to assist the launch of space vehicles, thus reducing their weight and costs. It consists of several pairs of evacuated hollow tubes a few centimetres in diameter held up by fast-moving projectiles inside them. These projectiles, known as *bolts,* are connected to the tubes by magnetic levitation. Vehicles for freight or passengers are then suspended from the tubes by means of a *bearer* that is magnetically levitated from the passing bolts. The bolts provide thrust to the bearer, as the combination acts as a linear electric motor.

Tubes have a station at each end, either on the ground or on marine platforms. At the spaceport or airport, the *drive station* must accelerate bolts and fire them along the *drive tubes*. At the other end, the *return station* turns the bolts round and sends them back in the *return tubes,* after which the drive station turns them around again in a continuous flow. These operations use magnetic forces.

This paper uses a worked example to illustrate the equations and indicate general feasibility. The numbers quoted are illustrative and not definitive. In the example, the bearer and vehicle receive a thrust of about 4.5 megaNewtons (MN). They reach an altitude of 50 km at a speed above 5500 km/hour, comparable to the performance of a first-stage rocket.

The same technology, at lower altitude, may be useful for launching aircraft, reducing the weight and costs of air travel and eliminating the greatest cause of noise around airports. Furthermore, there are potentially smaller-scale applications in civil engineering, e.g., bridge building or cable cars over wide chasms.

1.1. Advantages

- The skyway is more versatile than existing rocket launch ramps that use electromagnetic acceleration [1], as it can be taken to high altitudes where air resistance is much lower. The skyway can be much longer, allowing craft to achieve greater speeds before having to use their own power, thus saving weight and fuel, and increasing the payload. Gentler accelerations are possible, opening up use to the wider public.
- No new materials need to be developed. By contrast, the space elevator [2] requires a 40,000 km cable capable of supporting its own weight. Carbon nanotubes have this potential but are still proving difficult to develop beyond lengths of millimetres. The rotating cable [3] also requires carbon nanotubes. Neither of these can be built with state-of-the-art materials such as Kevlar® [4].
- A skyway can be constructed from the ground up. This greatly lowers the costs compared to the space elevator, which must be lowered from geostationary orbit. Ground-up construction means that pilot projects and small applications can be undertaken with far lower initial risk, starting at a small scale in the laboratory. Experience can be gained at each stage of development as the scale is increased.
- Using it for air travel would improve the economics of developing the skyway for space launching. A skyway could launch a jet aircraft right up to its cruising altitude and speed, significantly reducing the noise and fuel consumption of takeoff.

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- Supersonic air travel becomes more attractive. It just needs a longer, higher skyway than subsonic travel.

Private or public investment could be used. In the eighteenth and nineteenth centuries, canals and railways were built by private interests, whereas most major infrastructure projects in the twentieth century (including space flight) were undertaken by governments. In the twenty-first century, the pendulum seems to be shifting back to private enterprise.

1.2. Contents

The remaining sections are as follows:

2. Tube Levitation

An object in free fall experiences a gravitational force towards the earth's centre, causing it to travel in a parabola or, over a longer distance, an ellipse. Bolts in a tube follow the somewhat different curve illustrated in Figure 1. In the preferred design, they hold up the tube by a levitation force normal to their direction of travel. Because the levitation forces are not vertical, some of the tube's weight causes tension, which is transmitted to the top, where the bolts support all the weight. There is little or no tension at the base.

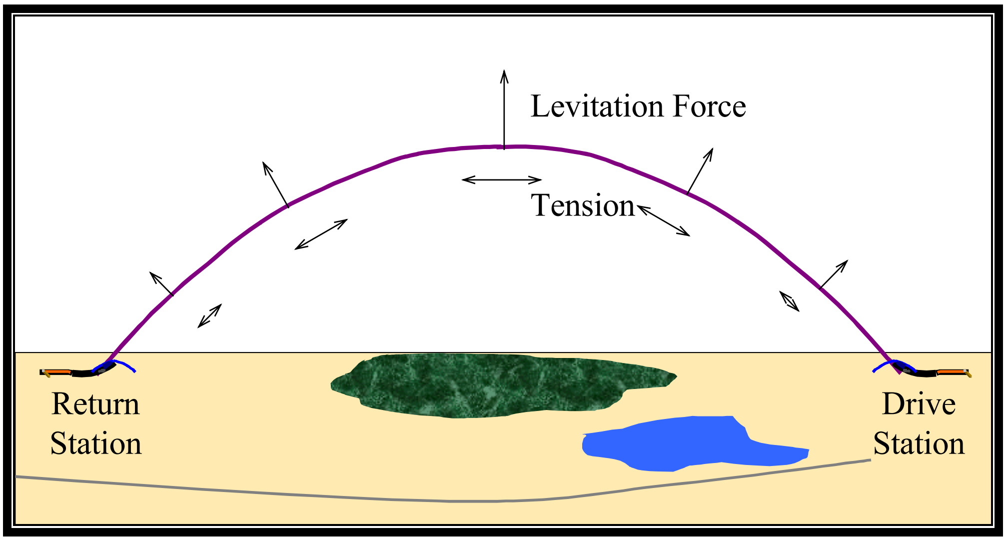

Figure 1 Shape of Curve indicating Tension and Normal Forces

2.1. Trajectory

The equations of motion of a bolt reduce to a differential equation of the form

$$\ddot{y} = f(\dot{y}, y)$$

A dot denotes differentiation with respect to time. The details are given here. The equation can be solved numerically by the Runge-Kutta method.

At any point (x, y), the tube will have an inclination ψ, and its weight at that point will be supported partly by the bolts as they pass and partly by tension in the tube. From the diagram in Figure 2, we can see that the tension increases with height and balances the normal force from a bolt. In fact, if the tube's weight per metre is w, the tension is $T = wy + T_0$, where T_0 is the tension at the surface station, which can be zero. To see this, consider a small section of tube of length δl from *A* to *B*. Its weight $w\delta l$ is supported by a levitation force of $w\delta l \cos\psi$ and a balancing tension $\delta T = w\delta l \sin\psi$, i.e., $\delta T = w\delta y$. From there, assuming uniform weight, we obtain the tension

$$T = \int w dy = wy + T_0$$

The mass of material of density T and tensile strength S required to support this tension is $\rho T/S$ per metre. For example, Kevlar® 149 has strength 3450 megaPascal (MPa) and density 1.47 g/cm^3. At height 50 km and tube weight 50 N/m, the weight of Kevlar® required is 10 N/m (i.e., about 1 kg out of 5 kg mass per metre of the tube). Savings could be made by tapering the tube's weight at lower elevations, but this has not been considered in the calculations.

