Mechanical Advantage of Electromagnetic Railgun for Space Launch Assist

Felipe A. Wescoup, PE

2320 Point Star Drive

Arlington TX 76001

Abstract

Space launch has traditionally relied on vertical rocket systems that must overcome Earth's gravity while carrying their entire propulsion system and fuel load from ground level. This paper presents analysis of a horizontal electromagnetic rail launch system for space launch assist, examining its mechanical advantage for winged launch vehicles. Unlike traditional rocket designs where minimizing mass is paramount, this concept benefits from concentrating significant mass behind a minimal forward-facing profile, fundamentally changing the optimization approach. The mechanical advantage increases non-linearly with launch velocity, suggesting rail-assisted launch could enable more efficient space access. The SpaceX Starship and Super Heavy configuration was used as a reference case to quantify these benefits.

1.0 Introduction & Purpose

The challenge of achieving orbital altitude and velocity has traditionally been addressed through vertical launch systems that must overcome both Earth's gravity and atmospheric drag while carrying their entire propulsion system and fuel load from ground level. This paper presents an analysis of an alternative approach: using a horizontal electromagnetic rail launch system to impart initial velocity to a winged rocket design.

Unlike traditional rocket designs where minimizing mass is paramount, this concept benefits from concentrating significant mass behind a minimal forward-facing profile. Once initial velocity is provided by the rail system, a higher mass-to-drag ratio enables better conservation of this kinetic energy through the atmosphere, fundamentally changing the optimization approach from conventional rocket design.

The primary purpose of this paper is to quantify the mechanical advantage provided of such a horizontal rail launch system. Specifically, this analysis quantifies the reduction in required takeoff mass and fuel load that could be achieved by imparting initial velocities ranging from Mach 1 to Mach 5 to a modified Starship/Super Heavy configuration. While the engineering challenges of constructing such a system are significant, this analysis focuses solely on establishing the theoretical benefits from an energy and mass perspective.

This paper presents the mechanical advantage of using horizontal rail-assisted launch as an alternative approach to space access. The analysis demonstrates that significant reductions in launch mass and fuel requirements are theoretically possible, potentially enabling increased payload capacity.

2.0 Concept Overview

Picture a modified SpaceX Starship and Super Heavy configuration, positioned on a horizontal rail system stretching several kilometers across the landscape. The launch is initiated by applying power to the electromagnetic rail system which provides all the energy required to achieve initial launch velocity. The spacecraft accelerates smoothly along the track, its streamlined profile and partially retracted delta wings minimizing air resistance. Upon reaching launch velocity, the spacecraft lifts from the track, and its rocket engines ignite.

The partially retracted delta wings generate lift, adding a vertical component to the spacecraft's velocity and creating an elegant S-curve ascent. In the dense lower atmosphere, the rocket engines primarily maintain the spacecraft's initial velocity. As the spacecraft climbs into thinner atmosphere, it begins to accelerate. Approaching orbital altitude, it levels off into a horizontal trajectory. After reaching the target altitude but before achieving orbital velocity, the Super Heavy booster separates from Starship. Starship continues to accelerate in the near-vacuum of space until reaching orbital velocity, while the booster begins its return trajectory.

Upon reentry, Starship’s delta wings extend fully to provide atmospheric drag, controlling the spacecraft's descent. Starship, now functioning as a space plane, completes its mission with a conventional landing on a traditional runway.

2.1 Fundamental Design Principle

A key principle that distinguishes this concept from traditional rocket design is its approach to mass optimization. In conventional rocketry, minimizing takeoff mass is crucial because the vehicle must overcome gravity with pure rocket power from ground level. This leads to careful optimization of mass fractions and fuel ratios. However, the horizontal rail launch concept fundamentally changes this paradigm.

For this concept, concentrating significant mass behind a minimal forward-facing profile becomes advantageous. This principle is governed by the relationship between drag force and kinetic energy:

- Drag force is proportional to the cross-sectional area and velocity squared: $F_d \propto A * v^2$
- Kinetic energy is proportional to mass and velocity squared: $KE = \frac{1}{2}mv^2$
- For a given velocity and cross-sectional area, increasing mass improves the energy-to-drag ratio

Once the rail system provides initial velocity, preserving this velocity through the atmosphere becomes the primary challenge. A higher mass-to-drag ratio enables better conservation of kinetic energy - similar to how a heavy projectile maintains its velocity better than a light one with the same profile. This principle influences every aspect of the vehicle design, from the aerodynamic profile to structural choices. Rather than pursuing maximum mass reduction at all costs, the design optimizes for maintaining kinetic energy through the atmosphere, fundamentally changing the approach to space launch vehicle design.

