INTRODUCTION TO TRAJECTORIES

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Entry, Descent, and Landing Systems Short Course
10th International Planetary Probe Workshop
San Jose, California
June 15-21, 2013

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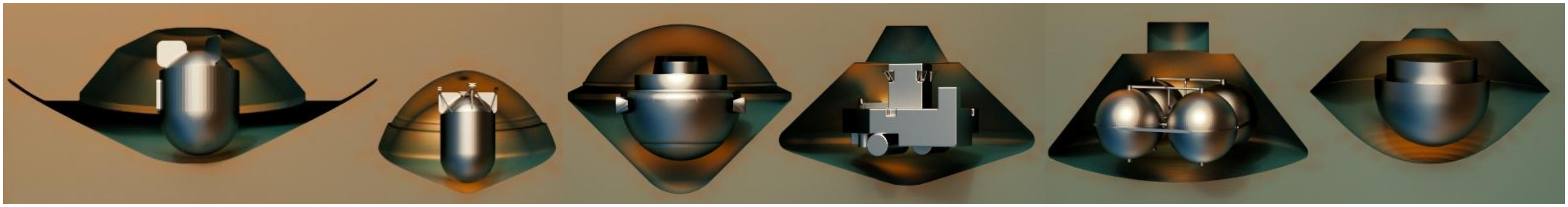

Entry, Descent, and Landing Systems Short Course

Subject: Introduction to Trajectories

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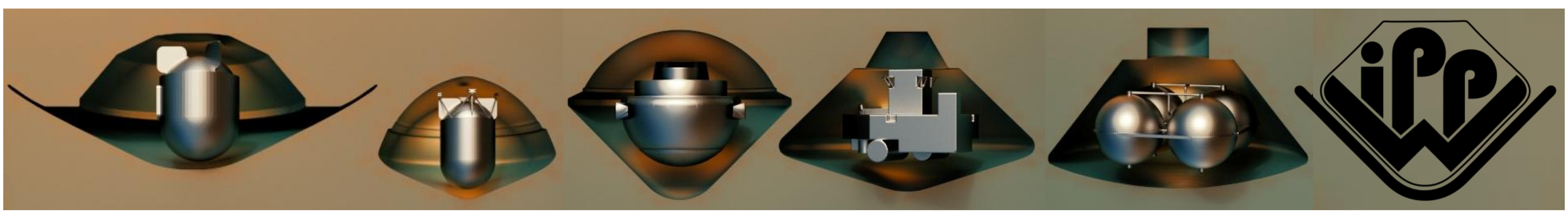

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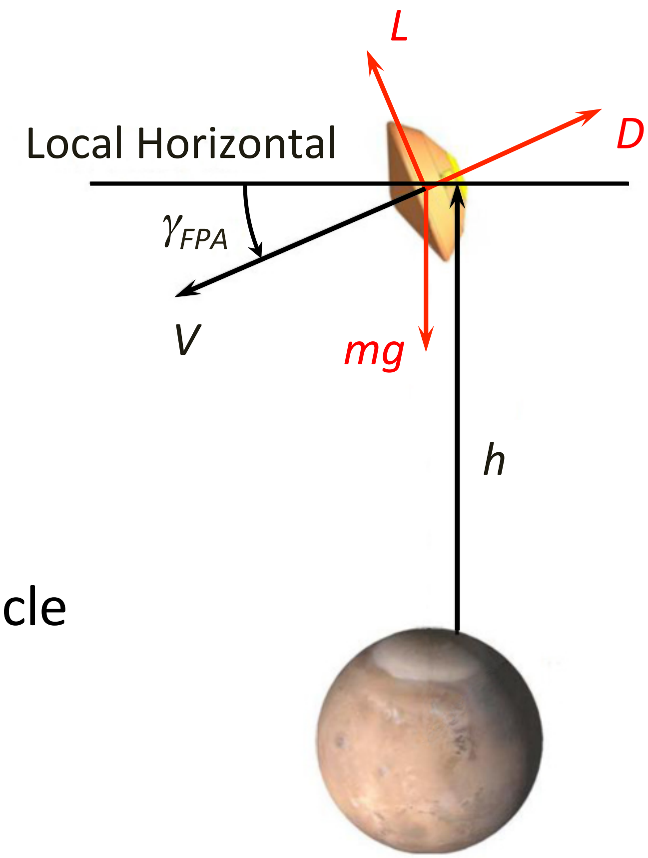
Definition of Trajectory

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



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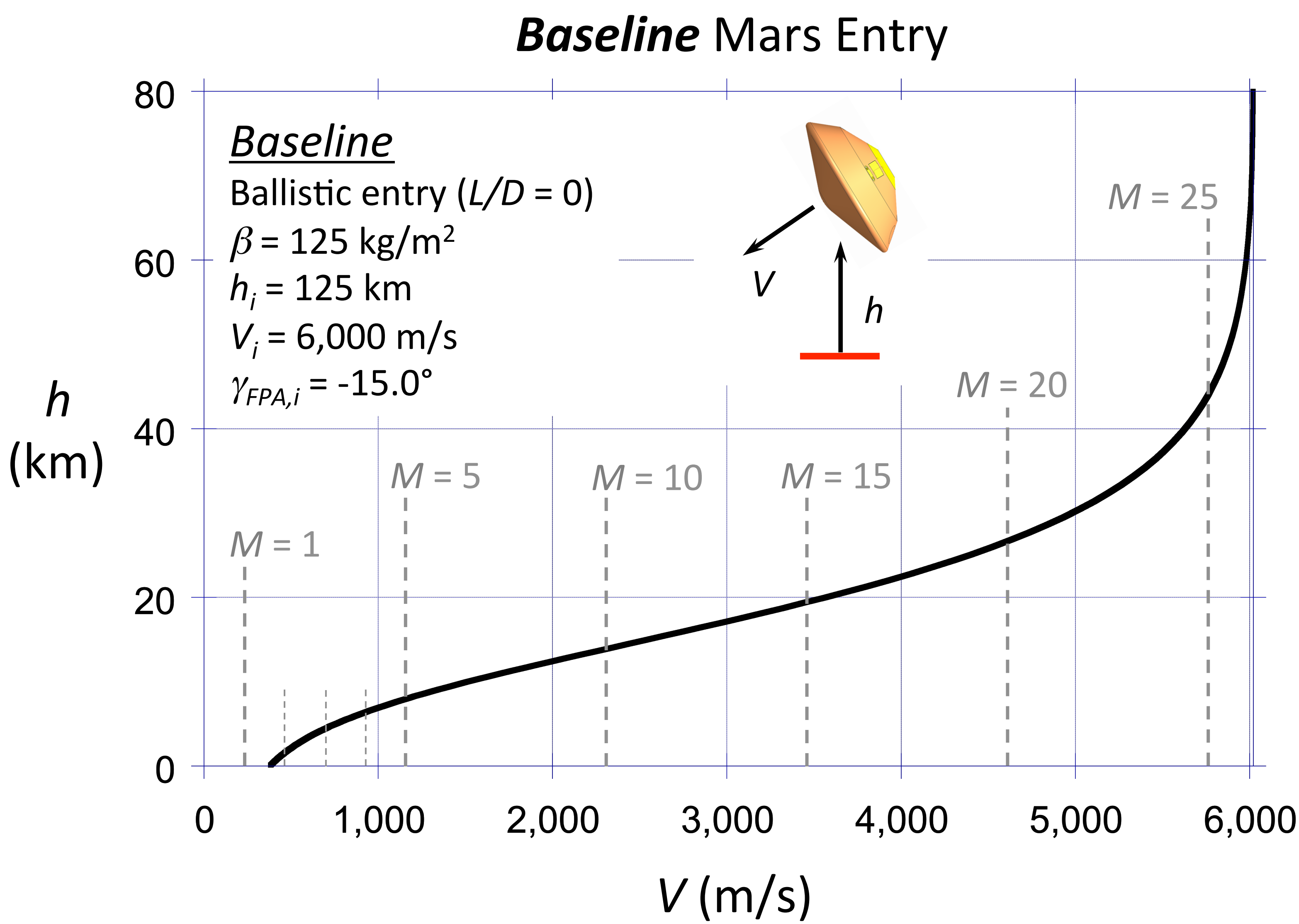
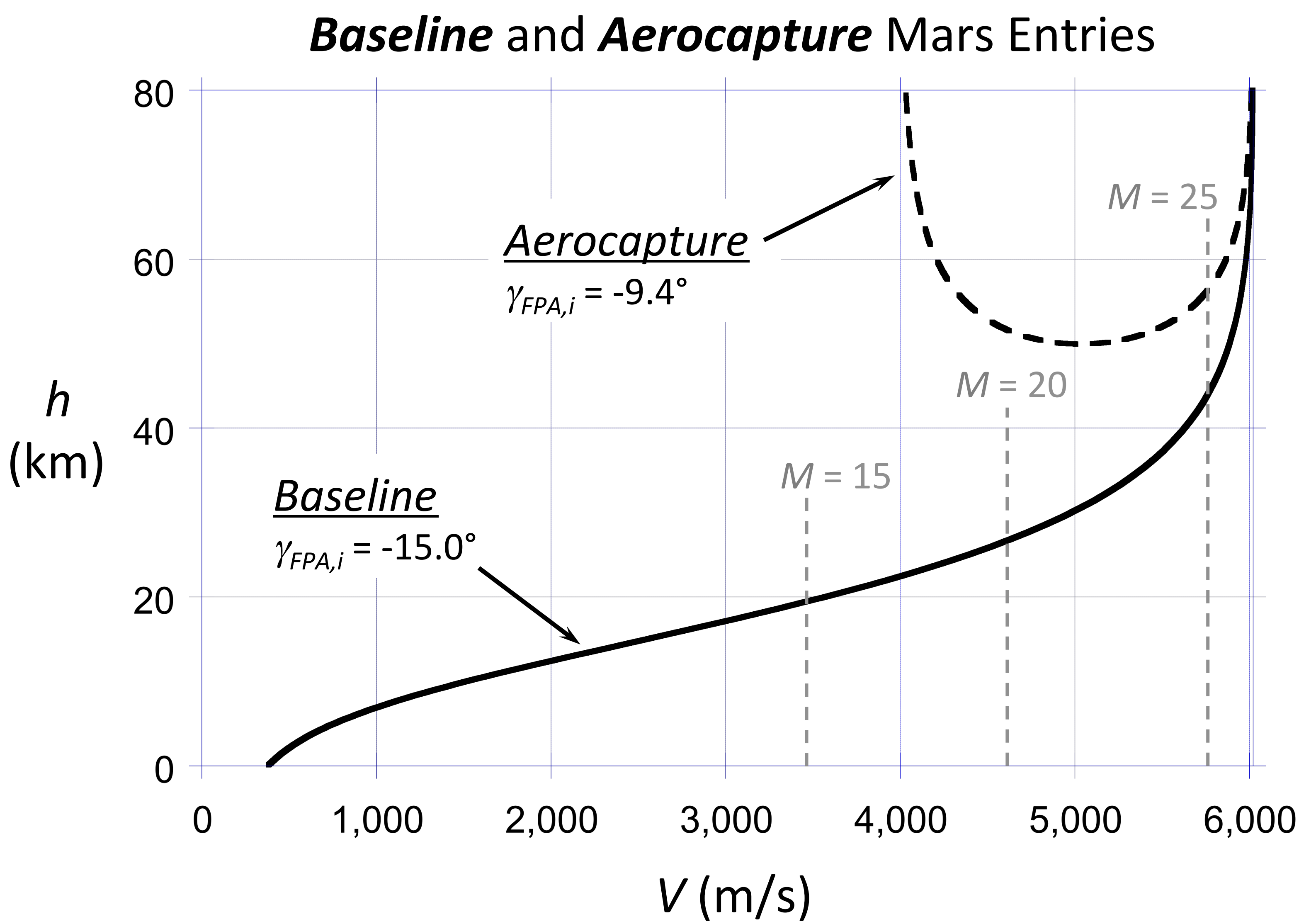
Velocity-Altitude Diagram



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

Equations for these quantities are shown on slides 34 and 35.

