



INTRODUCTION TO TRAJECTORIES

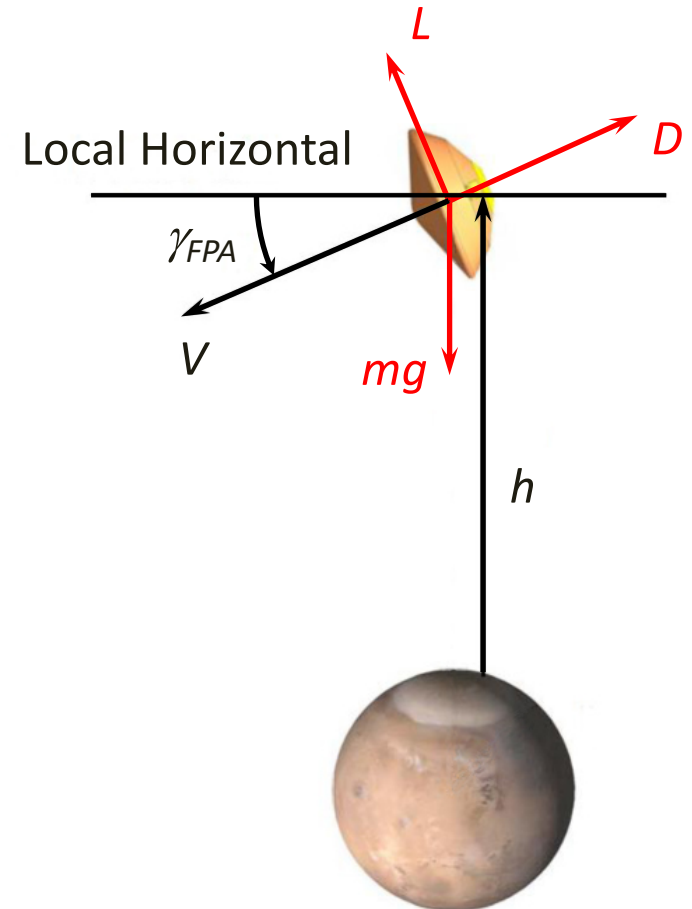
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*Entry, Descent, and Landing Systems Short Course
10th International Planetary Probe Workshop
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Definition of Trajectory

