Mars Entry, Descent, and Landing Parametric Sizing and Design Space Visualization Trades

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Entry, descent, and landing (EDL) is a multidimensional, complex problem, which is difficult to visualize in simple plots. The purpose of this work is to develop a systematic visualization scheme that could capture Mars EDL trades as a function of a limited number of variables, such that programmatic design decisions could be effectively made with insight of the design space. Using the Mars Science Laboratory (MSL) as a basis, contour plots have been generated for key EDL figures of merit, such as maximum landed elevation and landed mass as a function of four input parameters: entry mass, entry velocity, entry flight path angle, and vehicle L/D. Additionally, sensitivity plots have been generated in an attempt to capture the effects of varying the fixed input parameters. This set of EDL visualization data has been compiled into a Mars EDL handbook to aid in pre-phase A design space exploration and decision making.

Nomenclature

DSM = Design Structure Matrix
EDL = Entry, Descent, and Landing
FPA = Flight Path Angle
L/D = Lift to Drag Ratio
MER = Mars Exploration Rovers
MSL = Mars Science Laboratory
PESST = Planetary Entry System Synthesis Tool
POST = Program to Optimize Simulated Trajectories
TPS = Thermal Protection System

I. Introduction

INTERPLANETARY mission design is a complex problem in which the physics are often obscured by the dimensionality of the problem. To more easily visualize interplanetary mission design information, contour plots are created, which generally convey the following information: launch and arrival dates, launch and arrival energy (C3), local solar time, solar longitude, and other parameters important to the specific mission under consideration. These plots are generally referred to as pork chop plots, because their resulting shape resembles a pork chop. Entry, descent, and landing is an analogous multidimensional problem, which is also difficult to visualize. This work attempts to package similar parametric sizing and visualization trade space data into EDL pork chop plots, to aid future Mars program planning during the conceptual design phase. These plots allow for mapping and exploration of the EDL design space and rapid assessment of EDL design implications across future mission opportunities and landing constraints.

The creation of the pork chop plots is based on the premise that Mars EDL can be parameterized across five major variables: vehicle ballistic coefficient, vehicle lift-to-drag ratio, entry velocity, entry flight path angle, and

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atmospheric density[1]. For the contour plots generated thus far, a constant packaging density is assumed. This allows entry mass to be used as a surrogate for ballistic coefficient, since the forebody geometry is also fixed. Additionally, the arrival date at Mars is fixed, so atmospheric density is not included in the design space parameterization. Using these four design variables, contour plots are generated for landed mass, landed elevation, conditions at parachute deploy (Mach, altitude, and dynamic pressure), peak heat rate, total heat load, and peak deceleration.

The resulting contour plots, which form the basis for a Mars EDL Mission Design Handbook, were generated using the Planetary Entry System Synthesis Tool (PESST), which incorporates the following EDL disciplinary models into a single framework: entry system geometry, aerodynamics, trajectory and flight dynamics, thermal response, terminal descent analysis, and weights and sizing. The disciplinary analyses are a combination of industry-standard programs, such as Mars-GRAM, as well as more approximate engineering models used to increase run time and allow for widespread access to the tool. In the following section, a more detailed explanation of the tool, along with the assumptions behind it, is presented.

II. Planetary Entry System Synthesis Tool (PESST)

The Planetary Entry System Synthesis Tool (PESST) was initially created in 2005 within the Space Systems Design Lab at Georgia Tech[2]. Modifications and improvements were made to this initial version to create the EDL contour plots of this investigation. Figure 1 depicts the design structure matrix (DSM), showing the various disciplines included in the tool and the corresponding links between them. Each of these different disciplines is represented by a Matlab function, and they are all integrated within a Matlab m-file, that passes the necessary data between the various disciplines. Currently, only the feed forward links exist. Part of the future work of this task will be to add the feedback links shown in Figure 1. A brief description of the analysis methodology for each discipline is given below.

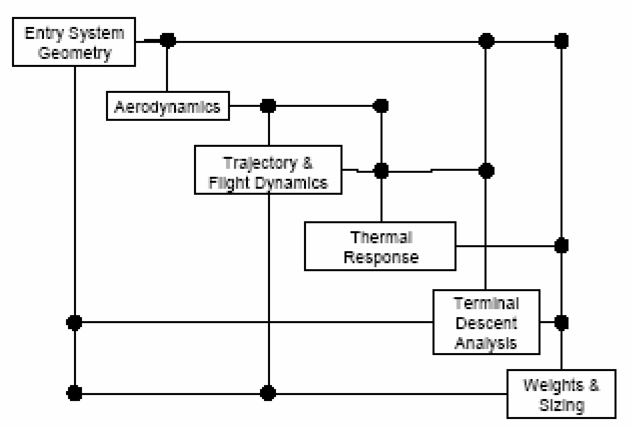

Figure 1. Design Structure Matrix for PESST.

