Applied Mechanics and Materials Vol. 437 (2013) pp 93-97
© (2013) Trans Tech Publications, Switzerland
doi:10.4028/www.scientific.net/AMM.437.93

Route Length, Curve Radius and Layout of Evacuated Tube Maglev Space Launch System

Yaoping Zhang[1, 2, a]

[1]Institute of Evacuated Tube Transportation, Xijing University, Xi'an 710123, China

[2] Institute of Evacuated Tube Transportation, Southwest Jiaotong University, Chengdu 610031, China

[a]tubetrans@hotmail.com

Keywords: evacuated tube maglev, space launch, route length, curve radius, launch angle, layout

Abstract. Current space launch is expensive and low-efficient because the invalid load----rocket and fuel in it occupies over 80% of the total launch weight. A solution to reduce the space launch cost and increase the launch efficiency is to construct the evacuated tube, pump air out from the tube and have the maglev vehicle loaded with the spacecraft run in it; the spacecraft fly out the tube when the maglev is accelerated to ultra-speed, e.g. 5km/s even 8km/s in the tube. By this way, the first class of the rocket could be saved, so that the launch cost would be low and lead the large scale space exploitation to become reality in the soon future. As for the tube construction, the route layout should be concerned on at first. Because of the engineering restriction, the height at the tube end wouldn't be very high, and the embedding depth wouldn't be very deep, practically about 8km. However, the tube length will be 700km at least, a completely straight tube or a completely curve tube (on a single circle) would lead a too small launch angle. Thus both of them are not feasible. Reasonable tube routes in vertical section will include two or more than two segments, for example, a straight tube segment and a curve tube segment, or two or more than two curve segments in different radius or different curve direction.

1 Introduction

Steps to probe and exploit the outer space are growing faster and larger. Today all launch missions are performed by rockets that take a large amount of fuel, occupying over 80% of the total launch weight. It badly increases the launch cost and decreases the launch efficiency, furthermore restricting the course for probing and exploiting the space. In order to solving these problems in space launch, it is prospective to construct the evacuated tube, pump out air from the tube[1-5], have the maglev loaded with the spacecraft run in it, accelerate the maglev up to a high speed over 3km/s, even 7km/s, then have the spacecraft fly out the tube at the end. Because the spacecraft has reached a high speed on ground, the first class of rocket could be saved. When the spacecraft arrives at a height more than 100km where air is rarefied, the rocket starts work to drive the spacecraft into the predetermined orbit.

James Powell had suggested to use such an evacuated tube maglev (ETM) for space launch some years ago, pointed out that it was much less cost than full rocket launch [6-8]. Today, necessary technologies for ETM space launch are more matured. It is the time to begin the potential project. There are a great number of technologies relating to ETM space launch. Only the tube route length, curve radius and tube layout of ETM space launch are discussed in this paper.

2 Necessary tube route length

In the precondition of meeting space launch requirements, shorter route is always expected. In the accelerating stage, based on the concern on astronauts, cargo and spacecraft devices, the acceleration is always limited to a low level. For astronauts, the sustained acceleration (non-instantaneous) shouldn't exceed $2g$ (g=9.81m/s^2) in any stage. For cargo and spacecraft devices, it shouldn't exceed $10g$. The calculating relation between the launch speed v (the speed when the spacecraft fly out from the tube end), acceleration a and the route length S is $S=\frac{\upsilon^2}{2a}$. Taking the launch speed υ 3~8km/s, supposing the acceleration a invariable in the whole acceleration stage and taking its value 1~10*g*, then the necessary shortest tube length is calculated as shown in Table 1.