Energy and Aeroheating

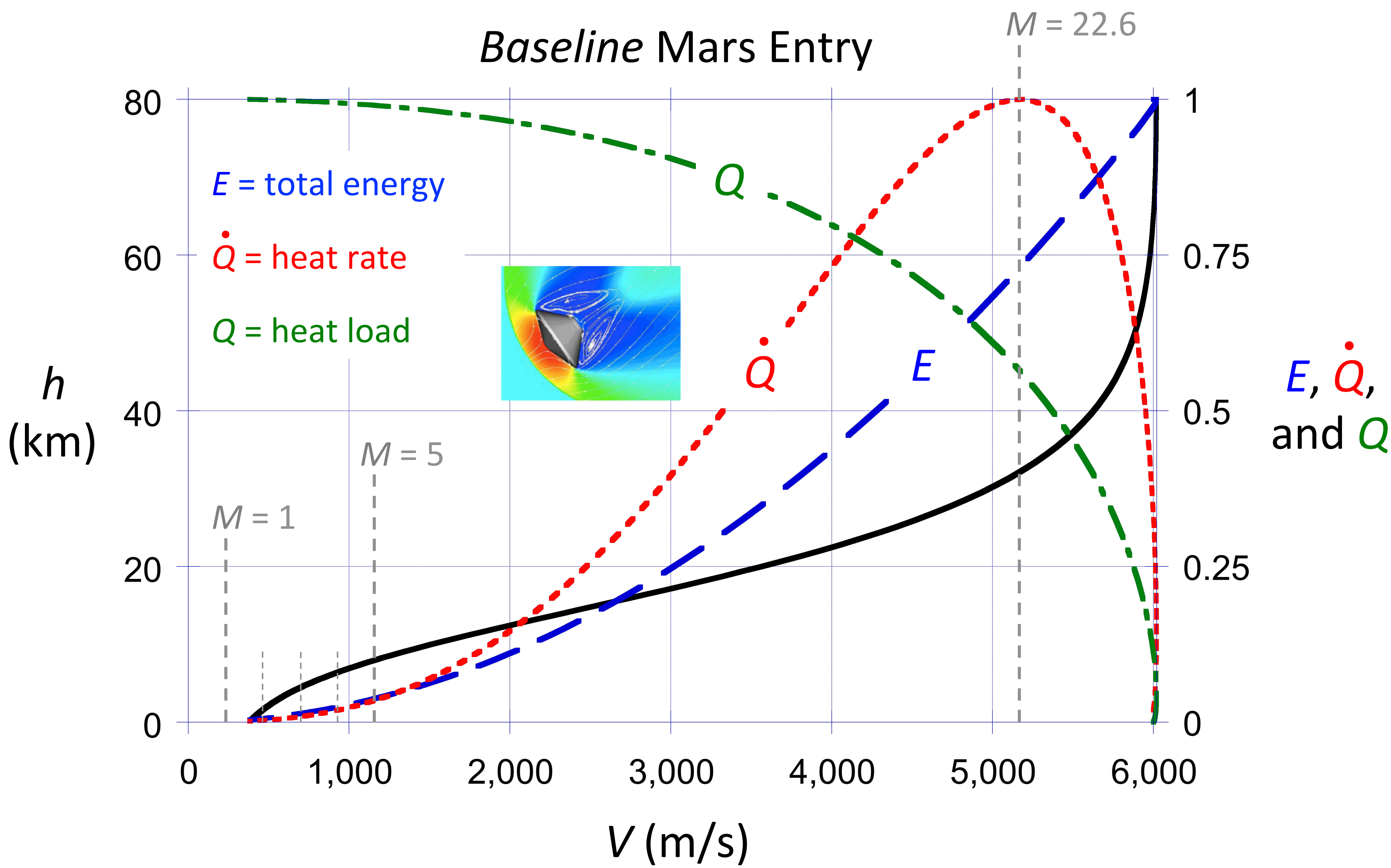
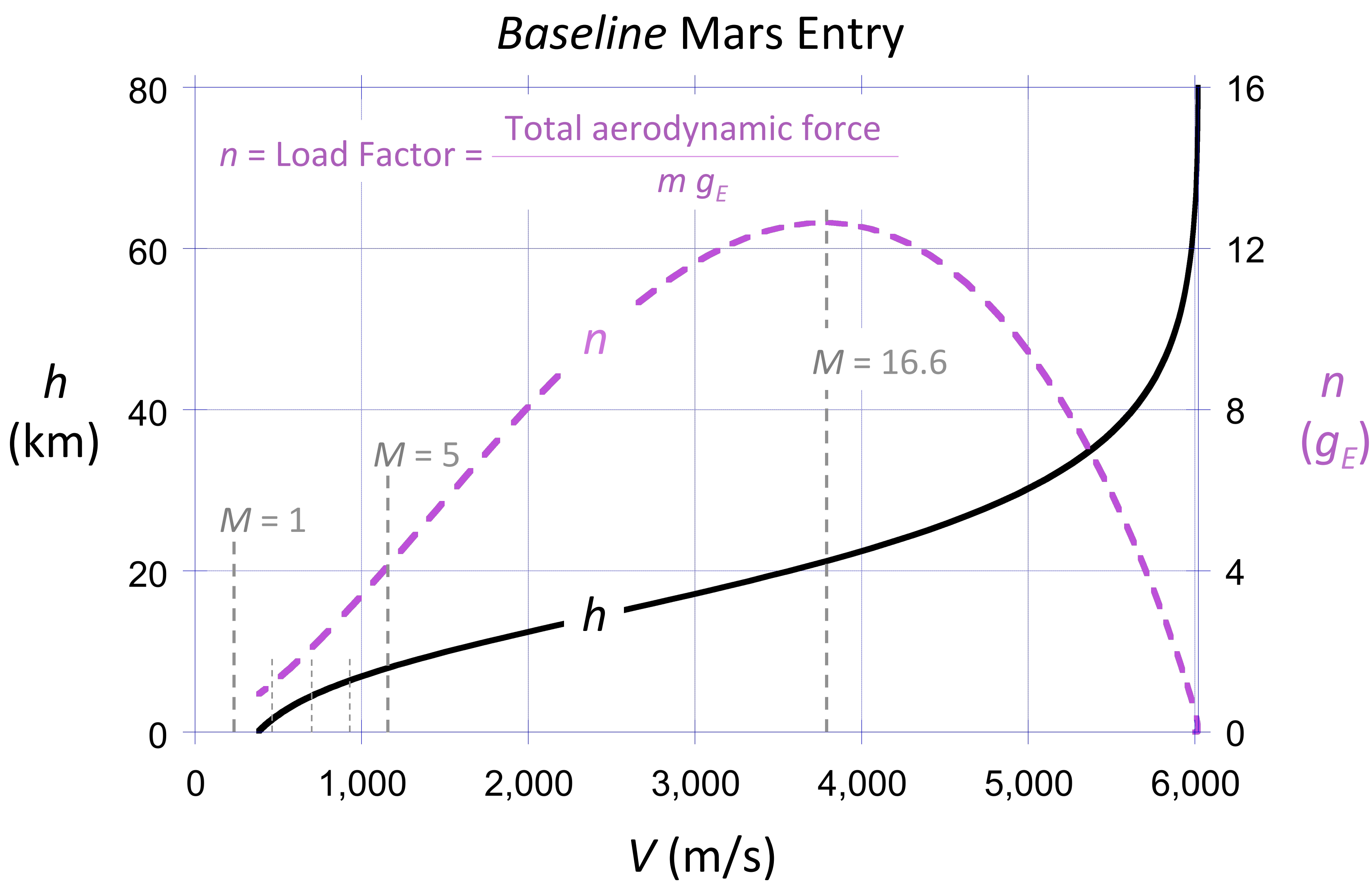


Image credit: NASA

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

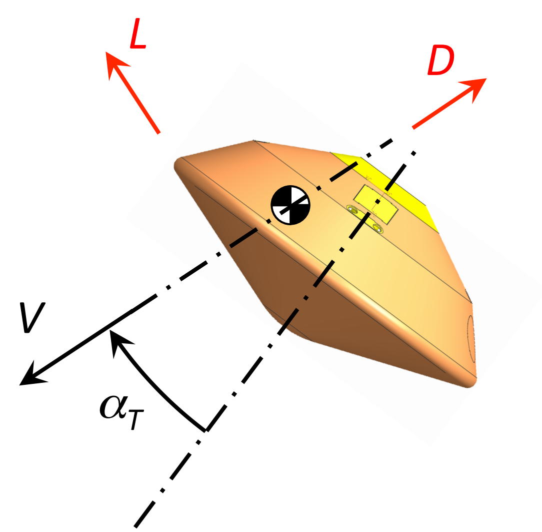
Lift to Drag Ratio, *L/D*

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* ≠ 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

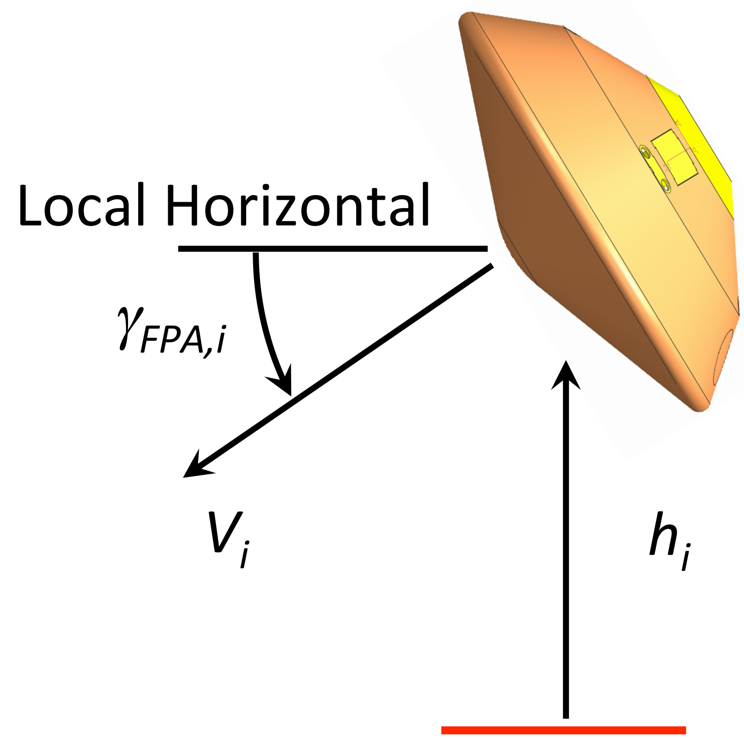
- initial velocity, V_i
- initial flight path angle, $\gamma_{FPA,i}$ (negative as shown)