A. Entry System Geometry

Four simple geometries can be chosen within PESST, each with its own specific set of inputs: sphere-cones, biconics, capsules, and microprobes. PESST calculates key parameters for the selected geometry, including aerodynamic reference area, surface area, wetted area, length, and volume. A surface mesh is also generated for the chosen geometry in order to discretize the surface for aerodynamic calculations.

B. Aerodynamics

PESST uses modified Newtonian theory to determine the aerodynamic coefficients of the entry body. In Newtonian aerodynamic theory, local pressure coefficient is solely a function of vehicle geometry, which has been computed in the form of a triangular mesh. For each panel, the pressure coefficient is calculated using Eq. (1).

$$C_P = C_{P\max} \sin^2 \delta \tag{1}$$

C_{pmax} is the stagnation point pressure coefficient, which can be approximated as constant for a given atmosphere, and δ is the local angle between the incoming velocity vector and the geometric body. The velocity vector can be represented in terms of angle of attack, α, and sideslip angle, β. The pressure coefficient is then calculated for each triangular panel represented in the surface mesh. Breaking the coefficients for each panel into their representative body axis components – C_x, C_y, and C_z – the overall forces in the body axes can be determined by summation, and normalized by the aerodynamic reference area, S_{ref}, to maintain units of force. This method generates aerodynamic coefficients for input angles of attack and sideslip. Repeating the entire process at varying angles of attack populates tables of lift and drag coefficients as functions of angle of attack. These tables are then used to propagate the atmospheric trajectory.

C. Trajectory & Flight Mechanics

A spherical planet model is used to approximate Mars. Local gravitational acceleration is determined throughout the trajectory as a function of planetocentric altitude according to an inverse square gravity model. For the contour plots in this study, the atmosphere of Mars is based on Mars-GRAM 2005, which provides temperature, pressure, and density at a given altitude, as a function of date, time, latitude, longitude, and dust tau. PESST, however, can also simply use and exponential atmosphere, to allow the tool to be distributed to others.

Simulation of atmospheric flight within PESST is performed using a three degree-of-freedom trajectory analysis specially developed for this application, which has been validated against POST for various entry conditions. The entry trajectory is determined by integrating the equations of motion, assuming a constant mass, non-thrusting vehicle, yielding longitude, latitude, radial position, relative azimuth, relative flight path angle, and relative velocity as functions of time. This integration requires the calculation of gravity, atmospheric density, specific lift force, and specific drag force at each time step. In addition to these required variables, several auxiliary variables are calculated at each time step. Landing site relative altitude is calculated based upon an input landing site terrain elevation. Mach number is determined from relative velocity and the reference speed of sound. Dynamic pressure, ballistic coefficient, downrange, and deceleration are determined from standard expressions. While lift appears explicitly in the equations of motion and can therefore be included, there is currently no guidance algorithm implemented. This is to be left for future development.

Within the trajectory analysis, several different events can be modeled that are typically encountered by planetary probes. These include parachute or ballute deployment, a separation (e.g., backshell) event, and parachute or ballute release. Any of these events can overlap and be triggered independently. An event can also be used to terminate the simulation. An event begins when a designated variable passes through a preset “trigger value” with either increasing or decreasing slope. The variables that can be used to trigger events include dynamic pressure, Mach number, altitude, density, deceleration, velocity, and time.

D. Thermal Response

Using the appropriate trajectory information, stagnation-point heat rate is calculated. The stagnation point convective heat rate is determined according to the Sutton-Graves equation.

$$\dot{q}_{conv} = k \cdot (\rho / r_n)^{0.5} \cdot V^3 \tag{2}$$

In Eq. (2), k is a constant based on the planetary atmosphere, ρ is the free stream density, r_n is the nose radius, and V is the vehicle velocity. Stagnation-point heat load is calculated by integrating the appropriate heat rate relation over the trajectory. For this analysis, a fixed heatshield mass is used based on parametric mass-estimating relationships. An offline code has been written, however, that chooses an appropriate TPS type and sizes its thickness based on the heating environment of a particular trajectory[3]. In future work, this will be included in PESST as an iterative process between entry mass and TPS sizing.

E. Terminal Descent Analysis

The current terminal descent analysis consists of a gravity turn trajectory performed by numerically integrating the equations of motion of a vehicle following the gravity turn control law. The gravity turn control law was originally developed for the 1966-1968 lunar Surveyor landings and specifies that a spacecraft’s thrust vector is maintained in the orientation opposite its velocity vector. Typically, the termination of a gravity turn is when nadir angle, relative velocity, and height above ground level are all zero.

