INTRODUCTION TO TRAJECTORIES

Juan R. Cruz and Michelle M. Munk
Atmospheric Flight and Entry Systems Branch
NASA Langley Research Center

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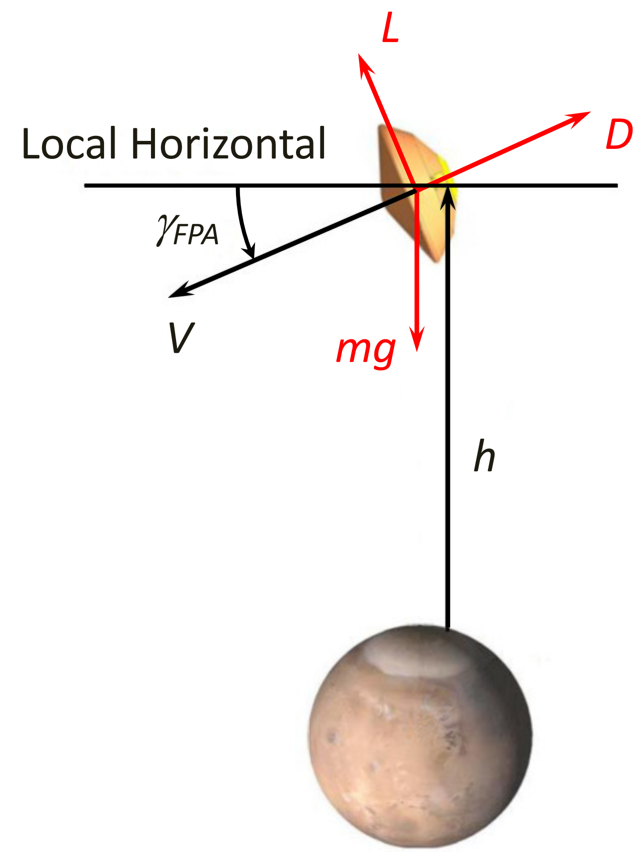
Image credit: NASA / JPL-Caltech

Version 3

Definition of Trajectory

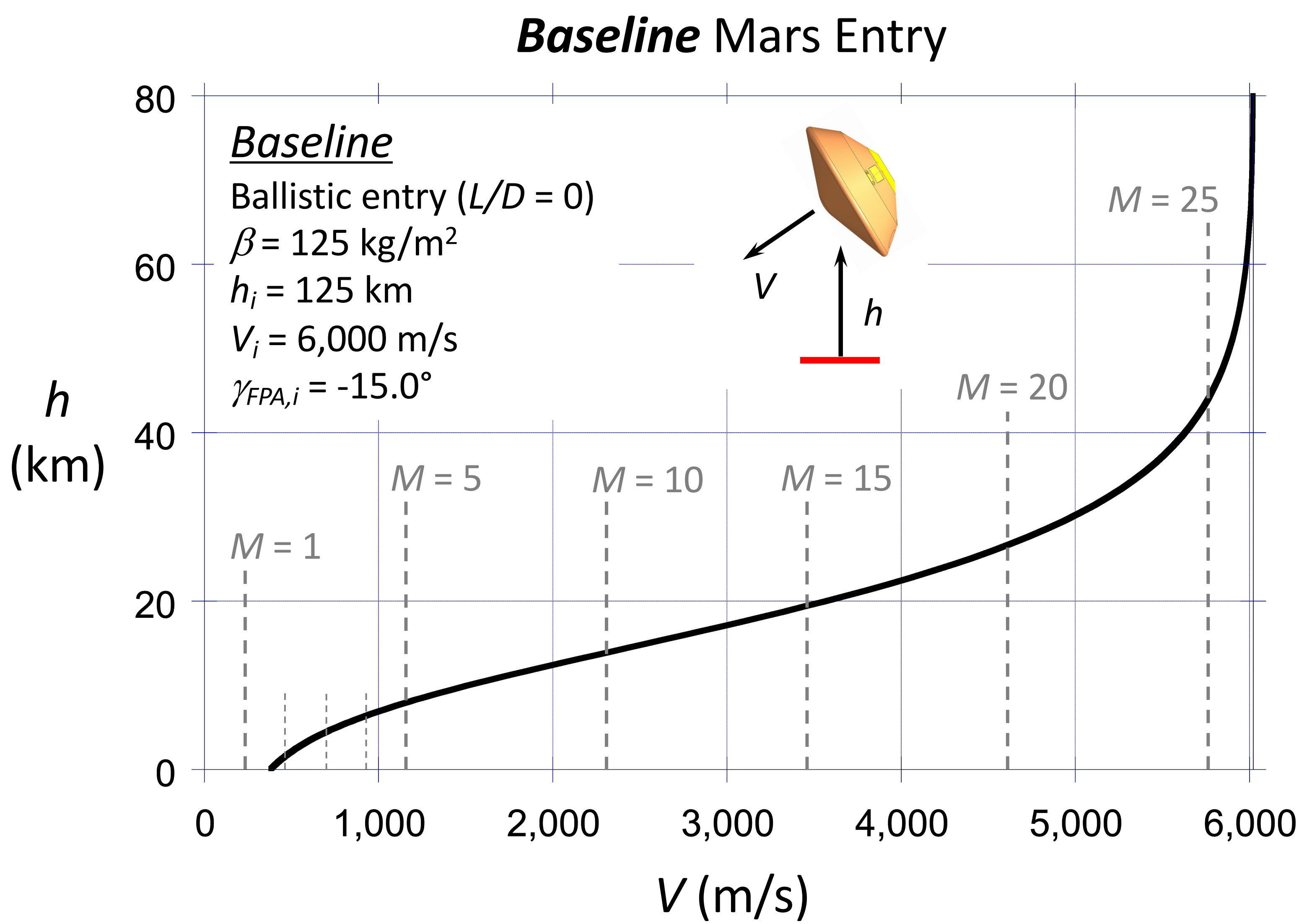
Trajectory

- The flight path taken by an entry vehicle
- Described by its state variables
  - latitude and longitude
  - azimuth (flight direction wrt. north)
  - altitude, *h*
  - velocity, *V*
  - flight path angle, γ_{FPA}
- Driven by the forces acting on the entry vehicle
  - aerodynamic
    - lift, L and drag, D
  - gravity, *mg*
  - propulsive



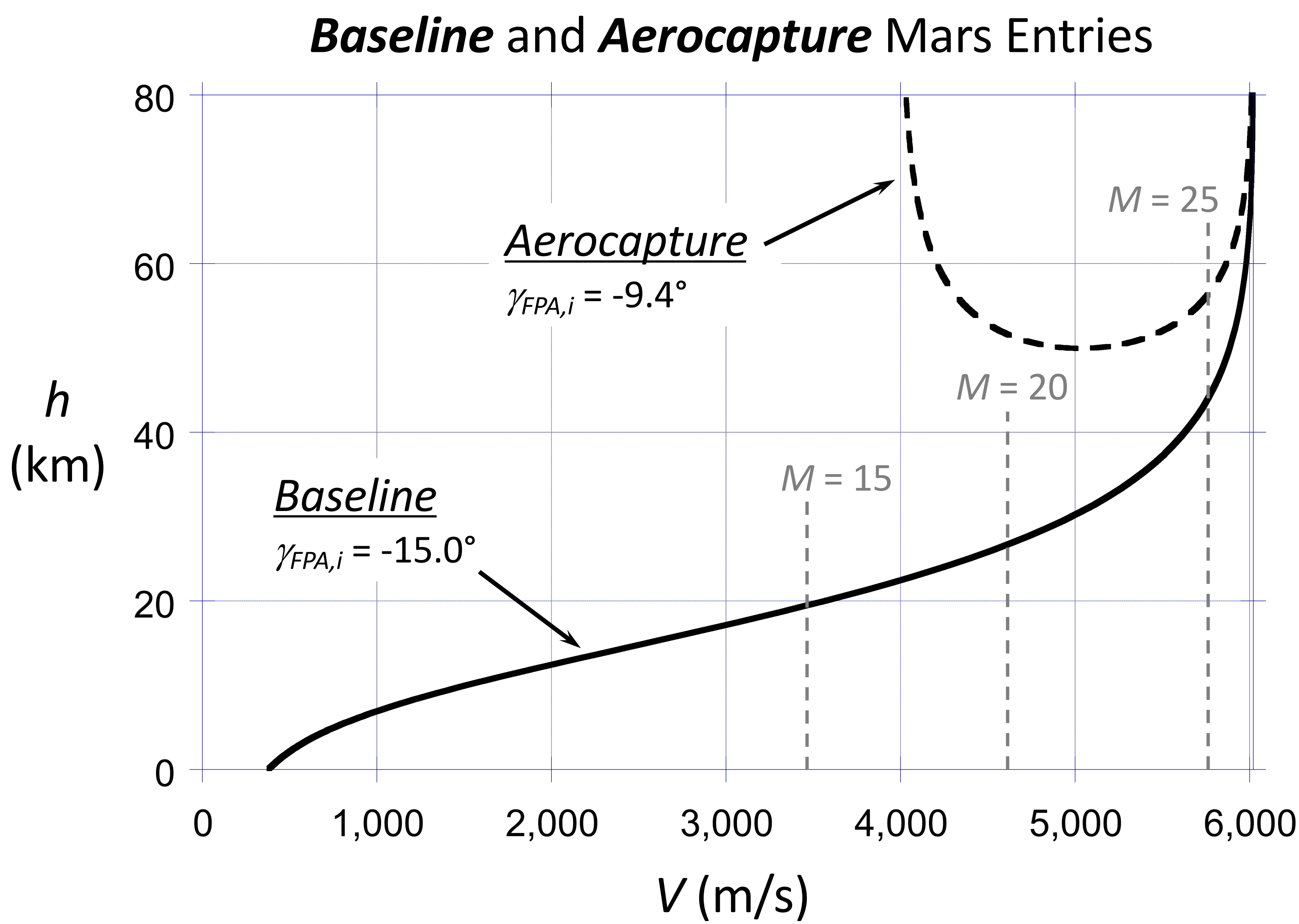
Images credit: NASA / JPL-Caltech

Velocity-Altitude Diagram



Entry vehicle image credit: NASA / JPL-Caltech

Velocity-Altitude Diagram



Energy and Aeroheating

Energy and aeroheating will be described in terms of the following three quantities:

E = ***Total Energy*** metric
= (Kinetic Energy + Potential Energy)$_{\text{Nondimensionalized}}$

Nondimensionalized wrt. the Total Energy of the *Baseline Mars Entry* at atmospheric interphase

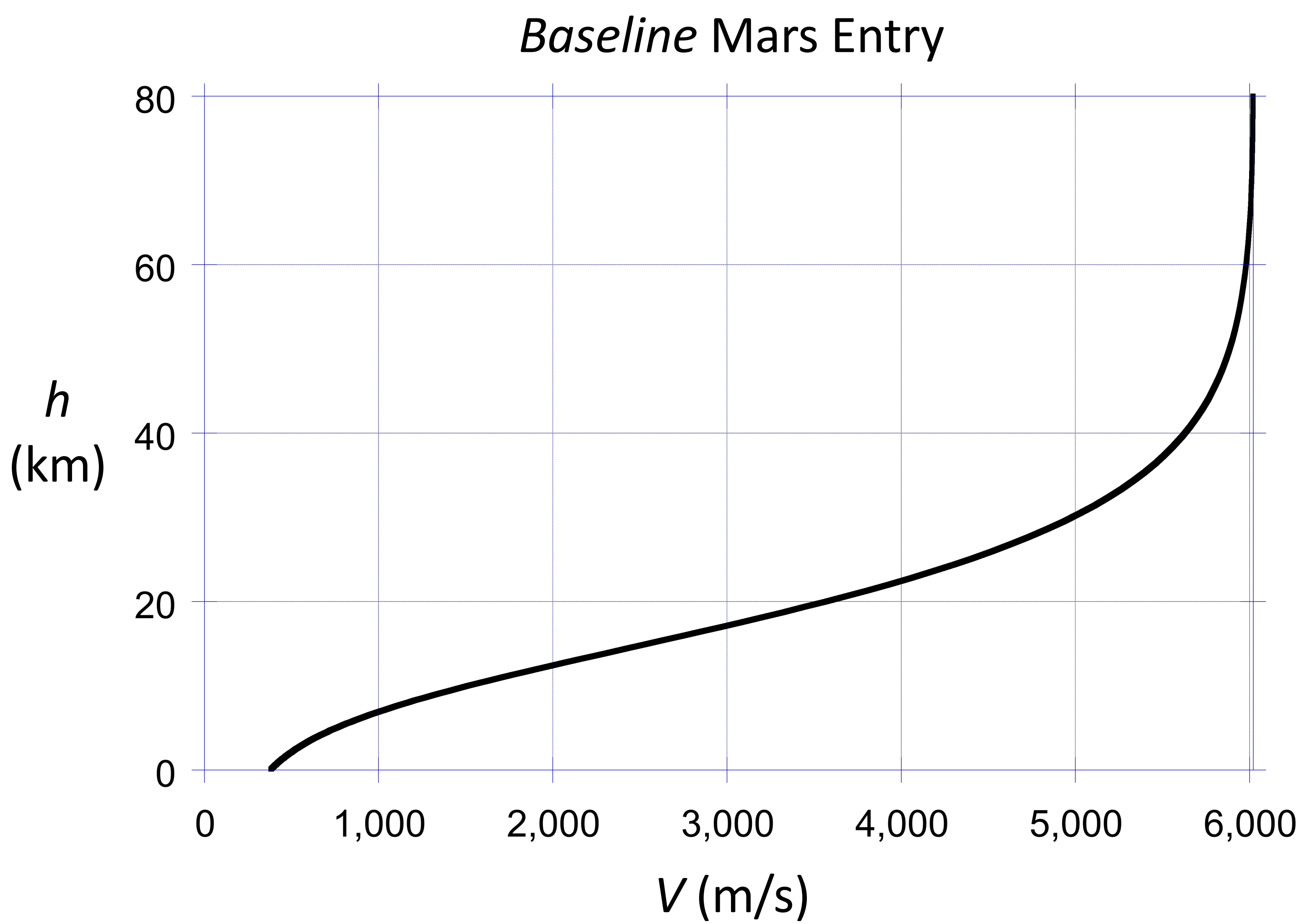
$\dot{Q}$ = Aerothermodynamic convective ***heat rate*** metric, $\propto \rho^{\frac{1}{2}} V^3$

Nondimensionalized wrt. the maximum convective heat rate of the *Baseline Mars Entry*

Q = Aerothermodynamic convective ***heat load*** metric, integration wrt. time of $\dot{Q}$ starting at entry interphase, $\propto \int_{t_i}^{t} \dot{Q}\, dt$

Nondimensionalized wrt. the convective heat load of the *Baseline Mars Entry* at landing

Energy and Aeroheating



Energy and Aeroheating

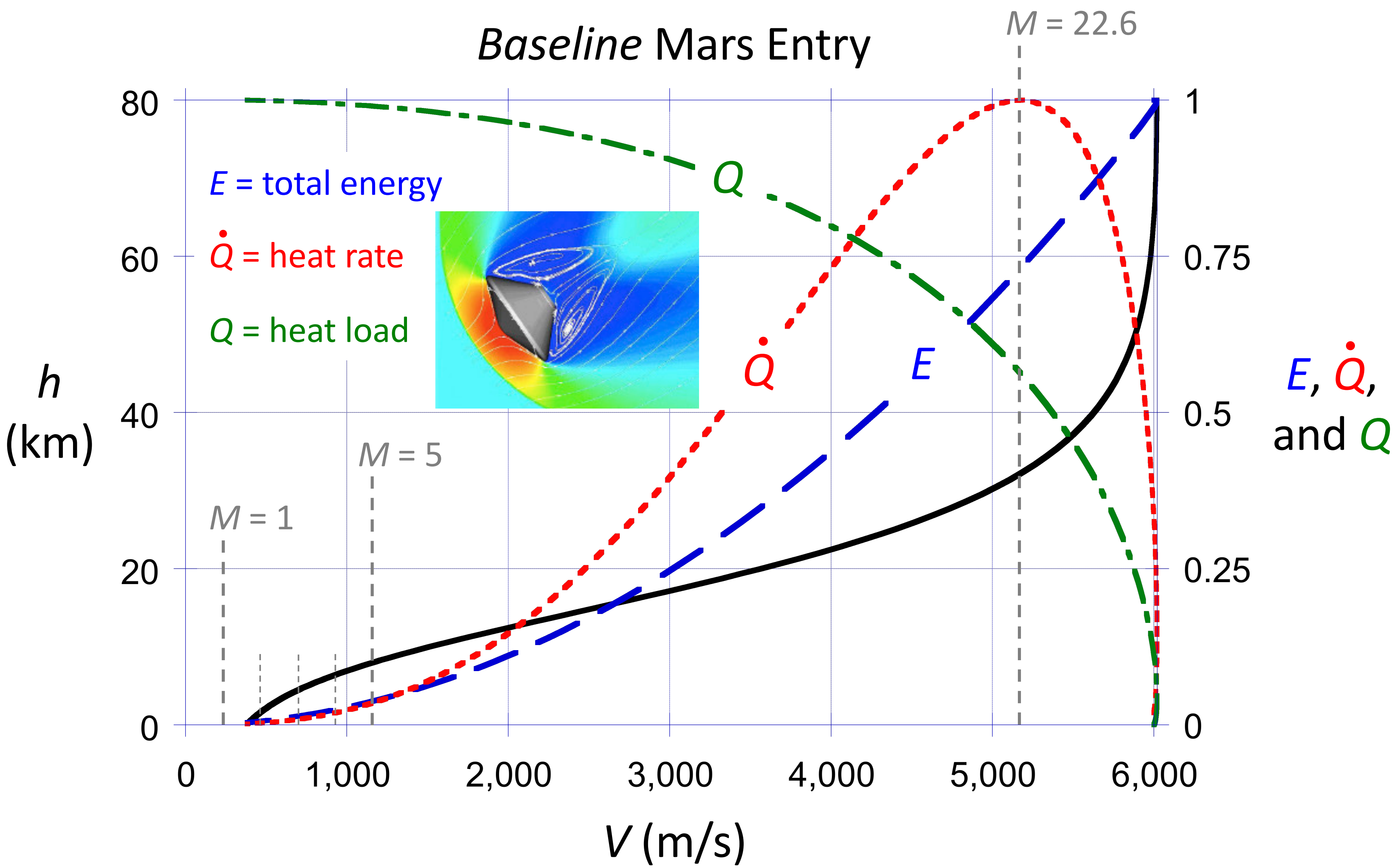
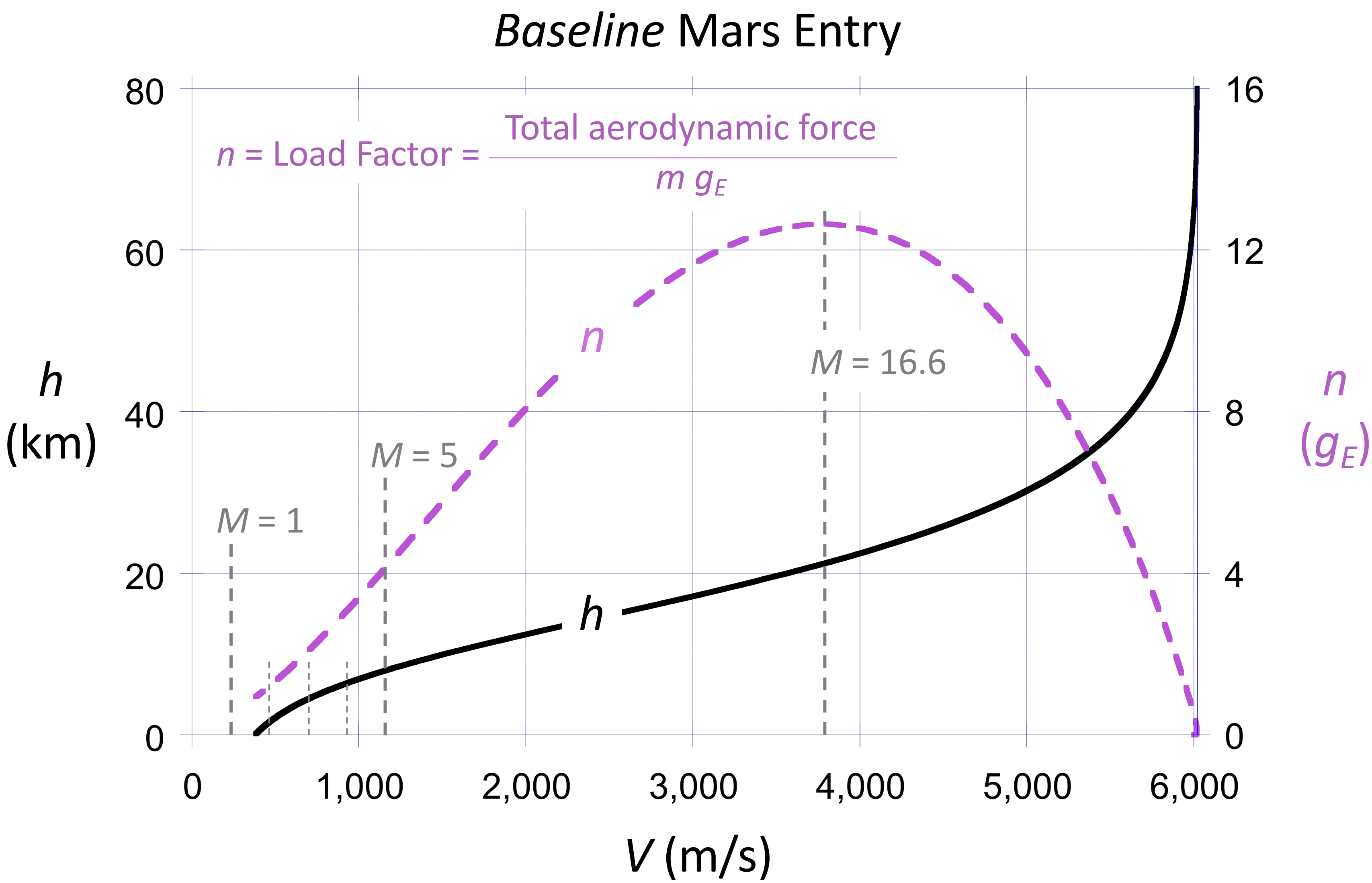


