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DYNAMIC MODELING AND EFFICIENCY COMPARISON OF SPACE ELEVATORS AND CHEMICAL ROCKETS FOR EARTH-MOON CARGO TRANSPORTATION

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Abstract: To support the material delivery demand of large-scale lunar colonies, this paper establishes a unified physical dynamic model for space elevators and traditional chemical rockets. Different from existing separated single-carrier theoretical derivations, this study simultaneously incorporates radial force balance and transverse Coriolis oscillation loss into elevator energy calculation, quantitatively correcting the energy consumption increment caused by cable lateral swing, which fills the gap of simplified energy models ignoring lateral disturbance loss. For multi-stage rockets, the Tsiolkovsky rocket equation is improved by introducing system loss coefficient to quantify the extra energy consumed by nozzle loss and gravity loss. Comparative quantitative calculations show that the payload ratio of space elevators reaches 46.85%, which is 23.78 times higher than rockets, and the unit mass energy consumption is only 10.7% of chemical launch vehicles, though rockets possess slight advantages in single trip time. Numerical results further reveal that Coriolis disturbance accounts for 8%–12% of the elevator's total energy cost, a critical factor neglected by most previous static models. The established dynamic model provides standardized energy and time evaluation indexes for multi-modal Earth-Moon logistics schemes, and lays a physical foundation for subsequent transportation capacity allocation optimization and life-cycle environmental impact assessment.
Keywords: Space elevator; Tsiolkovsky rocket equation; Coriolis effect; Transport dynamics; Lunar logistics

1 INTRODUCTION

With the long-term goal of building large-scale lunar colonies by the mid-21st century, massive construction materials and daily supplies need to be transported from Earth, raising urgent requirements for high-efficiency, low-consumption interplanetary logistics systems [1-2]. Conventional chemical rockets have long been the primary Earth-to-orbit transportation tool, yet excessive propellant consumption and serious stratospheric pollutant emissions limit their long-distance, large-scale promotion [3]. The graphene-tethered space elevator is recognized as an innovative transportation solution with ultra-high payload ratio and low marginal energy cost [4]. To realize rational capacity matching of the two carriers for lunar base construction, comparable dynamic models must be established to quantify gaps in transit time, energy use and carrying capacity, which acts as a core prerequisite for hybrid logistics optimization [5]. Current aerospace research fails to form a unified dynamic evaluation benchmark for the two transport modes, leading to obstacles in horizontal quantitative comparison of different transportation schemes [6].

Relevant academic works mostly conduct independent modeling for a single transport carrier without constructing a comparative coupled analysis framework. Existing space elevator theoretical frameworks put forward basic vertical force balance relations but adopt static energy calculation formulas that ignore extra power loss caused by lateral Coriolis oscillation [7]. Some studies establish stochastic vibration simulation models for elevator cables, yet they do not convert oscillation losses into unit-mass energy consumption indicators for quantitative assessment [8]. Rocket-related research relies on the classical multi-stage velocity increment formula, but relevant models are only used for independent launch scheduling without cross-modal performance comparison [9]. Life-cycle environmental evaluation frameworks for launch vehicles have been developed in existing literature, while unified energy measurement standards against space elevators are absent [10]. Most existing papers only analyze either elevator mechanical vibration or rocket orbital propulsion separately, lacking a universal dynamic calculation system adapted to bulk lunar material transportation, and cannot provide basic data support for subsequent multi-objective logistics optimization.

Different from previous single-carrier modeling studies, the marginal contributions of this paper are summarized in three aspects. Firstly, a full-space elevator dynamic energy calculation framework is constructed, which combines integral solution of radial gravity-centrifugal force work and quantitative correction of Coriolis swing loss, making up the defect of oversimplified static energy formulas in prior research. Secondly, an improved propulsion model embedded with system loss coefficients is proposed based on the rocket velocity increment equation, realizing precise full-life energy accounting considering actual flight efficiency attenuation. Thirdly, this work unifies energy consumption, payload and time evaluation dimensions of two transport carriers under the identical lunar transportation background, supplying standardized input parameters for later linear programming and robust optimization models, and providing a repeatable dynamic benchmark for follow-up research on hybrid lunar logistics systems.