For the integration, two-dimensional gravity turn trajectories are assumed to occur over a flat planet. Manipulation of the two force equations for the x and y directions gives the equations below for the rate of change of the nadir angle ($\dot{\psi}$) and acceleration in the direction of flight ($\dot{v}$). Here, a_L is instantaneous acceleration due to lift, a_T is instantaneous acceleration due to thrust, and a_D is instantaneous acceleration due to drag.

$$\begin{aligned} \dot{\psi} &= \frac{a_L - g \sin\psi}{v} \\ \dot{v} &= g \cos\psi - a_T - a_D \end{aligned} \tag{3}$$

A final required relationship is a description of vehicle mass change over time. This is given by the definition of specific impulse, which can be rearranged to give the equation below. Here, T is the total thrust of the engines, I_{sp} is specific impulse, and g_0 is the reference gravitational constant (9.81 m/s²).

$$\dot{m} = -\frac{T}{g_0 I_{sp}} \tag{4}$$

F. Weights and Sizing

The heatshield, backshell, and parachute masses are all based on parametric mass-estimating relationships, similar to those developed for the Mars Science Laboratory (MSL) rover mission. The heatshield and backshell masses scale with the aeroshell diameter, while the parachute mass scales with the parachute diameter.

III. Baseline Entry Configuration and Assumptions

Figure 2 illustrates the nominal entry timeline modeled in PESST, based on a 1500 kg entry mass. For the nominal case shown, the relative entry velocity is 7000 m/s at a relative flight path angle of -13°. Parachute deployment is triggered by Mach number in this simulation, and occurs at Mach 2.2. Heatshield separation occurs ten seconds later, based on a Mach 0.8 trigger value. Lander separation occurs 20 seconds later, when terminal descent is also initiated. Finally, for the nominal case, the lander touches down at zero velocity at an altitude of nearly 2 km with respect to the MOLA aeroid.

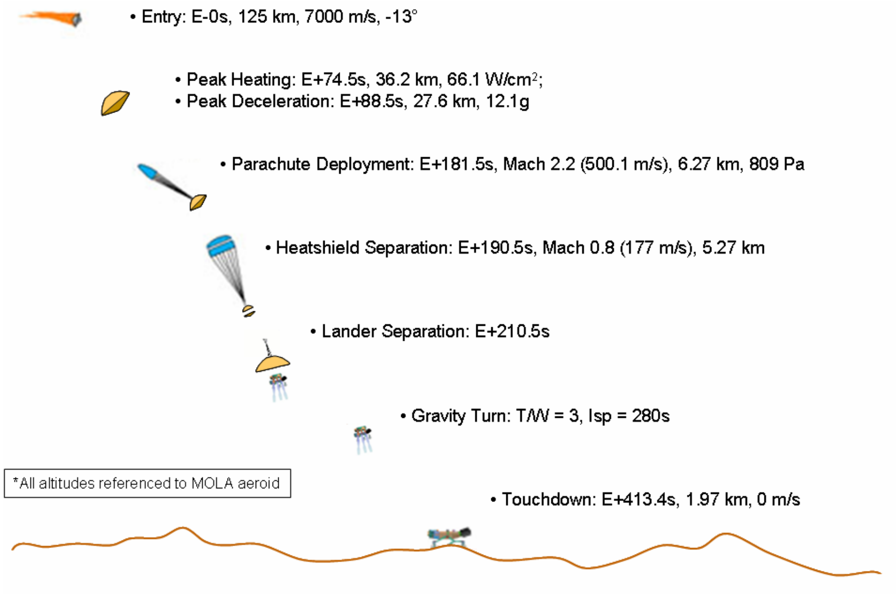

Figure 2. Baseline Mars EDL events timeline.

A single geometry was used in generating the contour plots, based on the Viking-heritage aeroshell, a larger version of which is also being flown on MSL. Figure 3 illustrates the shape and dimensions of the Viking aeroshell. In scaling the aeroshell, the angles given remain constant, while the radii and diameters scale linearly with maximum diameter. The maximum diameter is chosen based on a given entry mass and a constant packing density (entry mass divided by volume). Therefore, ballistic coefficient does not need to be included as an independent parameter, since the configuration and packing densities remain constant. Figure 4 illustrates how the maximum aeroshell diameter varies as a function of entry mass for three values of packing density. The Mars Exploration Rovers represent the maximum

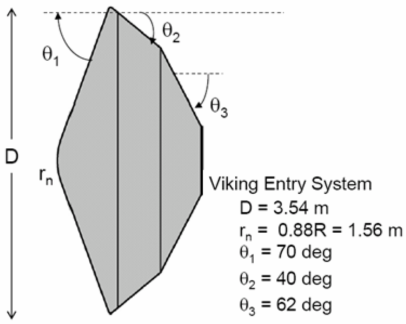

Figure 3. Dimensions of Viking-heritage biconic aeroshell.

constraint on packing density. The value chosen for this analysis is 152.5 kg/m3, based on MSL.

