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Lunar transportation scenarios utilising the Space Elevator

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Abstract

The Space Elevator (SE) concept has begun to receive an increasing amount of attention within the space community over the past couple of years and is no longer widely dismissed as pure science fiction. In light of the renewed interest in a, possibly sustained, human presence on the Moon and the fact that transportation and logistics form the bottleneck of many conceivable lunar missions, it is interesting to investigate what role the SE could eventually play in implementing an efficient Earth to Moon transportation system. The elevator allows vehicles to ascend from Earth and be injected into a trans-lunar trajectory without the use of chemical thrusters, thus eliminating gravity loss, aerodynamic loss and the need of high thrust multistage launch systems. Such a system therefore promises substantial savings of propellant and structural mass and could greatly increase the efficiency of Earth to Moon transportation.

This paper analyzes different elevator-based trans-lunar transportation scenarios and characterizes them in terms of a number of benchmark figures. The transportation scenarios include direct elevator-launched trans-lunar trajectories, elevator-launched trajectories via L1 and L2, as well as launch from an Earth-based elevator and subsequent rendezvous with lunar elevators placed either on the near or on the far side of the Moon. The benchmark figures by which the different transfer options are characterized and evaluated include release radius (RR), required Δv, transfer times as well as other factors such as accessibility of different lunar latitudes, frequency of launch opportunities and mission complexity. The performances of the different lunar transfer options are compared with each other as well as with the performance of conventional mission concepts, represented by Apollo.

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1. Introduction

In recent years the Space Elevator (SE) concept has been receiving an increasing amount of attention within the space community. In light of the renewed interest in a, possibly sustained, human presence on the Moon and the fact that transportation and logistics form the bottleneck of many conceivable

lunar missions, it is interesting to investigate what role the SE could eventually play in implementing an efficient Earth to Moon transportation system. The elevator allows vehicles to ascend from Earth and be injected into a trans-lunar trajectory without the use of chemical thrusters, thus eliminating gravity loss, aerodynamic loss and the need of high thrust multistage launch systems. Such a system therefore promises substantial savings of propellant and structural mass and could greatly increase the efficiency of Earth to Moon transportation.

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This paper discusses some basics of elevator-launched trajectories and investigates several basic scenarios for reaching the Moon utilizing SEs, based on both the Earth and the Moon. These scenarios are characterized and compared in terms of release radius (RR), required Δv, transfer times, lunar site accessibility and frequency of launch opportunity. It is intended to present some of the fundamental options available. Many of the variations and combinations possible, can be derived from the cases discussed here and deserve further investigation.

2. The Earth–Moon system

The Moon revolves around the Earth with a period of 27.3 days (angular velocity 13.2°/d) and a semimajor axis of 384,400 km. The lunar orbital plane (LOP) is inclined towards the ecliptic by 5.1° and its line of nodes rotates with a period of 18.6 years. This causes the LOP inclination relative to the Earth's equatorial plane (inclination to ecliptic 23.5°) to vary between 28.6°(23.5° + 5.1°) and 18.4°(23.5° − 5.1°) with the same period [1].

The Earth–Moon system has five points of equilibrium called Lagrangian points that are indicated in Fig. 1. For this topic especially the L1 and L2 points are interesting as they are vital to the construction of lunar elevators or offer themselves as staging points for lunar missions with and without the SE. L1 has a mean

distance of 57,900 km and L2 of 64,400 km from the center of the Moon [2].

The Moon's motion is tidally locked to that of the Earth, such that the same side of the Moon always faces the Earth, which is a prerequisite for the construction of lunar elevators (LE) running through L1 or L2.

3. Apollo type mission

The Apollo type mission concept shall serve as a conventional reference mission against which the different elevator based concepts may be compared. Just as the other scenarios only the upward leg of the trip will be discussed.

The major steps of the mission are as follows:

(a) Launch to parking in low Earth orbit (LEO).
(b) Trans-lunar injection from LEO.
(c) Coast phase with minor course correction maneuvers.
(d) Arrival and insertion into low lunar parking orbit (LLO).
(e) Powered descent to lunar surface.

Steps (a), (b), (d) and (e) constitute the major expenditure in Δv, while step (c) constitutes most of the travel time (~ 72 h) [3]. Table 1 shows the Δv values for the Apollo 16 flight.

The entire lunar surface is accessible by varying the inclination of LLO, which can be done through minor targeting maneuvers early in the trans-lunar trajectory.