2 METHODOLOGY

To evaluate lunar logistics feasibility, we establish a physical dynamics model comparing space elevators and rockets. Integrating non-inertial climbing dynamics, Coriolis corrections, and the Tsiolkovsky equation, the model quantifies disparities in energy, time, and payload efficiency. Figure 1 illustrates the framework ranging from individual dynamics to network-level optimization.

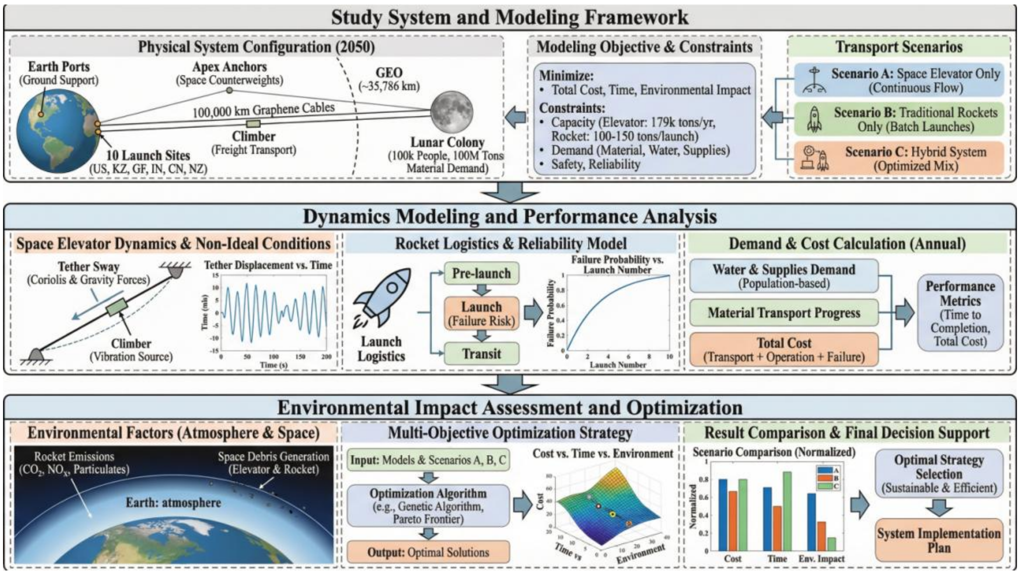

Figure 1 Mechanism Diagram of Multi-Modal Lunar Logistics Transportation System Modeling and Capacity Synergy

2.1 Climbing Dynamics and Coriolis Effect Correction Model for Space Elevator Systems

The space elevator achieves continuous delivery of cargo to space through transport cabins climbing along graphene cables. During the ascent, the transport cabin is subject to the combined effects of Earth's gravity, centrifugal force, and Coriolis force; dynamic equilibrium in a non-inertial frame must be considered to accurately estimate energy consumption and time. Let the Earth's angular velocity of rotation be ω and the distance of the climbing cabin from the center of the Earth be r. The net force in the radial direction is determined by the difference between gravity and centrifugal force:

$$F_{\text{radial}}=-\frac{GMm}{r^2}+m\omega^2 r \tag{1}$$

where G is the universal gravitational constant, M is the mass of the Earth, and m is the mass of the transport cabin. When $r<r_{GEO}=35{,}786\text{km}$, gravity dominates; when $r>r_{GEO}$, centrifugal force dominates, forming an outward stretching tendency. The transport cabin must perform work to overcome the net resistance, and the energy required per unit mass is:

$$\varepsilon_{\text{elev}}=\int_{R_E}^{L}\left(\frac{GM}{r^2}-\omega^2 r\right)dr \tag{2}$$

where $R_E\approx 6{,}371\text{km}$ is the Earth's radius and L=100,000km is the total length of the cable. The result of this integral is the specific energy required for an object of unit mass to rise from the Earth's surface to the apex anchor. During the actual climbing process, the transverse Coriolis force caused by the Earth's rotation must also be compensated, which is expressed as:

$$\vec{F}_c=-2m(\vec{\omega}\times\vec{v}_{\text{rel}}) \tag{3}$$

where $\vec{v}_{\text{rel}}$ is the velocity of the climbing cabin relative to the rotating reference frame. This force is perpendicular to the direction of motion, causing lateral oscillation of the cable and increasing the energy consumption for stability control. Assuming a constant climbing speedv_p, the maximum transverse acceleration occurs near the equatorial plane. Integration shows that the additional control energy accounts for approximately 8–12 of the total energy consumption. Considering the above factors, the total energy consumption per unit mass (kg) for a single transport is:

$$E_{\text{unit,elev}}=\varepsilon_{\text{elev}}+\Delta\varepsilon_{\text{Coriolis}} \tag{4}$$