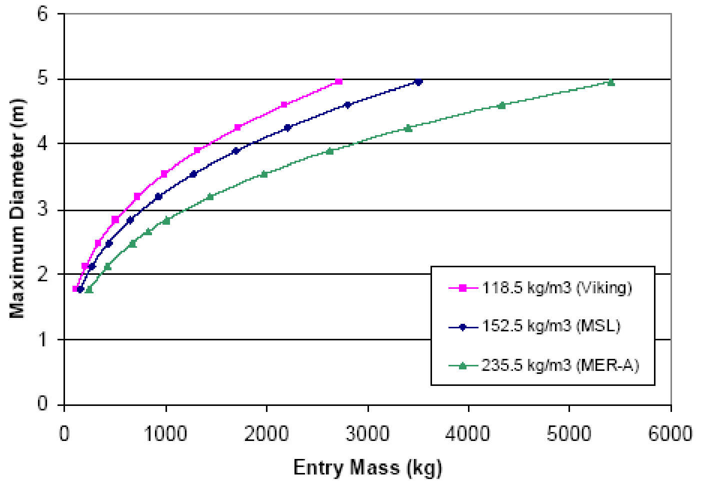

Figure 4: Maximum aeroshell diameter as a function of entry mass.

In addition to the aeroshell geometry, other parameters were held constant in generating the contour plots, and are listed in Table 1. The arrival conditions, arrival date and time, and arrival atmospheric conditions are fixed. Additionally, the size and performance of the parachute are held constant, based on MSL-type values. Finally, conditions pertaining to the EDL event sequence, such as the various triggers, are fixed, as illustrated in Figure 2. These parameters were chosen to represent the maximum capability of a Mars EDL system given current technology, in terms of maximum landed elevation or landed mass capability. In particular, the earliest that terminal descent can be initiated is when the heatshield is released, which can not occur until the entry system has reached subsonic conditions. While terminal descent can be initiated later, Mach 0.8 will result in the maximum possible landed elevation.

Table 1: Baseline PESST inputs.

Parameter	Value	Units
Arrival Latitude	0	deg
Arrival Longitude	0	deg
Azimuth	0	deg
Arrival Date	10/8/16	mm/dd/yy
Arrival Time	12:00:00	hr:min:sec
Dust Tau	1.55	
Mach at Chute Deploy	2.2	Mach
Chute C_D	0.67	
Chute Diameter	19.7	M
Terminal Descent Initiation	0.8	Mach
Vehicle T/W	3	
Thruster Isp	280	s

The nominal case presented in Figure 2 is for a ballistic entry – no lift. Lift provides additional control authority during atmospheric entry, and can be used to achieve crossrange, reduced peak deceleration or heat rate, increased downrange, and increased chute deploy altitude (or higher surface elevation, additional mass, timeline margin, etc.). PESST currently has no guidance algorithm for the lifting entries; therefore the L/D in the contour plots represents vertical lift only.

In general, for a given entry velocity and entry mass, as the flight path angle becomes more shallow, the landed elevation should increase. For the ballistic case, this is true, but when lift is added, lofting can have an effect on the expected trend. Figure 5 plots three trajectories (altitude vs. velocity) with different flight path angles and an L/D of 0.1. The trajectory with a flight path angle of -15° does have a higher landed elevation than the -18° case. When the flight path angle

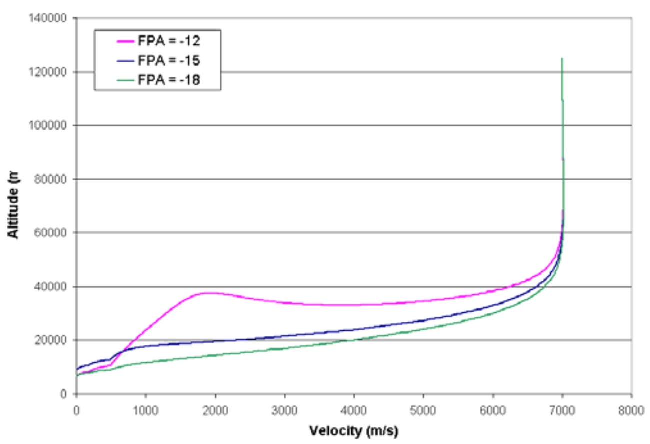

Figure 5. Effect of lofting on entry trajectories with an L/D of 0.1.

is reduced to -12°, however, the landed elevation decreases again due to lofting. Starting at a steep flight path angle, as the angle becomes shallower, the landed elevation increases as expected, but only up to a certain point. As the flight path angle becomes even shallower, lofting begins to become important, and the landed elevation begins to decrease again. This implies the existence of an optimum flight path angle to maximize landed elevation and an additional benefit which guidance could play in a lifting entry. Future work will include guided entries to obtain maximum benefits from introducing lift to the entry vehicle.