Table 1 Necessary tube route length for ETM space launch (unit: km)

a (g=9.81m/s^2) \ υ (km/s)	3	4	5	6	7	8
1g	459	816	1276	1837	2500	3265
2g	230	408	638	918	1250	1632
3g	153	272	425	612	833	1088
4g	115	204	319	459	625	816
5g	92	163	255	367	500	653
6g	77	136	213	306	416	544
7g	66	117	182	262	357	466
8g	57	102	159	230	313	408
9g	51	91	141	204	278	363
10g	46	82	128	184	250	327

According to the results of Table 1, the shortest tube route length 327km is acceptable for not manned space launch. For manned space launch, no necessary to pursue 8km/s launch speed, 5km/s launch speed is considerable, so the shortest tube route length 638km is acceptable. By the above both cases, 700km is suggested as the reference length in the primary analysis and research.

3 The minimum curve radius of the tube route

In order to attaining the launch angle as possible as large, fitting to engineering condition or reducing construction cost, it's necessary to consider setting right curve at right section of the tube, including the level curve, the vertical curve or the spiral curve. The restriction factor for setting curves is the curve radius, exactly the minimum curve radius which depends on the centrifugal acceleration. The calculating relation between the segment speed υ_s (the speed when the spacecraft run at the segment where a curve is ready to set), centrifugal acceleration a_c and the minimum curve radius r_c is $r_c=\frac{\upsilon_s^2}{a_c}$. The segment speed υ_s will be 0~8km/s, here taking 1~8km/s; supposing the centrifugal acceleration a_c invariable in the whole acceleration stage and taking the value 1~10*g*, then the necessary minimum curve radius for the level curve is calculated as shown in Table 2. For the vertical curve, the centrifugal acceleration a_c should be added the weight of the gravity acceleration.

Table 2 Minimum curve radius of the ETM space launch tube route (unit: km)

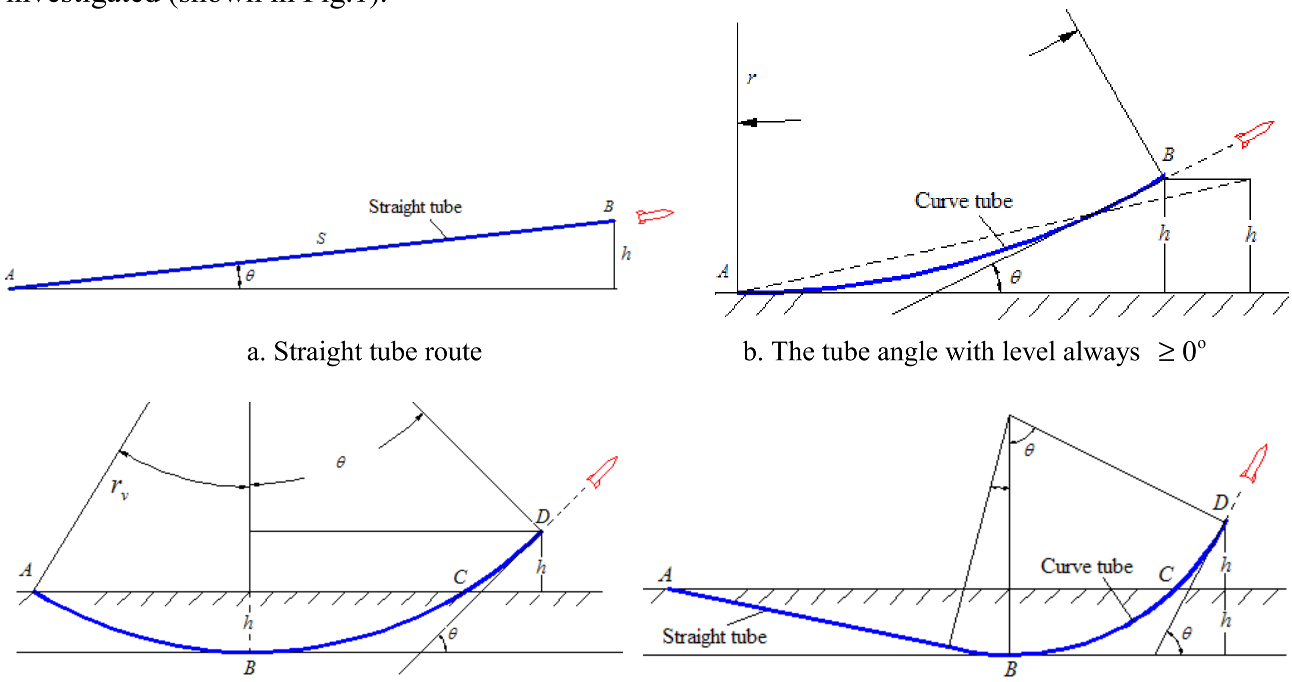
a_c (g=9.81m/s^2) \ υ_s (km/s)	1	2	3	4	5	6	7	8
1g	102	408	918	1632	2551	3673	5000	6530
2g	51	204	459	816	1276	1837	2500	3265
3g	34	136	306	544	850	1225	1667	2177
4g	26	102	230	408	638	918	1250	1633
5g	20	82	184	327	510	735	1000	1306
6g	17	68	153	272	425	612	833	1088
7g	15	58	131	233	364	525	714	933
8g	13	51	114	204	319	459	625	816
9g	11	45	102	181	283	408	556	726
10g	10	41	92	163	255	367	500	653