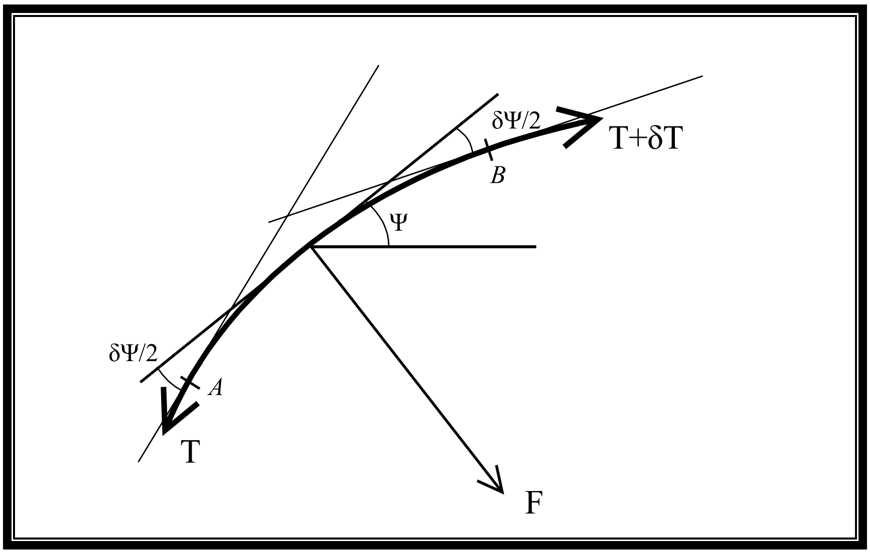

Figure 2 Forces over a small segment *AB* of the tube

The tube's weight results in a force $w\delta l \cos\psi$ on the bolts normal to the direction of motion. In addition, the tension causes a force: the slope of the tube changes by an angle $-\delta\psi$ over the length δl, yielding a force on the bolts of $2T\sin(-\delta\psi/2)$, which comes to $-T\delta\psi$, which is $-(wy + T_0)\delta\psi$. Hence, the force F on a bolt spaced s from its neighbours is

$$F = \int_0^s w\cos\psi dl - \int_{l=0}^{l=s} (wy + T_0) d\psi$$

Applying the chain rule and using $\dot{s} = V$, this gives

$$F = sw\cos\psi - s(wy + T_0)\dot{\psi}/V$$

The spacing varies with velocity such that $s = s_0 V/V_0$. Therefore

$$F = \frac{s_0 w}{V_0}\left[V\cos\psi - (y + T_w)\dot{\psi}\right]$$

Here the notation $wT_w = T_0$ has been used.

The equations of motion for a bolt are therefore

$$\ddot{x} = \frac{F}{m}\sin\psi$$

$$\ddot{y} = -g - \frac{F}{m}\cos\psi$$

To convert this to $\ddot{y} = f(\dot{y}, y)$, we obtain expressions for $\dot{\psi}$, $\ddot{x}$, V and $\dot{x}$ as follows. By differentiating $\tan\psi = \dot{y}/\dot{x}$ we get

$$\dot{\psi} = \frac{\dot{x}\ddot{y} - \ddot{x}\dot{y}}{V^2}$$

The equations of motion give

$$\ddot{x} = -(\ddot{y} + g)\tan\psi = -(\ddot{y} + g)\frac{\dot{y}}{\dot{x}}$$

The levitation force is normal to the direction of travel and so does not affect their speed, which is subject only to the gravity of the bolts' own weight. Hence, at a height y their kinetic energy balances their potential energy, giving $\frac{1}{2}mV_0^2 = \frac{1}{2}mV^2 + mgy$, where m is a bolt's mass, V is its speed, V_0 is its initial speed, and g is 9.81 metres/sec. Therefore

$$\dot{x}^2 + \dot{y}^2 = V^2 = V_0^2 - 2gy$$

Writing $C = ws_0/mV_0$, we obtain $\ddot{y} = f(\dot{y}, y)$ as

$$\ddot{y} = \frac{-gV + C\left[g(y + T_w)\dot{y}^2/V^2 - (V^2 - \dot{y}^2)\right]}{V - C(y + T_w)}$$

In the example, an additional weight factor of 40% has been allowed for the effects of cross winds (see Section 3.3). For the target height of 50 km in the example, a suitable velocity at the surface station when no launch is taking place is 4.1 km/sec at 56°, giving a horizontal range of 150 km.

2.2. Magnetic Levitation

Magnetic levitation is a proven technology in rail transportation [5]. Its use has been limited because the cost-benefit balance for that application is marginal. Energy-efficient superconducting systems have been demonstrated [6]. The Swiss Metro team has worked on evacuated tube trains since the late 1970s [7]. Recent work has shown that high-temperature superconductors are becoming practicable [8, 9] with liquid nitrogen cooling rather than liquid helium. Permanent magnets can be used in combination with superconductors to give stable levitation, exploiting the so-called Meissner effect in which the superconductor effectively acts diamagnetically by directing flux in the optimal direction to oppose the applied field exactly.

There is a cheaper, simpler system known as Inductrack [10]: closed-loop coils at ambient temperature move over permanent magnets arranged in a Halbach array [11]. However, it suffers losses in the coils that are too great for the present application. The losses are caused by electrical resistance leading to magnetic drag. According to Post [12], the lift/drag ratio is inversely proportional to velocity. At the median bolt velocity of 3.4 km/sec, the ratio is 1:900. An improved design using a thin plate instead of Litz wire coils [13] gives nearly twice this ratio, giving in the example a drag force per bolt of $F_M = 90$ mN (milliNewtons) based on 160 N median levitation force. A bolt will lose roughly 4 metres/sec velocity over the length of a tube (about 190 km) in the example.

In this configuration, the power loss per metre is VF_M/s. Although the losses seem small, they equate to a power loss per tube in the steady (i.e., idle) state of 35 MW (megawatts), a rather large amount that would negate the intended energy savings.