IV. Results

The contour plots in the Mars EDL mission design handbook contain information on the following metrics as a function of entry mass, relative entry velocity, relative entry flight path angle, and vertical L/D:

- Landed Mass
- Landed Elevation
- Downrange
- Peak Deceleration
- Peak Heat Rate
- Total Heat Load
- Chute Deploy Altitude
- Chute Deploy Dynamic Pressure

Each set of contours plots a set of performance metrics as a function of entry mass and entry flight path angle, for a given entry velocity and vertical L/D. Figure 6 presents an example set of contour plots, plotting maximum landed elevation in red and landed mass in blue for a ballistic entry. Flight path angle is on the vertical axis and entry mass is on the horizontal axis. Each of the four plots represents a different value of entry velocity, as indicated in the key.

The white areas on the above plots represent infeasible cases. In this case, these are a result of the trajectory “skipping-out” of the atmosphere at shallow flight path angles. Therefore, this constraint sets the lower boundary on flight path angle. The upper boundary, which does not appear on these plots, would be set by constraints on landed elevation, heating, and/or deceleration. The handbook also contains similar plots for downrange, for deceleration, heat rate and heat load, and for parachute deployment altitude and dynamic pressure. All of the contour plots for the ballistic case are not presented here for conciseness.

In addition to the ballistic case, the handbook contains plots pertaining to lifting cases. Figure 7 plots contours of landed mass and elevation for a vertical L/D of 0.1. As explained above, the curved shape is a result of the lofted trajectories for shallow flight path angles. Another observation is that the “skip-out” boundary occurs at a steeper flight path angle for a given set of entry parameters when lift is added. The current version of the EDL handbook contains plots for values of L/D up to 0.3.

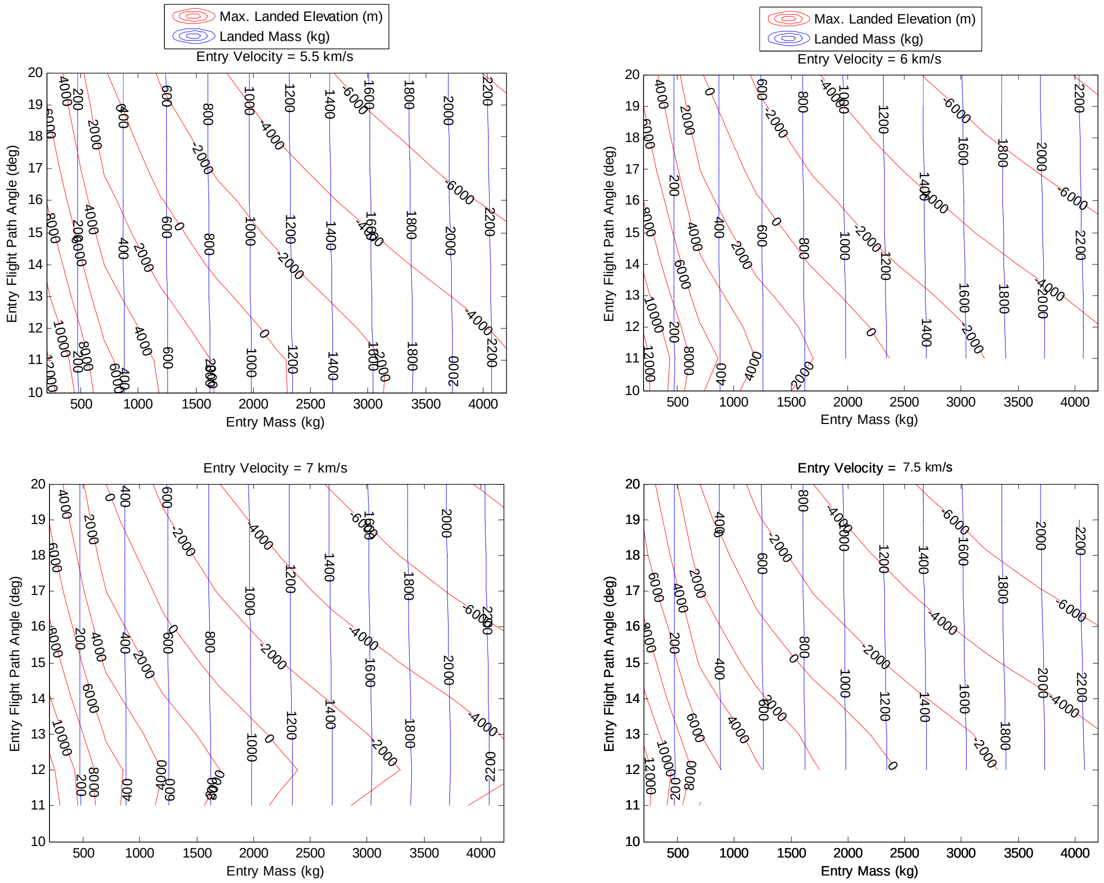

Figure 6. Contour plots of landed mass and maximum landed elevation for a ballistic entry.