For the *Baseline Mars Entry* in this presentation:

h_i = 125 km

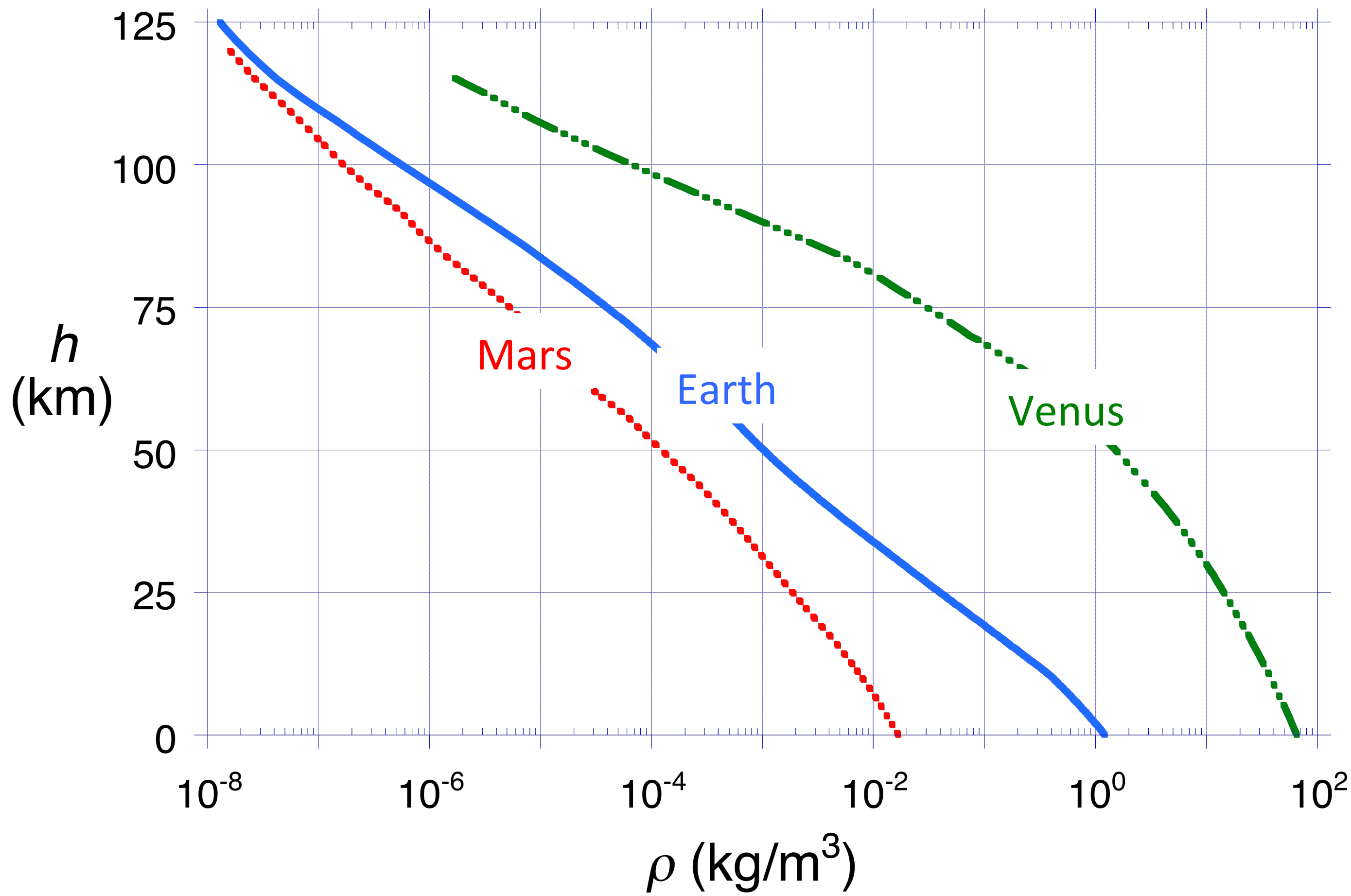
V_i = 6,000 m/s

$\gamma_{FPA,i}$ = -15°



Entry vehicle image credit: NASA / JPL-Caltech

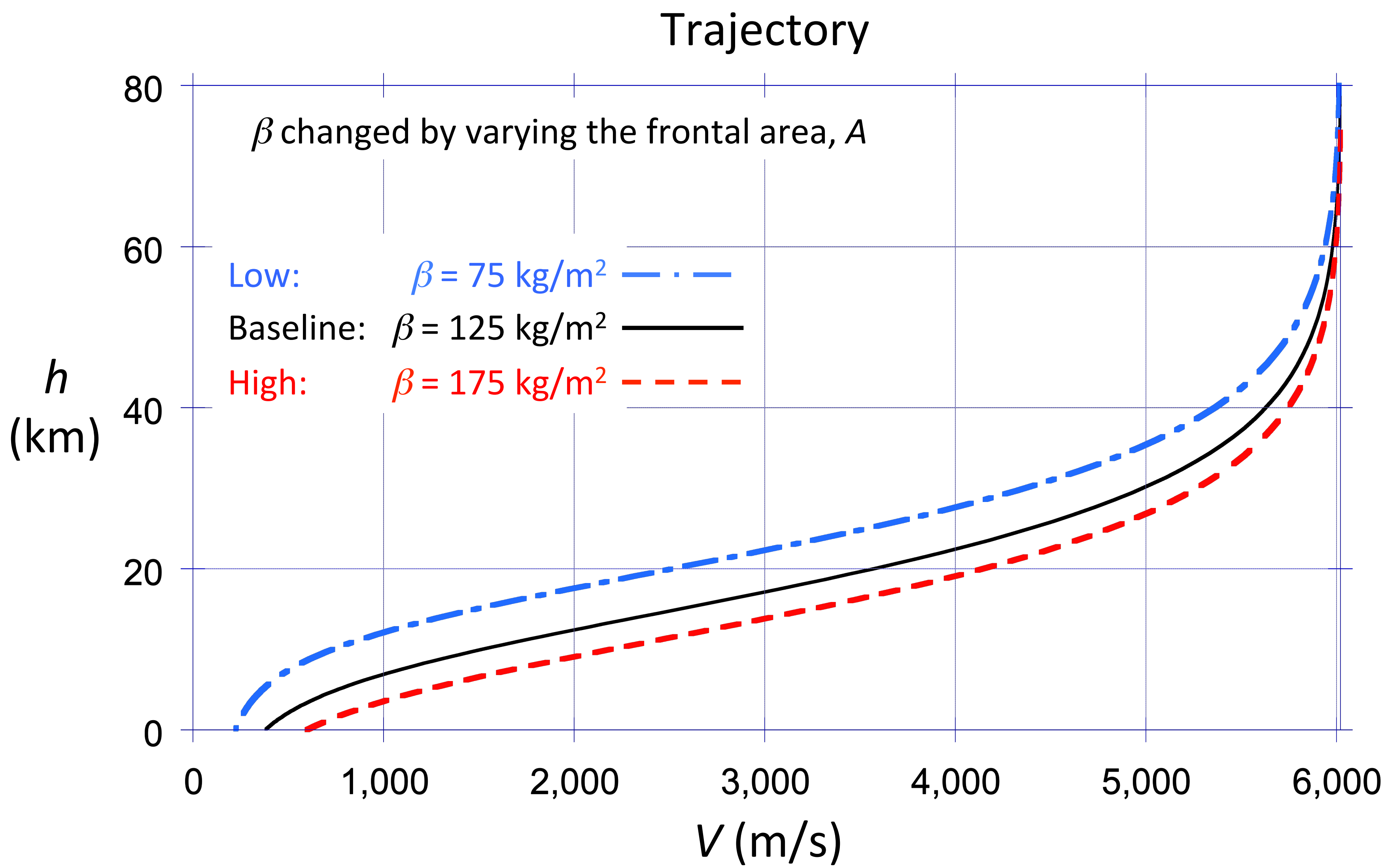
Key Factors Affecting the Trajectory – Atmosphere and Gravity



	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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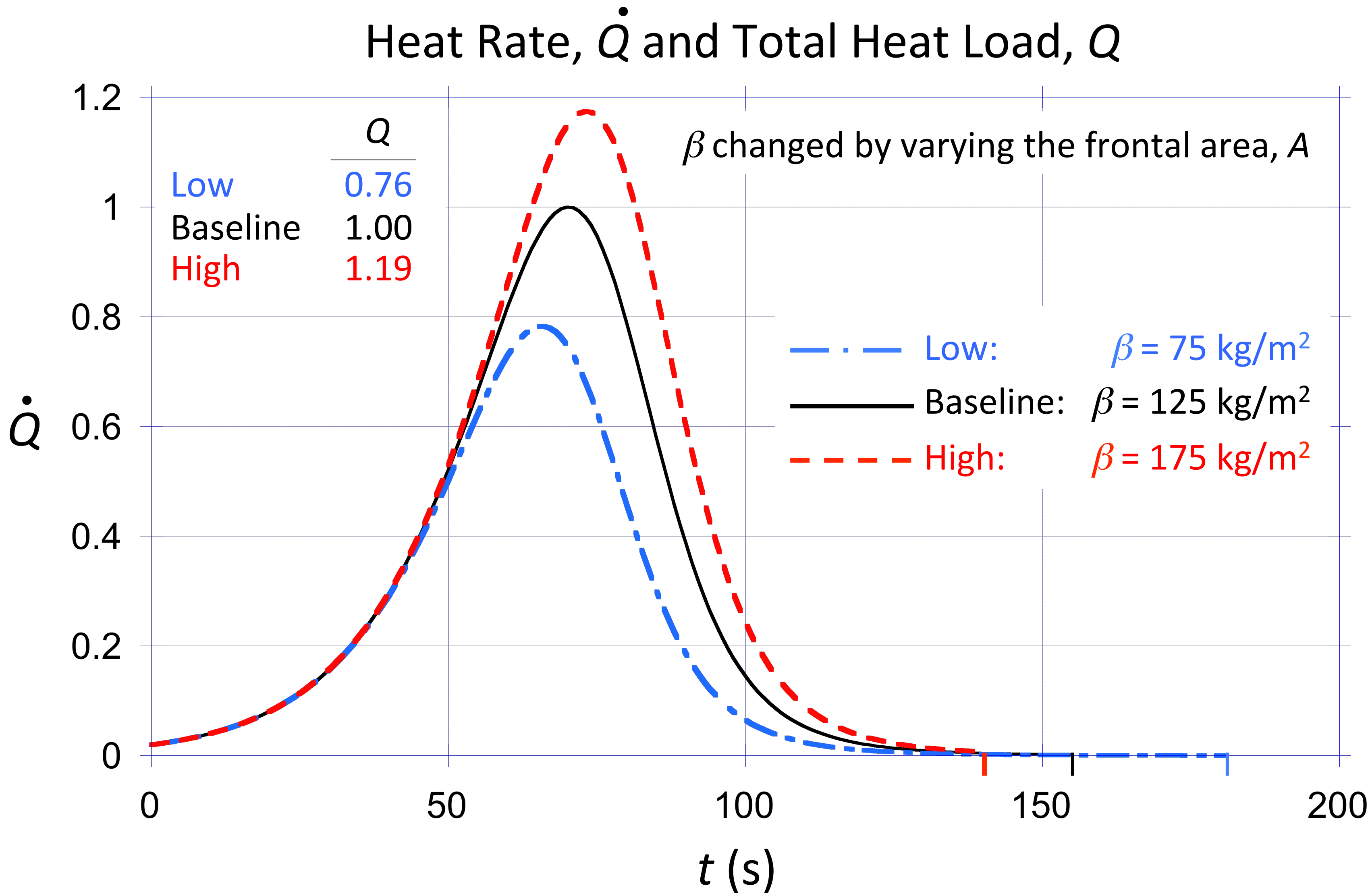