Levitation purely by means of permanent magnets would be energy efficient. However, Earnshaw's theorem [15] tells us that such levitation cannot be stable in all three dimensions because of a basic property of magnetic, electrostatic and gravitational fields, namely that they are divergence free. We therefore need to use induction coils for stabilization but not for the main levitation force.

2.3. Stabilization

Related studies of magnetic bearings for flywheels that store electrical energy show the feasibility of an energy-efficient method [14]. The application of this work to the skyway consists of permanent magnets in both the tubes and the bolts, supplemented by coils in the bolts. They are so arranged that they carry no current in the stable position, but when they move away from the stable position, currents are induced in them so that they exert a restoring force. There are commercial versions of similar technology that use electronic controls to set the restoring forces. They are somewhat more expensive but give better energy efficiency. This is the preferred approach.

In the skyway, the upper inside of a tube carries a Halbach array of permanent magnets. Each bolt carries a complementary permanent-magnet array, together with the stabilization coils. The bolt magnets are arranged to repel those in the tube. The best available material for the magnets in the bolts is neodymium iron boron (NIB)[16]. For the tubes, ferrites are preferred. Although ferrites are weaker, they are non conducting and so do not suffer losses due to eddy currents. NIB is a conductor, but the bolts experience a steady field and so do not have significant eddy currents.

To minimize losses caused by electrical resistance, electronic controls detect the currents in small sensor coils and amplify them, with suitable damping, in larger coils, the power coming from induction due to moving past permanent magnets. With good design, quite low losses need be incurred. This is the state of the art in commercially available magnetic bearings. Assuming a power saving of a factor of 100 by these means gives a revised estimate of 350 kW per tube power consumption.

The force on a magnet is

$$\frac{B_1 B_2 A}{8\pi \times 10^{-7}}$$

Here, B_1 is the magnetic flux density of the magnet, B_2 is the applied magnetic field, and A is the effective surface area. NIB is commercially available up to 1.2 T (Tesla) and ferrites up to 0.4 T. To achieve a maximum force of 240 N, we need A=12 cm^2. In the example, the bolts are 10 cm long, and so tracks 1 cm wide overachieve this.

2.4. Vacuum

The vacuum in the tube eliminates most of the aerodynamic drag on the bolts. The general formula for aerodynamic drag is applicable to a vehicle in open air rather than to objects moving in a tube. A thought experiment indicates that the air between bolts will collect immediately in front of and beside the following bolt, which will collide frequently with most of the air particles, accelerating them to its velocity. They will collide with the sides of the tube, which will decelerate them again. Thus, there will be a continual loss of momentum due to air friction with the sides. At low densities, these will be the dominant collisions, as particles will not often collide with each other.

In a tube of radius r, most of the air is concentrated in pockets within a distance $2r$ in front of a bolt. In effect, the moving bolts perform a supplementary pump action, pushing residual air from the tubes to the stations, where conventional vacuum pumps are installed. These could be cryogenic, diffusion, turbomolecular or ion pumps. To exploit and enhance this pump action as fully as possible, a scoop consisting of concentric conical vanes on the front of each bolt is proposed (Figure 3).

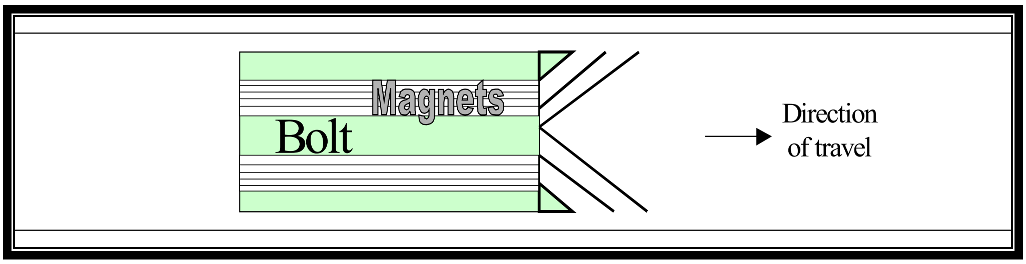

Figure 3 Scoop at front of bolt

The particles' lateral velocity v will be Maxwellian about an average determined by the temperature of the tube walls (300 metres/sec at 300° K). We need to consider the particles in front of a bolt and also those in the gap between a bolt and the walls of the tube. For the particles in front, the average time between collisions with the side is r/v. Typically, the bolt's velocity V will be much greater, and so the air particles will predominantly travel forward with velocity V and have their momentum exchanged every r/v seconds. If the average density is N particles per cubic metre and the separation between bolts is s, there will be $\pi r^2 sN$ particles exchanged every r/v seconds. The rate of momentum loss will be

$$\frac{\pi r^2 s m_A N V}{r/v}$$

where $m_A = 2.7\times10^{-26}$ kg is the mass of an air particle. To this must be added the effect of collisions in the gap at the side. Here, the average time between collisions with the side is d/v for a gap width d. There will be $\pi r d s N$ particles exchanged every d/v seconds, and the rate of momentum loss is

$$\frac{\pi r d s m_A N V}{d/v}$$

Summing gives the force per bolt as

$$2\pi r s m_A v N V$$

The power loss per metre length of tube is therefore

$$2\pi r m_A v N V^2$$

A vacuum of 10^{-8} Torre (1.3*10^{-6} Pascal, 1.3*10^{-8} mbar, 1.3*10^{-11} times atmospheric pressure, which is that found at 480 km altitude) is well within the state of the art [17]. Here $N = 3.4\times10^{14}$ particles per cubic metre, r is 2 cm, giving a drag force in the example of about 0.4 μN and a power loss per tube (assumed 190 km long) of approximately 140 Watts (W), an acceptable level.

3. Station Design

There will be a station at each end of a cluster of tubes, either on the ground or at sea. For each pair of tubes, the station has to turn round the bolts from the incoming tube and send them back through the return tube. They must balance the momentum used by the craft being launched and offset the effects of wind. A station has to ensure that the bolts are on a course to intercept the craft. The drive station provides the momentum required by the craft. The return station provides a velocity (speed and angle) such that the return tube can partly support the drive tube if the craft is extracting so much momentum that the drive bolts can no longer support the tube.