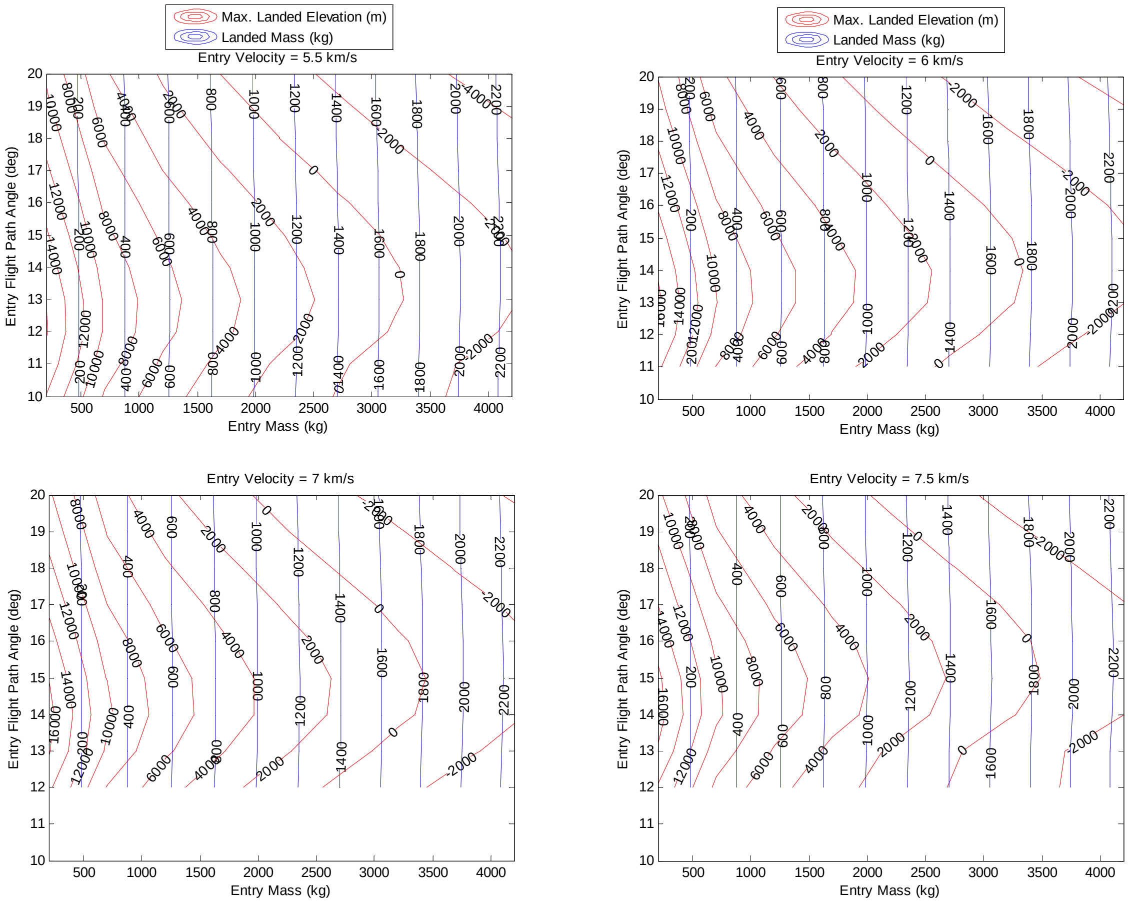

Figure 7. Contour plots of landed mass and landed elevation for a vertical L/D of 0.1

From the full set of contour plots, the benefit of adding lift to the entry vehicle becomes apparent, as shown in Figure 8. Here, parachute deployment altitude and maximum deceleration are plotted separately, to better illustrate the results. For the baseline 1500 kg entry mass and 7000 m/s entry velocity, increasing vertical L/D from 0 to 0.3 results in an increase in parachute deployment altitude from 4,000 m to 13,000 m and peak deceleration decreasing from 17.5 g’s to 13 g’s. The increase in parachute deployment altitude can be used to increase the site elevation or to increase the landed mass at a given site elevation.