Departure to the Moon from the Earth's surface via a short LEO parking orbit is usually possible twice
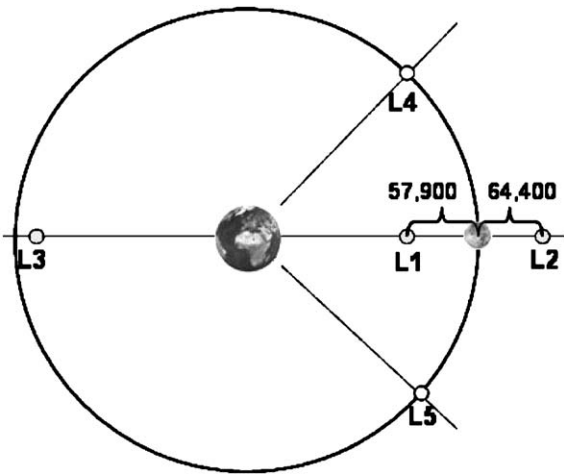

Fig. 1. Points of equilibrium in the Earth–Moon system.

Table 1
Δv requirements for Apollo 16 [3]

Maneuver	Δv (m/s)
Launch to LEO	$\sim 11,600$[a]
TLI	3050
Coast	(0)
LOI + circulization	850 + 90
Descent	2040
Total	17,630

[a]Burke J.D., 2004, pers. comm.

a day when the achievable LEO orbit is coplanar with the desired lunar transfer orbit. However, the frequency of access to a specific lunar site from LLO depends on its latitude. Near equatorial sites and near polar sites are almost continuously accessible from equatorial or polar lunar orbits, respectively. For intermediate latitudes there are two descent opportunities within 27 days provided the LLO inclination is higher than landing site latitude [4].

Similar phasing restrictions apply for ascent from the lunar surface and rendezvous with a return vehicle in LLO. Mentioned restrictions can be relaxed at the price of additional Δv expenditure, if plane changes in LLO are considered.

4. Basics of elevator-launched trajectories

Once a payload has been released from the SE the usual laws of orbital mechanics apply to any free flight transfer trajectory. However, there are important differences in dealing with classical rocket-powered trajectories (RPT) and elevator-launched trajectories (ELT) at the point of trajectory insertion.

  I. All elevator-launched trajectories lie in the equatorial plane of Earth.
 II. The two major insertion parameters, insertion altitude and insertion velocity, cannot be altered separately but rather are mutually dependent.
III. Any given insertion point is accessible every 24 h.
IV. The flight-path angle at insertion is zero.

All points are constraints narrowing down the solution space for ELT. While a fixed launch plane as stated in (I) is commonly encountered when calculating trajectories, (II) is fairly unfamiliar from calculating RPTs. Using rockets from a fixed initial altitude it is possible to attain any apogee altitude by varying the Δv applied during insertion. Likewise it is technically possible to control the velocity at a specific apogee by varying the eccentricity of the transfer trajectory, which is done by varying the insertion altitude and velocity. Usually an initial orbit is given and the Δv required for transferring to a specific target orbit is to be calculated. For ELTs the situation is quite different since the only parameter that can be varied is the release altitude, automatically also determining insertion velocity.

4.1. Apogee radius and apogee velocity

Injection altitude is the single parameter that automatically determines apogee altitude and apogee velocity. They can be derived as follows (radii from center of Earth are used instead of altitude).

We start with some equations describing any Hohmann transfer ellipse:

$$v^2 = \mu_E \left(\frac{2}{r} - \frac{1}{a} \right), \tag{1}$$

$$a = \frac{r_{apo} + r_{peri}}{2}. \tag{2}$$

Eq. (1) describes the velocity v in an elliptic orbit around Earth as a function of the radius vector r, where μ_E is the product of the gravitational constant and the mass of Earth and a is the semimajor axis of the specific orbit, which can be expressed in terms of its perigee r_{peri} and its apogee r_{apo} through (2). In (2) a can be substituted using (1) with values at perigee. In order to get a function of the release radius we substitute velocity at perigee v_{peri} through

$$v_{peri} = r_{rel} \omega_E, \tag{3}$$

where ω_E is the angular velocity of Earth (7.292970×10^{-5} rad/s) and r_{rel} is the release radius from the SE, which is equal to r_{peri}.