In continuous operation, incoming bolts arrive on the *ramp* that turns them to the horizontal. Then they proceed to the *ambit* that turns them around, after which they go back up the ramp. These are illustrated in Figure 4, in which some of the ramp is in a tunnel, some of it supported by a gantry and some of it supported by short tubes *(support tubes)*. This represents a compromise between depth of tunnelling and height of support tubes. The ambit and accelerator pair are at surface level or in shallow trenches. The details will depend on site conditions.

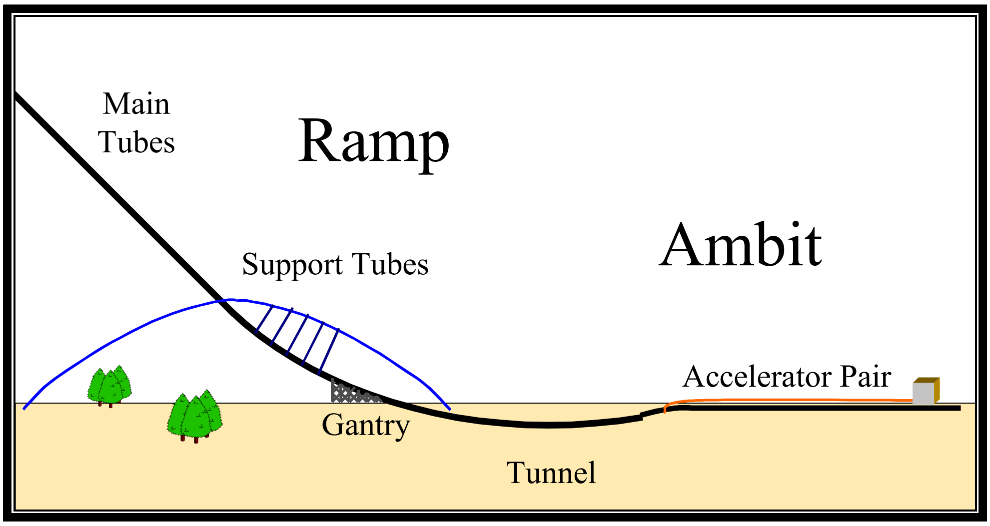

Figure 4 Side View of Ramp, Ambit and Accelerator Pair

For starting up and taking down, there will be an accelerator and decelerator (called an *accelerator pair*) at each station. The decelerator slows the incoming bolts to a speed at which they can be turned aside in a reasonable distance without successive bolts getting too close together. They can then be stored. The accelerator does the opposite. It would be possible to use the accelerator pair in continuous operation and have a much smaller ambit, but the coils required would cause considerable power losses.

As illustrated in the plan view (Figure 5), the preferred design has a large ambit to avoid deceleration and acceleration. At first sight, that appears to involve a considerably greater length of track, but it has the advantage that powerful superconducting magnets can be used in the ambit, whereas the accelerator pair needs oscillating electromagnets (acting as the primary of a linear synchronous motor). Linear acceleration needs a length $\frac{1}{2}V^2/a$ for velocity V and acceleration $a = F/m$, force over mass, whereas an ambit needs a radius $R = V^2/a$ and hence a track 4π as long. However, superconducting magnets can be assumed to have five times the magnetic field strength of oscillating electromagnets, and so the ambit and accelerator pair dovetail nicely, as illustrated.

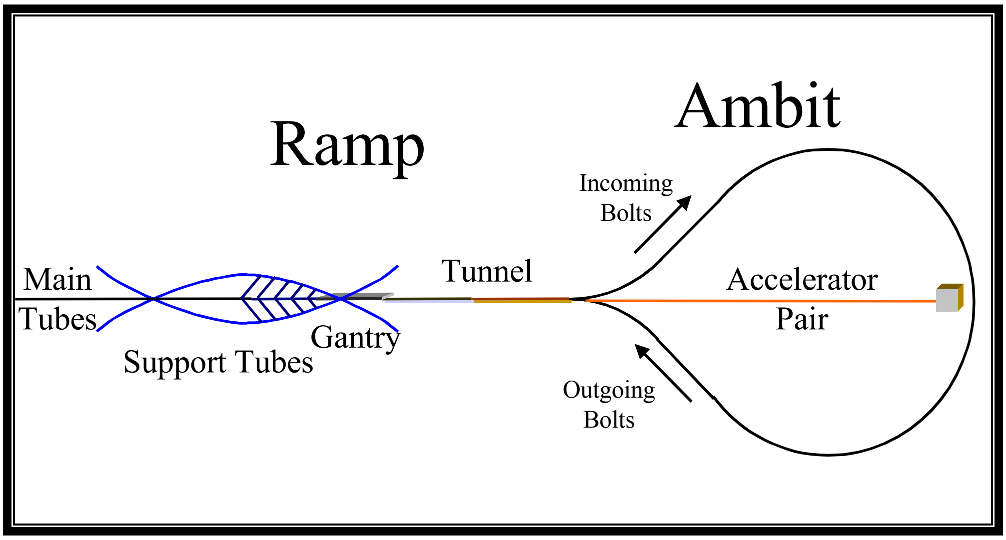

Figure 5 Plan View of Ramp, Ambit and Accelerator Pair

In the accelerator pair, oscillating electromagnets (acting as the primary of a linear synchronous motor) are needed to provide the necessary thrust. Superconducting magnets have not so far been found capable of coping with the alternating current that would be needed.

NIB (in the bolt) is commercially available with magnetization up to 1.2 T (Tesla). Commercially available superconducting magnets can apply a 10 T field, but an ordinary electromagnet is unlikely to exceed 2 T. In the accelerator pair, we assume the bolt can be oriented optimally to take advantage of its full length (10 cm in the example). If A=40 cm^2, the force on a bolt is 3800 N in the accelerator pair. In the superconducting tunnel, it is about 19,000 N (1.9 tons). The maximum tension is then about 5 MPa, well below NIB's quoted tensile strength of 80.

In the example, the maximum bolt velocity during a launch (see Section 5) is 4.3 km/sec., and so the accelerator pair needs to be about 2.4 km long. The ambit radius needs to be 1 km.