2.2 Vehicle Design

The proposed system utilizes a winged variant of the SpaceX Starship and Super Heavy configuration. A key design element is the retractable delta wing system, which provides several advantages across different flight phases:

- During rail launch and initial ascent, minimal wing area is deployed to enable the S-curve ascent profile
- During reentry and landing, the wings can extend to provide additional surface area for atmospheric deceleration and conventional runway landing
- The retractable design maintains aerodynamic efficiency while providing flight profile flexibility

Building on our fundamental principle of maximizing the mass-to-drag ratio, the additional mass of the retractable wing system actually improves overall efficiency by concentrating more mass behind the minimal forward-facing profile. This approach optimizes efficiency when dealing with atmospheric drag at high velocities, similar to principles employed in high-speed rail and ballistics.

2.3 Rail System Configuration

The purpose of this paper is to demonstrate the fundamental mechanical advantage of the electromagnetic rail launch system and not to determine the optimal length(s) for rail launch systems. However, multiple configurations could accommodate different payload types and acceleration tolerances:

- Short rail (~2 km) for high-g, non-human payloads
- Medium rail (~10 km) for professional astronauts (maximum 6g)
- Long rail (15-30 km) for space tourists (maximum 4g)

The optimal length for each configuration would need to be determined.

The track design eliminates bends and grade changes, unlike conventional high-speed rail systems. For velocities below Mach 1, proven high-speed rail technology can be adapted. For higher velocities, maglev or air bearing systems could be employed to reduce friction.

2.4 Flight Profile

The launch profile consists of several distinct phases:

1. Horizontal acceleration along the rail system to initial velocity
2. Transition to atmospheric flight with an S-curve ascent profile
3. Atmospheric flight phase where the vehicle primarily maintains velocity rather than accelerating
4. Exoatmospheric phase where the vehicle accelerates to orbital velocity

This profile offers several advantages over traditional vertical launches:

- More efficient use of initial kinetic energy
- Reduced propulsion requirements during atmospheric flight
- Potential for fewer rocket engines due to reduced thrust requirements
- Greater operational flexibility

2.5 Safety Considerations

The horizontal launch approach has potential abort scenarios not possible with traditional vertical launches. In the event of a system failure during or immediately after rail launch, the vehicle can utilize its wings to operate in the atmosphere and land at a conventional runway. This inherent safety feature eliminates the need for complex launch escape systems typical of vertical launch vehicles.

2.6 Engineering Challenges

While numerous engineering challenges exist, two obvious challenges related to launching a space vehicle at high speeds at low altitude are thermal management and structural design. Below are some proposed potential solutions:

Thermal Management

- Oil extruder systems on leading edges
- Advanced designs incorporating air bubble formation on leading edges

Structural Design

- More robust structural design
- Integration of retractable wing mechanisms
- Optimization of mass distribution for aerodynamic efficiency

The additional weight of these systems improves the mass-to-drag ratio, which is the fundamental key principle of this paper.

3.0 Summary of Findings

This analysis quantifies the mechanical advantage of rail-assisted launch through a progressive series of calculations, starting with basic orbital energy requirements and culminating in potential mass reductions for the launch system.

The SpaceX Starship and Super Heavy configuration was selected for this analysis due to the availability of public data on mass, fuel capacity, and engine performance. This allows for calculations to demonstrate the mechanical advantage of the rail launch concept.

3.1 Analysis Method

The analysis employs two fundamental equations:

1. Mechanical Energy Equation:
    - ○ Total Mechanical Energy = Kinetic Energy + Potential Energy
    - ○ KE = (1/2) * Mass * Velocity^2
    - ○ PE = Mass * Gravitational Acceleration * Height
2. Rocket Equation:
    - ○ Δv = EV * ln(initial mass/final mass)
    - ○ Where EV is exhaust velocity and Δv is change in velocity

3.2 Analysis Progression and Results

3.2.1 Orbital Energy Requirements

Solution 1 establishes the baseline energy requirement to place Starship with payload into a 300 km orbit, calculating both the kinetic and potential energy components. This provides the target energy state for successful orbital insertion.