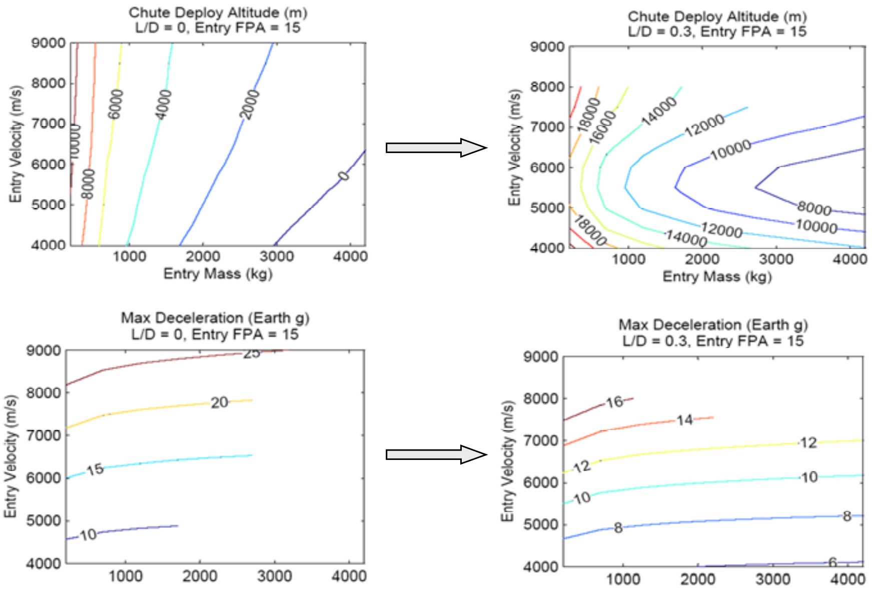

Figure 8. Benefits of adding vertical lift on parachute deployment altitude and peak deceleration.

A. Mission Design Example

Using the baseline case as a starting point, an example of how the contour plots could be used during conceptual-level mission studies is illustrated here. In general, the entry velocity is chosen early in the design process, and is based on the interplanetary trajectory. For this example, a relative entry velocity of 7 km/s is used. Next, certain constraints must be set on the system, which are listed in Table 2. These values are based on the limitations of previously flown or currently planned missions[4].

Table 2. Mission design example – constraints on EDL system.

Constraint	Value	Units
Peak Heat Rate	150	W/cm^2
Total Heat Load	3750	J/cm^2
Peak Deceleration	15	Earth g's
Chute Deploy Dyn. Press.	750	Pa

The contour plots can then be used to limit the size of the trade space based on the given constraints. For the ballistic case illustrated, these constraints actually limit the trade space severely, as can be seen in Figure 9 and Figure 10. The grayed out areas represent the areas of the design space that violate one or more of the constraints. From Figure 9, it can be seen that the constraint on peak deceleration eliminates flight path angles greater than approximately 14°, depending on the entry mass. The constraint in integrated heat load eliminates flight path angles less than approximately 11.5°. The peak heat rate constraint, however is not active. From Figure 10, the effect of the dynamic pressure constraint can be seen.

Figure 11 then illustrates these constraints on flight path angle and entry mass superimposed on the contour plot of maximum landed elevation and landed mass. As can be seen, there is a small design space available that meets all of the constraints. Therefore, it can be concluded that to meet the given constraints and for a ballistic entry with an entry velocity of 7 km/s, the maximum possible landed mass is slightly more than 800 kg. This would correspond to an entry mass of about 1700 kg and a flight path angle of -12°, and would result in a maximum landed elevation of about 2 km. Conversely, if a more ambitious landed elevation of 4 km were desired, the maximum landed mass would be slightly less than 600 kg. If a greater landed mass were desired, however, the constraints would either need to be relaxed, or a different entry velocity or value of L/D would need to be considered.

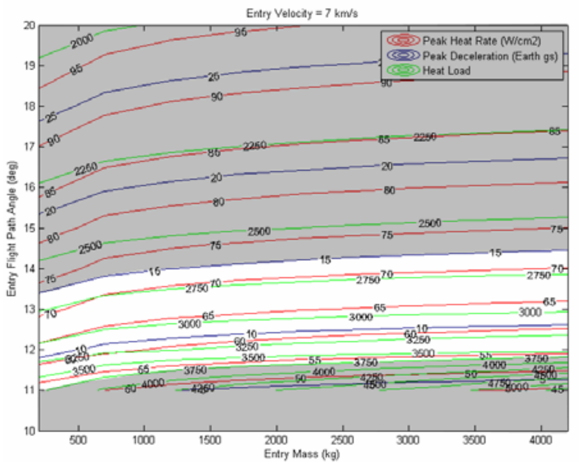

Figure 9. Limits on EDL design space due to heating and deceleration constraints.

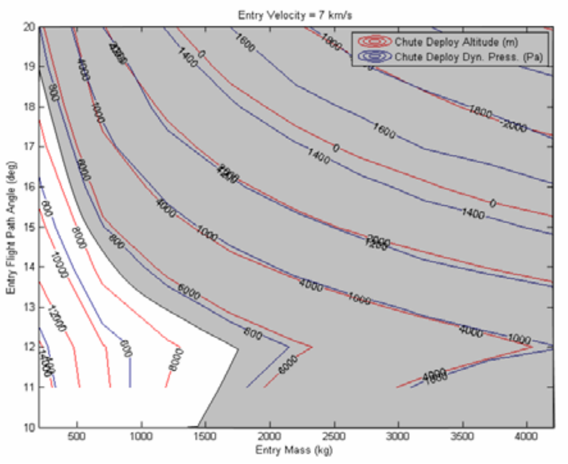

Figure 10. Limits on EDL design space due to chute deploy dynamic pressure constraint.