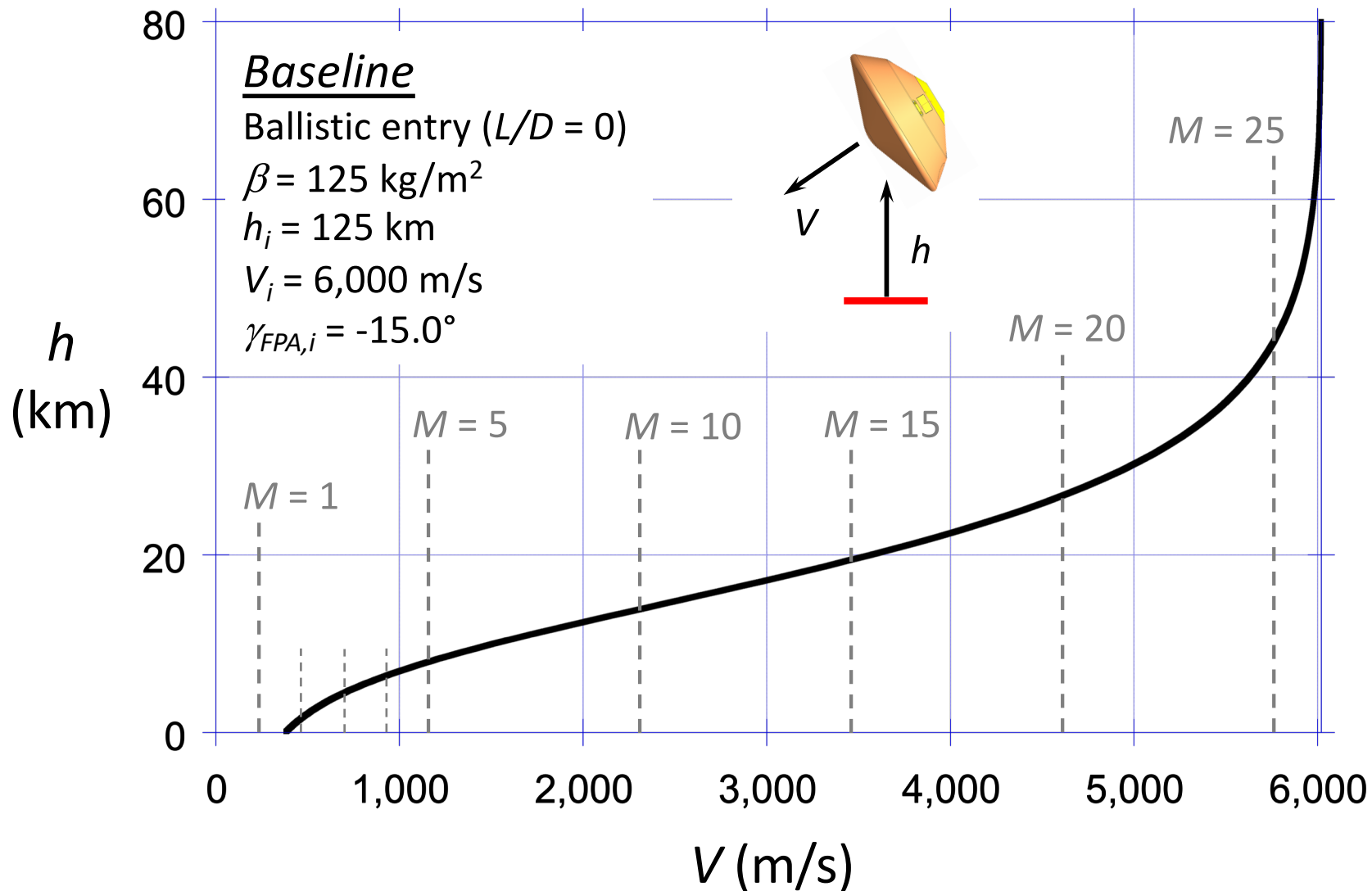
Trajectory

- 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



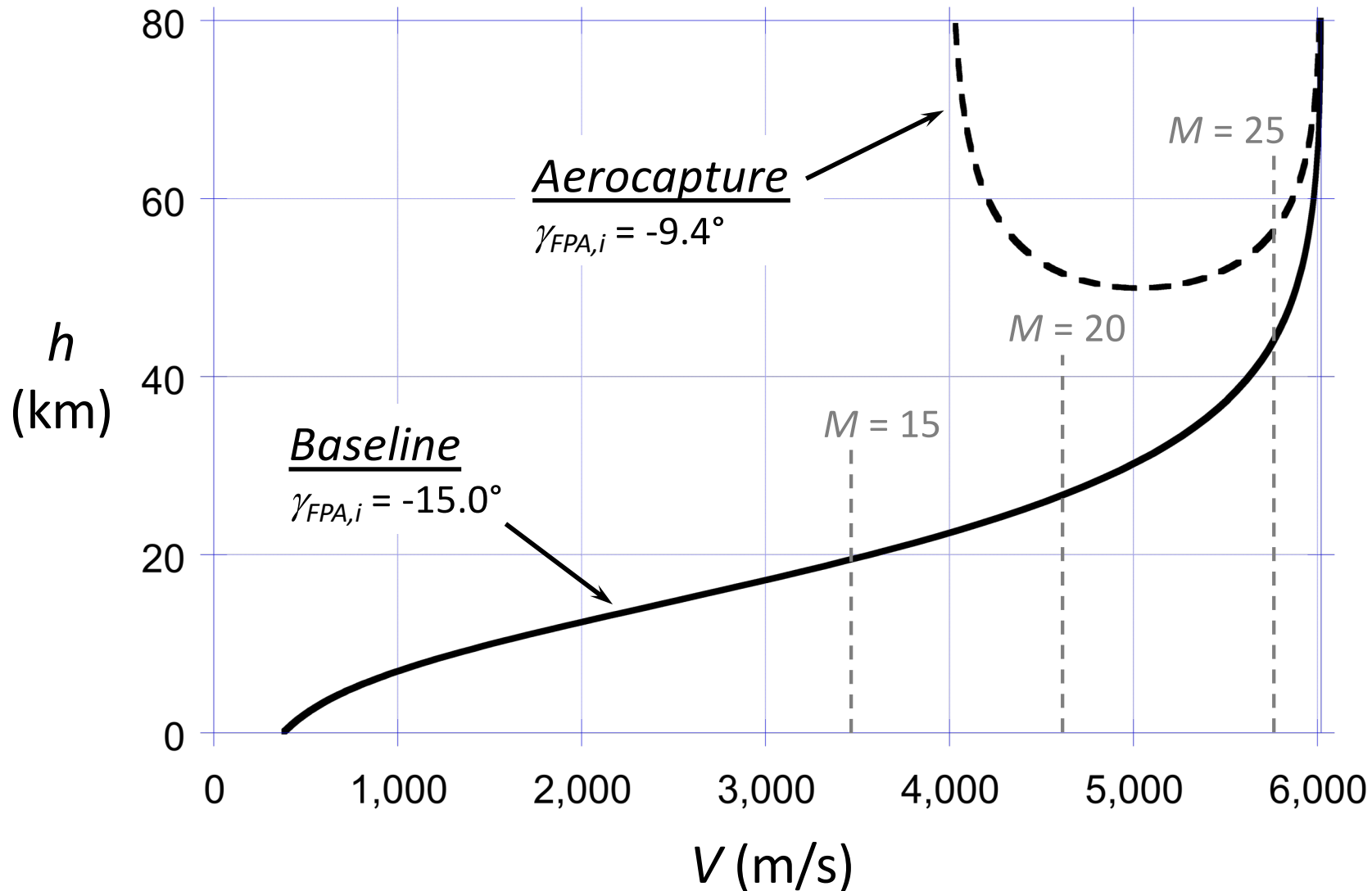
Velocity-Altitude Diagram

Baseline Mars Entry



Velocity-Altitude Diagram

Baseline and Aerocapture Mars Entries



Energy and Aeroheating

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

E = **Total Energy** metric

= (Kinetic Energy + Potential Energy)_{Nondimensionalized}

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

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

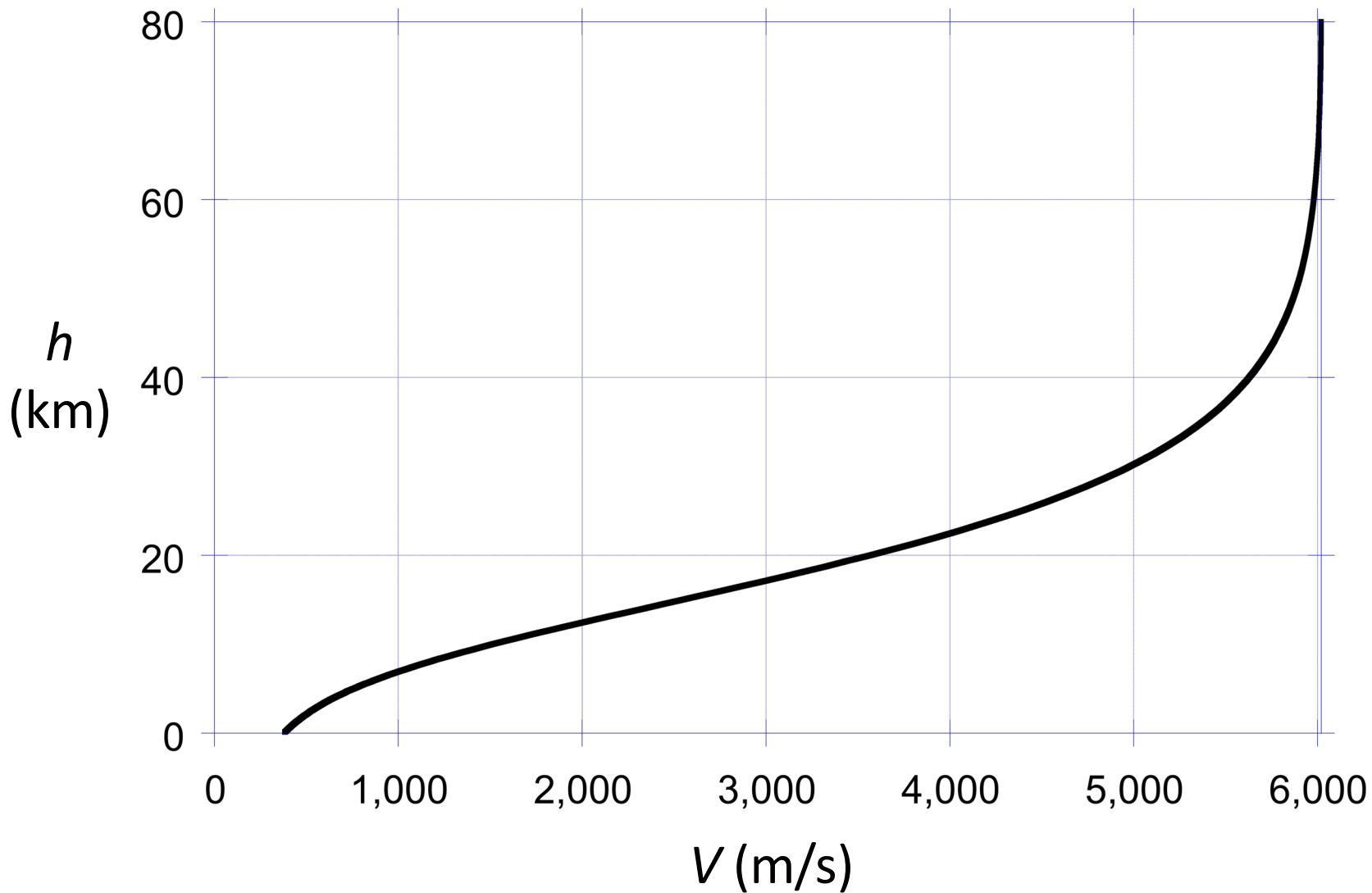
Nondimensionalized wrt. the maximum convective heat rate of the *Baseline Mars Entry*

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

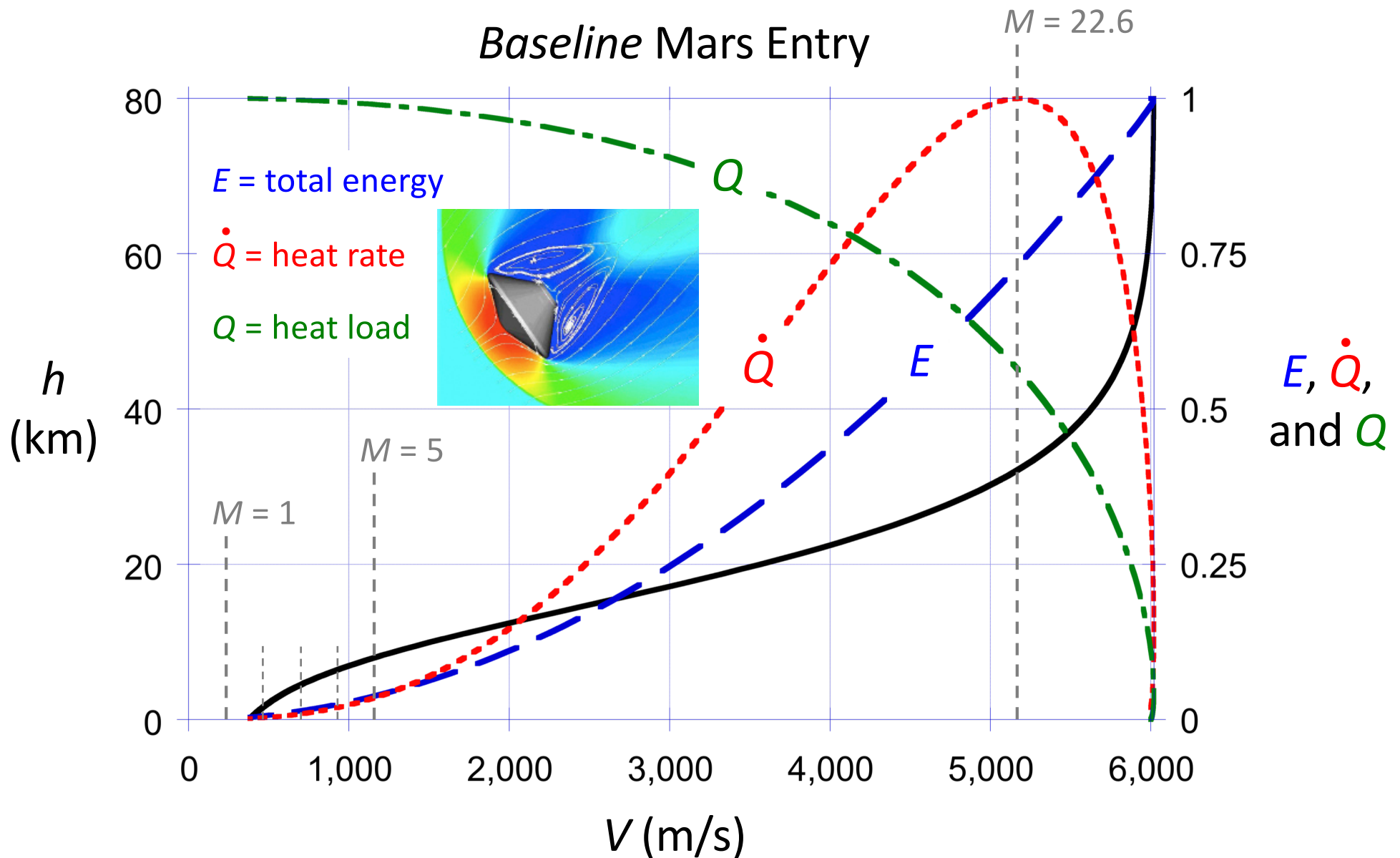
Nondimensionalized wrt. the convective heat load of the *Baseline Mars Entry* at landing