Image credit: NASA

Deceleration



Key Factors Affecting the Trajectory – Entry Vehicle

Ballistic Coefficient, β

A measure of the entry vehicle aerodynamic loading

$$\beta = \frac{\text{Vehicle Mass}}{\text{Drag Coefficient} \bullet \text{Aero Reference Area}} = \frac{m}{C_D A}$$

The drag coefficient, C_D, will principally depend on the shape of the entry vehicle and the Mach number, M

Dimensions: [Mass/Length^2]

Typical Unit: kg/m^2

For the *Baseline Mars Entry* example in this presentation, β = 125 kg/m^2

Key Factors Affecting the Trajectory – Entry Vehicle

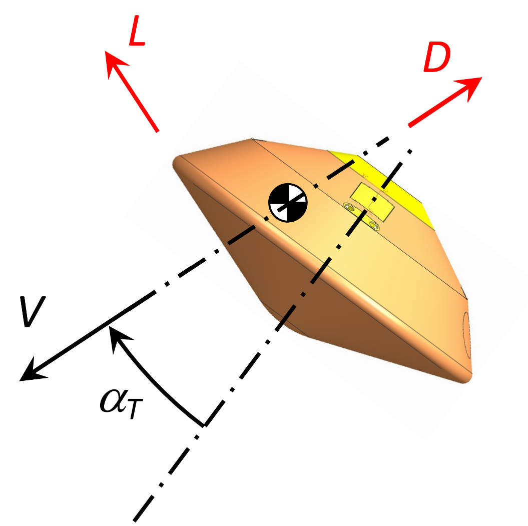
Lift to Drag Ratio, *L/D*

A measure of the lift efficiency of an entry vehicle

A ***ballistic*** entry means that $L/D = 0$. The *Baseline Mars Entry* example in this presentation is ballistic.

Generating Lift with an Axisymmetric Entry Vehicle

- An axisymmetric vehicle with its center of mass on its axis of symmetry will trim at zero degrees total angle of attack, α_T. At $\alpha_T = 0°$ it will have drag, but no lift. Thus, $L/D = 0$.
- Moving the center of mass off the axis of symmetry will cause the vehicle to trim at $\alpha_T \neq 0°$.
- At $\alpha_T \neq 0°$ the entry vehicle will generate lift. Thus, $L/D \neq 0$. Note: Nose down yields lift up – it is not a wing!
- For a given off-axis position of the center of mass, lift will be in a specific direction with respect to the entry vehicle. The direction of this lift with respect to the trajectory can be controlled by rolling the entry vehicle.



Entry vehicle image credit: NASA / JPL-Caltech

Key Factors Affecting the Trajectory – Initial Conditions

Also influencing the trajectory are the initial conditions:

At an initial altitude, h_i

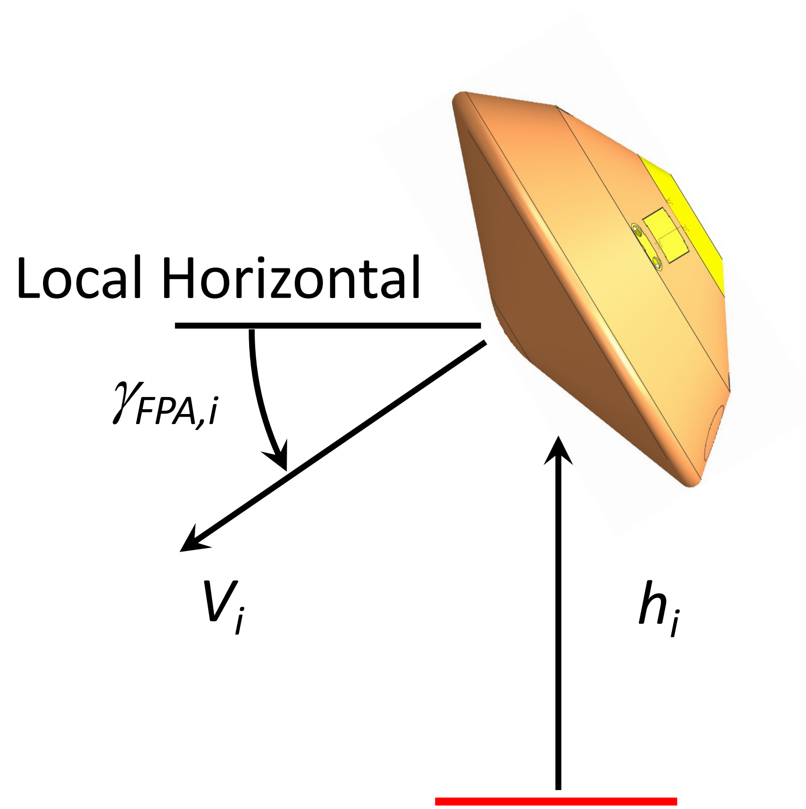
- initial velocity, V_i
- initial flight path angle, $\gamma_{FPA,i}$ (negative as shown)