3.1. Support above the Surface

The overall vertical extend of the ramp required (height plus depth of tunnel) is given by $2R\sin^2\frac{\theta}{2}$, 400 metres in the example when θ is 56°. To achieve the best turning circle, superconducting magnets are needed above and below ground, preferably cooled with liquid nitrogen. If the tunnel goes to 100 metres depth, then the supporting tubes must rise above 300 metres. Neglecting a small addition due to deflection, the overall arc length of the ramp (above and below ground) is $R\theta$ (θ in radians), which comes to 900 metres. Of this, 400 metres is tunnel, 200 metres is gantry, and the rest is supported by tubes. The tunnel and gantry achieve an inclination θ_G of about 38°.

The supporting tubes have to sustain a load of $mV^2\sin(\theta-\theta_G)/s$ per main tube, about 27 MN (or 2700 tons) if there are 10 main tubes. (Consider a mass m travelling at velocity V deflected by an angle α. The change of momentum is $mV\sin\alpha$. If they are spaced s apart, their rate of arrival is V/s. So the resultant force — rate of change of momentum — is $mV^2\sin\alpha/s$.)

Effectively, the support tubes are taking a fraction equal to $\sin(\theta-\theta_G)$ of the total force, about 0.32. As the supports only have to attain a few hundred metres of height, they can enjoy a lower bolt velocity and ambit radius if there are several to each main tube. Using ten times the number of support tubes needed shares the load so that the supports only need a tenth of the ambit radius (100 metres) compared with the main ambit. Similarly, the ramps for the support tubes are one tenth the size (an overall vertical extent of 40 metres); they may be underground, supported by pylons or a combination.

The angle of inclination of the main tubes can be varied by varying the bolt velocity in the support tubes. The support tubes are also used for deflection.

3.2. Stabilization

To maintain the overall balance and minimize tension in the tube, the stations must adjust bolt velocities as vehicles take off and land. In addition, active controls are needed to take account of head, tail and cross winds. The complexity of the control problem is comparable to that handled by automatic systems on sailing vessels, although the scale is obviously much greater. Computer simulation will need to be followed by wind tunnel measurements of scale models.

The skyway is stable in the vertical direction, since extra load merely lowers the overall height. Additional stability can be gained by allowing some variable tension in the tubes at the stations. Lateral stability comes from an inherent stiffness due to the momentum of the travelling bolts, but this results in lateral forces at the stations, which have to be countered by varying the deflection and inclination — turning into the wind. Sensors for motion and wind will need to be placed along the length of the skyway. The stations need to be able to vary the angles as wind gusts are experienced. Each station must deflect bolts in the outgoing tube sufficiently to compensate for the forces experienced by bolts in the incoming tube.

3.3. Cross Winds

The worst case of wind is of a strong gusting cross wind. This paper does not attempt to analyze the oscillation modes, although that will be essential, but simply looks at severe cases to verify that the forces needed are adequate.

The pressure of wind on an object is given approximately by $P=\frac{1}{2}\rho_A v^2 C_d$ where ρ_A is air density (about 1.25 kg/m^3 at sea level), v is wind speed and C_d is the drag coefficient. A tube with circular cross section has a drag coefficient of approximately 1, although work on electrical power cables has shown that improved designs can reduce this to about 0.7 [18]. Assuming this improved drag coefficient, a hurricane force wind (v=30 metres/sec, force 11 on the Beaufort scale) at low altitude will exert a pressure of 400 Pascal (Pa). However, at high altitudes in the jet stream, winds can reach 180 knots (110 metres/sec) at an air pressure of 300 mbars (0.375 kg/m^3 air density). The wind pressure is then 1600 Pa. It is reasonable to assume that one tube can partly shield others, so a mean wind pressure of 1000 Pa is suggested. On a tube of 5 cm diameter, this is a force per metre of 50 N or 100 N per bolt (equivalent to just over 10 kg weight). Magnets in the bolts and tubes must handle this force. The bolt velocity in the example allows for it. It is a factor of 30 below the maximum force achieved in the bearer. It sets an upper limit on the density of permanent magnets needed in the tube.

3.4. Total Tube Deflection

The jet stream does not operate at all altitudes but only between 20,000 and 40,000 ft (6-12 km). This affects a tube length of up to 20 km. ascending and the same descending, giving a force per tube in the example of 2 MN. Since the force caused by a deflection of α is $mV^2\sin\alpha/s$, we can calculate the total deflection ϕ of a tube due to a strong jet stream as approximately 14°. Hence, the stations must be able to deflect the tube laterally by this angle, so that the tube above the adverse jet stream will follow the correct course, allowing for similar deflections in the rising and falling parts of the tube.

It may be that, with careful design, the drag coefficient can be reduced further. Help may come from the observation that low-level winds are often opposite to those at high level, partly cancelling out the effects and reducing the deflection needed at the station.

3.5. Steering

Steering at the stations is necessary to deal with winds and varying loads. Steering is carried out above the ground; otherwise, wide tunnels would be needed. Steering needs to respond within a few seconds to changing wind conditions. To minimize tension in the tubes, the response time should be substantially less than the time a bolt takes to reach the station after it has been deflected by wind.

The support tubes are aligned with the main tubes, but they are tilted to either side. They are attached to it via cables. Varying the bolt velocities in the tilted support tubes will deflect the main tubes and may affect the inclination. The velocity variation will be limited to 25% of maximum to avoid travelling bolts getting too close. Hence, the maximum and minimum forces satisfy $F_{\max} = 4F_{\min}$, and these forces must satisfy $F_{\max} - F_{\min} = F_{dfl}$, the greatest deflection force needed. Therefore, $F_{\min} = \frac{1}{3}F_{dfl}$, and $F_{\max} = \frac{4}{3}F_{dfl}$.

A suitably positioned support tube tilted at angle ξ exerts orthogonal force components equal to $(\sin\xi, \cos\xi)$ times its total force. Hence the lift from the tilting tubes is $(F_{\max} + F_{\min})\cot\xi$, which is $\frac{5}{3}F_{dfl}\cot\xi$. In the example, setting ξ to 45° means that the inclination and deflection forces are in balance. The total force to be exerted by the support tubes is $\sin(\theta - \theta_G)\max(\sec\xi, \csc\xi)$ of the load from the main tubes, a proportion of about 0.45. At a ratio of ten to one, we will use 46 (i.e., 23 pairs) so that they can have ambits one tenth the size.