By Table 2, for manned space launch, when the speed reaches 5km/s, the minimum curve radius is 1276km; for not manned space launch, when the speed reaches 8km/s, the minimum curve radius is 653km. When the speed is less than 3.5km/s, minimum curve radius 700km could meet requirement, regardless to not manned or manned space launch.

4 Route layout of ETM space launch system

4.1 Vertical layout

The tube route is very long, but the height at the tube end would be very small. The practical maximum height is about 8km, for example, in the case the tube end was located on Chinese Qinghai-Tibet Plateau where the height of the top mountain is over 8km. This would lead the launch angle at the tube end to be very small, not more than 20^{o}. By the superconductivity span scheme suggested by James Powell, the height at the tube end could reach 20km which was quite favorable for increasing the launch angle. Anyway, vertical layout of ETM focuses on attaining launch angle as possible as large. In order to attaining a large launch angle, four types of vertical layout are investigated (shown in Fig.1).



a. Straight tube route　　b. The tube angle with level always $\geq 0^{o}$

c. Partial tube route under ground　　d. Tube route partially in curve

Fig. 1 Some various tube routes when not considering the earth curvature

By the layout in Fig. 1a, the tube route doesn't include any vertical curve. S, h and θ is respectively the tube length, height at the tube end and the launch angle. If $S = 700$, $h = 8$, then $\theta = \arcsin\dfrac{h}{S} = \arcsin\dfrac{8}{700} = 0.6552^{\circ}$. Such a launch angle is too small and not feasible for space launch. Thus this layout is unreasonable.

By the layouts in Fig. 1b and Fig. 1c, the whole tube routes are in curve, and don't include any straight line. Specifically, in Fig. 1b, the tube route is a vertical curve. Apparently the launch angle at point D is larger than that in straight line as shown in Fig. 1a, and the launch angle will become larger when the curve radius becomes smaller.

Just as the maximum height at the tube end is limited, the maximum embedding depth is also limited. As shown in Fig. 1c, supposing the maximum embedding depth is also equal to h, then the necessary curve radius r_v can be calculated by Eq. (1):

$$r_v \arccos\frac{r_v - 2h}{r_v} + r_v \arccos\frac{r_v - h}{r_v} = S \tag{1}$$

The vertical radius would be in a range $r_v \sim \infty$. Taking $h = 8$ km, $S = 700$ km, by Eq. (1) the r_v can be calculated, $r_v = 5252$ km. It is close to the minimum curve radius 6530km when the acceleration is $1g$ and the launch speed is 8km/s (see Table 2). It means that this curve radius can meet all cases on the acceleration and the segment speed. It also means that in some cases, such as acceleration $2g$ and the segment speed 4km/s, a smaller radius is feasible. Thus it's not necessary to set the whole tube route in the vertical curve, namely the tube route partially in vertical curve is more reasonable (as shown in Fig. 1d).