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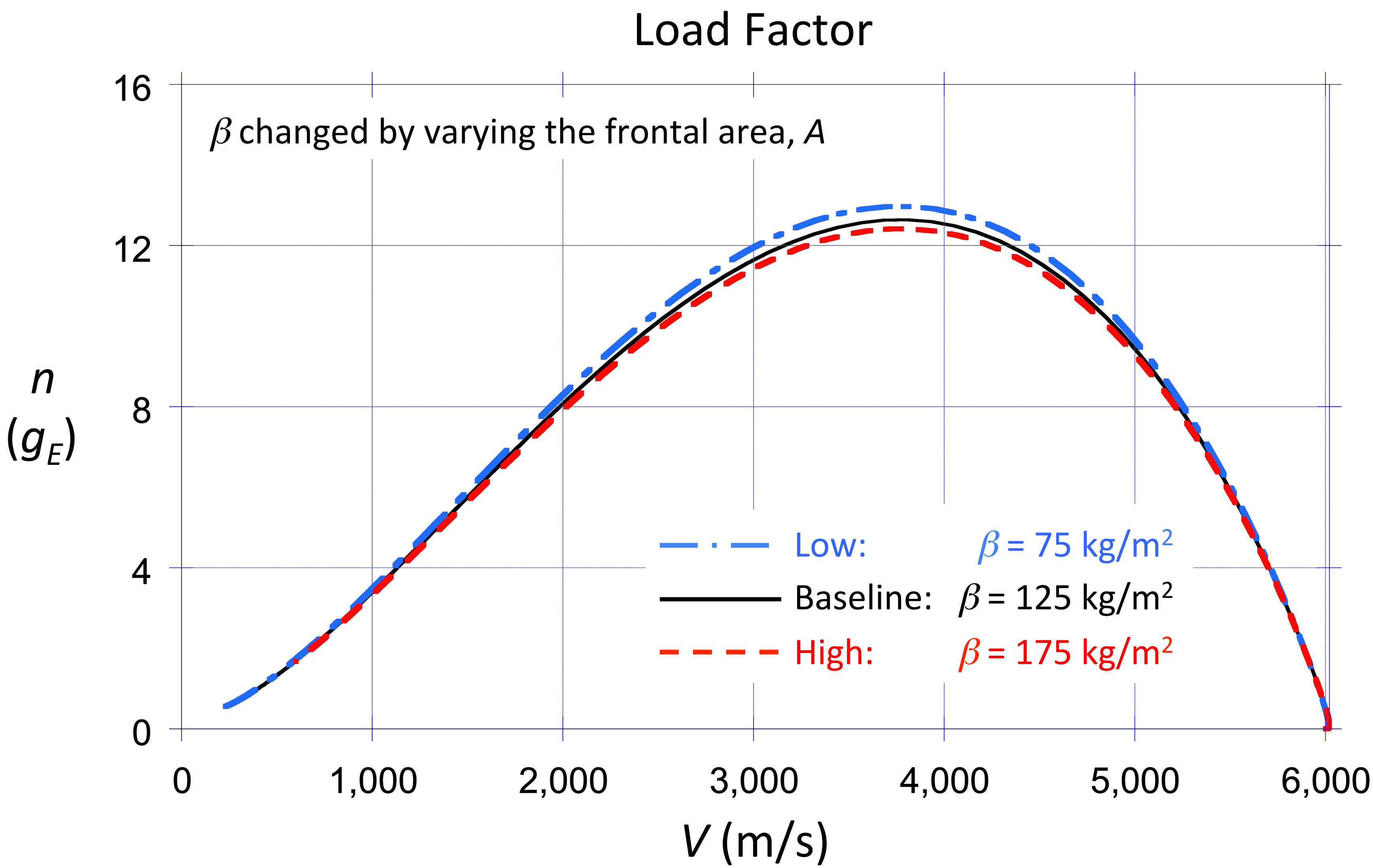
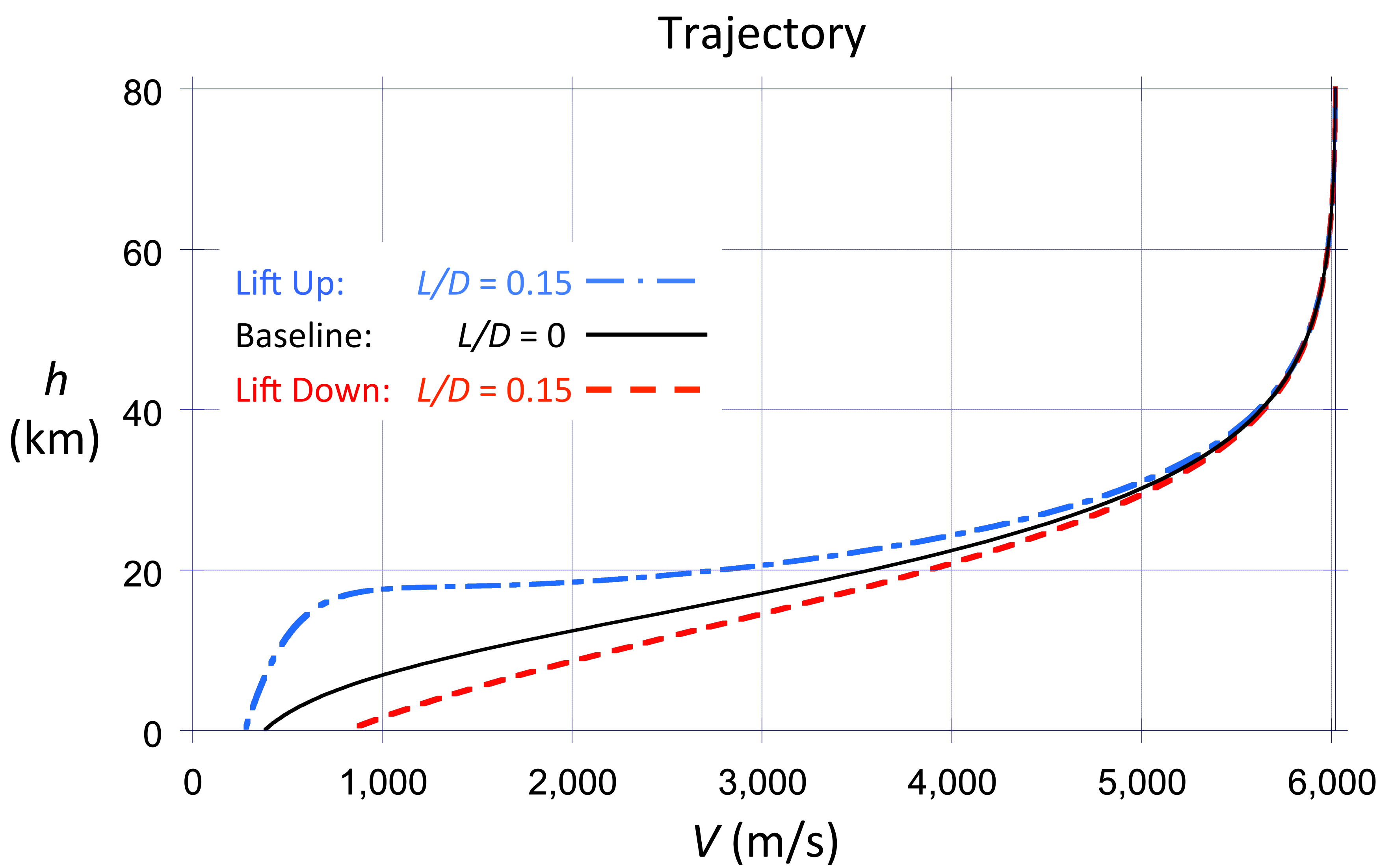