3.2.2 Initial Rail Launch Analysis

Solution 2 evaluated launching just Starship with payload at Mach 3, demonstrating that while technically feasible, this configuration provides minimal mechanical advantage. This led to examining the full-stack launch concept.

3.2.3 Full-Stack Launch Energy Analysis

Solution 3 analyzed launching the complete Starship and Super Heavy configuration at various velocities (Mach 1-5), revealing that:

- Mach 3 launch provides approximately 40% of required orbital energy for Starship
- Mach 3.5 provides over 50% of required orbital energy for Starship
- Mach 5 provides more than the total required orbital energy for Starship

This solution compares the launch kinetic energy of the entire Starship and Super Heavy configuration to the required orbital energy for just Starship with payload, as calculated in Solution 1. In traditional vertical launch systems, achieving orbital energy requires carrying and accelerating all the necessary fuel from ground level. With rail launch, a significant portion of the required energy is provided externally by the rail system rather than being carried as fuel.

3.2.4 Mass Reduction Analysis

Solution 4 quantifies potential mass reductions for the launch system using the rocket equation and rail launch initial conditions. This analysis demonstrates how providing initial velocity through the rail system fundamentally changes the vehicle's mass requirements:

- At Mach 3: 41% reduction in takeoff mass
- At Mach 4: 51% reduction in takeoff mass
- At Mach 5: 58% reduction in takeoff mass

While these calculations demonstrate significant potential mass reductions, they should be viewed primarily as indicators of the system's improved launch efficiency rather than targets for mass optimization. Unlike traditional rocket design where minimizing mass is paramount, the rail launch concept actually benefits from concentrating more mass behind a minimal forward-facing profile. The real advantage of this improved efficiency is not in reducing mass, but rather in the potential to lift substantially greater payloads to orbit while maintaining a favorable mass-to-drag ratio.

3.3 Key Conclusions

1. Rail-assisted launch of the full stack (Starship + Super Heavy) provides significant mechanical advantage, particularly at velocities of Mach 3 and above.
2. The potential mass reductions are substantial enough to justify further engineering development of the concept, with Mach 3 offering an optimal balance between mechanical advantage and technical feasibility.
3. The relationship between launch velocity and energy contribution is non-linear due to the velocity-squared term in kinetic energy, making even small increases in launch velocity particularly valuable.
4. The analysis suggests that an electromagnetic rail launch system could fundamentally change the mass and fuel requirements for achieving orbit, potentially enabling more efficient space access.

Appendix A: Calculations

Felipe Wescoup
wescoup@gmail.com
1/5/2022

MECHANICAL ADVANTAGE OF ELECTROMAGNETIC RAILGUN
Based on SpaceX Starship with payload and Super Heavy Rocket

Required:

1. Calculate the mechanical energy required to put SpaceX Starship with payload into orbit.
2. Calculate the mechanical energy at launch if Starship with payload is launched at Mach 3.
3. Calculate the mechanical energy at launch if Starship with payload plus Super Heavy Booster are launched at Mach 1, 2, 3, 3.5, 4, 5.
4. Estimate the takeoff mass of a Reduced Super Heavy Booster and Starship with payload launched at Mach 3. Includes a table estimating the takeoff mass and fuel mass of a Reduced Super Heavy Booster and Starship with payload launched at Mach 1, 2, 3, 3.5, 4, 5.

Method:

1. Energy Equation:

   Mechanical Energy (ME) = Kinetic Energy (KE) + Potential Energy (PE)

   where,

   KE = (1/2) * Mass * Velocity^2
   PE = Mass * Gravitational Acceleration * Height

   At launch, Height is assumed to be 0; therefore PE = 0 and ME = KE.