Rearranging and simplifying gives the following relation between release radius and apogee radius:

$$r_{apo} = \frac{2r_{rel}\mu_E}{2\mu_E - \omega_E^2 r_{rel}^3} - r_{rel}. \tag{4}$$

For the relation between release radius and apogee velocity v_{apo} we apply (1) to the point of apogee while substituting a and r_{apo} with (2) and (4) respectively, and get the following:

$$v_{apo} = \sqrt{\frac{4\mu_E^2 - 4r_{rel}^3 \omega_E^2 + r_{rel}^6 \omega_E^4}{r_{rel}^4 \omega_E^2}}. \tag{5}$$

With (4) and (5) we can calculate the following values for Hohmann orbits with their apogee in the vicinity of L1, L2, and lunar orbit. (Table 2)

Both (4) and (5) can also be solved for r_{rel} resulting in lengthy expressions with mostly complex

Table 2
Release radius and apogee speed for Hohmann transfer to L1, Lunar Radius and L2

	L1	Lunar	L2
Apogee (km)	326,400	384,400	448,900
Velocity at apogee (m/s)	573	493	427
Release radius (km)	50,630	50,960	51,240

Fig. 2. Apogee velocity and radius vs. release radius.

Fig. 3. Transfer time vs. target radius (Hohmann).

which the integration is performed.

$$\frac{mv_{esc}^2}{2} = \int_{r_{esc}}^{\infty} mg_0 \frac{R_E^2}{r^2}\, dr. \tag{6}$$

Since we are launching from the elevator $v_{esc} = r_{esc}\omega_E$ must apply. Substituting and solving for r_{esc} gives us

$$r_{esc} = \sqrt[3]{\frac{2g_0 R_E^2}{\omega_E}} \approx 53,100\, km. \tag{7}$$

4.3. Travel time

Total travel time (TTT) to a specific target orbit is composed of ascent time and free flight time (FFT). Using Hohmann transfers, travel time Δt_H is

$$\Delta t_H = \pi \sqrt{\frac{r_{rel}^3 \mu_E^2}{(2\mu_E - \omega_E^2 r_{rel}^3)^3}} + \frac{r_{rel} - R_E}{v_{asc}}. \tag{8}$$

The first term expresses the Hohmann transfer time, the second ascent time of the vehicle from Earth to release altitude. R_E is the radius of Earth and v_{asc} the ascent speed on the SE ($\sim 200\, km/h$ [5]). r_{rel} must be determined using (4). Fig. 3 shows how transfer time from Earths surface relates to different target radii for elevator-launched Hohmann transfers.

solutions, depending on the type of problem. Fig. 2 shows apogee radius and apogee velocity as functions of release radius.

The plot begins at a release radius of 42,200 km, which is the radius of geostationary orbit. Only payloads released above this point are placed on outward bound transfer trajectories. The upper boundary chosen is at a release radius of 51,500 km which takes a payload well beyond L2 at approx. 448,900 km.

4.2. Escape radius

The theoretical upper boundary for an elliptical orbit about Earth is the escape radius r_{esc}, i.e. the point at which a released payload is placed on an escape trajectory from Earth. The escape velocity v_{esc} can be calculated from Eq. (6), which states that for escape the kinetic energy of an object with mass m must be at least equal to its negative potential energy with respect to infinity. g_0 is the gravitational acceleration at ground level, R_E the radius of Earth and, r the radius over
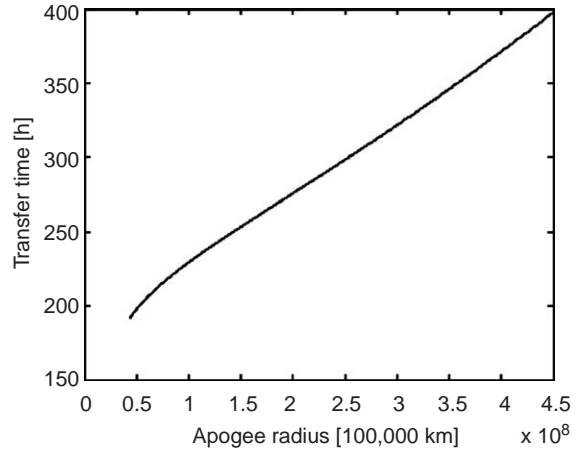
5. Direct elevator-launched lunar trajectory

This mission mode is the closest elevator based scenario to a conventional Apollo type mission. It makes use of the elevator for launch and TLI, but thereafter uses conventional propulsion to enter LLO and carry out a powered descent to the lunar surface.

Different shapes of trajectories for this case are shown in Fig. 4.

The problem of finding a suitable trajectory in this case presents itself as the problem of finding a combination of release radius r_{rel} and phase angle λ_1 at entry into the Moon's sphere of influence (SOI) that results in the desired perilune, while keeping both travel time and Δv for lunar orbit insertion (LOI) as small as possible. In this case a LLO of 120 km altitude was chosen, which is comparable to the lunar parking orbit of Apollo 16.