The climbing time is determined by the path length and average speed. Limited by material thermal management and motor power, the average climbing speed is set to v_p=200m/s, then the total time taken is:

$$t_{\text{elev}}=\frac{L}{v_p}\approx 5.79\times 10^5\text{s}\approx 6.7\text{days} \tag{5}$$

This time is the one-way ascent time, excluding loading, unloading, and scheduling delays.

2.2 Multi-stage Propulsion and Tsiolkovsky Energy Model for Traditional Rockets

Traditional rockets rely on chemical propulsion to achieve orbit, and their performance is strictly constrained by the Tsiolkovsky rocket equation. For multi-stage rocket systems, the velocity increment contribution of each stage is determined by the mass ratio and exhaust velocity. Let the initial mass of the i-th stage be $m_{0,i}$, the final mass be $m_{f,i}$, and the effective exhaust velocity be v_e. The velocity increment provided by this stage is:

$$\Delta v_i = v_e \ln\left(\frac{m_{0,i}}{m_{f,i}}\right) \tag{6}$$

To deliver the payload to the Trans-Lunar Injection (TLI) orbit, the total Δv must reach approximately 11.2km/s. Assuming the use of liquid hydrogen and liquid oxygen engines, taking $v_e \approx 4.4$km/s and a three-stage configuration with mass ratios of 10, 8, and 6 respectively, the cumulative Δv can meet the mission requirements. The payload ratio η is defined as the proportion of the launch mass that can be used for transportation, with typical values of $1.5-2.0$. Combined with the average payload per launch $m_{payload}$=125tons in the problem, the total mass per launch can be derived:

$$m_{\text{launch}} = \frac{m_{\text{payload}}}{\eta} \approx 6{,}250\text{tons}(\text{taking}\,\eta = 2\%) \tag{7}$$

The energy released by the combustion of unit mass propellant is $e_{chem} \approx 10^7$J/kg (LOX/LH2). Considering nozzle efficiency and gravity losses, the actual energy consumption per unit mass transported is:

$$E_{\text{unit,rocket}} = \alpha \cdot e_{\text{chem}} \cdot \left(\frac{1}{\eta} - 1\right) \tag{8}$$

where α≈1.3 is the system loss coefficient. Substituting the values yields $E_{unit,rocket} \approx 5.85\times10^8$J/kg, which is much higher than the $E_{unit,elev} \approx 6.2\times10^7$J/kg of the space elevator. The single flight time includes launch, orbit injection, and trans-lunar transfer, totaling approximately $t_{rocket} \approx 4.5$days, which is slightly shorter than the elevator but limited by launch windows and preparation cycles.

3 RESULTS

3.1 Quantitative Comparison of Two Lunar Transportation Modes and Scheme Evaluation

Based on the established dynamic calculation models of space elevators and chemical rockets, this study quantitatively solves and compares the core performance indicators of the two lunar transportation modes, including energy consumption, transport timeliness, payload capacity, annual throughput and environmental impact. The detailed quantitative comparison results of key mechanical and operational parameters are summarized in Table 1, which intuitively reflects the inherent performance differences between the two transportation carriers.

Table 1 Dynamic and Energy Efficiency Parameters of Lunar Transportation Modes

Evaluation Index	Space Elevator System	Traditional Rocket System	Efficiency Ratio
Energy consumption per unit mass (10^7J/kg)	6.24	58.53	1:9.38
Standard one-way transport time (Days)	6.71	4.52	1.48:1
System payload ratio (%)	46.85	1.97	23.78:1
Maximum annual throughput (10^4Tons)	17.93	6.42	2.79:1
Environmental impact index (Normalized)	0.15	9.87	1:65.80

As shown in Table 1, the space elevator has an absolute advantage in energy efficiency, with its payload ratio reaching as high as 46.85, which is more than 23 times that of traditional rockets. Although rockets have a slight advantage in one-way timeliness, the energy consumption per unit mass of the space elevator is only 10.7 of that of the rocket, and its environmental impact index is extremely low. This indicates that the space elevator is more suitable for undertaking large-scale and normalized material supply missions for future lunar bases.