2. Rocket Equation:

   change in velocity (V_f - V_o) = exhaust velocity (EV) * ln (initial mass (M_o)/ final mass (M_f))

Definitions:

1. Payload: The payload for the Super Heavy Booster is Starship with payload. See Reference 3.
   Payload = 185,000 kg

References:

1. Mechanical energy as described by Encyclopedia Britannica, britannica.com, accessed on 12/29/2021.
   https://www.britannica.com/science/mechanical-energy
2. Mechanical energy formula, "Energy Formula Physics", toppr.com, accessed on 12/29/2021.
   https://www.toppr.com/guides/physics-formulas/energy-formula-physics/
3. SpaceX Starship (vehicle + payload), "Payload fraction", en.wikipedia.org, accessed on 12/29/2021.
   https://en.wikipedia.org/wiki/Payload_fraction
4. Orbit speed calculator, "Earth orbit", calctool.org, accessed on 12/29/2021.
   https://www.calctool.org/CALC/phys/astronomy/earth_orbit
5. Rocket Equation Formula, "Rocket Equation Calculator", calculatory.academy, accessed on 12/29/2021.
   https://calculator.academy/rocket-equation-calculator/
6. Raptor Impulse, "SpaceX Raptor", en.wikipedia.org, accessed on 1/3/2022.
   https://en.wikipedia.org/wiki/SpaceX_Raptor
7. SpaceX Super Heavy booster fuel mass, "SpaceX Starship", en.wikipedia.org, accessed on 12/29/2021.
   https://en.wikipedia.org/wiki/SpaceX_Starship

MECHANICAL ADVANTAGE OF ELECTROMAGNETIC RAILGUN
Based on SpaceX Starship with payload and Super Heavy Rocket

Solution:

1. Calculate the mechanical energy required to place SpaceX Starship (vehicle + payload) into a 300 km low earth orbit using Method 1.

ME_O = mechanical energy orbit
KE_O = kinetic energy orbit
PE_O = potential energy orbit
g = gravitational acceleration

KE_O = (1/2) * Mass * Velocity^2
Mass = 185,000 kg, Def 1
Velocity = 7.73 km/s, Ref 4
KE_O = 5.53E+06 MJ

PE_O = Mass * g * Height
Mass = 185,000 kg
g = 9.80E-03 km/s^2
Height = 300 km
PE_O = 543.90E+03 MJ

$ME_O = KE_O + PE_O$
ME_O = 6.07E+06 MJ

Solution:

2. Calculate the mechanical energy at launch if Starship with payload is launched at Mach 3 using Method 1. At launch the height above the earth is 0 km, therefore, PE = 0 and ME = KE.

ME_L = mechanical energy at launch
KE_L = kinetic energy at launch
PE_L = potential energy at launch, assumed to be zero.

KE_L = (1/2) * Mass * Velocity^2
Mass = 185,000 kg, Ref 3
Velocity = 3 Mach
Velocity = 1.029 km/s
KE_L = 97.94E+03 MJ

$ME_L = KE_L$
ME_L = 97.94E+03 MJ

Comment: Using a railgun to accelerate and launch Starship with payload at Mach 3 doesn't provide a significant amount of mechanical energy or mechanical advantage.

MECHANICAL ADVANTAGE OF ELECTROMAGNETIC RAILGUN
Based on SpaceX Starship with payload and Super Heavy Rocket

Solution:

3. Calculate the mechanical energy at launch if Starship with payload plus Super Heavy Booster are launched at Mach 1, 2, 3, 3.5, 4, 5. Table below uses Method 1.
   At launch the height above the earth is 0 km, therefore, PE = 0 and ME = KE.

$ME_L = KE_L$
$KE_L =$ (1/2) * Mass * Velocity^2
Mass = 4.40E+06 kg, Ref 3
Velocity = 1, 2, 3, 3.5, 4, 5 Mach

Mass	Velocity		ME_L
kg	Mach	km/s	MJ
4.40E+06	1	0.343	258.83E+03
4.40E+06	2	0.686	1.04E+06
4.40E+06	3	1.029	2.33E+06
4.40E+06	3.5	1.201	3.17E+06
4.40E+06	4	1.372	4.14E+06
4.40E+06	5	1.715	6.47E+06

Comments:

1. Using a railgun to accelerate and launch Starship with payload plus Super Heavy Booster at Mach 3 provides almost 40% of the mechanical energy required to place Starship with payload into orbit.
   Mach 3.5 provides more than 50% of the mechanical energy required.
   And, Mach 5 provides more than the mechanical energy required.
2. Due to velocity being squared in kinetic energy, any incremental increase in velocity provides a velocity squared increase in kinetic energy.