Energy and Aeroheating

Baseline Mars Entry

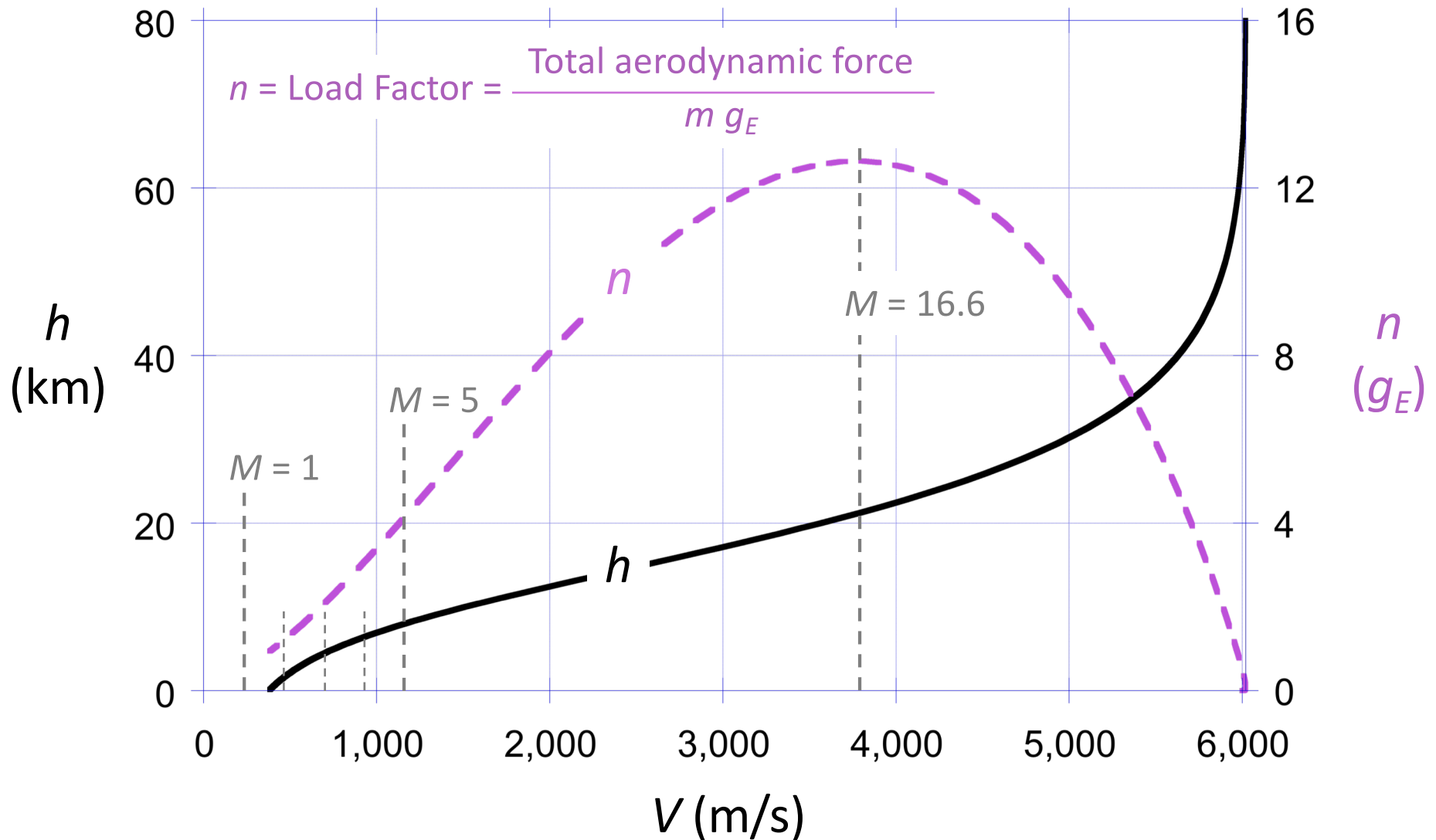


Energy and Aeroheating



Deceleration

Baseline Mars Entry



Key Factors Affecting the Trajectory – Entry Vehicle

Ballistic Coefficient, β

A measure of the entry vehicle aerodynamic loading

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

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

Dimensions: [Mass/Length²]

Typical Unit: kg/m²

For the *Baseline Mars Entry* example in this presentation,
 $\beta = 125 \text{ kg/m}^2$

Key Factors Affecting the Trajectory – Entry Vehicle

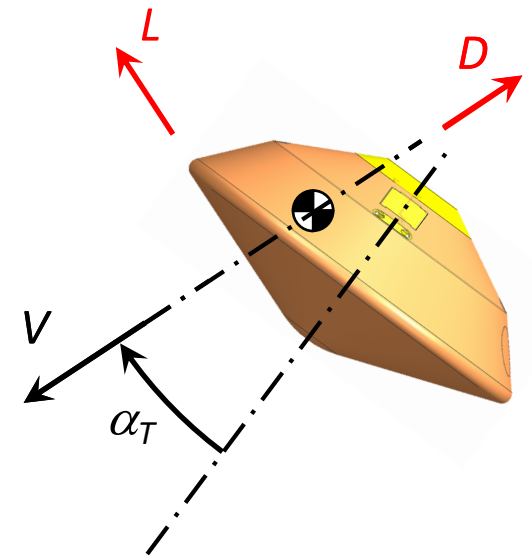
Lift to Drag Ratio, L/D

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 $\alpha_T = 0^\circ$ 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 $\alpha_T \neq 0^\circ$.
- At $\alpha_T \neq 0^\circ$ 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.



Key Factors Affecting the Trajectory – Initial Conditions

Also influencing the trajectory are the initial conditions:

At an initial altitude, h_i

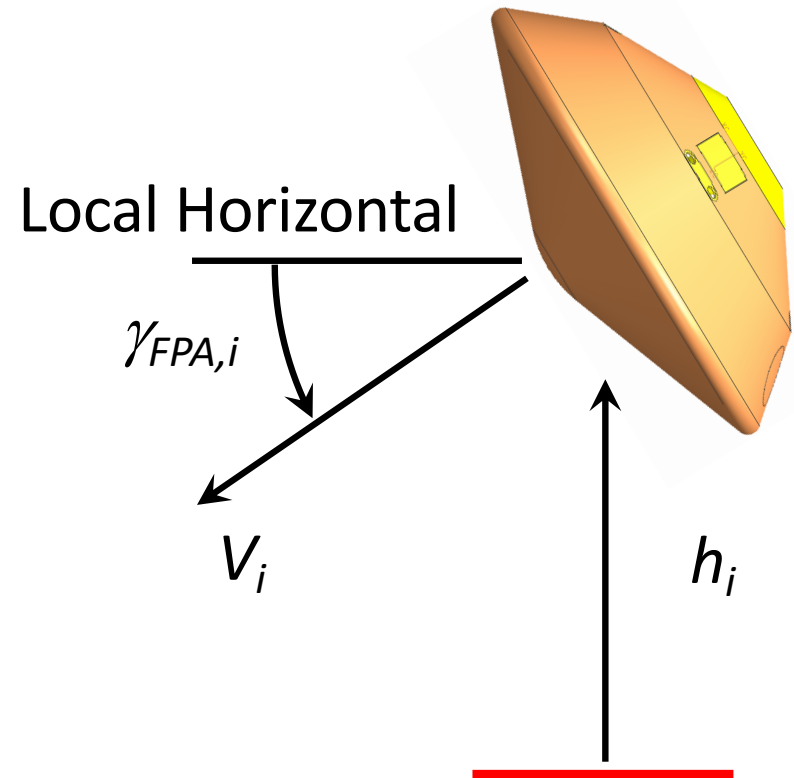
- initial velocity, V_i
- initial flight path angle, $\gamma_{FPA,i}$ (negative as shown)

For the *Baseline Mars Entry* in this presentation:

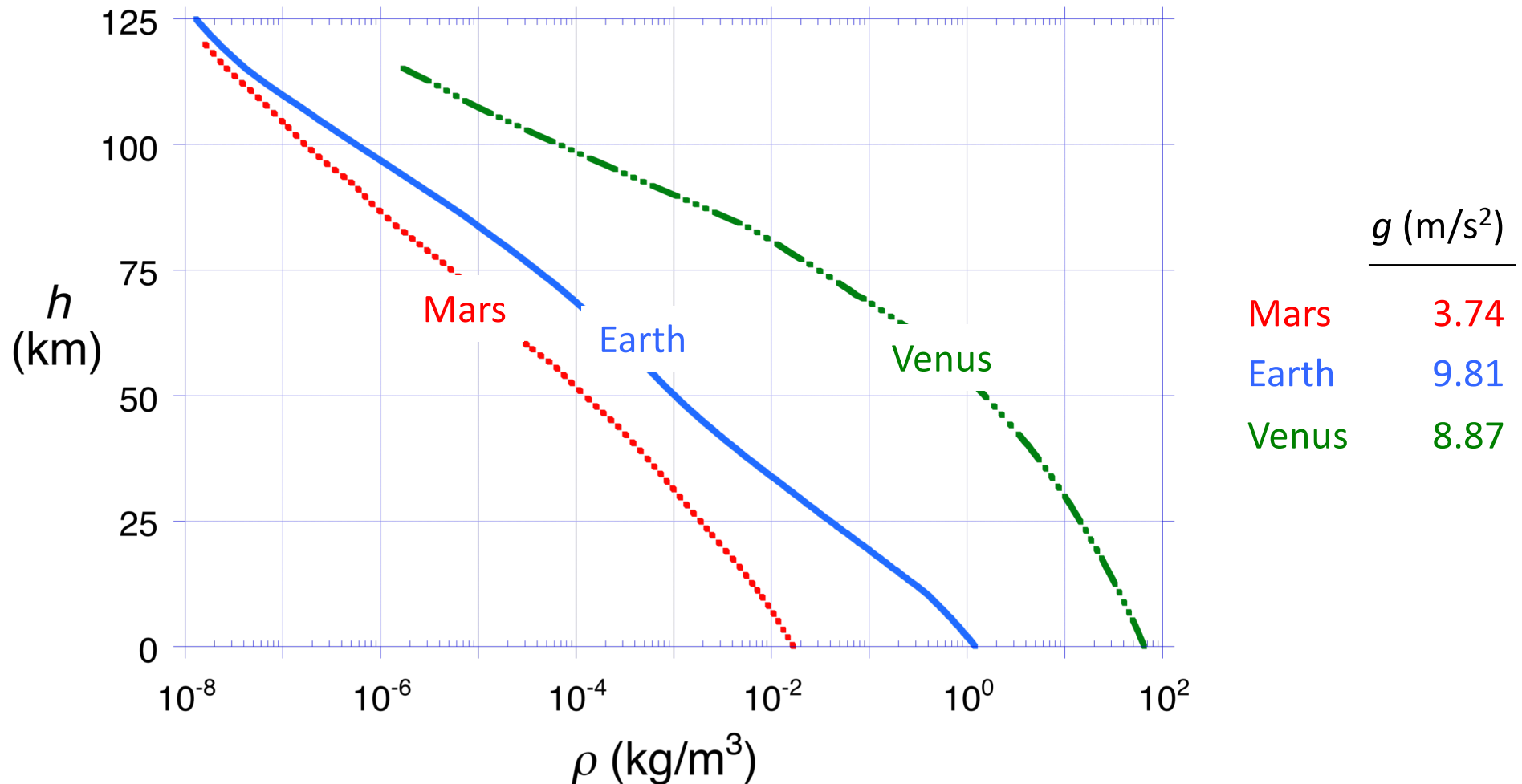
$$h_i = 125 \text{ km}$$

$$V_i = 6,000 \text{ m/s}$$

$$\gamma_{FPA,i} = -15^\circ$$



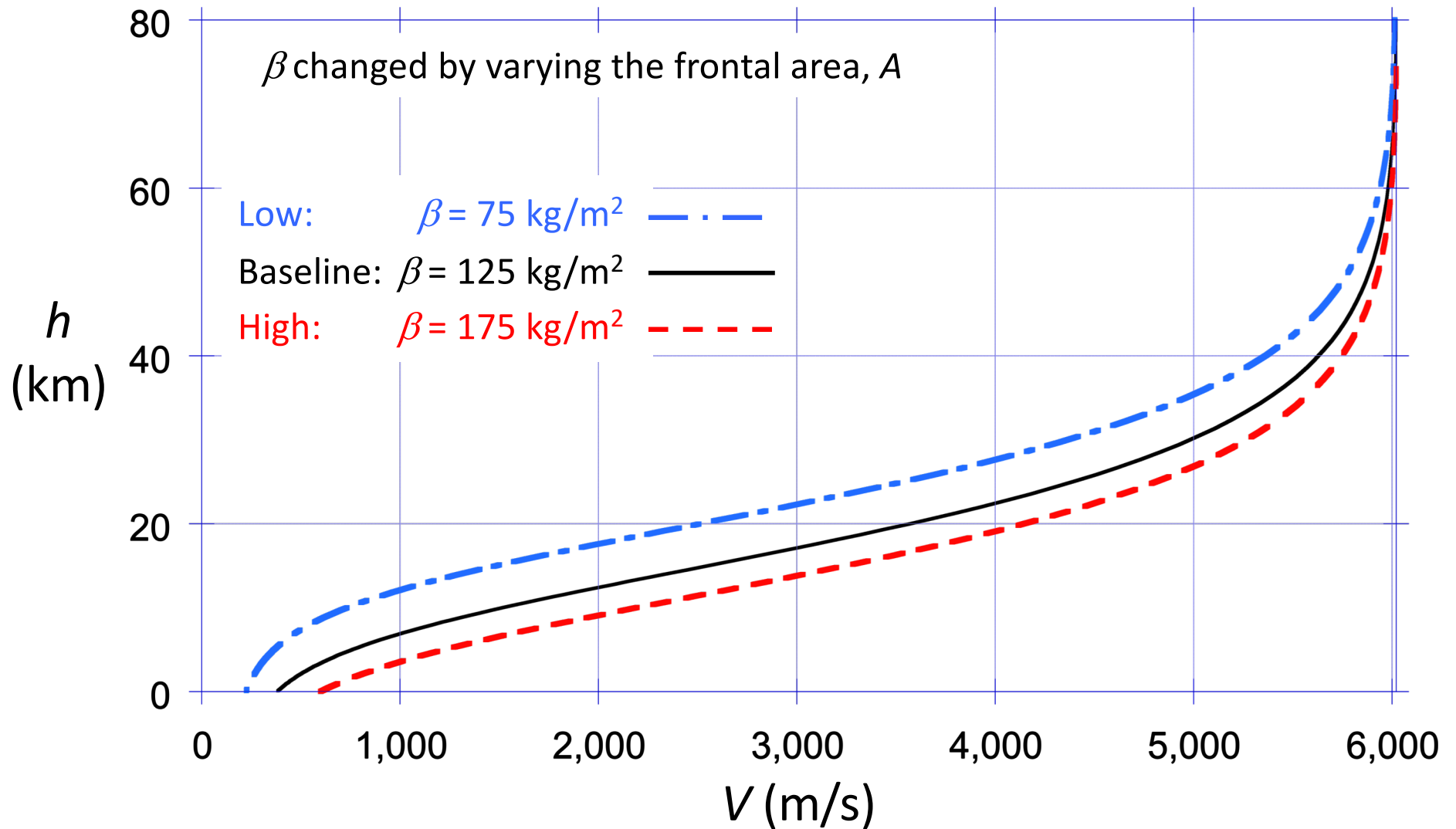
Key Factors Affecting the Trajectory – Atmosphere and Gravity



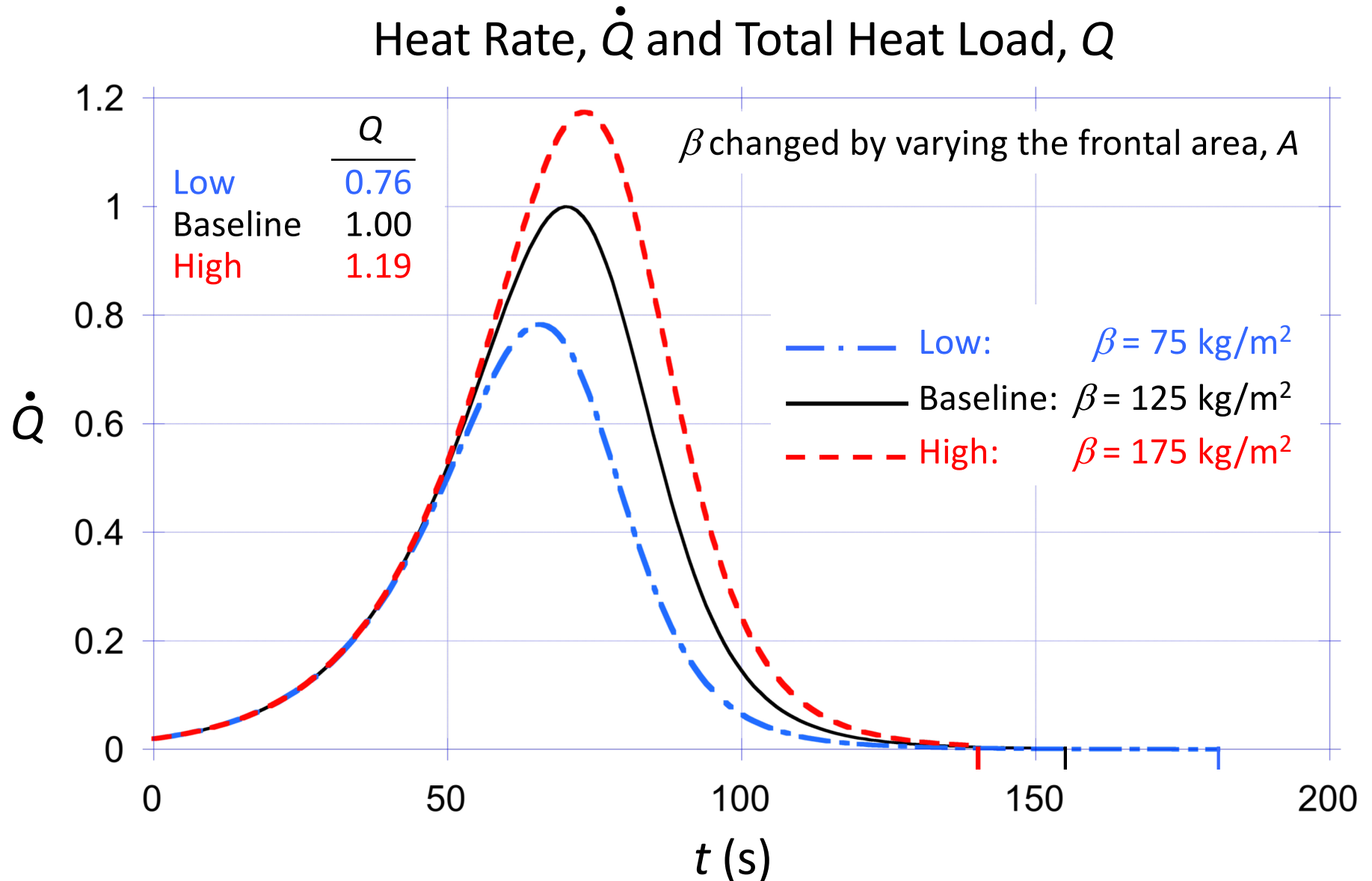
- NOAA, NASA, and USAF: U.S. Standard Atmosphere, 1976, NASA TM X-74335, 1976.
- Seiff, A. et al.: Measurements of Thermal Structure and Thermal Contrasts in the Atmosphere of Venus and Related Dynamical Observations: Results from the four Pioneer Venus Probes, *Journal of Geophysical Research*, Vol. 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