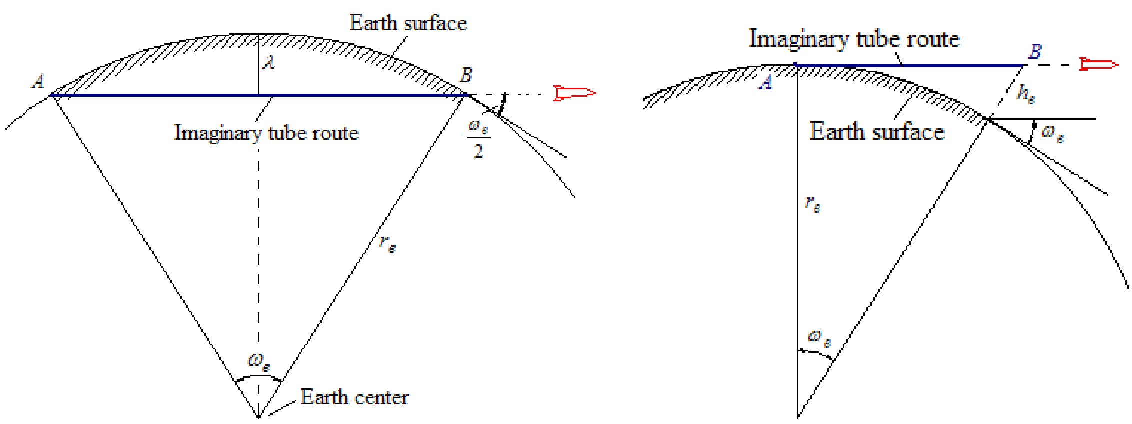
4.2 On the earth curvature

The tube length for ETM space launch system is very long, so the earth curvature shouldn't be neglected when paving the tube route. As shown in Fig. 2a, when the curve chord $\overline{AB}$ (imaginary tube position) is 700km, the chord distance to the earth surface is λ.

$$\lambda = r_e - \sqrt{r_e^2 - (\frac{700}{2})^2} = 6371 - \sqrt{6371^2 - 350^2} = 9.621\,\text{km},$$

The relative angle (launch angle) $\frac{\omega_e}{2} = \arcsin\frac{S}{2r_e} = \arcsin\frac{350}{6371} = 3.15^\circ$.

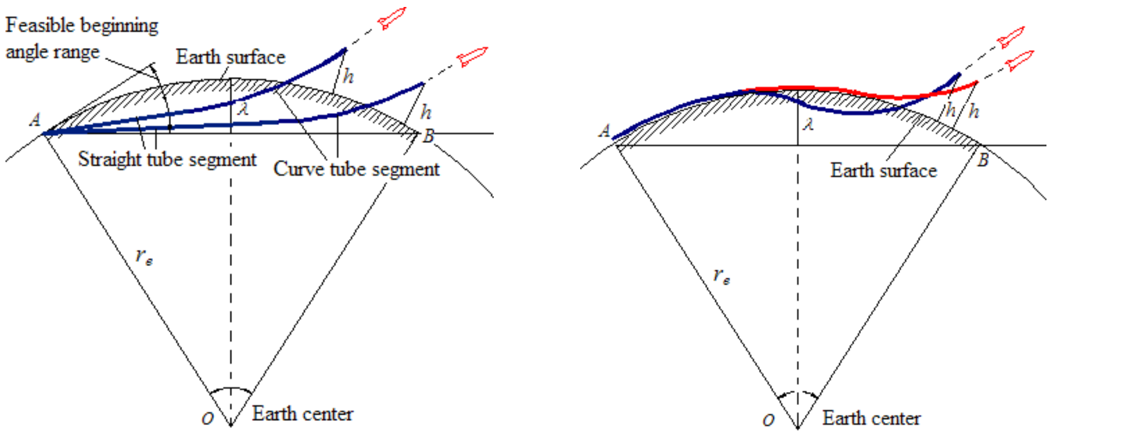
It means even if not setting vertical curve, a launch angle 3.15° could be attained only by the natural earth curvature. However, the embedding depth would be too big a little.