Effect of Lift



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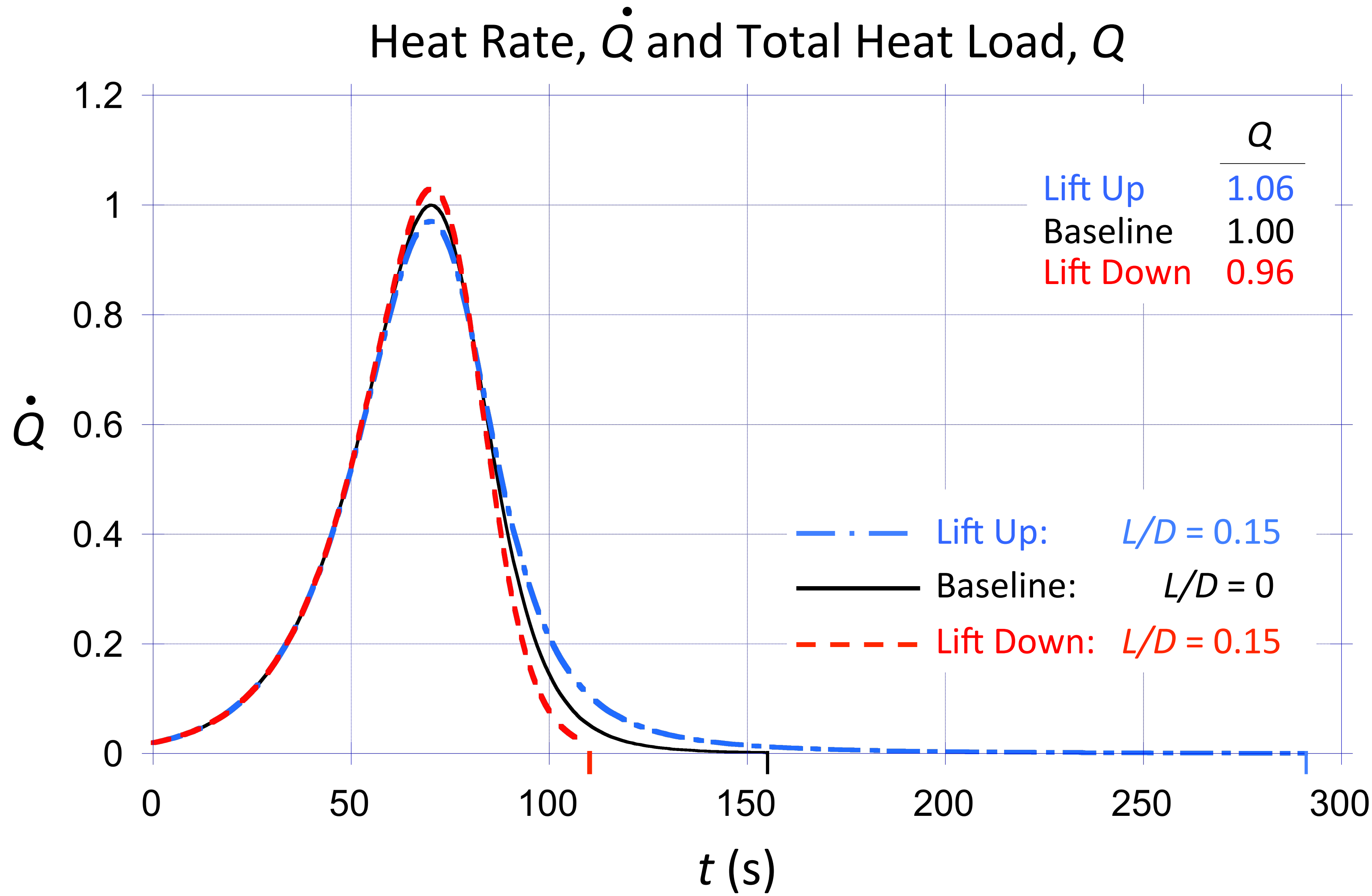
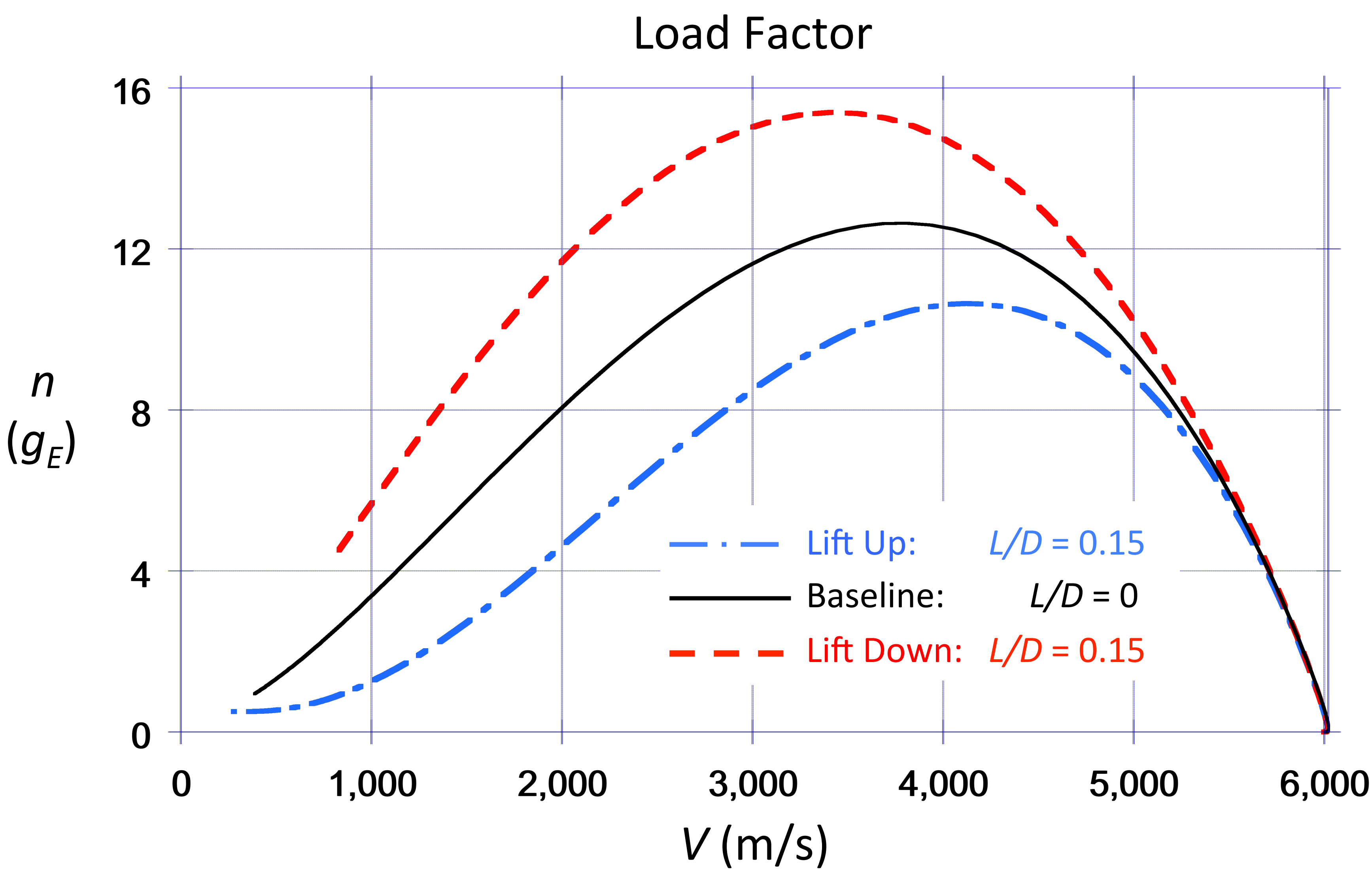
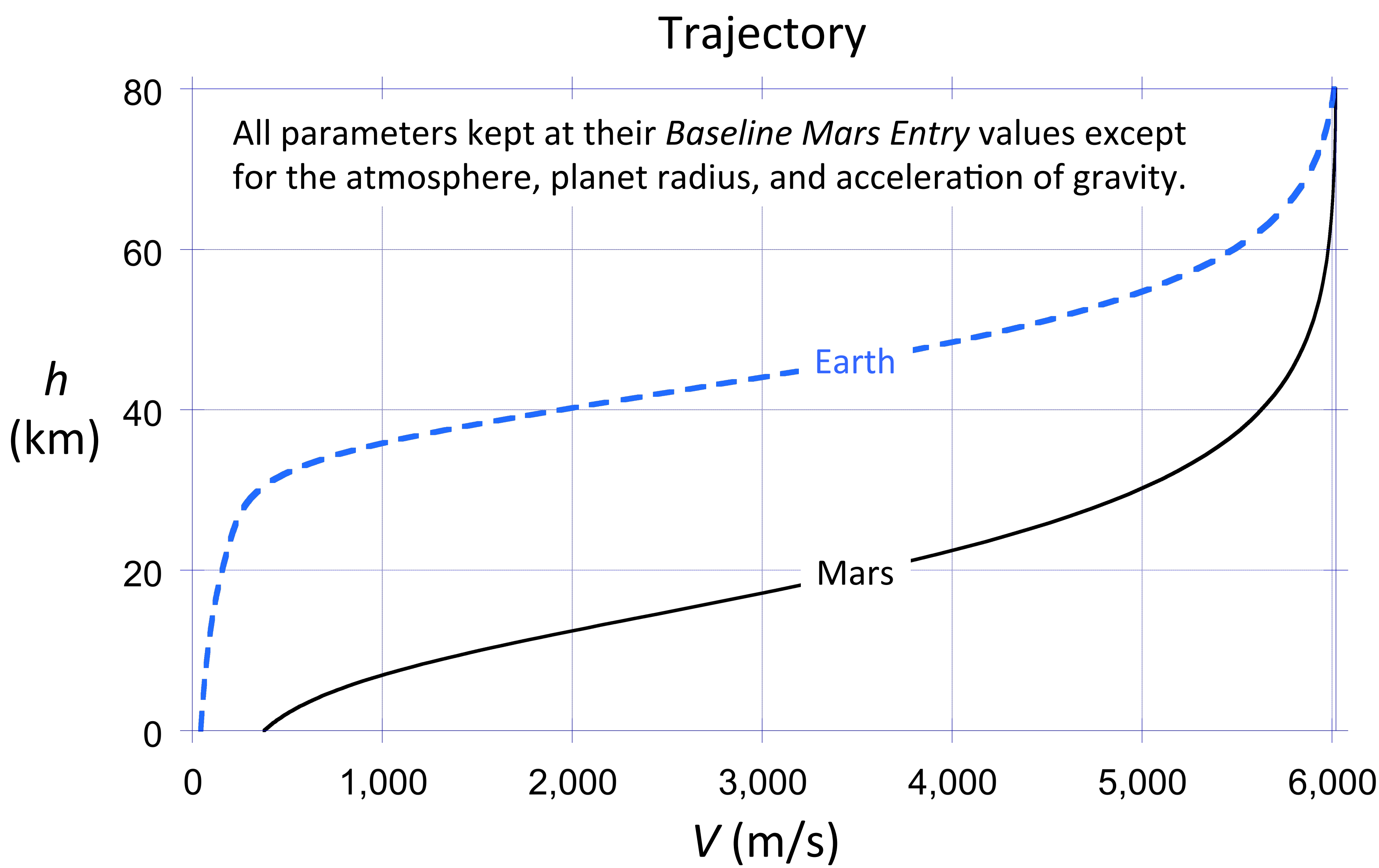