For the *Baseline Mars Entry* in this presentation:

h_i = 125 km

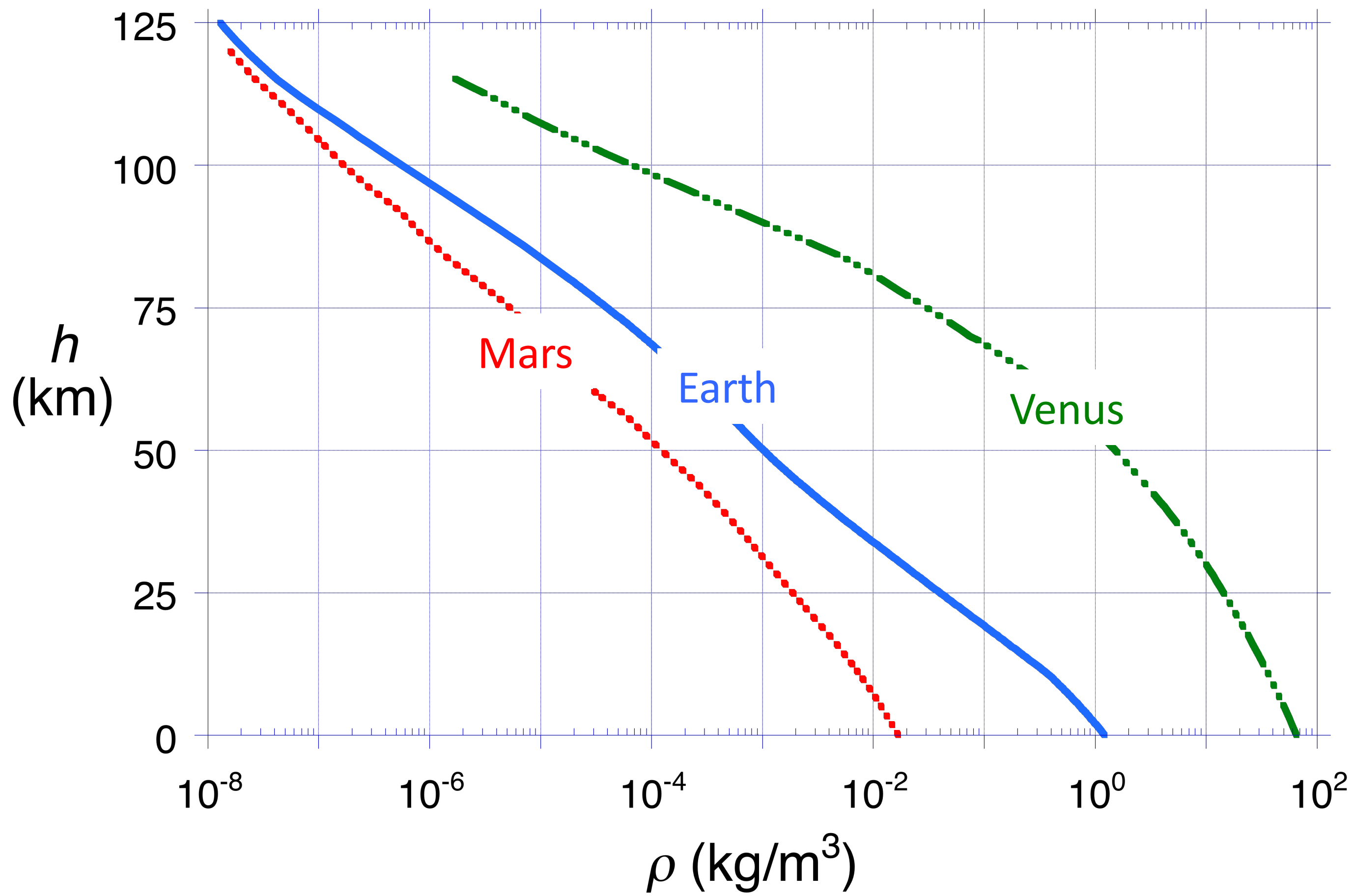
V_i = 6,000 m/s

$\gamma_{FPA,i}$ = -15°



Entry vehicle image credit: NASA / JPL-Caltech

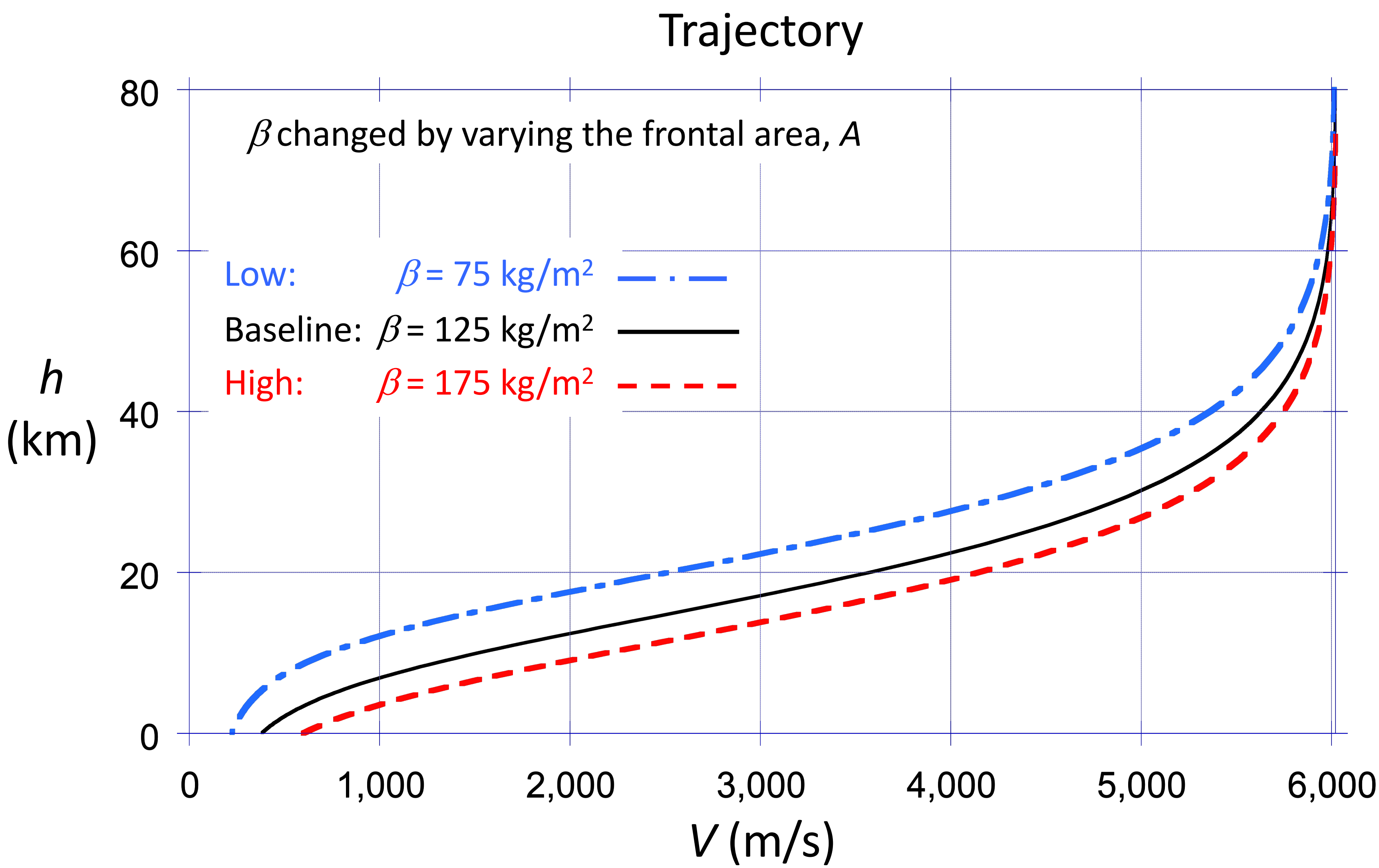
Key Factors Affecting the Trajectory – Atmosphere and Gravity



	g (m/s^2)
Mars	3.74
Earth	9.81
Venus	8.87

- NOAA, NASA, and USAF: U.S. Standard Atmosphere, 1976, NASA TM X-74335, 1976.
- Seiff, A. et al.: Measurements of Thermal Structure and Thermal Contrasts in the Atmosphere of Venus and Related Dynamical Observations: Results from the four Pioneer Venus Probes, *Journal of Geophysical Research*, Vol. 85, No. A13, pp. 7903-7933, 1980.
- Seiff, A. and Kirk, D. B.: Structure of the Atmosphere of Mars in Summer at Mid-Latitudes, *Journal of Geophysical Research*, Vol. 82, No. 28, 1977.