Solutions for the trajectory were investigated by using a 2-D patched conics approach [6], modified by introducing (3) to reflect the specific case of ELTs. An optimization algorithm was applied to find combinations of r_{rel} radius and λ which minimizes the required Δv while staying close to the desired perilune. Multiple runs with different starting values for r_{rel} and λ show that within a certain margin travel time, being a combination of ascent time and FFT to lunar SOI, can be reduced at the price of moderately higher Δv at LOI.

Table 3 shows the values for several different trajectories with a perilune of 122 km. The first two columns describe the trajectory in terms of release radius r_{rel} and point of entry into lunar SOI λ. Columns 3 and 4 show the Δv for LOI and the travel time (ascent time + coast time = TTT from surface to entry into lunar SOI). The fifth column shows the difference in
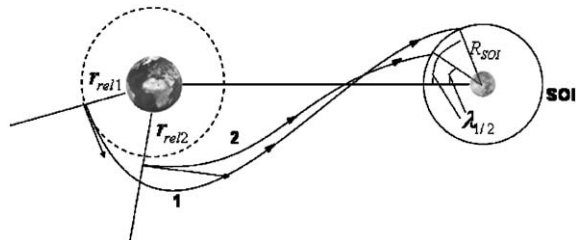
Table 3
Trans-lunar trajectories (perilune 122 km)

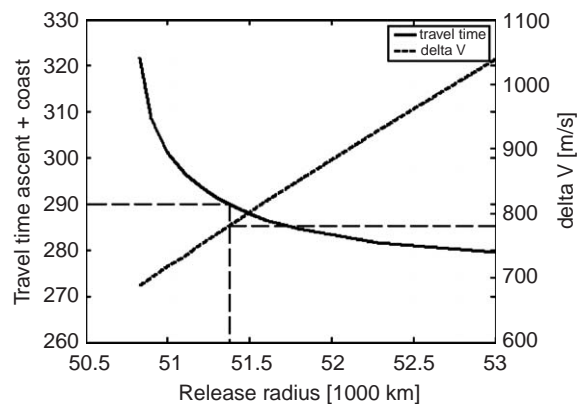| r_{rel} (km)	λ (°)	Δv LOI (m/s)	Δt (h)	$\Delta \theta$ (°)
50,830	51	690	222 + 99.5 = 321.5	171
51,000	36.5	717	223 + 78 = 301	161
51,400	27	785	225 + 64.5 = 289.5	152
51,800	22	851	227 + 58 = 285	148
53,000	15	1040	233 + 46 = 279	133

Fig. 5. Δv and time from surface to LOI vs. RR.

anomaly $\Delta \theta$ for the vehicle from release to entry into lunar SOI, and is an indication of the shape of the trajectory, e.g. for $r_{rel} = 50,830$ km, $\Delta \theta = 171°$ the vehicle follows a 'slow' low energy trajectory close to a Hohmann-type transfer ($\Delta \theta = 180°$).

Fig. 5 plots results for travel time and Δv at LOI over the RR. It illustrates how travel time can be reduced at the cost of Δv. This trade off seems effective upto a release radius of around 51,500 km (travel time $\sim$ 285 h), thereafter further increase of release radius and Δv only cause an increasingly marginal improvement. Broken lines indicate the example of the third trajectory shown in Table 3.

After LOI, Δv requirements for powered descent to the surface are comparable to those of Apollo ($\sim$ 2050 m/s).

Similar to a conventional RPT, it is possible to choose the inclination of LLO at will by means of minor impulsive maneuvers early in the trans-lunar
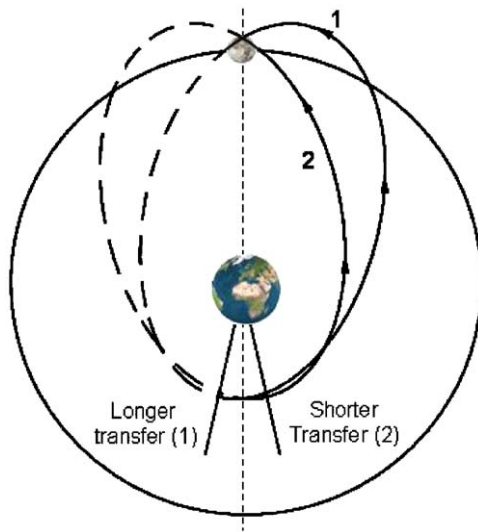

Fig. 4. Different transfer trajectories (1/2) dependent on release radii r_{rel1}/r_{rel2}.

Fig. 6. Transfer trajectories for correct timing of rendezvous with the Moon at intersection between TOP and LOP.

Fig. 7. Lunar elevators in the rotating Earth–Moon field of potential.