The support tubes are responsible for a combined angle of turn for both inclination and deflection of $\arccos(\cos(\theta - \theta_G)\cos\phi)$, about 23° in the example, giving a supported arc length of 400 metres covering a horizontal rectangle of approximately 280×70 metres.

3.6. Oscillations

The motion of a bolt along a tube causes an oscillation in the tube at a period determined by its velocity. In fact, the period is s/V, which has a median value of 0.5 millisecond (frequency of 2 kHz) in the example. In this time, the bolt will accelerate the tube upwards, after which it will rise for half the period and then fall under gravity for the other half. The distance amounts to 0.3 microns, well within the proposed millimetre-scale clearance between the bolts and the tube.

3.7. Effect of Earth's Rotation

The design should account for the effect of the earth's rotation.

Consider first a cluster of tubes connecting two stations at the same latitude. If the bolts travel at the same speed relative to the earth's surface in each direction, then those travelling from west to east will be faster than those travelling from east to west; they will therefore have a higher velocity. This leads to a centrifugal force about the centre of the Earth of

$$\frac{m(V \pm \Omega R_E \cos\zeta)^2}{R_E \cos\zeta}$$

where R_E is the Earth's radius, Ω is its angular velocity, and ζ is the latitude. The difference between the eastward and westward velocities is $4mV\Omega$, about 1.2 N in the example at a temperate latitude. Therefore this small tension exists between the drive and return tubes.

For two stations at the same longitude but different latitudes, there is an effect due to the faster rotation velocity of the earth's surface nearer the equator, the coriolis force. The effect on southbound bolts and their associated tube counterbalances the opposite effect northwards, because the force is proportional to the north-south velocity. The force is $\pm mV\Omega\sin\zeta$, giving a net tension of about 0.4 N in the example.

Normally, two stations will have different longitudes and latitudes. The two effects then combine as a vector sum.

4. Methods of Erection

One method is to use an inflatable tube filled with helium gas. The inflatable tube is attached to a single drive and return tube pair for their whole length. A diameter of 1.3 metre at ground pressure will provide 5 kg of lift per metre length. The three tubes are laid out between the drive and return stations, and the helium tube is inflated. As the tubes rise, the inflatable tube expands in line with the reduction in atmospheric pressure. The tubes will rise to a level at which they can be supported by the bolts. In the example, this point is reached at a central height of about 7 km.

To support the tube at this height, a greater number of bolts is needed than at the full height. Bolt spacing of about 60 cm (instead of 2 metres) achieves this at the same speed (4.1 km/sec) as is used for the high altitude. This avoids having to build a special high-speed accelerator for use during erection.

Once the tubes can be supported by the bolts, they can be raised by adjusting the angle of inclination, and the helium tube can be deflated. The initial inclination is only 34°, somewhat below the 38° provided by the fixed part of the ramp (tunnel and gantry). Water ballast is proposed for the nearest parts of the tubes to keep them down to the required angle during erection. As the tubes rise further, the ballast can be drained out and the velocities of the bolts reduced to avoid excess tension. The tubes must be capable of sufficient expansion for the required height, which involves a 25% increase in length. Expansion joints will be needed to allow this without significantly increasing its tension.

The excess bolts used to erect the first tube pair are removed for use with further tubes. These can be erected by dragging them along the tubes already in place by means of devices that are spaced at intervals along the new tube pair and crawl along the existing pair. This minimizes the weight of the initial construction. Later, tubes can be taken down in a similar manner for servicing, maintenance and repairs without having to bring down the whole structure. Further tubes can be added to increase the payload and overall reliability.

Ideally, the first pair of tubes to be raised should assume the necessary shape for smooth passage of bolts at high speed. Otherwise, there is a danger of rupturing it when the first bolts are projected by the stations at a high enough speed for them to reach the high point. A suggested solution is to have a small specialized set of startup bolts. They are battery powered and capable of propelling themselves if their initial momentum is insufficient to carry them right through the tube. They would be useful in clearing the residual air from the tubes to reduce air drag during startup.

The site will need to be about 150 km long for the example, preferably in an unpopulated area for safety reasons. Ultimately, after a lot of experience has been gained, erecting a smaller skyway in a built-up area will hopefully be more acceptable than having jet aircraft taking off overhead. In that case, temporary pylons are a possible method of support before inflating the helium tube.

4.1. Boosting and Quiescence

The station must be able to accelerate bolts from rest at startup, or after routine maintenance, to a velocity sufficient to carry them through the tube to the other station. Between the ambit and the ramp, it must also be able to boost the velocity to compensate for losses and to take loads.

During quiescence, it needs to be able to divert incoming bolts to the accelerator pair to retard and stop them for maintenance or removal from service. This involves precisely timed automated switching at the junction of the ambit with the accelerator pair.

To bring the skyway down, either of the erection methods described is reversible.

4.2. Vacuum Pumping

The stations need to maintain the vacuum by continual pumping. Normal practice is to use roughing pumps down to 10^{-2} Torre and use these as backup to high-vacuum pumps. Although the tubes have a wide bore (40-50 mm), they are long enough to sustain a considerable pressure gradient internally.

Even though 10^{-8} Torre is reached at the station, there may be parts of the tubes at only 10^{-1} Torre. The first few bolts will encounter significant air resistance, of the order of 2 N.

The drag force of $2\pi rsm_A vNV$, being proportional to the velocity V , causes the velocity to decay exponentially as

$$V = V_0 e^{-2\pi rsm_A vNV}$$

From this formula, we can compute the initial velocity V_0 that a bolt needs cover the length L of the tube before stalling as

$$V_0 = 2\pi rsm_A vNL$$

Given a length of 190 km and a maximum initial velocity of 4.1 km/sec, we need to be able to pump the tube down to a number density of $N = 10^{22}$ or about 3×10^{-1} Torre. This is within the achievable vacuum without recourse to exceptional measures.

5. Vehicle Levitation and Propulsion

A proportion of the bolts' speed supports the weight of vehicles. The bearer can deflect the bolts (and hence the tube) downwards to support its weight and that of a craft; it can retard the bolts to derive thrust. Thus it can obtain a force vector by controlling two independent directions. Energy efficiency is less of an issue than in levitating the tube, as a launch only takes a few minutes, whereas the tube has to be levitated for much or all of the time.