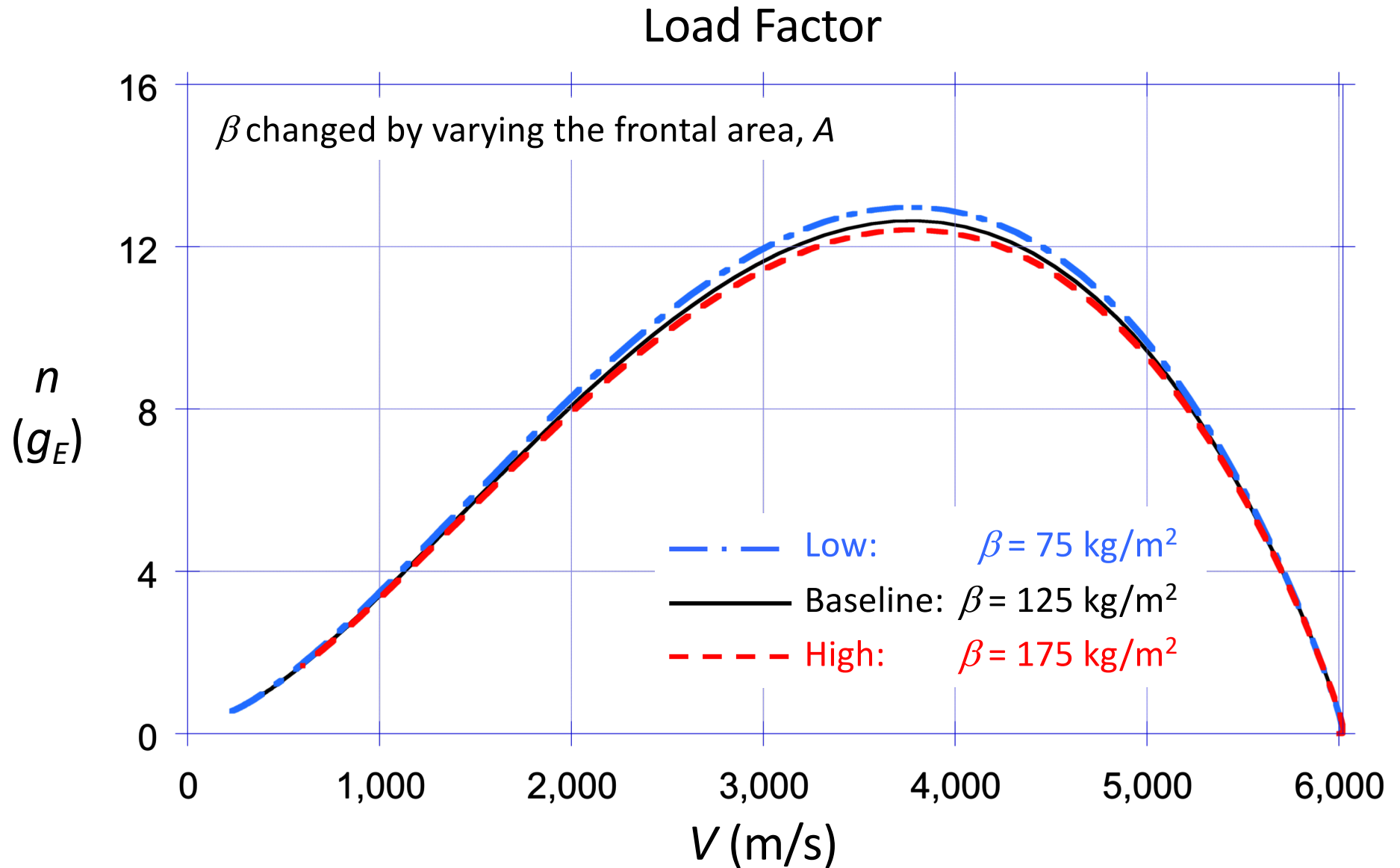
Trajectory



Effect of Ballistic Coefficient

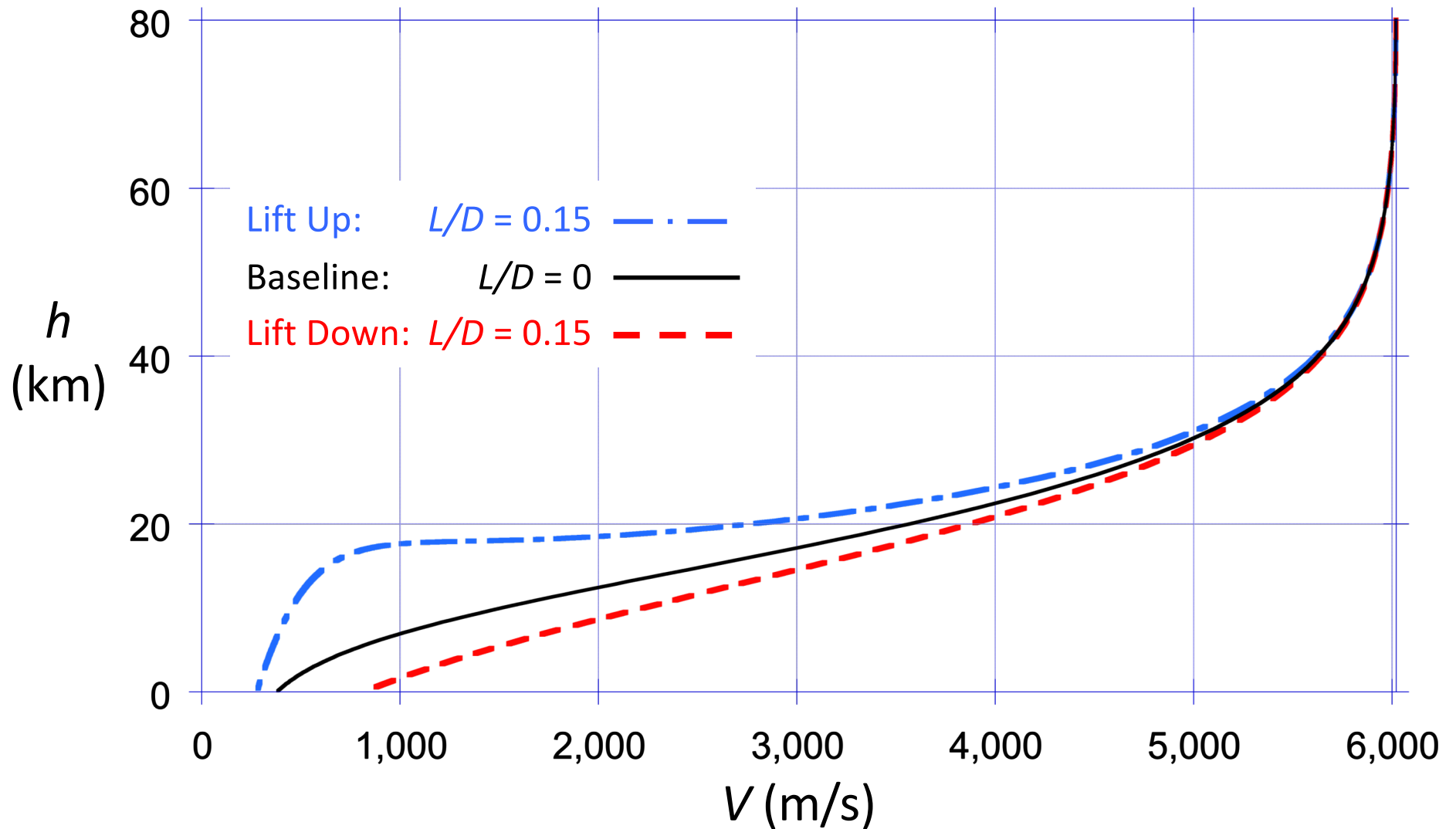


Effect of Ballistic Coefficient