Fig. 8. Velocities at rendezvous with lunar elevator.

trajectory. Therefore on direct elevator-launched lunar trajectories all lunar latitudes are accessible.

In contrast to conventional missions, launch opportunities with the SE only occur approximately every 13.5 days. This is due to the fact that the launch plane (and thus the TOP) is fixed. Launch therefore is only possible when the Moon passes through Earth's equatorial plane, which it does twice per Sideric Month ($\sim$ 27.3 d). It is possible that the SE is up to 180° (or 12 h) away from the position required for injection into the Hohmann transfer orbit leading to rendezvous with the Moon as it passes through the equatorial plane. In this case, which is depicted in Fig. 6, it is necessary to launch from a greater altitude on a higher energy trajectory that either takes more (case 1) or less (case 2) time to reach the desired target at the desired time.

Phasing requirements in LLO are similar to conventional RPT missions.

6. Rendezvous with L1 and L2 elevators

The principal of lunar elevators (LE) is different from that of Earth-based elevators. The two different possibilities for installing lunar elevators are, an elevator that runs from the near side of the Moon towards Earth to some point beyond L1 (L1E) or an
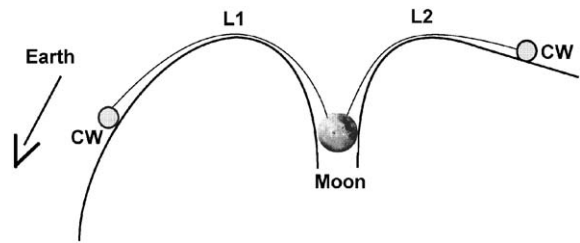
elevator anchored to the far side of the Moon and running out beyond L2 (L2E). Both are aligned with the radius from the center of Earth to the center of the Moon. The L1E is stabilized by a counter weight (CW) that is placed closer to Earth than L1 such that the sum of gravitational accelerations of Earth and Moon and centrifugal acceleration on it is directed towards Earth. Likewise the L2E relies on a CW placed beyond L2, generating a net force away from both the Earth and the Moon. Employing the analogy of gravity wells, Fig. 7 illustrates how the elevators are 'strung over' the two Lagrange Points, that constitute maxima in the rotating potential field of the Earth–Moon system.

Rendezvous with lunar elevators is an interesting option for lunar transfers because it does away with the maneuvers of LOI and powered descent to the surface, both of which are expensive in terms of Δv. If the rendezvous takes place sufficiently far away from the Moon so that the acceleration by the Moon can be neglected, the only expenditure in Δv is what is required to match the apogee velocity of the vehicle to the velocity of the LE at apogee radius. Assuming a Hohmann transfer, Fig. 8 illustrates the situation at the point of rendezvous which must be on the line of intersection between the lunar orbital plane (LOP) and the transfer orbit plane (TOP).

Table 4
Minimum Δv rendezvous with L1E

	18.4°	23.5°	28.6°
Minimum Δv (m/s)	225	285	345
Rendezvous radius (km)	261,250	261,050	260,740
Release radius (km)	50,102	50,100	50,097
Travel time (h)	919	$218.6 + 84.8 + 616.8 = 920.2$	921.5

Fig. 9. Rendezvous radius vs. Δv for L1E.

v_{lunar} is the velocity of the lunar elevator traveling in the LOP at the rendezvous radius. v_{apo} is the apogee speed of the vehicle traveling in the TOP (Earth equatorial plane). i is the inclination of both planes, which can range from 18.4° to 26.6°.

The Δv required can be described as

$$\Delta v = \sqrt{v_{\text{lunar}}^2 + v_{\text{apo}}^2 - 2 v_{\text{lunar}} v_{\text{apo}} \cos i}. \tag{9}$$

v_{lunar} can be expressed through:

$$v_{\text{lunar}} = \omega_{\text{M}} r_{\text{apo}}, \tag{10}$$

where ω_{M} is the angular velocity of the Moon. The velocities in (9) can be substituted through (10), (5) and (4), resulting in an expression for Δv that only depends on release radius r_{rel}. Numerically it is found that this function produces a minimum Δv of approx. 220 m/s for a release radius of 50,100 km with a corresponding rendezvous radius of 261,250 km, at an inclination of 18.4°. Table 4 shows minimum values and corresponding travel times for different inclinations.

The rendezvous radius of approximately 261,000 km shows that rendezvous with an L1E is more advantageous than with an L2E in terms of Δv requirements. Fig. 9 shows rendezvous Δv versus rendezvous radius for different inclinations.