a. Tube route completely underground b. Tube route completely on ground

Fig. 2 Relation between the imaginary tube route and the earth curvature

As shown in Fig. 2b, supposing paving the tube route from the start point A along with the tangent direction of the earth surface and also no vertical curve in the whole tube route, then the height at the end B would be h_e. $h_e = \sqrt{r_e^2 + S^2} - r_e = \sqrt{6371^2 + 700^2} - 6371 = 38.34\,\text{km}$. Such an end height is apparently impracticable for engineering. Thus the reasonable layout should be as shown in Fig. 3.



a. Tube partially in curve b. Partial tube matching with the earth curvature

Fig. 3 Reasonable tube route layouts

Fig. 3a shows the feasible beginning angle range and two reasonable tube routes that each one includes both straight tube segment and curve tube segment. Fig. 3b shows other two feasible tube routes in which partial tube segments extend along with the earth surface.

It needs to be explained that the so called earth surface in Fig. 2 and Fig. 3 is not certainly the sea level. It is at the height from which the start point *A* (tube beginning point) is located.

5 Summary

By calculating and analyzing, the necessary tube route length and the reasonable minimum curve radius of the tube route in various work situations are suggested. Furthermore, some conclusions on the tube route layout of ETM space launch come out as follows:

(1) It is unreasonable to set the whole tube in a straight line completely (as shown in Fig. 1a). For the tube length is very long but the height at the tube end is small, so that a full straight tube would lead to a too small launch angle. It means the tube route for the space launch should always include vertical curves.

(2) Based on the engineering reason and the cost consideration, a single curve tube route (whole tube on a same circle) is also unreasonable.

(3) Because the tube route is very long, the affection of the earth curvature for tube engineering shouldn't be neglected. The reasonable tube routes are always in an area between the tangent and the chord of the earth both passing through the start point *A* (see Fig. 3) where the chord distance is decided by the maximum embedding depth λ.

(4) There are two basic tube route types in vertical direction. One is that the first segment is the straight and extends between the tangent and chord, and the second segment is in the upwards vertical curve (see Fig. 3a). Another is that partial tube route can extend along with the earth surface curvature (see Fig. 3b).

In the further research, the level layout of the tube route and the possible maximum launch angle should be studied.

References

[1] Y. P. Zhang, Evacuated tube transportation and vacuum industry development, Vacuum, Vol. 43 (2006) 56-59 (in Chinese)

[2] Y. P. Zhang, Y. Y. Li, Role and position of ETT in the future comprehensive transportation system, 2007 ICTEC, The American Society of Civil Engineers, ASCE(2007) 2796-2803

[3] Y. P. Zhang, J. Y. Yu, M. X. Shen, et al, Affecting factors and numerical value calculation relating to vacuumizing time in evacuated tube transportation, IFOST 2011, Harbin, China(2011)246-249.

[4] Y. P. Zhang, Evacuated tube transportation routes: go through overhead, on ground, shallow underground or deeply underground? CTEE 2012, Nanjing (2012) 287-292

[5] Information on http://www.et3.com

[6] P. James, M. George, P. John, Is NTP the key to exploring space? AEROSPACE AMERICA, ISSN 0740-722X, 2004

[7] P. James, M. George, R. John, Maglev Launch: Ultra Low Cost Ultra/High Volume to Space for Cargo and Humans, SPESIF-2010 - Space, Propulsion, and Energy Sciences International Forum February 23, 26, 2010

[8] Information on http://www.startram.com