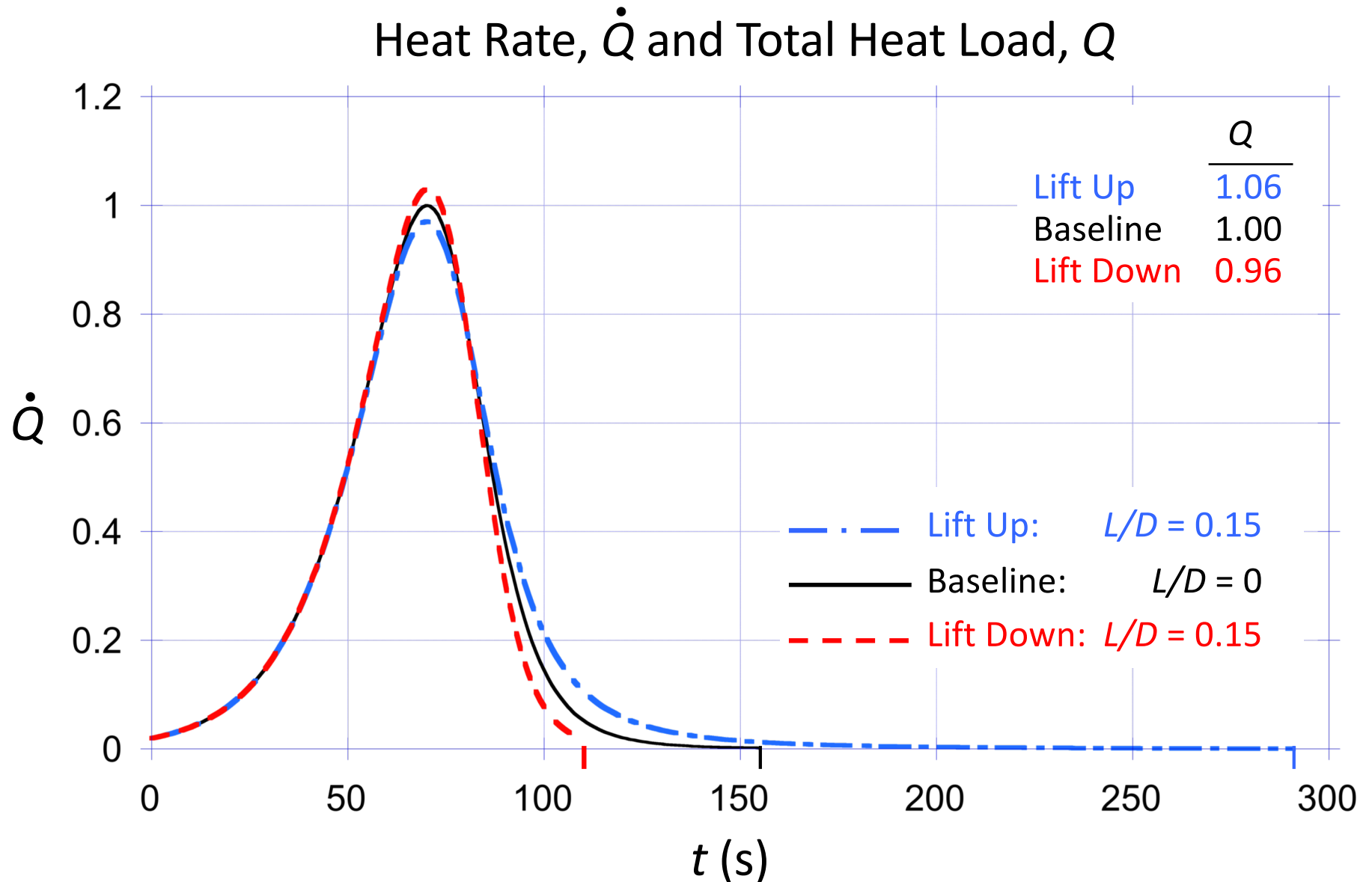


Effect of Lift

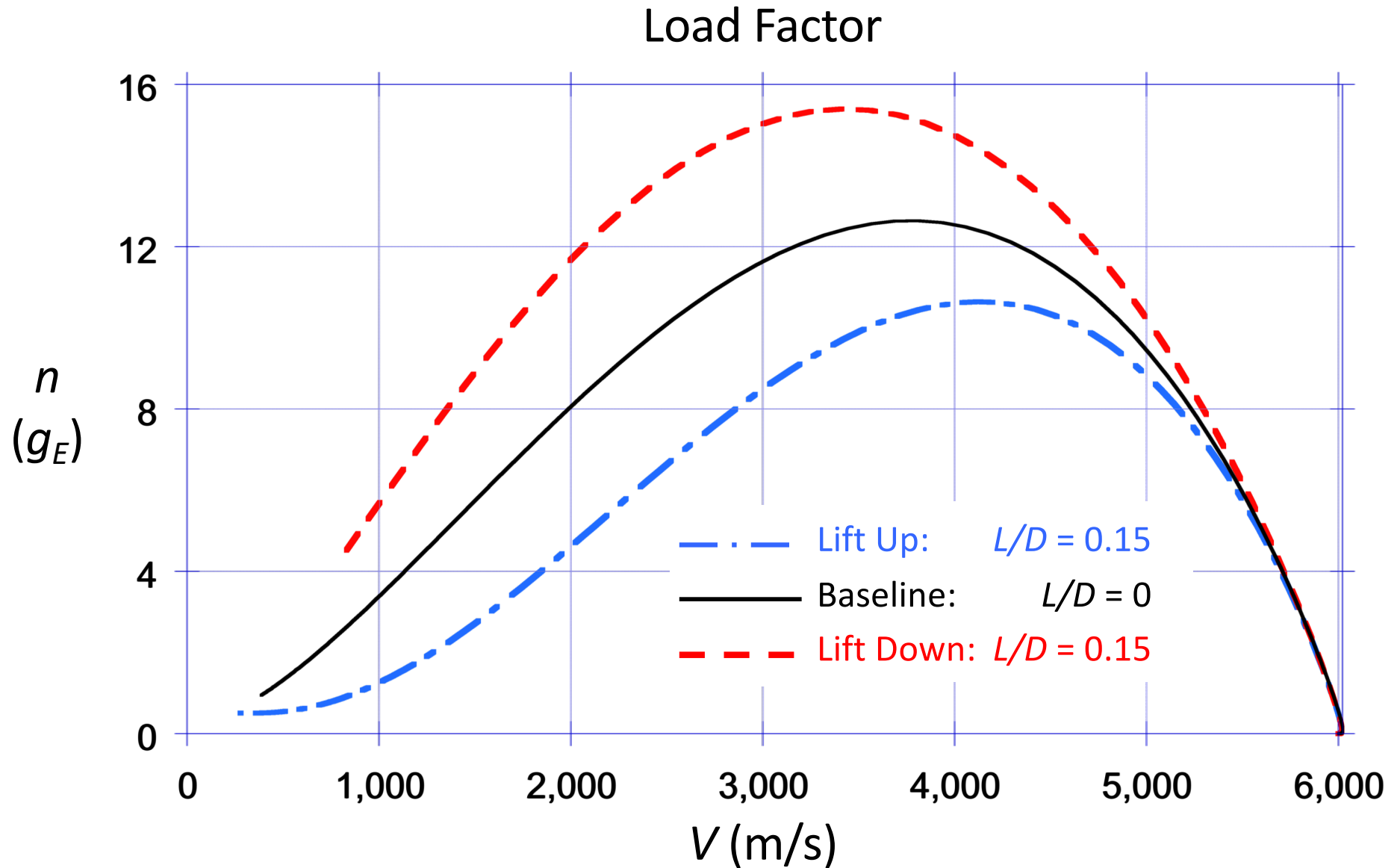
Trajectory



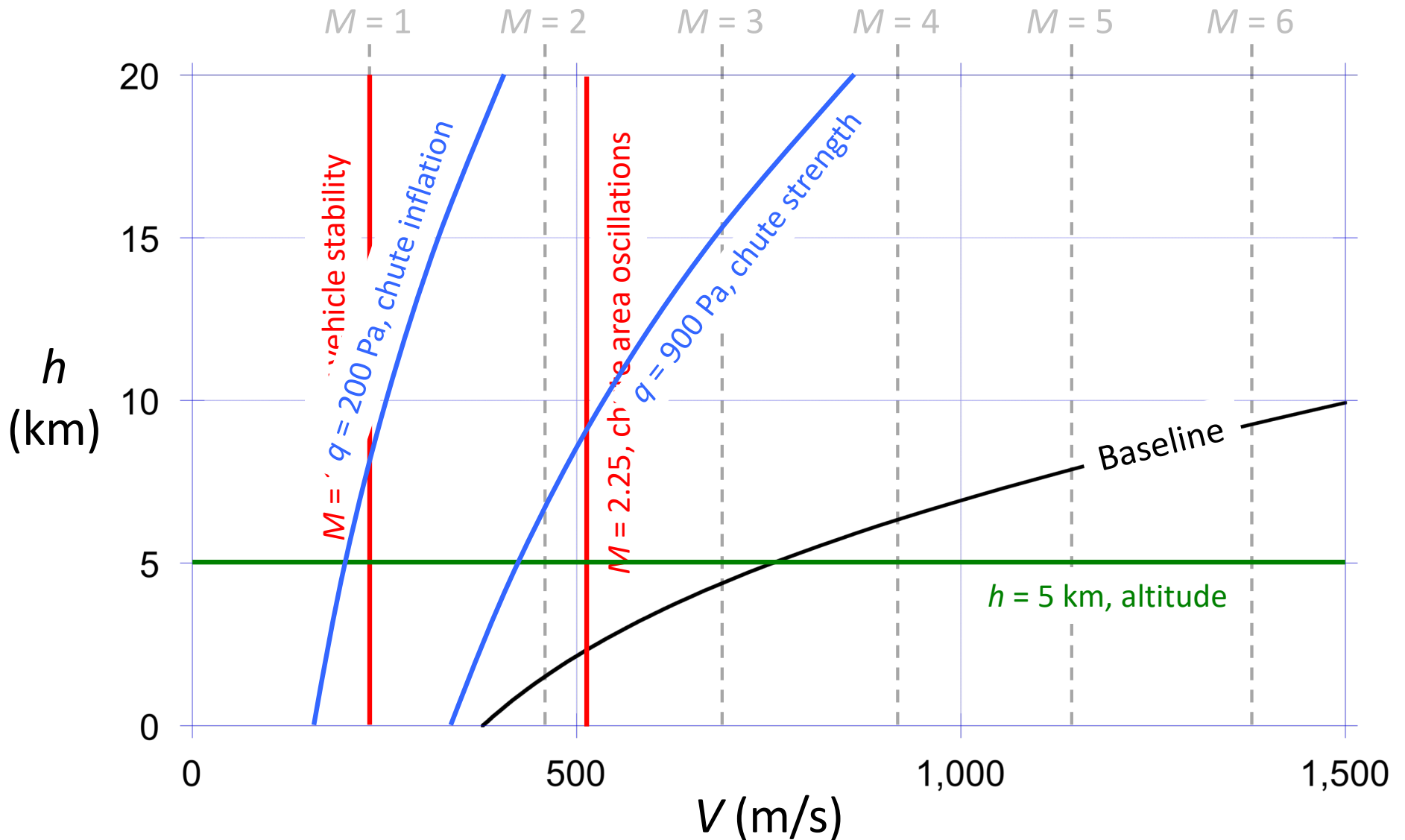