Effect of Ballistic Coefficient



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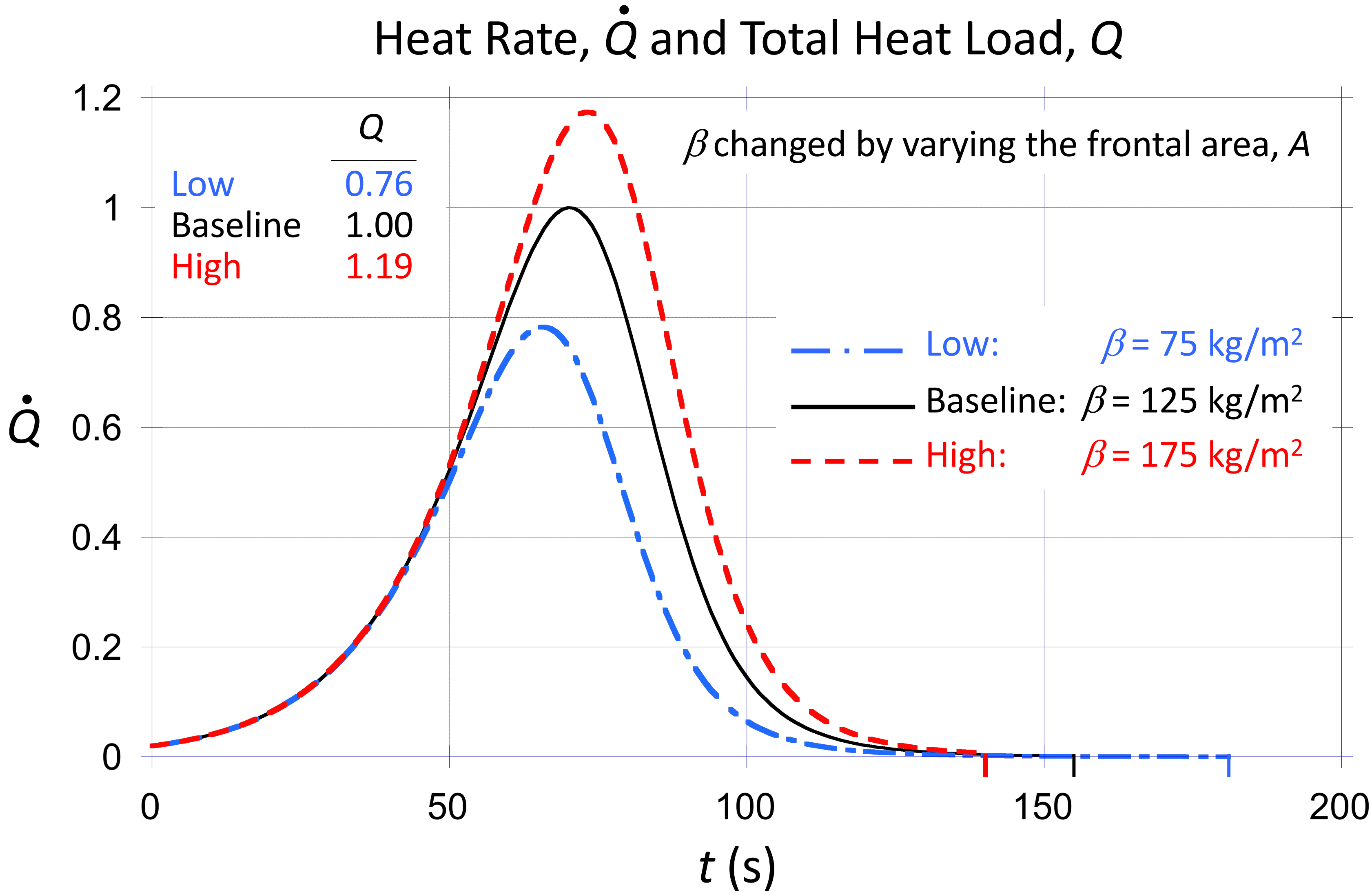

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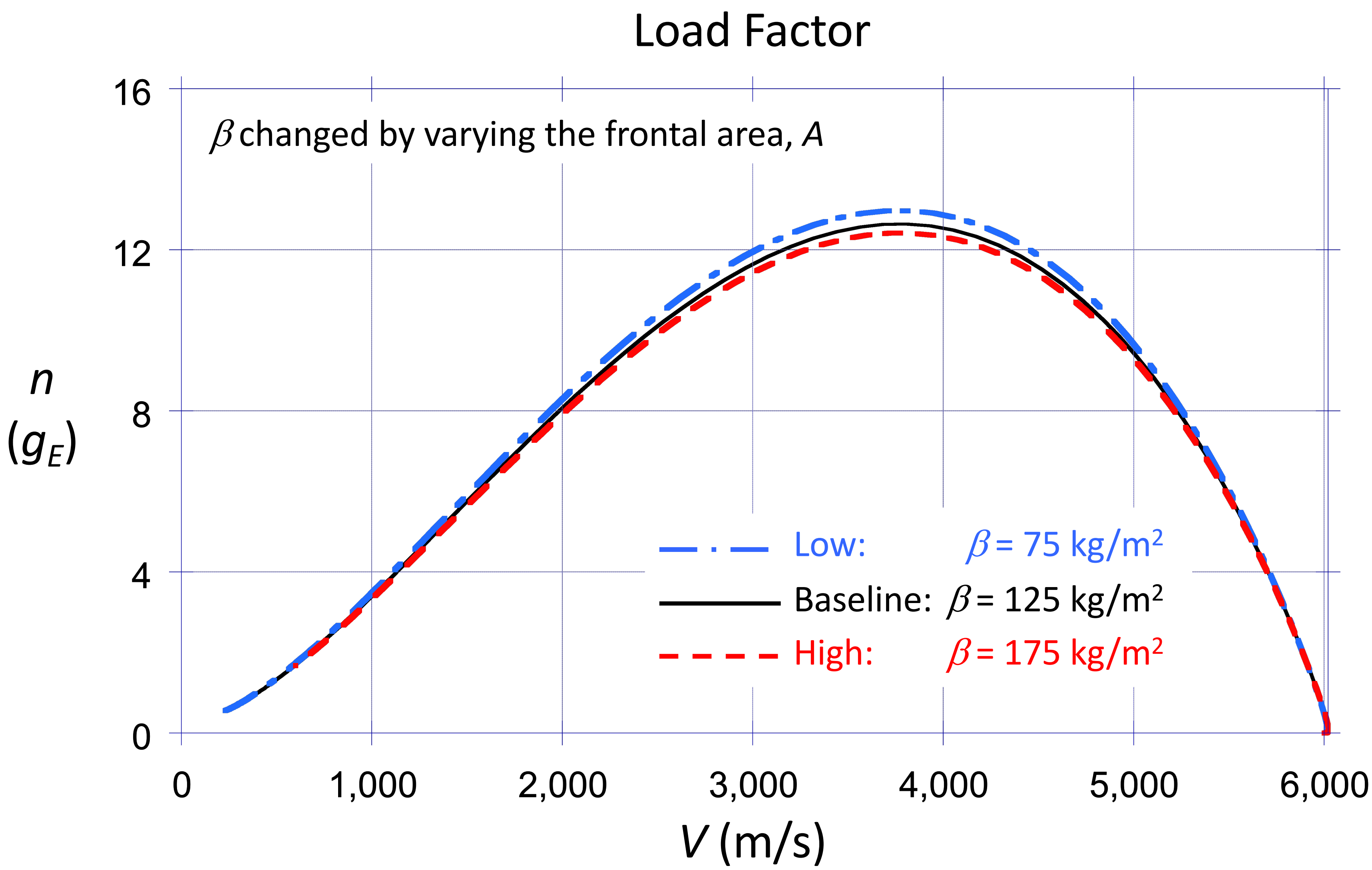
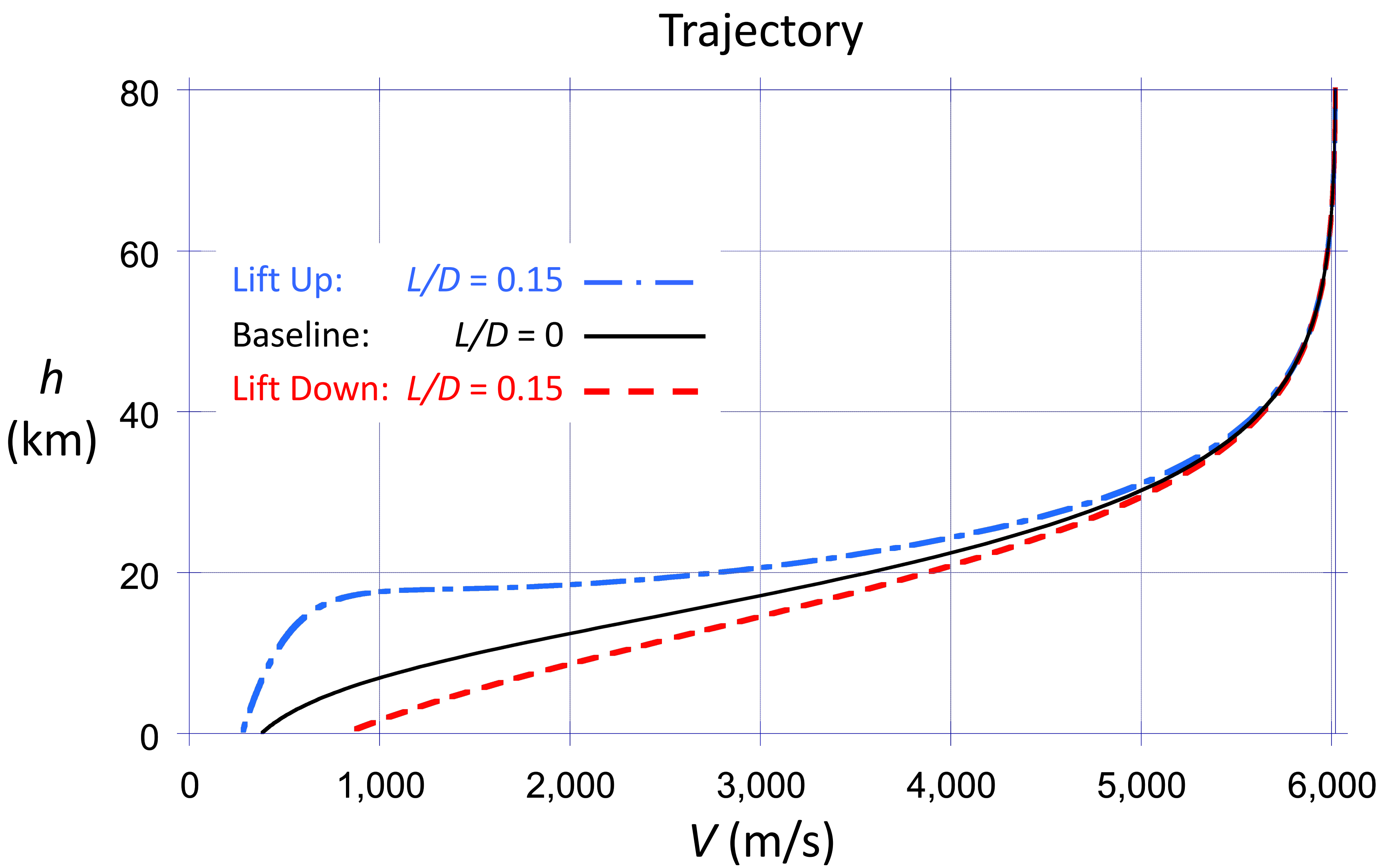