Effect of Lift



Effect of Planet's Atmosphere and Gravity



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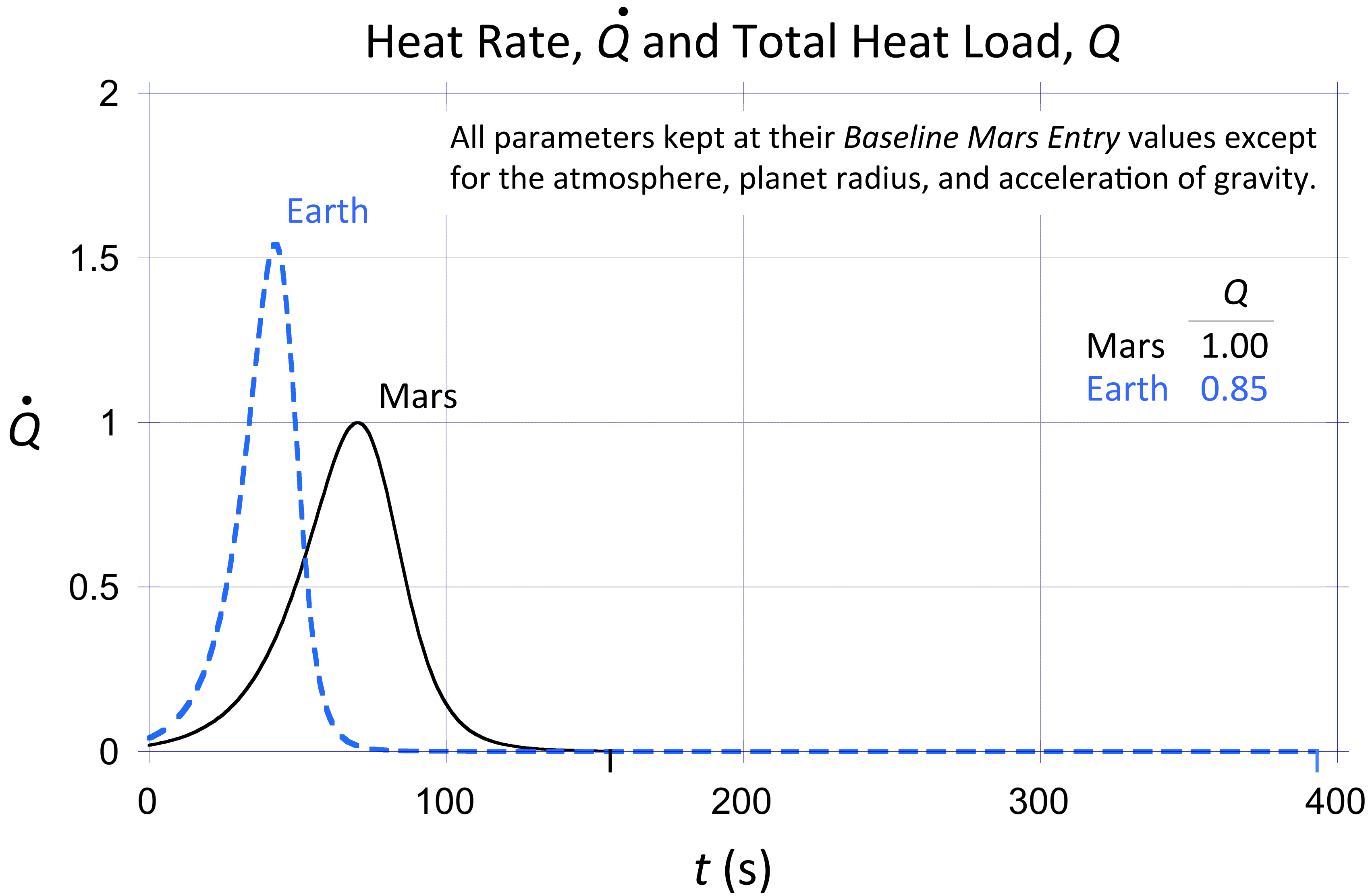
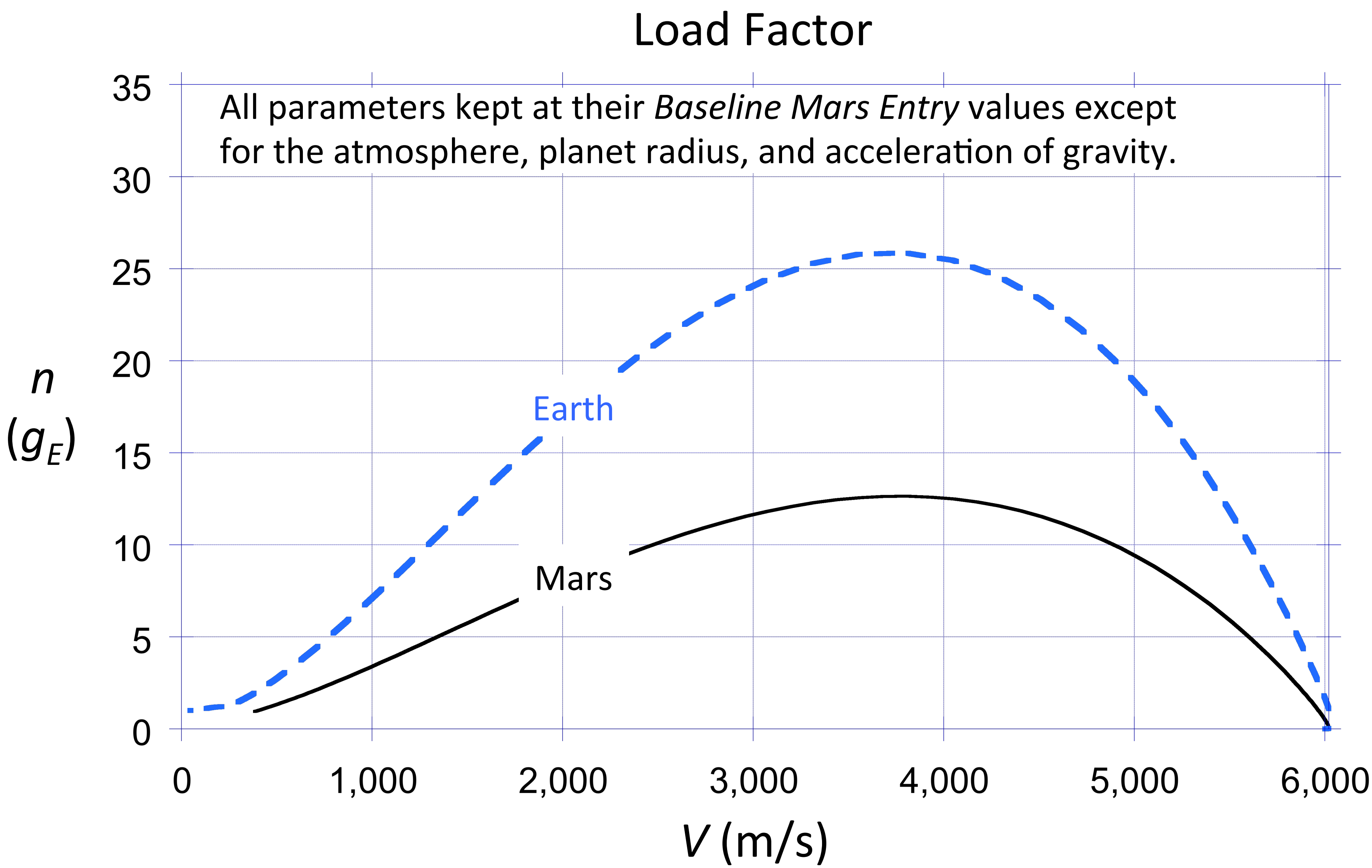
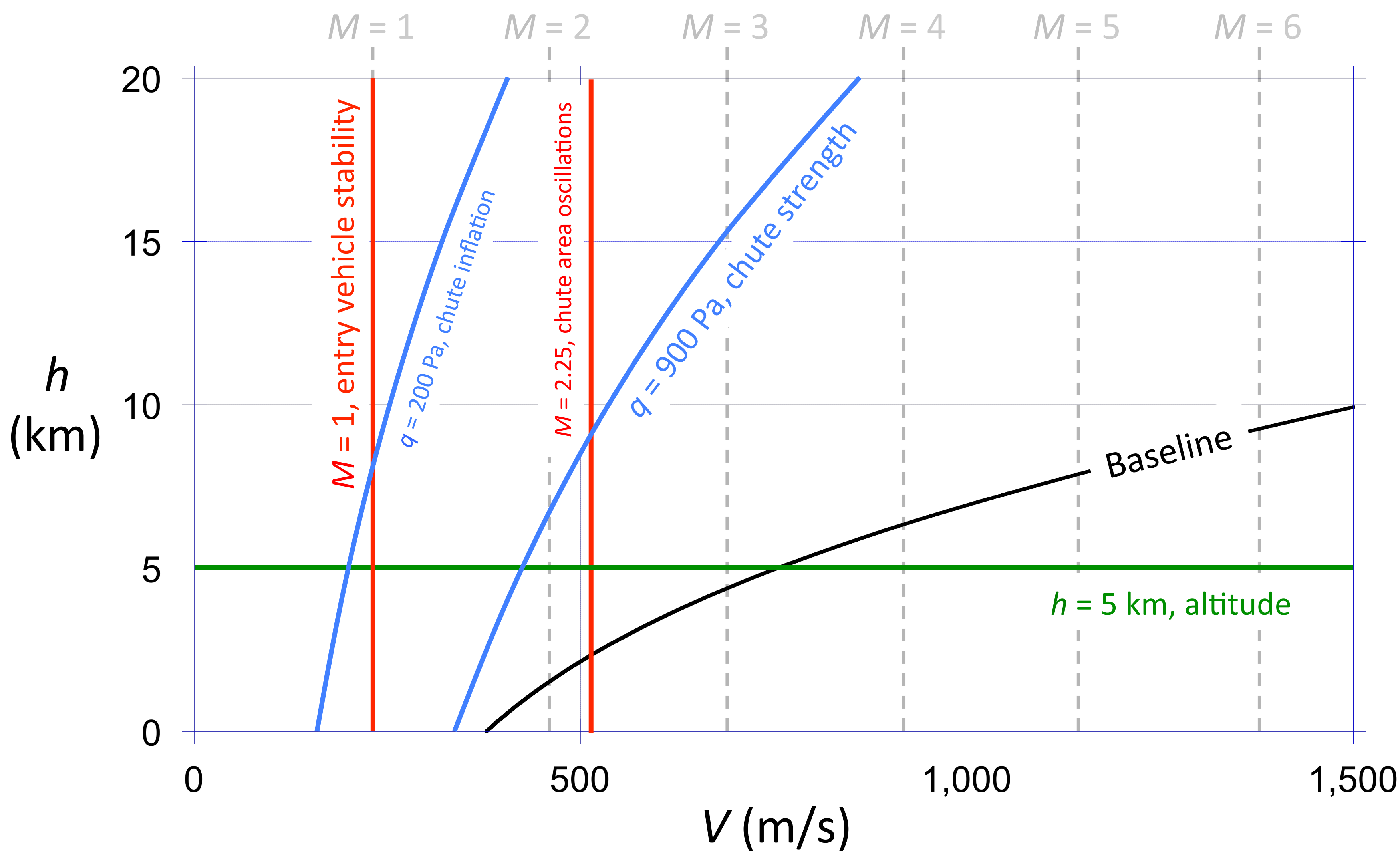