The craft will separate from the bearer when it reaches the desired speed and altitude. The bearer will then decelerate and return to the drive station. It is designed to have aerodynamic lift so as to maximize the available thrust for acceleration at high altitudes. The connection between the bearer and the bolts uses oscillating induction coils. It is a form of linear induction in which the bearer is dragged behind the passing bolts. The force calculation is similar to that for an accelerator pair at the stations, but this needs to be reduced, given the need for flexibility in the direction and rather less opportunity for optimization on the move. These considerations suggest a force F of 3 kN (kN) per bolt.

The available thrust FD/s depends on the length D of the bearer. Since the bolts are $s = 2$ metres apart, a 600-metre bearer will supply 900 kN of thrust per tube. Five drive tubes will give 4.5 MN or 450 tons. For comparison, this is three times the thrust developed by the space shuttle's main engines (without the solid rocket boosters).

Retarding the bolts by a force F causes a speed reduction $\sqrt{V^2 - FD/mV}$. In the example, this takes 440 metres/sec from a bolt velocity of 4.3 km/sec, keeping the average near 4.1 km/sec as required to support the tube. It is also possible to obtain a normal force by deflecting the bolts. For bolts of mass m spaced s apart travelling at velocity V deflected by an angle α , the resultant force (rate of change of momentum) is

$$\frac{mV^2 \sin\alpha}{s}$$

The bearer must deflect the bolts in the return tube by the same amount, giving a total force of

$$\frac{m(V^2 + V_r^2)\sin\alpha}{s}$$

for return velocity V_r . The force is useful for additional lift and for balancing the torsion effect due to thrust that is offset from the centre of gravity of the bearer and payload. The force is partly opposed by a tension force $T\alpha = wy\alpha$. At high altitudes, the tension force can reach 30% of the deflection force. However, the bearer does not need it at high altitudes, since it has enough speed to gain aerodynamic lift and attitude control.

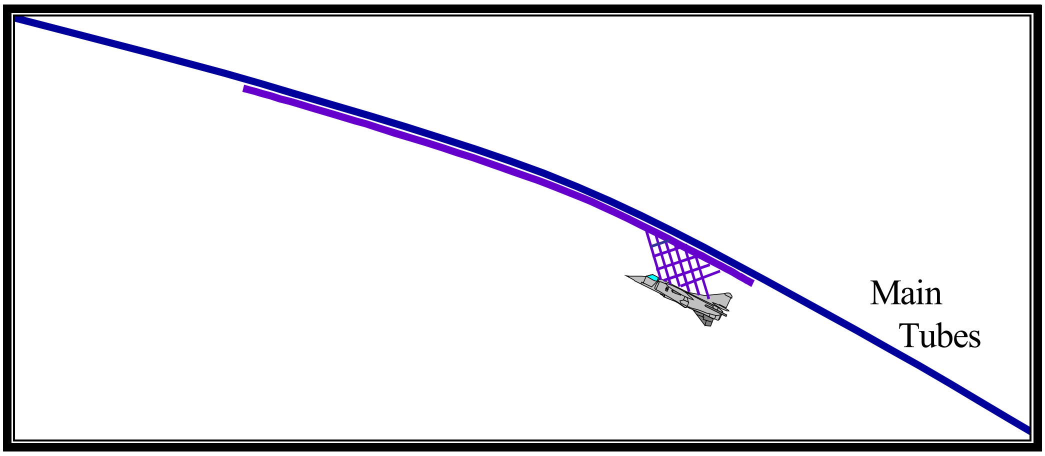

Figure 6 Bearer supporting a vehicle during launch

The bearer consists of a long forward section that obtains thrust and pulls a short rear section that carries the vehicle (Figure 6). The rear section needs to be able to flex to obtain lift at low altitudes, until it reaches a speed at which it achieves aerodynamic lift. The bearer is suspended below the tubes, leaving the top and sides free for connectors and other equipment.

6. Safety and Failure Scenarios

A system supported dynamically carries obvious risks of collapse. For comparison, consider a jet airliner. It has very limited glide capabilities and needs power to land. The design relies on redundancy between the engines. All jet airliners have more than one engine, so that they can continue flying if one fails. The skyway relies on redundancy between the tubes. In a system with five pairs of tubes, a failure of one or two can be contained.

However, it is worth considering emergency procedures for bringing a skyway down in the event of a disaster:

1. Terrorism and Acts of War: The skyway is vulnerable to surprise attack. A partial breakage should be containable, because the functioning tubes can support broken ones. However, a break in most or all of the tubes at once would lead to catastrophic failure. In many ways, this is comparable to the destruction of a bridge, as often happens during warfare, but there are different considerations.
2. Ejection of Bolts: Breaking a tube will cause the high-speed bolts to fly through the air, where their kinetic energy will rapidly be converted into heat; they will heat to 20,000-30,000° C almost instantly due to atmospheric friction, well above their vaporization temperature. The only bolts presenting a danger on the ground will be those already travelling downwards near a station. These will all fall short of the station, and so the ground under the skyway near a station will need to be kept clear in case of emergencies.
3. Falling Tubes: Once the tubes lose their supporting bolts, they will obviously fall. One way to limit the damage could be to have parachutes attached at intervals to slow down the fall. It may be worth designing the inflatable tube so that it automatically opens out to form a long narrow parachute in the event that it falls suddenly.
4. Collision with Aircraft: A collision, whether accidental or deliberate, would have much the same effect as an act of terrorism.
5. Loss of Vacuum: The tubes could start to leak. This would immediately be felt as a localized drop in bolt speed. The bolts themselves act as pumps, pushing the incoming air through to a station. This will be readily detectable, so that corrective maintenance can be planned before the leak becomes serious.

7. Economics and Future Directions

The NIB magnets are a large cost item. In these estimates, retail costs are used in an attempt to cover overheads. A 1 kg set of magnets (for a bolt) costs about £150 retail. To this must be added control electronics in each bolt, estimated at another £50. In the example, there will be 10 tubes each 190 km long containing 94,000 bolts, giving a total cost of £190 million. In the tubes, two tracks of magnet arrays will be needed. The weight per metre comes to about 2 kg, assuming they are ferrites, giving a cost per metre of about £10. This adds £20 million to the total. The tubes will need 1 kg of Kevlar® per metre, costing about £50, giving a total of £100 million. There will be expansion joints and vacuum-tight materials, probably amounting to another £20 million. These figures sum to £330 million.