Effect of Lift



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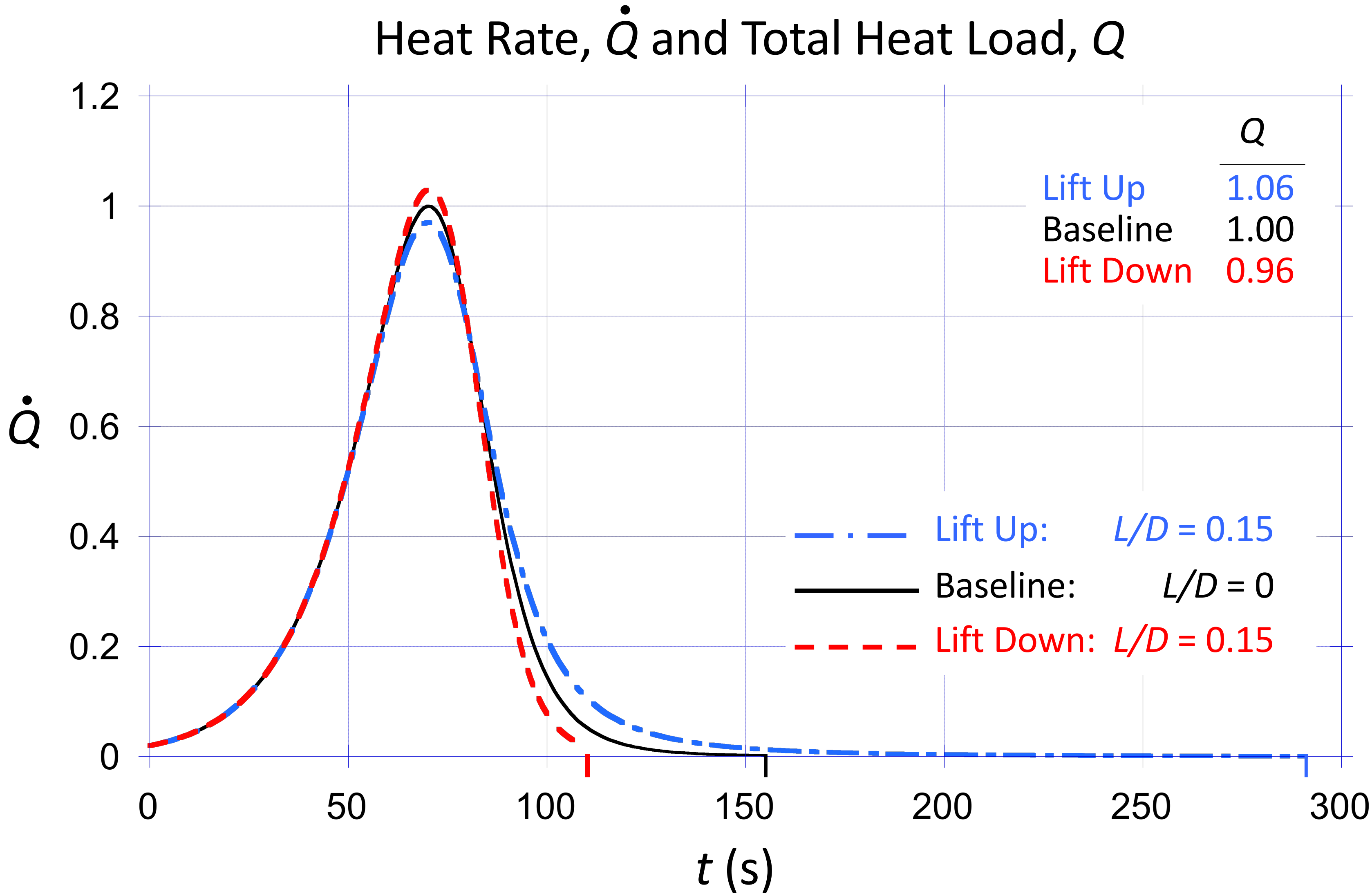
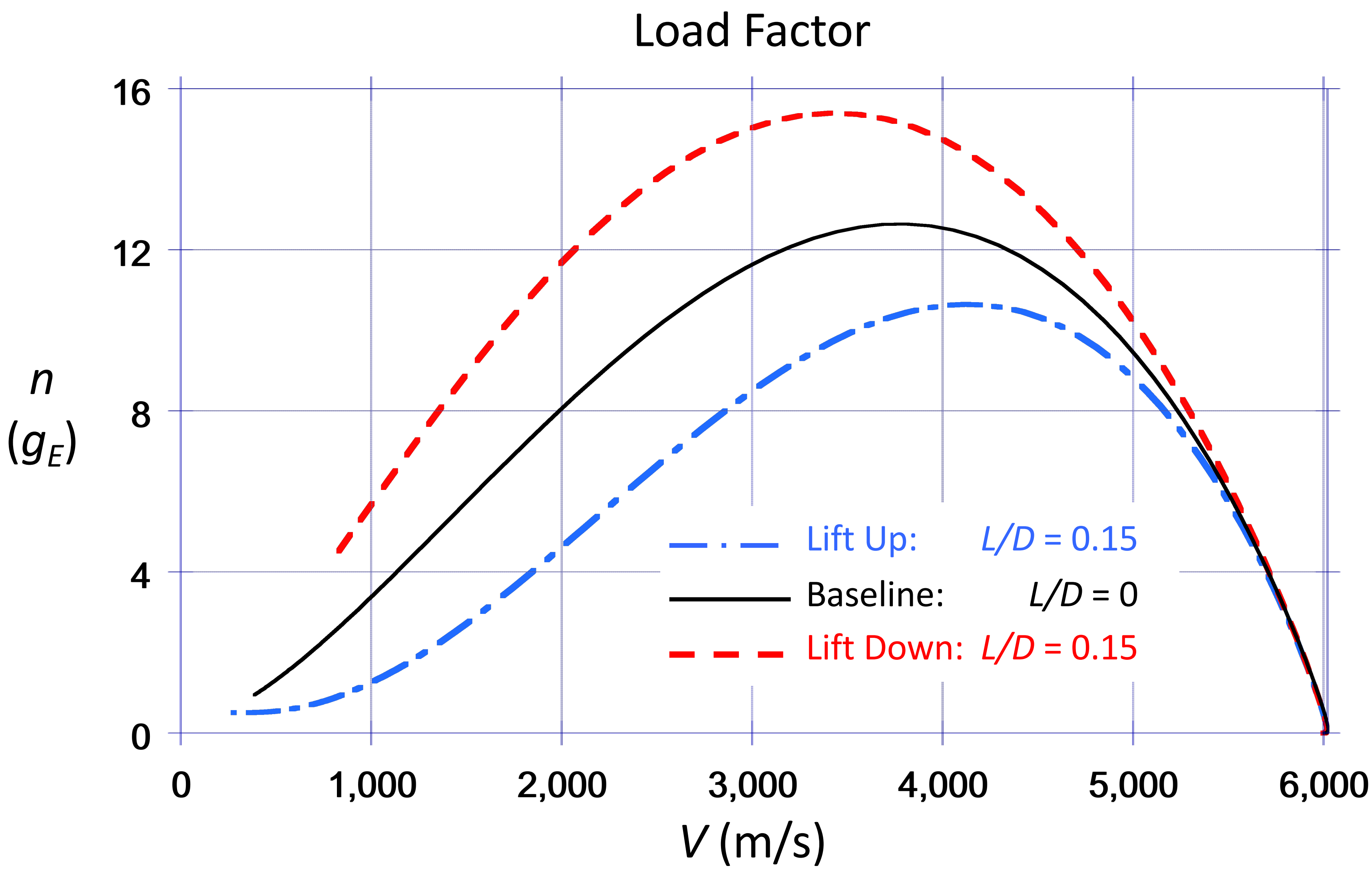
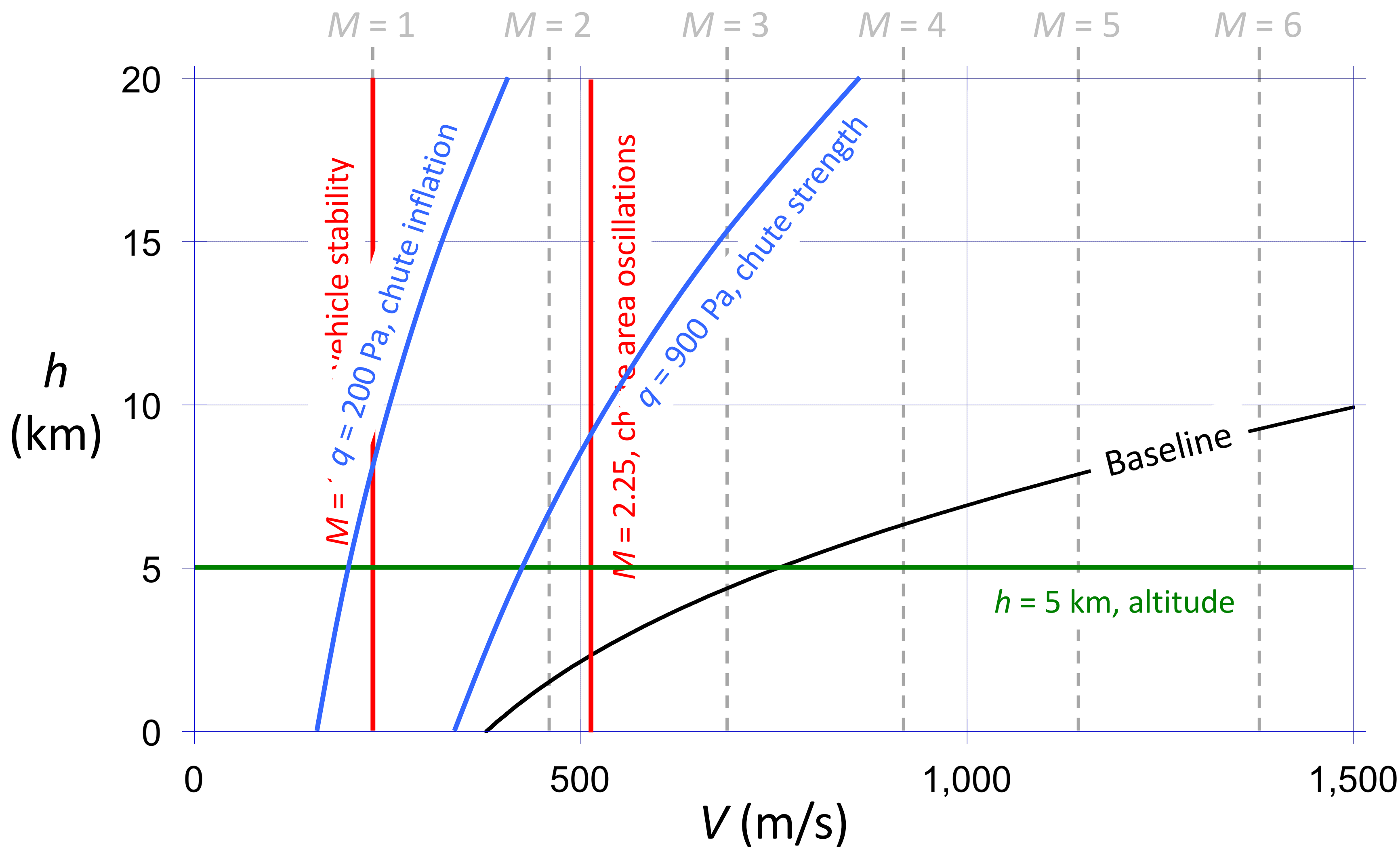