The gradient in the vicinity of the Δv minimum is small enough to enable variations in rendezvous radius without too significant impact on Δv requirements, which allows finding a compromise between Δv and travel time.
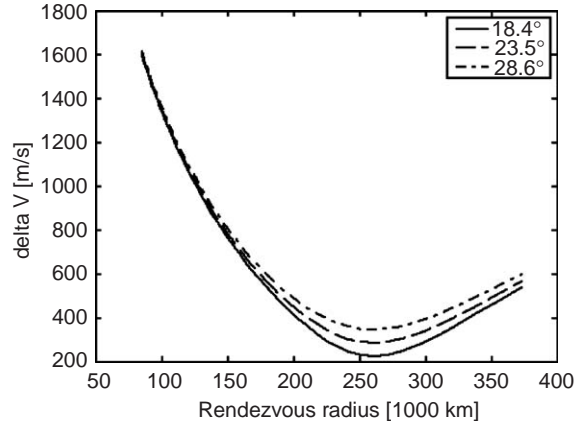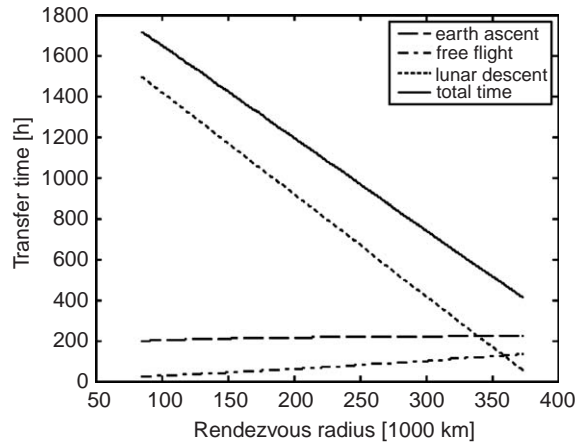

Fig. 10. Components of travel time via L1E.

The TTT for this mission mode can be described as:

$$\Delta t = \frac{r_{\text{rel}} - R_{\text{E}}}{v_{\text{asc}}} + \pi \sqrt{\frac{a^3}{\mu_{\text{E}}}} + \frac{r_{\text{lunar}} - R_{\text{M}} - r_{\text{apo}}}{v_{\text{asc}}}, \tag{11}$$

where R_{E} is the radius of Earth, r_{lunar} the radius of lunar orbit, R_{M} the radius of the Moon and v_{asc} is the speed of a climber along the elevator. The three terms represent the ascent time for the Earth-based elevator, the FFT, and descent time on the LE, in this order. a and r_{apo} can be substituted with (2) and (4). Fig. 10, which plots the relation of these three components as well as TTT over rendezvous radius, shows that the
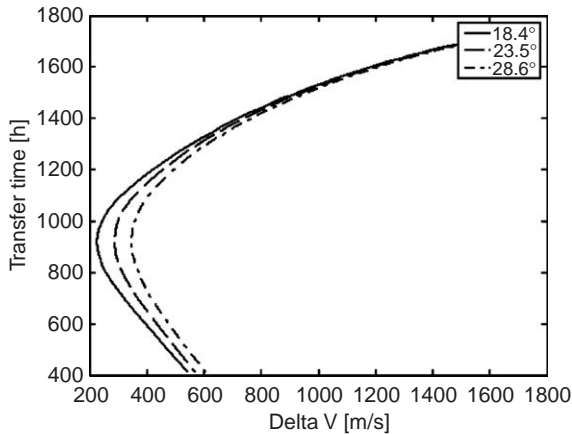
Fig. 11. Transfer times via L1E vs. Δv.

Table 5
Conventional vs. elevator-launched L1 mission

Δv L1 mission (m/s)	Conventional[a] (from LEO 185 km)	Elevator (Incl. 23.5°)
Injection to L1	3080	0
L1 rendezvous	710	420
Lunar descent	2500	2500
Total	6290	2920
Time (h)	$84 + 72 = 156$	$221 + 113 + 72 = 406$

[a]Hornik et al. [2].

Table 6
Conventional vs. elevator-launched L2 mission

Δv L2 mission (m/s)	Conventional[a] (from LEO 185 km)	Elevator (Incl. 23.5°)
Injection to L2	3149	0
L2 rendezvous	1230	830
Lunar descent	2500	2500
Total	6879	3330
Time (h)	$96 + 72 = 168$	$224 + 173 + 72 = 469$

[a]Hornik et al. [2].

lunar descent is the predominant component of the travel time and that it can be reduced significantly by raising the rendezvous radius.

Fig. 11 illustrates how transfer time can be slashed significantly for moderately higher Δv, e.g. from 920 h for 285 m/s to 630 h for 460 m/s.

For the lunar transfer via LE, only surface area in the vicinity of the LE anchor site is accessible, i.e. equatorial either on the near side or the far side.