Effect of Planet's Atmosphere and Gravity



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



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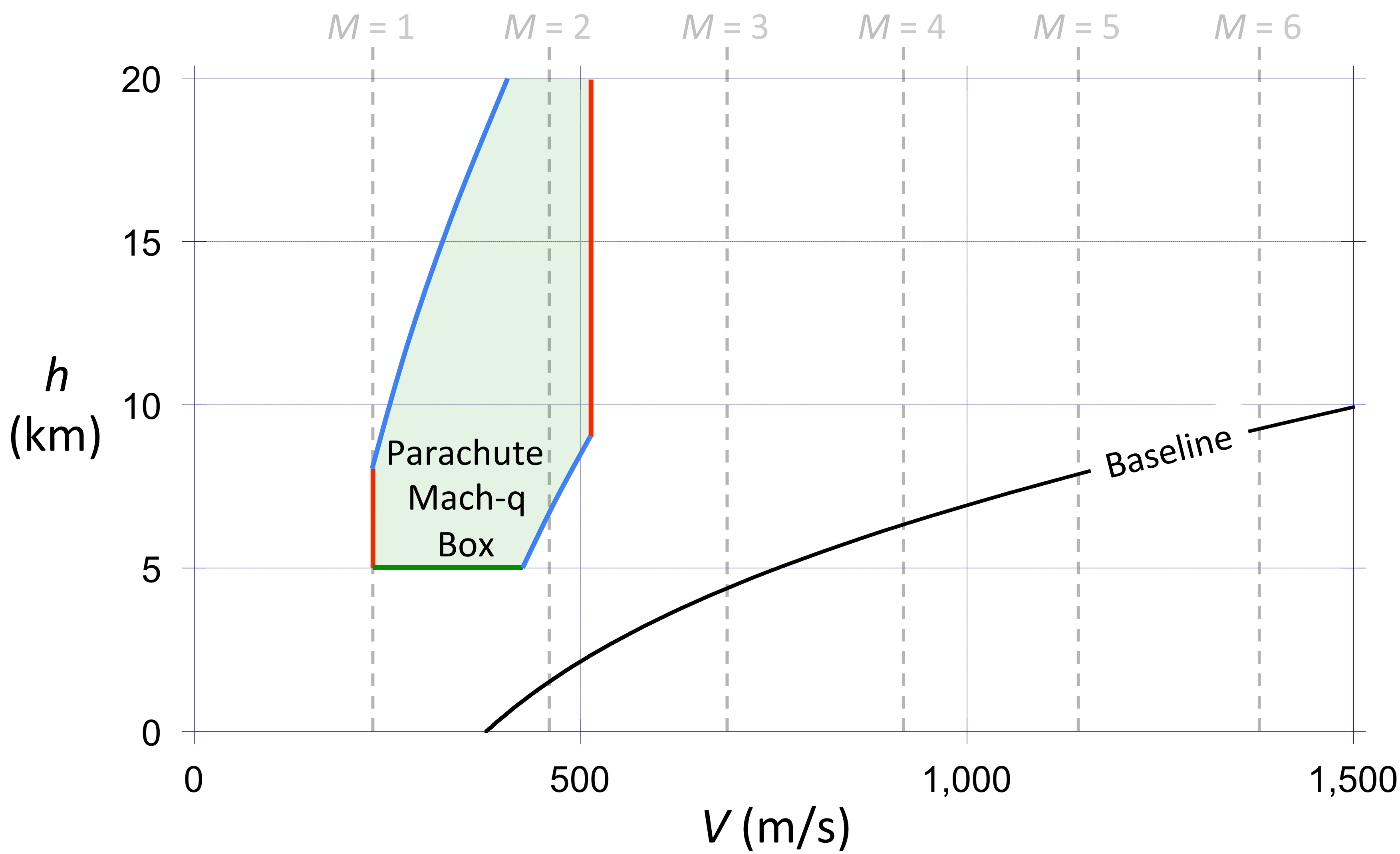
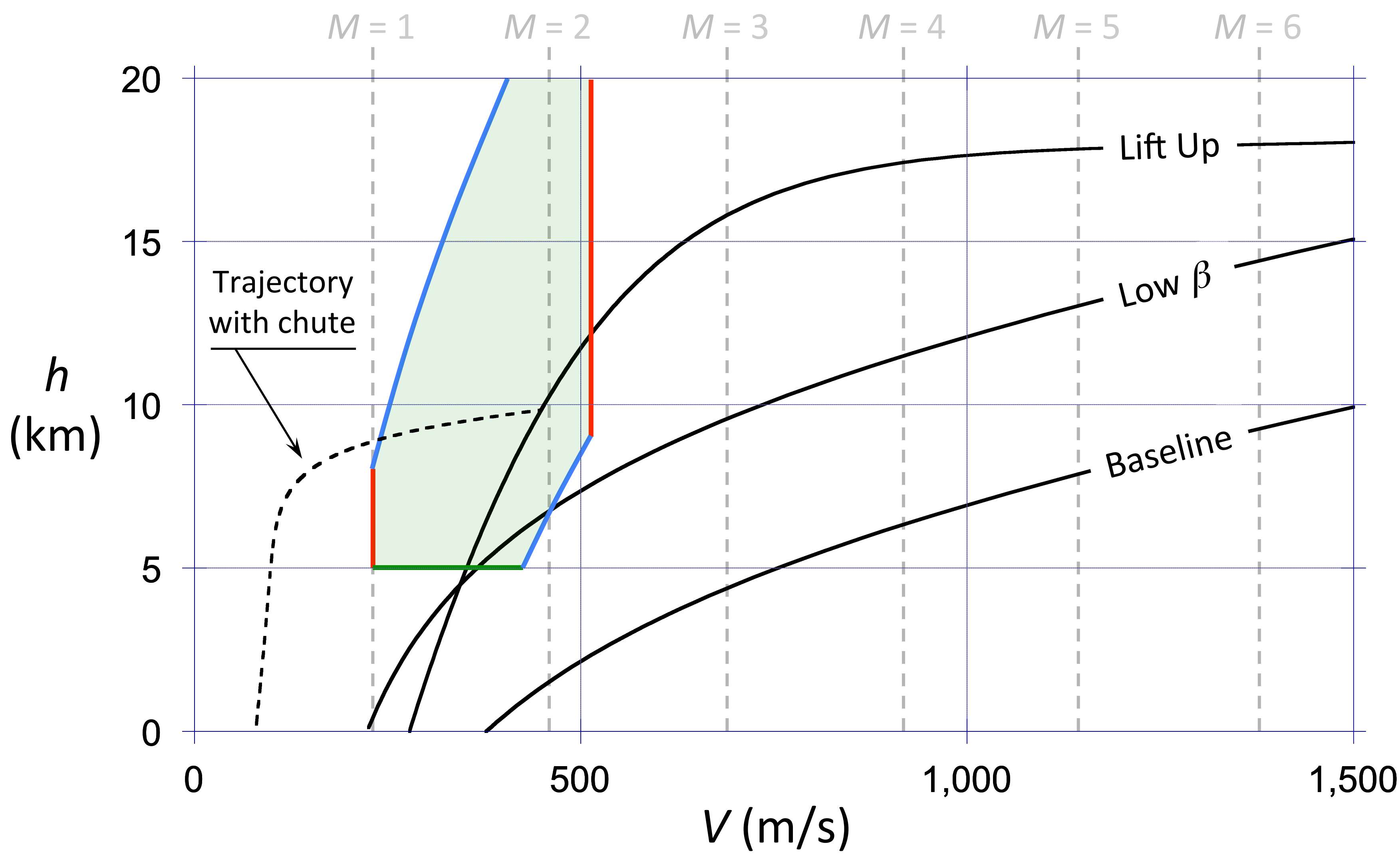