Effect of Lift



Descent: Parachutes, IADs, and the Mach-q Box



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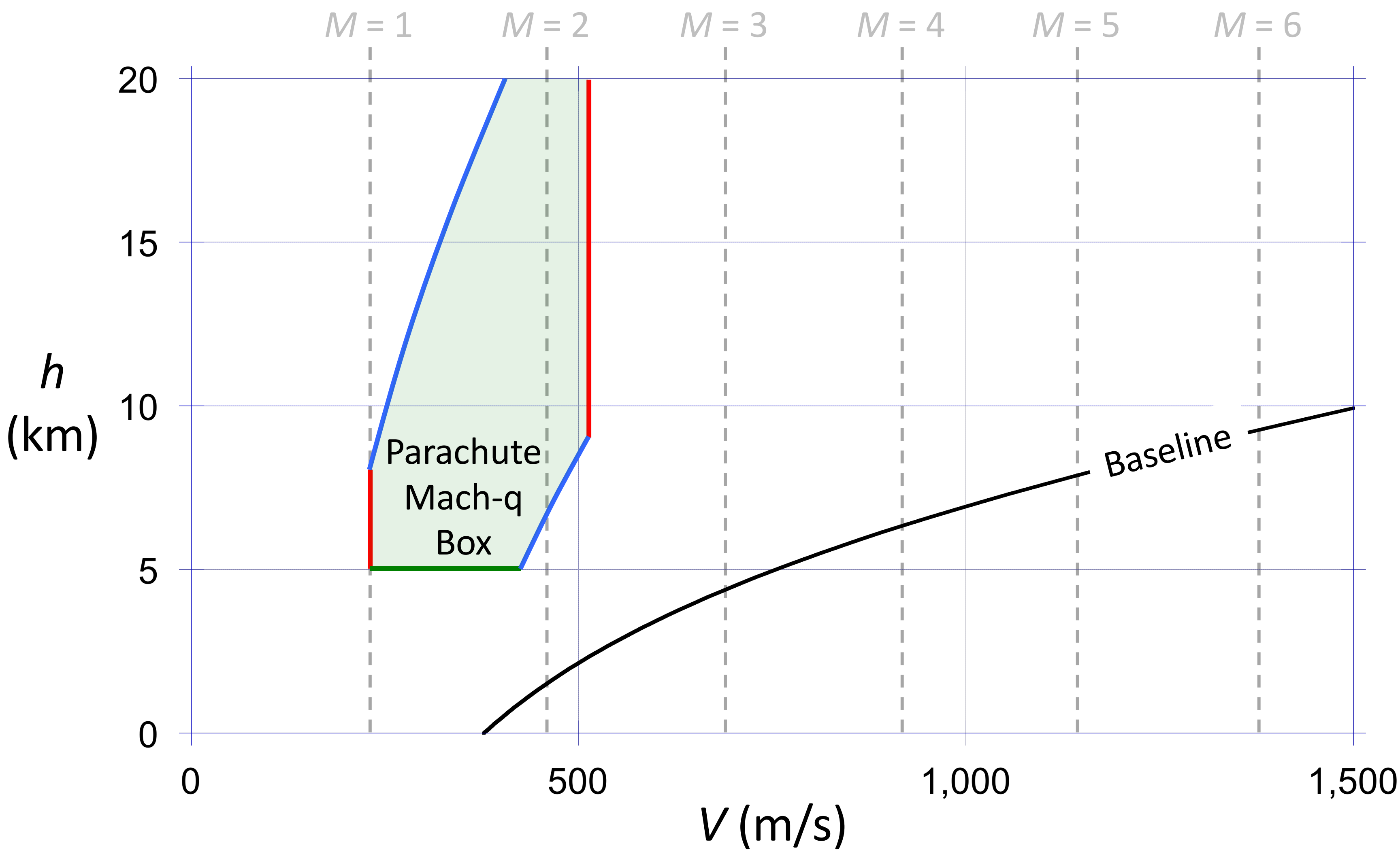

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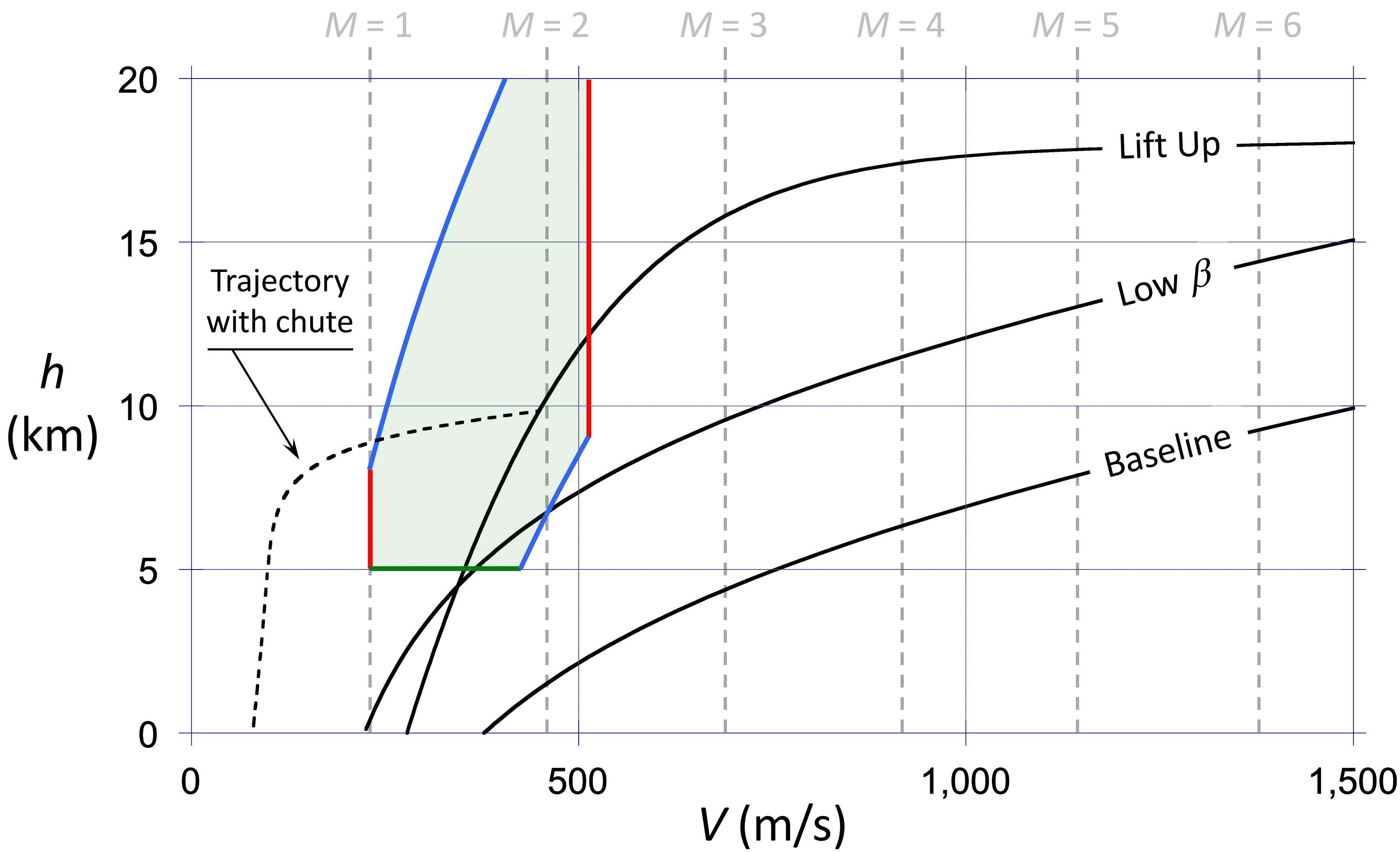