Lunar elevators pass through the Earth's equatorial plane simultaneously with the Moon. Therefore, like to the Moon, launch opportunities to them occur approximately every 13.5 days.

In terms of travel time and Δv, rendezvous with an L2 elevator is best as low as possible on it. However if rendezvous occurs too close to the lunar surface, the maneuver is likely complicated by lunar acceleration. Therefore a rendezvous at L2 is assumed for later comparison of mission modes.

7. Elevator-launched trajectories via L1 and L2

Trajectories via one of the Lagrangian points L1 and L2 have been considered for traditional missions. They are mainly attractive because the entire lunar surface is accessible from them at any time, and Δv requirements are almost independent of landing site (~ 2.5 km) [2]. This makes the Lagrangian points interesting as staging points, because plane changes and phasing times for site access are avoided. Furthermore

station keeping requirements are small and a L2-orbit is a suitable position for far-side relay infrastructure. Also they are always open for return from the surface. These advantages must be weighed against higher Δv requirements and transit times.

However, an elevator launch eliminates the substantial Δv requirement for injection to L1/L2, e.g. 3080 m/s/3149 m/s from LEO [2]. What remains is the requirement for rendezvous with L1/L2 and lunar descent. The former can be calculated through (10) inserting the radii for L1 and L2, respectively. Tables 5 and 6 compare conventional and elevator-launched L1 and L2 missions, respectively, in terms of Δv and travel time. Travel time is shown as the sum of its components ascent time (only for elevator), FFT (Eq. (8)), and a common descent time (~ 72 h [2]).

Considering the fact that Δv requirements for all ELT are much smaller than for RLT, it is interesting to investigate whether travel time can be reduced at
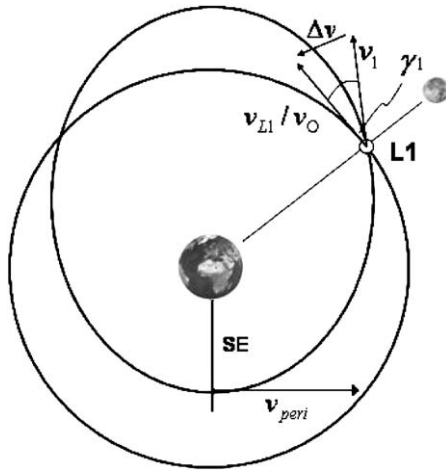
Fig. 12. Semitangential (higher energy) transfer.

Fig. 13. Travel time and Δv to L1 vs. release radius.

the cost of additional Δv compared to the Hohmann transfer, by following higher energy trajectories. While this is obvious for RLT, it is not always the case for ELT. Fig. 12 shows such a transfer for the case of a target radius at the distance of L1. The higher injection velocity is not relevant as it is provided by the SE. The Δv of interest is that required to change from transfer orbit velocity v_1 to the velocity of L1 v_{L1}. In case of a non-Lagrangian target orbit the normal circular orbit velocity v_O must be matched instead of v_{L1}. The approach is also applicable to rendezvous with LE.

Using a standard calculation for semitangential transfer [6] together with the SE specific characteristics (Eq. (3) and ascent time), the TTT and Δv can be calculated in relation to different release radii. Fig. 13 shows that TTT can be reduced at the expense of Δv. However, a minimum (i.e. at 280 h at a Δv of 1570 m/s) exists after which travel time increases despite an increase in total Δv.

This behavior can be explained by the combination of FFT and ascent time. Initially FFT drops rapidly because the slow part of the transfer ellipse near apogee is avoided, while the slow linear increase in ascent time is secondary. However, as the decrease in FFT flattens out near a release radius of 53,000 km, the slow increase in ascent time becomes predominant, resulting in an increase in TTT.

The same principle applies to trajectories via L2. Table 7 sums up the values for both cases. TTT is
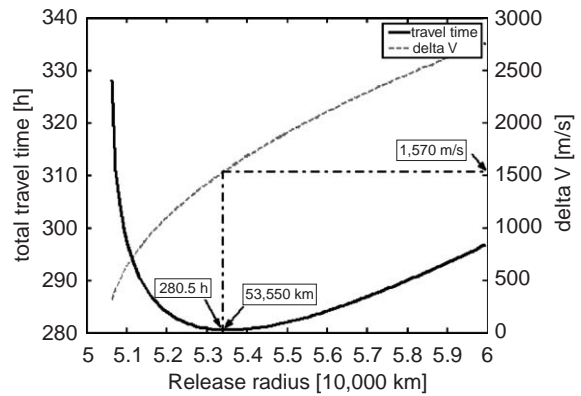
Table 7
Minimum time ELTs via L1 and L2

Minimum time Δv to L1/L2	ELT via L1 RR = 53, 550 km	ELT via L2 RR = 55, 320 km
Injection to L1	0	0
L1/2rendezvous	1570	1970
Lunar descent	2500	2500
Total	4070	4470
Time (h)	$236 + 44.5 + 72 = 352.5$	$245 + 55.5 + 72 = 372.5$

shown as the sum of ascent time, FFT to L1/L2 and descent time to lunar surface.