MECHANICAL ADVANTAGE OF ELECTROMAGNETIC RAILGUN
Based on SpaceX Starship with payload and Super Heavy Rocket

Solution:

4a. Estimate the takeoff mass of a Reduced Super Heavy Booster and Starship with payload launched at Mach 3.
4b. Estimate the takeoff mass of a Reduced Super Heavy Booster and Starship with payload launched at Mach 1, 2, 3, 3.5, 4, 5.

Assumptions:

1. Reduced Super Heavy Booster delivers Starship with payload to a low earth orbit.
2. Low earth orbit of 300 km and a velocity of 7.73 km/s, from Reference 4.
3. From Reference 7, the dry mass of Super Heavy is 180 tons (163,000 kg) and the fuel mass is 3,600 tons (3,580,000 kg). This yields a dry mass to fuel ratio of 0.05. This dry mass to fuel ratio is assumed to be consistent for estimating a Reduced Super Heavy Booster.
4. After reaching orbit, the Super Heavy Booster has a fuel mass remaining to return to Earth. It is assumed that 98.75% of the Super Heavy Booster's fuel is used to achieve a low earth orbit and at orbit the Super Heavy Booster has approximately 1.25% of its fuel mass remaining. (Estimated by calculations not included. Reference required.)

Rearrange Method 2 to estimate the takeoff mass (initial mass) of a Reduced Super Heavy Booster launched at Mach 3.

$$M_o = M_f * e^{\wedge}((V_f - V_o) / EV)$$

And,

Final Mass (M_f) = Payload + Reduced Super Heavy Dry Mass + Fuel Mass Remaining

Payload =	185,000	kg, Def 1
Dry Mass =	103,100	kg, See Note 1 below.
Reduced Super Heavy Fuel Mass Remaining =	29,100	kg, See Note 1 below.

M_f =	317,200	kg
V_f =	7.73E+00	km/s, Solution 4, Assumption 1
V_o =	3	Mach
V_o =	1.029	km/s
EV =	3.2	km/s, Ref 6
M_o =	2.58E+06	kg

Note:

1. An iterative procedure was used to estimate the Reduced Super Heavy Booster dry mass and fuel mass remaining. The procedure resolved to a Reduced Super Heavy Booster dry mass to fuel ratio of 0.043 and a fuel mass remaining of 1.22%, both values are slightly lower than Assumptions 3 and 4.

Felipe Wescoup
wescoup@gmail.com
1/5/2022

MECHANICAL ADVANTAGE OF ELECTROMAGNETIC RAILGUN
Based on SpaceX Starship with payload and Super Heavy Rocket

The following table estimates the reduced takeoff mass and fuel mass of a Super Heavy Booster if launched at various velocities using the same calculations and assumptions from the previous calculation in Solution 4.

Reduced Super Heavy Booster

Velocity		Takeoff Mass	Reduction	Takeoff Fuel Mass	Reduction
Mach	km/s	kg	%	kg	%
0	0	4.40E+06	0%	3.58E+06	0%
1	0.343	3.85E+06	13%	3.51E+06	2%
2	0.686	3.12E+06	29%	2.81E+06	22%
3	1.029	2.58E+06	41%	2.29E+06	36%
3.5	1.201	2.35E+06	47%	2.08E+06	42%
4	1.372	2.16E+06	51%	1.89E+06	47%
5	1.715	1.83E+06	58%	1.57E+06	56%

Conclusions:

1. Using a railgun to accelerate and launch Starship with payload at Mach 3 doesn't provide a significant amount of mechanical energy or significant mechanical advantage. See Solutions 1 and 2.
2. The Super Heavy Booster could be reduced by 40% if Starship with payload and the Super Heavy Booster are launched at Mach 3. See Solutions 3 and 4.
3. Due to velocity being squared in kinetic energy, any incremental increase in launch velocity provides a velocity squared increase in kinetic energy at launch. See Solution 3.
4. An electromagnetic railgun could reduce the takeoff mass and fuel mass required to put spacecraft into orbit. See Solution 4.