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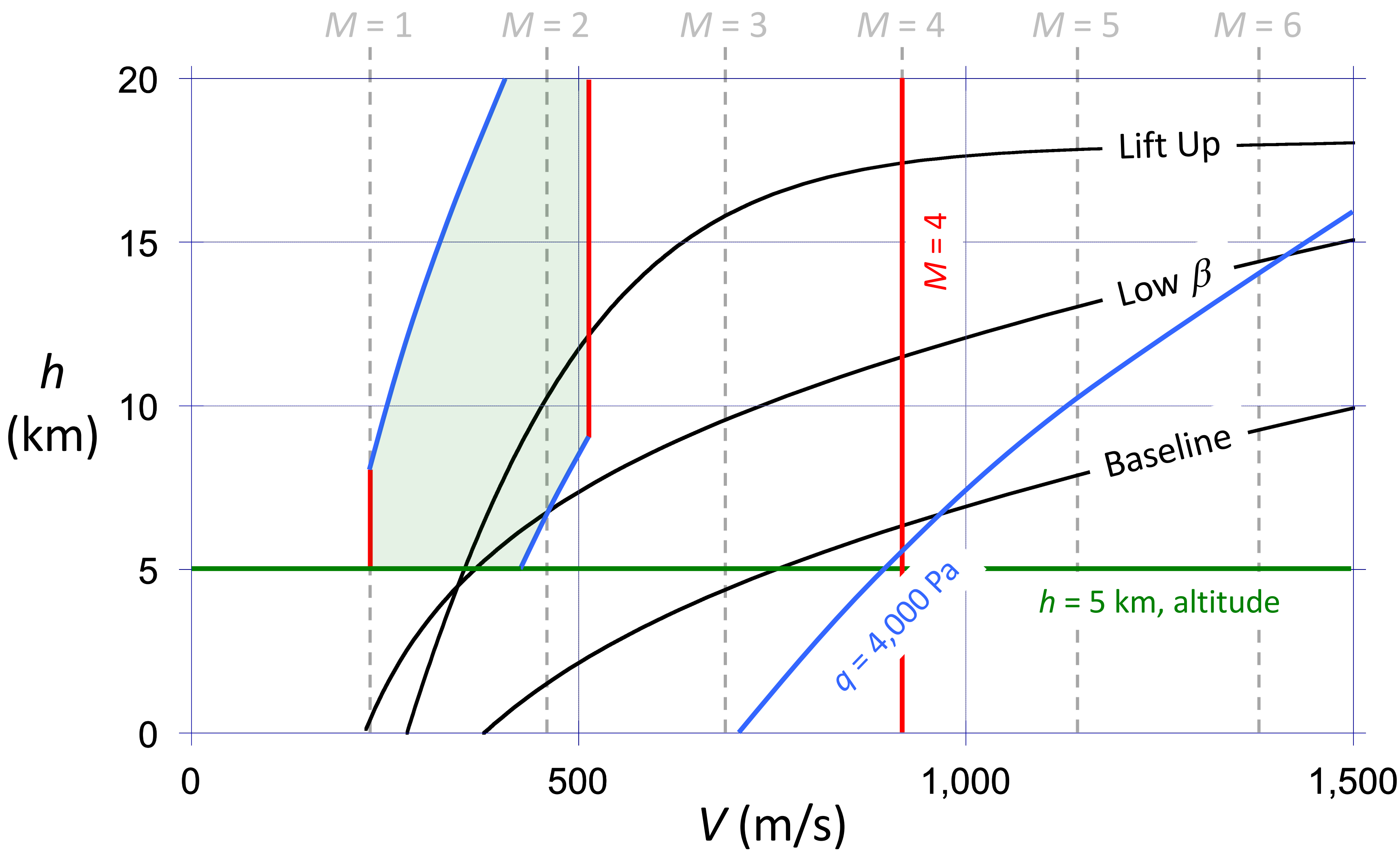
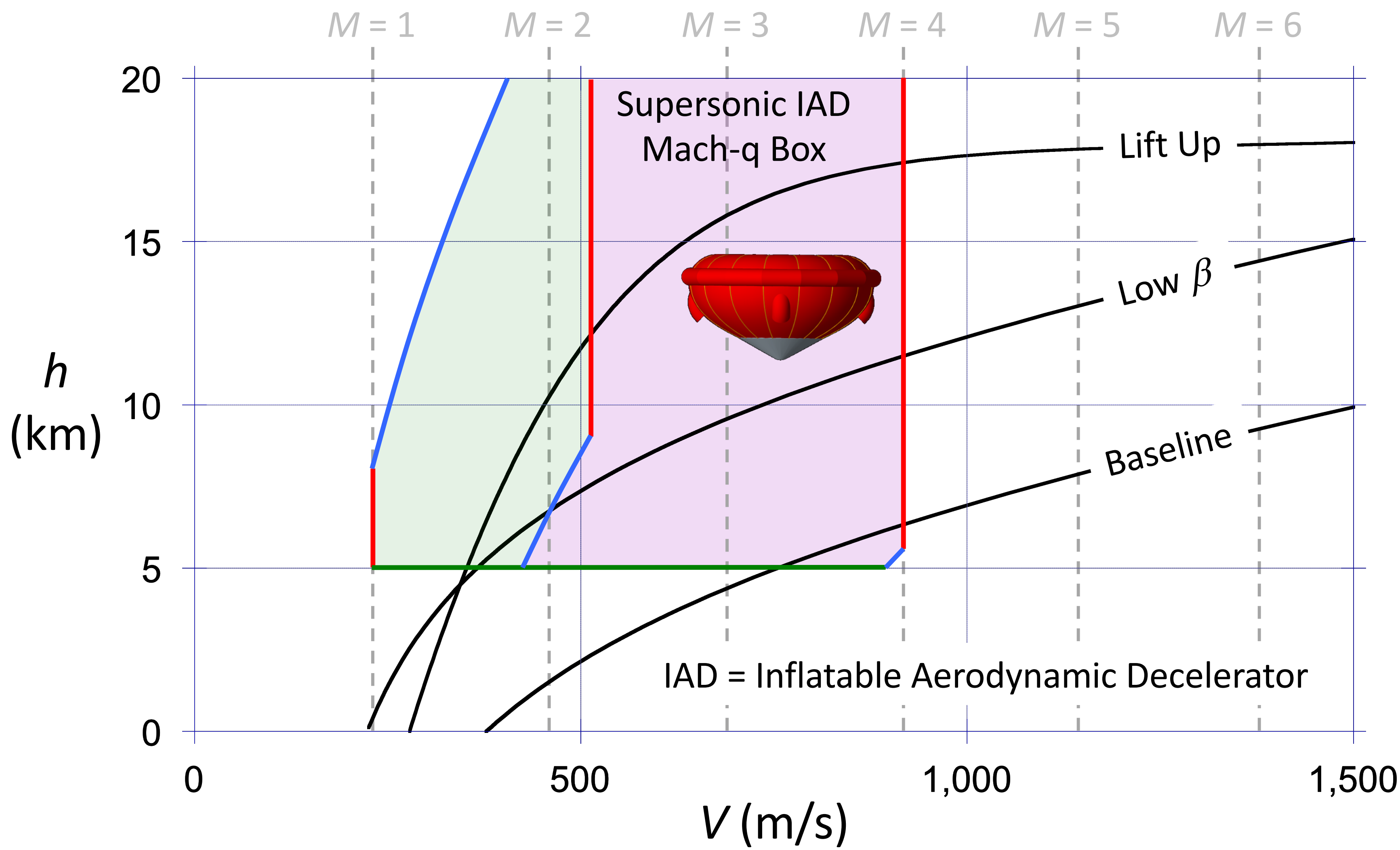


Descent: Parachutes, IADs, and the Mach-q Box



IAD image credit: Chris Tanner / JPL-Caltech

Other Considerations in Trajectory Design

- Constraints imposed by launch vehicle – aeroshell diameter, mass
- Available entry, descent, and landing technologies and their constraints
  - aeroshell shape & performance (e.g., C_D, L/D)
  - thermal protection system performance (e.g. peak heat load)
  - deployable aerodynamic decelerators (parachutes, IADs)
- Timeline and altitude – how much time and altitude are needed to complete all entry, descent, and landing tasks with margin and in the presence of uncertainties?
  - deployable decelerator deployment
  - heatshield release
  - radar lock
  - propulsive descent
- Trajectory guidance
- Propulsive terminal descent
- Precision and hazard avoidance landing