L1 and L2 pass through the equatorial plane with the Moon, making launch to them possible every 13.5 days.

8. Comparison of different mission modes

Table 8 summarizes the different investigated mission modes in terms of Δv requirements, total travel time, lunar surface accessibility, frequency of launch opportunities and phasing requirements. Conventional rocket-powered missions represented here by the case of Apollo 16, prove to have the

Table 8
Summary of different mission modes

	Δv (m/s)	Time (h)	Latitudes	Launch opportunities	Phasing
Apollo 16	17,630	98.5	Theoretically all	2/d	Yes
Direct ELT	2835	290	All	2/27d	Yes
ELT via L1 (min. Δv)	2920	406	All	2/27d	No
ELT via L1 (min. time)	4070	352.5	All	2/27d	No
ELT via L2 (min. Δv)	3330	469	All	2/27d	No
ELT via L2 (min. time)	4470	372.5	All	2/27d	No
ELT via L1E (min. Δv)	285	920	Equat. near side	2/27d	No
ELT via L1E reduced Δt	460	630	Equat. near side	2/27d	No
ELT via L2E rend. at L2	830	710	Equat. far side	2/27d	No

shortest TTT and to be the most flexible in terms of launch opportunities. However the Δv requirements are at least four times those of any elevator-launched mission mode, illustrating the substantial advantage that can be gained by using SE.

Out of the mission modes that only make use of the Earth-based SE, direct ELTs are best in terms of Δv and TTT. Depending on the desired lunar latitude, this must be weighed against the potentially higher phasing times of LLO staging as compared to staging at the Lagrangian points.

Unless staging at L2 is highly desirable as part of a far side communication infrastructure, trajectories via L2 appear to be inferior to other transfer options because of higher Δv and TTT. The same holds true for rendezvous with an L2 elevator as compared to an L1 elevator. The only scenario in which an L2 elevator appears to be justified is that of a far-side base or observatory at its anchor site.

Rendezvous with L1Es and L2Es require the lowest Δv and the longest TTT, which makes them suitable for unmanned cargo missions. However, a potentially serious drawback is that they are only suitable to support activities near the LE anchor sites. Moreover, the additional infrastructure required and the rendezvous with a tether in space add considerable complexity to these mission modes.

9. Conclusion

The basics of elevator-launched trajectories have been discussed and different scenarios for Earth to Moon transfer utilizing both terrestrial and lunar SE have been assessed in terms of Δv, travel time, lunar site accessibility, frequency of launch opportunity and phasing requirements. On these grounds they have been compared to each other as well as to a conventional lunar mission (Apollo 16).

All SE-based scenarios offer substantially reduced Δv requirements, while sharing the drawback of higher TTT.

This makes them attractive for cargo missions. In the case of human missions the advantage of lower Δv must be critically weighed against the disadvantages of longer travel time, such as radiation exposure (especially during the slow travel through the Van Allen Belt) and greater life support requirements. However, some of the drawbacks can possibly be mitigated if the SE can succeed in substantially reducing the importance of mass constraints for space missions. In this case additional mass allowance can be used towards improved shielding and life support as well as to reduce travel time, through added propulsive performance.

The investigated scenarios are not exhaustive in detail or in type, but rather are meant to stake out some of the basic possible options in utilizing SEs to reach the Moon. Many combinations and variations as well as completely different options are conceivable. Examples may include employing additional propulsive maneuvers at or after launch from the SE or partially descending LEs and then detaching for greater landing site range. Also return strategies will have to be evaluated, e.g. conventional reentry vs. elevator descent.

The advantages of elevator-based missions come at the, yet to be determined, price of putting in place the SE infrastructure. Therefore the SE will, likely, only

be justified for long-term large-scale space activities. If this is the nature of a lunar engagement however, the SE promises to be a very valuable component of an efficient Earth to Moon transportation system. As with any investment in infrastructure, the return of an SE will increase with scale and duration of its use.

The SE is a technology that deserves consideration for the future, despite substantial technical challenges, as it can play a vital role in supporting a sustainable human expansion into space, both to the Moon and elsewhere.

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