Effect of Lift



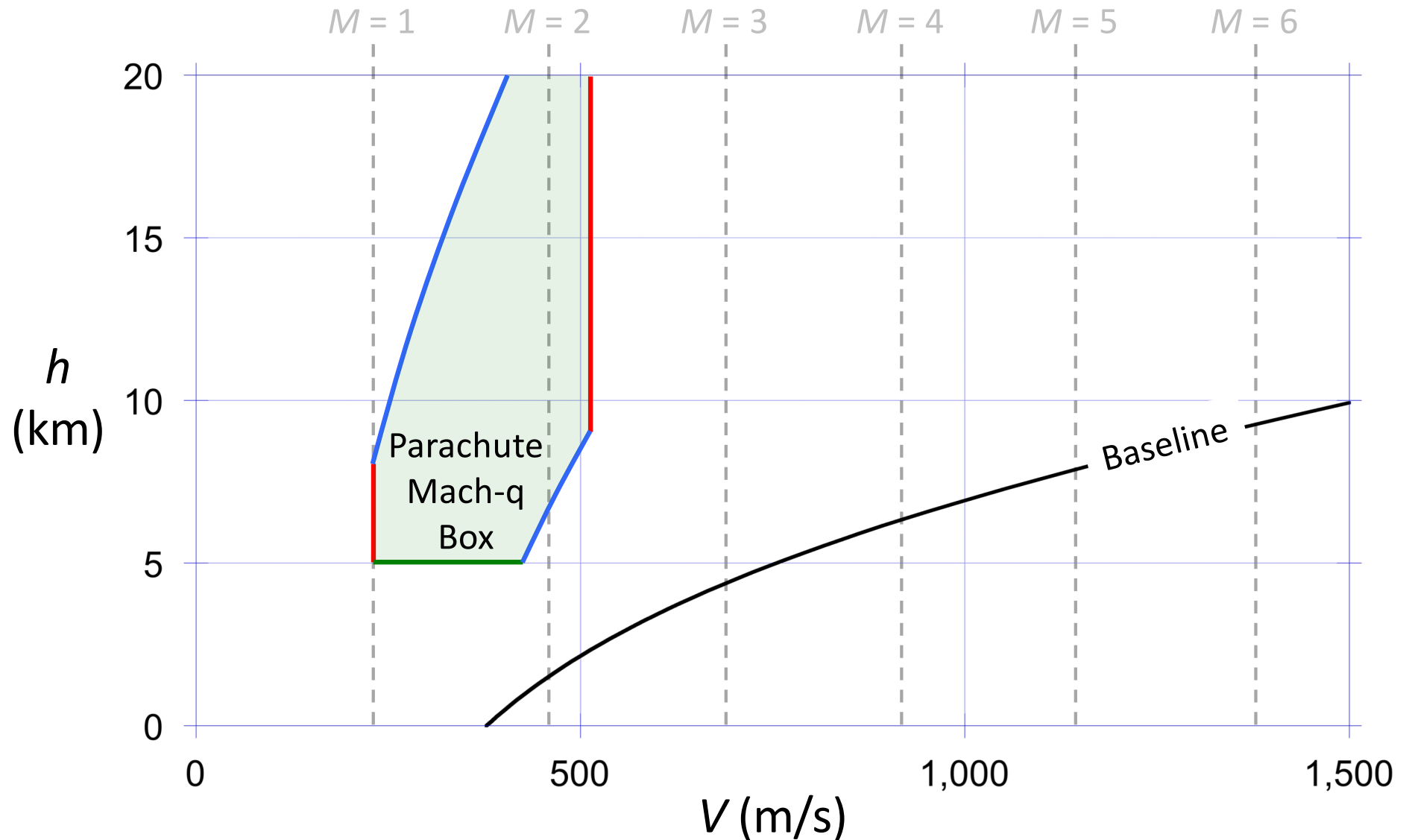
Effect of Lift



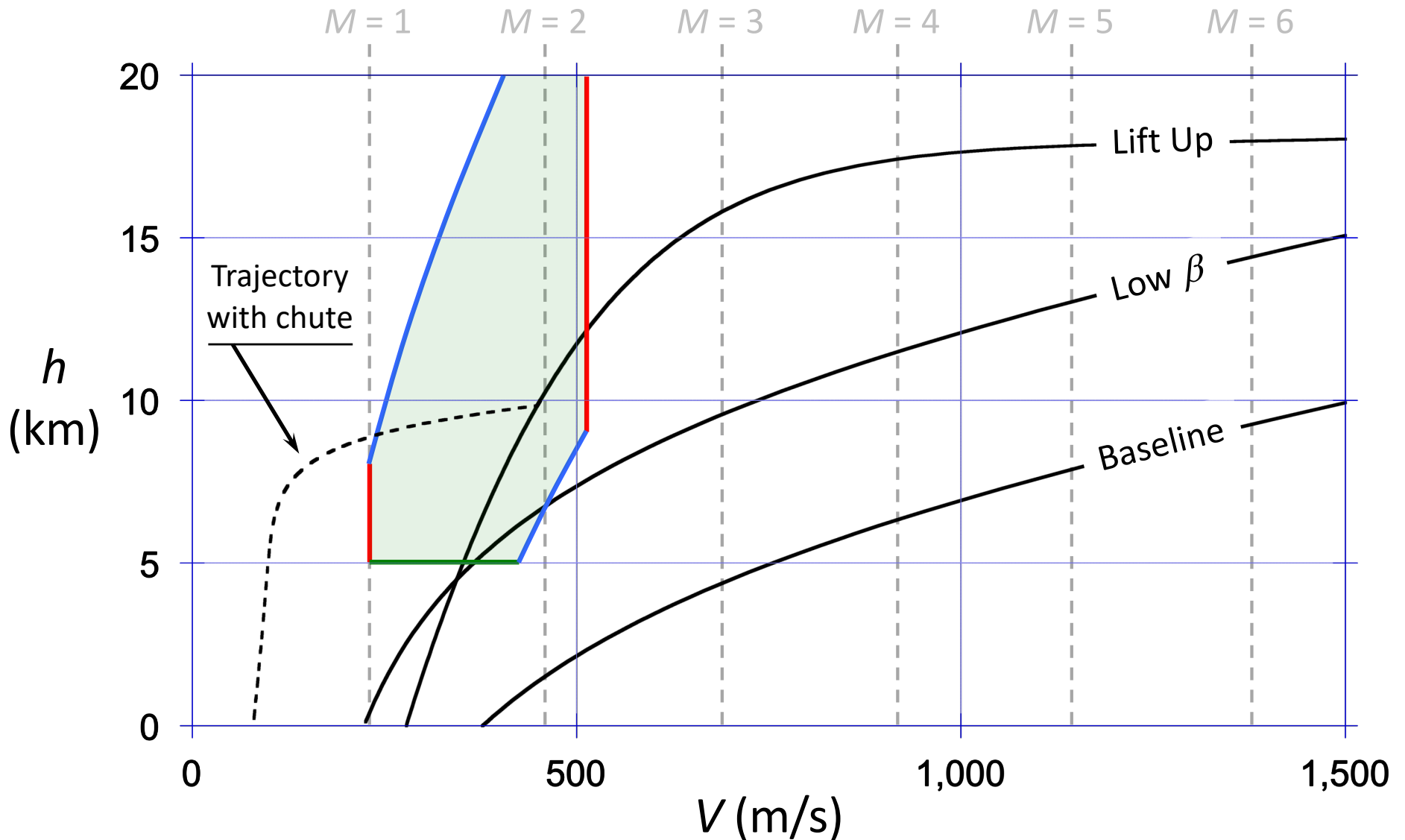
Descent: Parachutes, IADs, and the Mach-q Box