Descent: Parachutes, IADs, and the Mach-q Box



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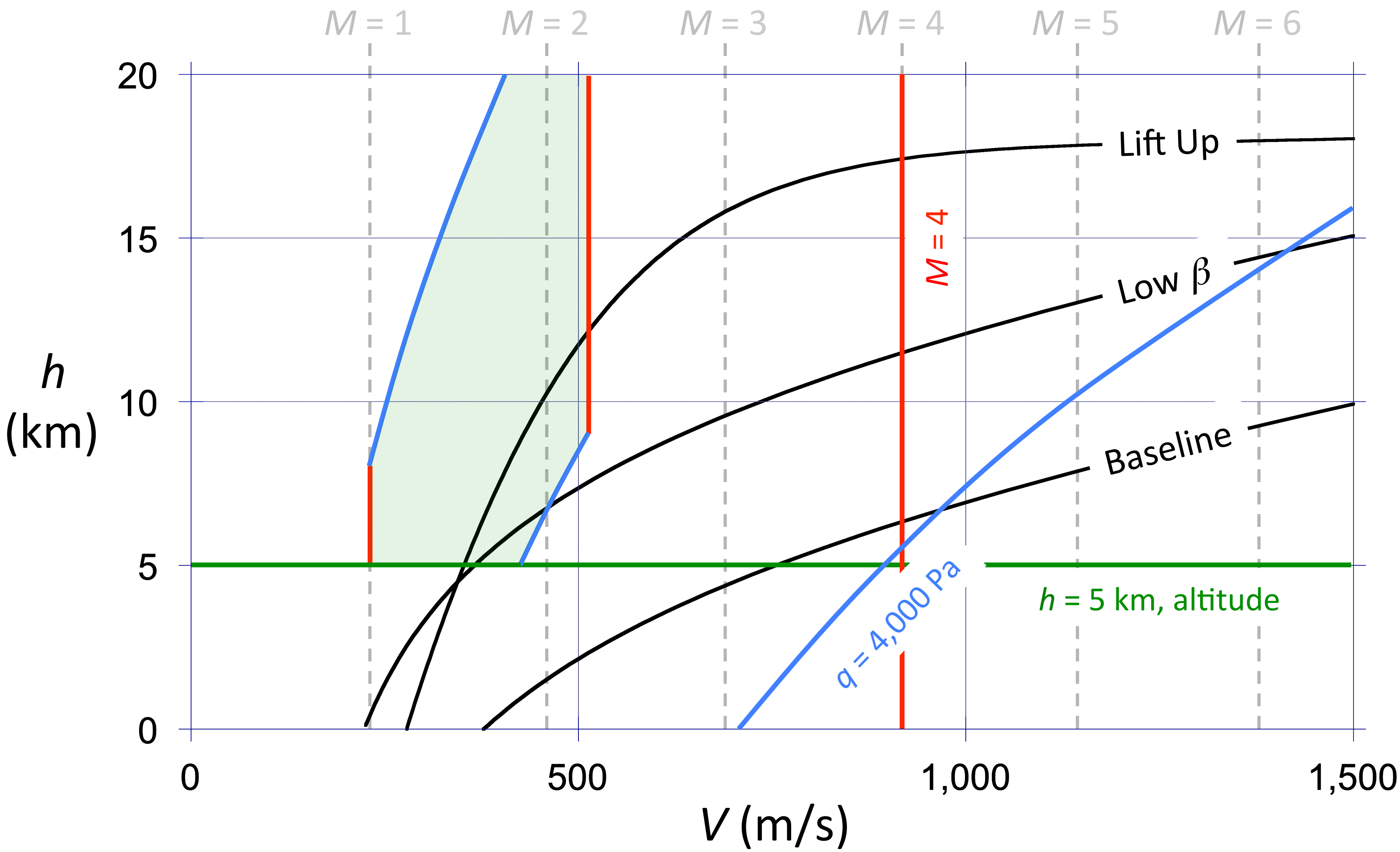
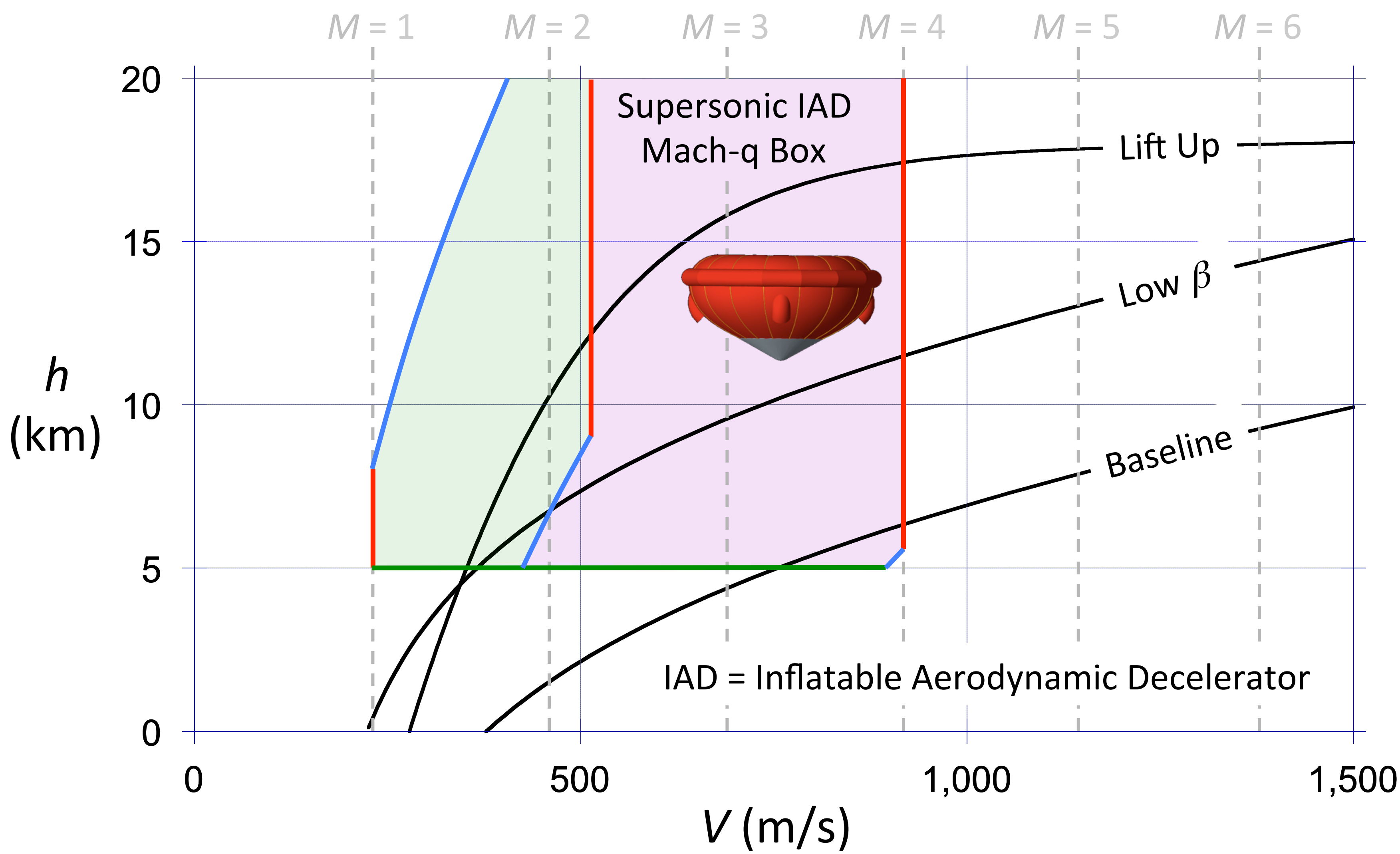


Descent: Parachutes, IADs, and the Mach-q Box



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

Additional Reading

1) Braun, R. D. and Manning, R. M.: Mars Exploration Entry, Descent, and Landing Challenges, *Journal of Spacecraft and Rockets*, Vol. 44, No. 2, pp. 310-323, March-April 2007.

2) Regan, F. J. and Anandakrishnan, S. M.: *Dynamics of Atmospheric Re-Entry*, AIAA, Washington, DC, 1992. (Chapter 7: *Re-Entry Vehicle Particle Mechanics*, covers much of the material in this presentation. Of particular interest are the closed-form solutions which yield significant insights regarding the nature of trajectories. See, for example, Case 4 starting on page 195.)

3) Gallais, P.: *Atmospheric Re-Entry Vehicle Mechanics*, Springer-Verlag, Berlin, 2007. (Chapter 9: *Zero Angle of Attack Reentry* covers some of the material in this presentation.)

4) Tewari, A.: *Atmospheric and Space Flight Dynamics, Modeling and Simulation with MATLAB® and Simulink®*, Birkhäuser, Boston, 2007.

5) Ball, A. J., Garry, J. R. C., Lorenz, R. D., and Kerzhanovich, V. V.: *Planetary Landers and Entry Probes*, Cambridge University Press, Cambridge, UK, 2007.

Symbols I

A	aerodynamic reference area (entry vehicle frontal area)
a_0	atmospheric speed of sound
C_D	drag coefficient
D	drag
E	total energy metric (nondimensionalized wrt. the total energy of the *Baseline Mars Entry* at atmospheric interphase)
g	acceleration of gravity
g_E	Earth acceleration of gravity
h	altitude above planet surface
h_i	altitude at initial contact with planet atmosphere (i.e., at atmospheric interphase)
H	atmospheric density scale height
KE	kinetic energy

Symbols II

K_{planet}	*convective* aeroheating constant to adjust for planet's atmosphere
L	lift
L/D	lift to drag ratio
m	mass
M	Mach number
n	sensed load factor
PE	potential energy
Q	aerothermodynamic convective heat load metric (nondimensionalized wrt. the convective heat load of the *Baseline Mars Entry* at landing)
$\dot{Q}$	aerothermodynamic convective heat rate metric (nondimensionalized wrt. the maximum convective heat rate of the *Baseline Mars Entry*)
q	dynamic pressure

Symbols III

R	planet atmosphere gas constant
r_P	planet radius
T_0	atmospheric temperature
t	time
t_i	time at initial contact with planet atmosphere (i.e., at atmospheric interphase)
$t_{landing}$	time at landing
V	velocity (airspeed)
V_i	velocity (airspeed) at initial contact with planet atmosphere (i.e., at atmospheric interphase)
α_T	total angle of attack
β	ballistic coefficient
γ	atmosphere ratio of specific heats
γ_{FPA}	flight path angle (positive above horizon)

Symbols IV

$\gamma_{FPA,i}$	flight path angle (positive above horizon) at initial contact with planet atmosphere (i.e. at atmospheric interphase)
ρ	atmospheric density
ρ_0	atmospheric density at planet surface
IAD	Inflatable Aerodynamic Decelerator

Points of Contact

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Equations of Motion

$$\frac{dV}{dt} = -\left(\frac{\rho V^2}{2\beta} + g\sin\gamma_{FPA}\right)$$

$$\frac{d\gamma_{FPA}}{dt} = \frac{1}{V}\left[\frac{V^2\cos\gamma_{FPA}}{r_P + h} + \frac{\rho V^2}{2\beta}\left(\frac{L}{D}\right) - g\cos\gamma_{FPA}\right]$$

$$\frac{dh}{dt} = V\sin\gamma_{FPA}$$

where,

$$\beta = \frac{m}{C_D A}$$

<u>Assumptions</u>

Constant acceleration of gravity

Circular planet

Equations neglect planet rotation

Exponential Atmosphere Model

Examples assume exponential (isothermal) atmosphere model

$$\rho = \rho_0 \exp\left(-\frac{h}{H}\right)$$

where,

$$H = \frac{RT_0}{g}$$

Speed of sound is calculated from

$$a_0 = \sqrt{gRT_0}$$

Note that the speed of sound is constant in this simplified atmosphere model.

Other Equations and Assumptions

$$M = \frac{V}{a_0}$$

$$q = \tfrac{1}{2}\rho V^2$$

$$n = \frac{qC_D A}{mg_E}\left[1 + \left(\frac{L}{D}\right)^2\right]$$

$$KE = \tfrac{1}{2} m V^2$$

$$PE = mgh$$

$$E = \frac{KE + PE}{\left(KE + PE\right)_{\text{Mars Baseline @ Entry}\,(t_i,\, h_i,\, V_i)}}$$

Other Equations and Assumptions

Nondimensional convective heat rate metric

$$\dot{Q} = \frac{K_{planet}\left(\rho^{\frac{1}{2}}V^3\right)}{\text{Max}\left(\rho^{\frac{1}{2}}V^3\right)_{\text{Mars Baseline}}}$$

Nondimensional convective heat load metric

$$Q = \frac{K_{planet}\left(\int_{t_i}^{t}\rho^{\frac{1}{2}}V^3\,\mathrm{d}t\right)}{\left(\int_{t_i}^{t_{landing}}\rho^{\frac{1}{2}}V^3\,\mathrm{d}t\right)_{\text{Mars Baseline}}}$$

$K_{planet} = 1$ for Mars; $K_{planet} = 1.092$ for Earth

Same aeroshell nose radius assumed for all cases

Example Cases

	Mars Baseline	Mars Aerocapture	Mars Low β	Mars High β	Mars Lift Up	Mars Lift Down	Earth
Vehicle							
β (kg/m^3)	125	125	**75**	**175**	125	125	125
L/D	0.00	0.00	0.00	0.00	**0.15**	**-0.15**	0.00
m (kg)	1,000	1,000	1,000	1,000	1,000	1,000	1,000
A (m^2)	5.333	5.333	**8.889**	**3.810**	5.333	5.333	5.333
C_D	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Atmosphere							
T_0 (K)	210	210	210	210	210	210	**288**
γ	1.33	1.33	1.33	1.33	1.33	1.33	**1.40**
R (J/kg•K)	188.9	188.9	188.9	188.9	188.9	188.9	**287.1**
H (km)	10.607	10.607	10.607	10.607	10.607	10.607	**8.429**
ρ_0 (kg/m^3)	0.0160	0.0160	0.0160	0.0160	0.0160	0.0160	**1.225**
a_0 (m/s)	229.7	229.7	229.7	229.7	229.7	229.7	**340.2**
Geodesy							
r_P (km)	3,396	3,396	3,396	3,396	3,396	3,396	**6,378**
g (m/s^2)	3.74	3.74	3.74	3.74	3.74	3.74	**9.81**
Initial Conditions							
h_i (km)	125	125	125	125	125	125	125
V_i (m/s)	6.0	6.0	6.0	6.0	6.0	6.0	6.0
$\gamma_{FPA,i}$ (deg)	-15.0	**-9.4**	-15.0	-15.0	-15.0	-15.0	-15.0

Values in **bold red** are changes from the *Baseline Mars Entry* example.