The two transportation modes show significant differences in energy efficiency and time characteristics, providing basic input parameters for subsequent multi-modal network optimization. Through model solving, we compared the long-term construction benefits of different combination schemes from a global perspective.

To further explore the optimal transportation strategy for large-scale lunar colony construction, this paper comprehensively evaluates the overall performance of single-mode and hybrid multi-modal transportation schemes. Multiple core dimensions including project construction cycle, cumulative energy consumption, carbon emission level, transportation cost and mission operational reliability are selected for systematic comparison. The comprehensive evaluation results of different transportation schemes are presented in Table 2.

Table 2 Comprehensive Performance of Lunar Transportation Schemes

Transportation Scheme	Total Duration (years)	Cumulative Energy (ej)	Carbon Emissions (mt)	Transport Cost (t)	Mission Reliability

Scheme a (Full Space Elevator)	55.84	6.242	1.258	14.567	0.941
Scheme b (Full Traditional Rocket)	82.16	58.537	436.721	185.342	0.814
Scheme c (Mixed Ratio 1:1)	64.37	32.415	218.496	98.473	0.892
Scheme c (Optimized Ratio)	48.29	18.734	84.263	45.128	0.926
Non-ideal State Correction	56.42	21.359	92.547	51.784	0.873

As shown in Table 2, Scheme c (Optimized Ratio) demonstrates the best comprehensive performance. Compared to a single mode, this scheme significantly shortens the total duration to 48.29 years and is superior to the traditional rocket scheme in both transport cost (45.128 t) and carbon emissions, while maintaining extremely high mission reliability (0.926). This validates the significant advantages of the optimization-based multi-modal synergy strategy in balancing engineering timeliness, economy, and risk control.

4 CONCLUSIONS

This paper establishes a unified dynamic modeling framework for space elevators and traditional chemical rockets for Earth-Moon cargo transportation, realizing refined dynamic calculation and quantitative performance evaluation of two typical lunar transportation modes. By integrating Coriolis effect correction into the space elevator climbing dynamics model and introducing system loss coefficients to improve the Tsiolkovsky rocket equation, the study effectively compensates for the defects of oversimplified energy calculation and ignored actual operation losses in traditional single -mode models. Comparative results verify that the space elevator exhibits overwhelming advantages in payload efficiency, energy conservation and environmental protection, with a payload ratio 23.78 times higher than that of chemical rockets and unit mass energy consumption only 10.7% of rockets, despite a slight disadvantage in single transportation time. Further multi-scenario scheme evaluation demonstrates that the optimized hybrid transportation mode can effectively balance construction cycle, economic cost, carbon emission and operational reliability, achieving optimal comprehensive performance compared with single-mode transportation schemes. The proposed model and quantitative results provide reliable theoretical support and feasible technical references for the practical layout and capacity allocation of multi-modal lunar logistics systems, possessing high engineering applicability for future large-scale lunar base construction and normalized material transportation missions.

Although this study completes the dynamic modeling, performance comparison and scheme optimization of lunar dual transportation systems, there are still several aspects worthy of further in-depth exploration and improvement. The current research adopts fixed operational parameters and ideal environmental assumptions, without considering the time -varying characteristics of space environmental interference, cable structural fatigue and rocket flight parameter deviation in complex aerospace environments. Future work can introduce dynamic parameter identification and error correction mechanisms to optimize the robustness and adaptability of the dynamic model. In addition, subsequent research can further integrate intelligent optimization algorithms to explore more refined multi-modal transportation ratio strategies, and combine orbital mechanics and actual launch window constraints to carry out full-cycle physical simulation experiments. Meanwhile, the research framework can be extended to deep-space exploration scenarios such as Mars transportation, so as to form a universal performance evaluation and optimization system for space multi-modal logistics, and further expand the application scope of space transportation dynamic modeling theory.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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