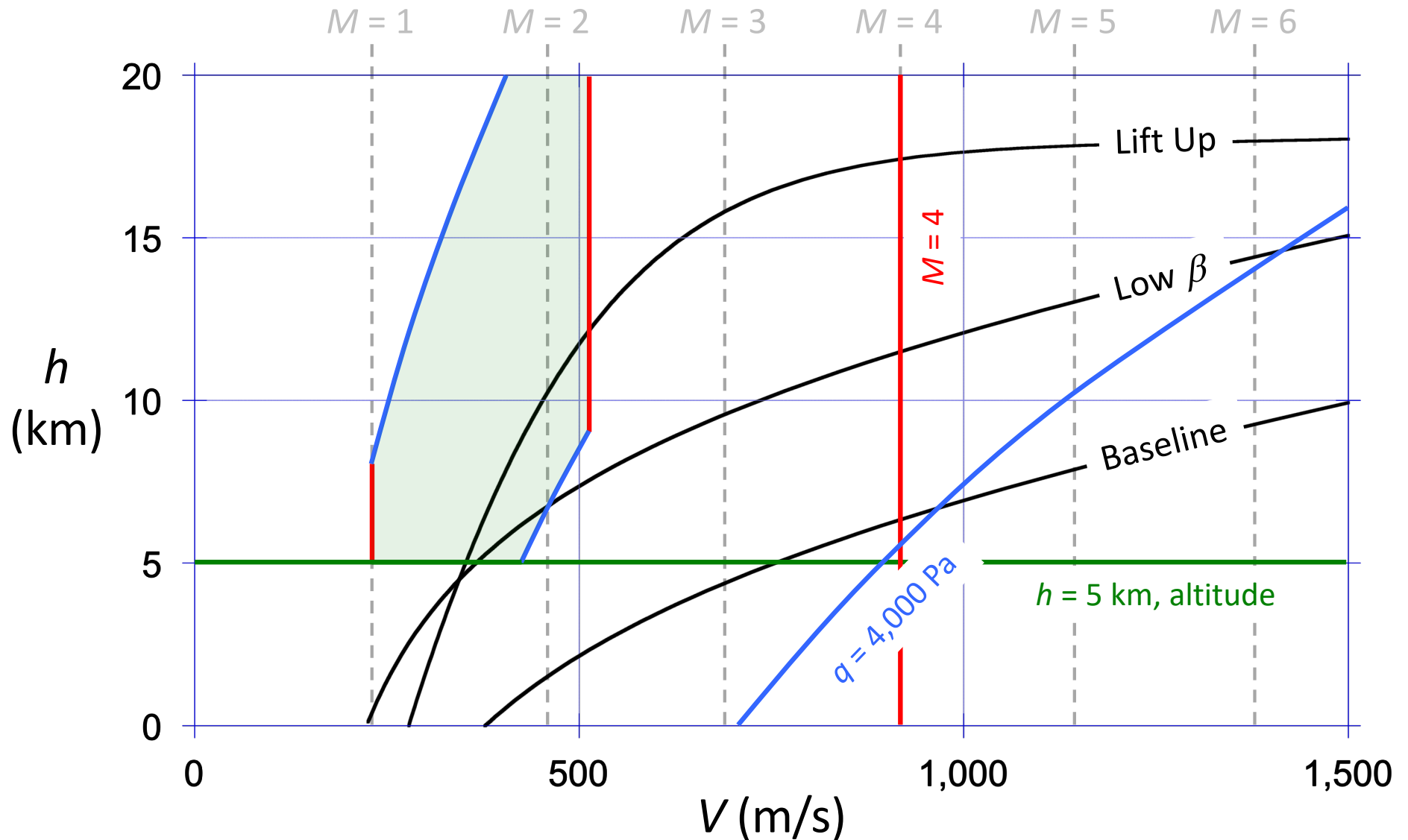
Descent: Parachutes, IADs, and the Mach-q Box



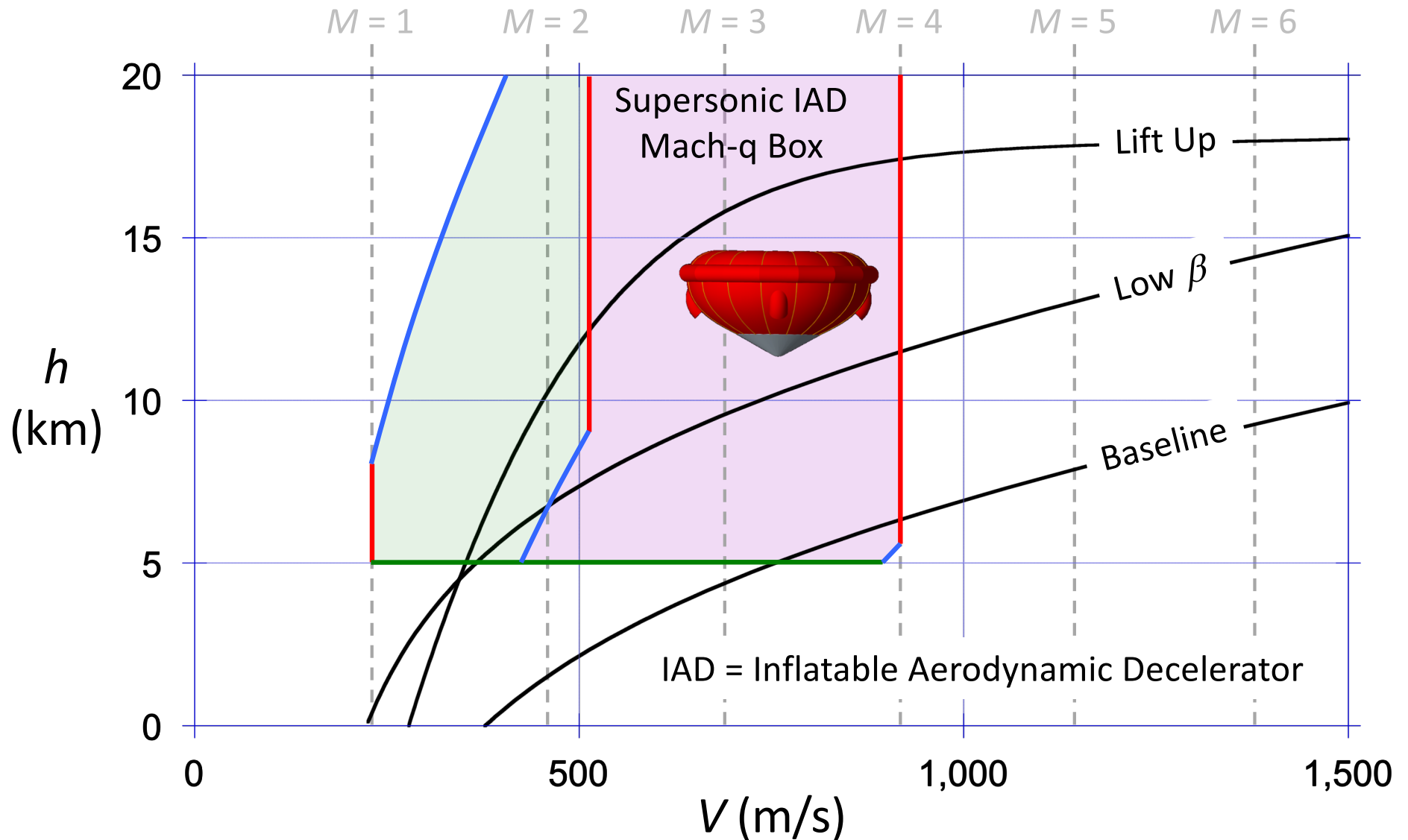
Descent: Parachutes, IADs, and the Mach-q Box



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



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



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