Each supporting tube is 1 km long, and there are 46 at each ground station. If they use the same technology as the main tubes, they will cost about £20 million.

The liquid-helium-cooled superconducting electromagnets at the stations are comparable to those used at CERN in Geneva. There, 27 km of tunnel are undergoing a reinstallation costing about 3.2 billion Swiss francs (£1400 million). The example skyway has 9 km of comparable tracks at each station, suggesting an approximate cost of £950 million for both. It is possible that using high-temperature superconductors could reduce this substantially, but it is difficult to estimate.

A bearer is comparable in complexity to an airliner and could cost £100 million.

At $2.50 per cubic metre, the helium gas needed during erection comes in at $500,000 (£300,000).

These figures total £1400 million. For the first skyway, there will be research and development costs to be recovered. The biggest single item is likely to be the construction of a 1:10 scale model costing one tenth of the full-size installation. Assuming the same again for other R&D costs suggests an uplift of 20%, giving an overall estimate of £1680 million ($3 billion). For comparison, estimates for the space elevator’s costs vary between $10 billion and $70 billion.

A typical rocket launch costs about $60 million. A skyway launch eliminates at least the expensive first-stage rocket and can triple the payload as well. This yields a benefit per skyway launch of about $150 million (£85 million). Hence, 20 launches would recover the capital costs.

7.1. Smaller-Scale Applications

Skyways scale down better than linearly in their dimensions, and the costs scale down in proportion. In addition, the number of tubes needed may be less. For aircraft launching, thrusts of 1 MN are sufficient (comparable to just over two jet engines). This can be achieved with one or two tube pairs instead of five. A height of 10 km (33,000 ft) is enough for noise abatement at airports, and a range of 40 km is enough to accelerate an aircraft at $\frac{1}{4}g$ to a subsonic cruising speed. Hence, the cost is about 8% of that needed for launching space vehicles. This is somewhat offset by the need for several bearers instead of just one to carry out a reasonable workload.

A skyway over the English Channel would cost a similar amount, much less than the present tunnel. It would be designed to carry many small loads rather than a few large ones so that it could offer an on-demand ferry service. It would operate at a low altitude, up to perhaps 1 km (3300 ft) over a 40 km span, so it would not have to deal with jet-stream winds.

At a still smaller scale, a cable car is feasible over mountain chasms, open water or conservation areas where pylons are impossible or unacceptable.

7.2. Larger-Scale Applications

The space-launch application worked by example in this paper matches the performance of a first-stage rocket such as the Russian Proton, attaining an altitude of 45-50 km and a velocity of 5800 km/h (1.6 km/sec). Technically, it is possible to go much higher at proportionately greater expense. A skyway 150 km high, 800 km range and with 15 tube pairs (i.e., nearly five times as big with three times the number of tubes, so 15 times as expensive as the example) would be able to launch 12-ton unmanned vehicles to orbital velocity (using 64g acceleration) several times a day.

Skyways hundreds or thousands of kilometres long could connect cities, so that high-altitude hypersonic aircraft can travel with energy efficiency without having to carry their own sources of power. A skyway 7000 kilometres long could launch a spacecraft to escape velocity with 1g acceleration, which would make it accessible to a wide section of the general population. To minimize tension and thus weight, it would be supported at each end by short skyways that reach to the same altitude. At these sizes, the costs do not scale linearly but are more favourable. Relatively little thrust is needed to maintain an aircraft at cruising altitude and speed. Only a couple of tube pairs would be needed. Moreover, once the bolts attain orbital velocity (13 km/h including enough to carry some load), there is no penalty in the size of the accelerator pair and ambit required, the ambit radius being about 8 km.

There is a proposal for a stream of orbiting particles to be used for space launching [19]. It is argued that they can travel through the upper atmosphere as well as in space, although they seem more attractive when they are above the atmosphere. That proposal requires a driving station in space. A skyway could support such a driving station hovering over one place rather than in orbit. First it could facilitate construction and then be used to transfer power and payload, avoiding the need for the stream to enter the atmosphere. The kinetic energy of the bolts can transmit power from the ground to the orbiting stream; they are effectively a means of storing and transmitting energy. Interplanetary craft can rise to orbital altitude on the skyway and then ride the orbiting stream to reach sufficient velocity for interplanetary travel, possibly assisted by an orbiting magnetic launcher.

7.3. Summary of Research Areas

Although the skyway does not rely on new materials, it presents a formidable engineering challenge. The key development is to support a structure dynamically using travelling bolts. The following are the principle areas for further research and early development:

1. Magnetic levitation is a proven technology that has been used in several transport projects notably in Shanghai, China. As far as this author knows, it has not been tested at very high velocities (4.3 km/sec as opposed to 600 km/hour). The preferred technology uses arrays of permanent magnets made of neodymium iron boron in the bolts, and the expected lack of flux change and consequent eddy currents needs to be confirmed experimentally.
2. A lot of work is needed on the control systems for the stabilization coils. Their ability to deal with buffeting cross winds must be modelled and then tested in the laboratory. The best combination of passive coils, analogue electronics and digital controls must be sought.
3. Wind management at the macroscopic level will involve some complex systems for sensor input. The steering mechanism must be examined in more detail.
4. Oscillation modes and frequencies need investigation.
5. The coupling of the bearer to the travelling bolts requires detailed investigation to ensure that it can be achieved without upsetting the levitation of bolts within the tube.
6. There is not much experience of using high-temperature superconductors. Trials and evaluations will be necessary, and these may reveal possible cost savings.
7. The vacuum in the tubes and ambits is high enough to allow electrostatic levitation, which could be lighter and cheaper than either permanent magnets or superconductors, permitting the ambit radius to come down. It merits investigation.
8. The control systems will require extremely high reliability, comparable to fly-by-wire systems in aircraft. The ability to achieve this at reasonable cost must be examined further.
9. The failure scenarios all need exhaustive testing.

Work can proceed from the laboratory scale upwards. Assuming successful trials in a laboratory and wind tunnel, a reasonable next stage would be a 1/100 scale installation covering 1.5 km.

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