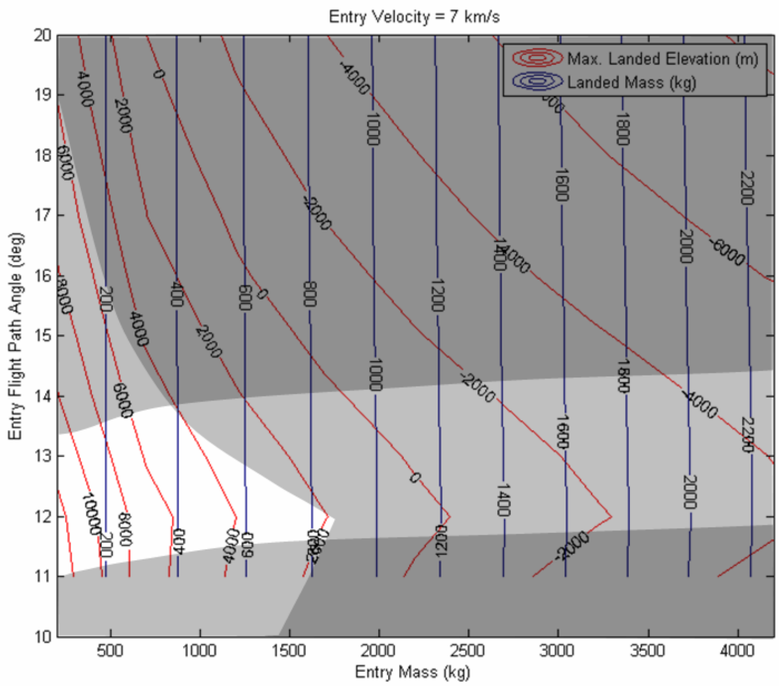

Figure 11. Available design space for mission design example.

B. Sensitivity Plots

In addition to the contour plots presented above, the handbook contains sensitivity charts which help to demonstrate the effect of changing the fixed input parameters on the key output metrics. As presented in Table 1, there are a number of variables that were held constant in generating the pork chop plots. The current mission design handbook only contains pork chop plots as a function of four input variables: entry mass, entry velocity, entry flight path angle, and vertical L/D. It also, however, contains 2-d sensitivity plots of a handful of the output metrics as a function of the following input variables:

- Arrival date and time
- Arrival conditions (latitude, longitude, azimuth)

- Atmosphere dust tau
- Parachute deployment Mach number trigger
- Parachute diameter and C_D
- Terminal descent initiation Mach number trigger
- Terminal descent engine thrust-to-weight ratio

In the sensitivity plots, all other variables are held constant, while the input variable of interest is varied. In the future, some of these may be added as input variables to the EDL contour plots, while others will remain as inputs to the sensitivity analysis.

Figure 12 and Figure 13 plot two example sensitivity plots, both varying the terminal descent engine thrust-to-weight ratio from 2 to 5 (baseline value is 3). Maximum landed elevation and landed mass are plotted as a function of thrust-to-weight for three different values of entry mass. Unlike with the contour plots, fewer dimensions can be visualized at one time, but it is useful in determining how important the input parameter is and the effect of varying it from its baseline value, at least in one dimension. These figures assume an entry velocity of 7 km/s and an entry flight path angle of -12º.

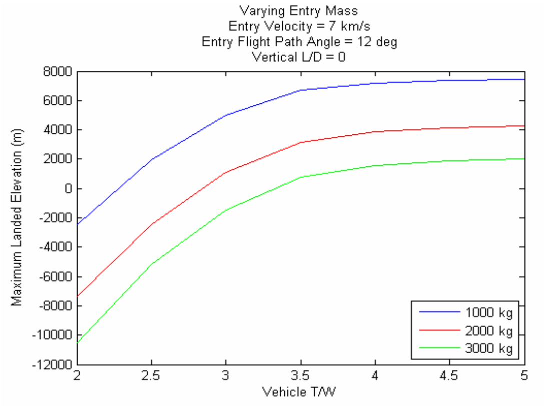

Figure 12. Sensitivity plot of maximum landed elevation to vehicle thrust-to-weight.

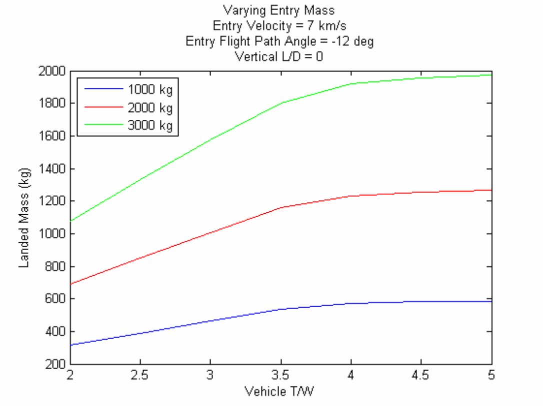

Figure 13. Sensitivity plot of landed mass to vehicle thrust-to-weight.

C. Limitations

The goal of creating a Mars EDL mission design handbook is to allow for visualization of the EDL design space to easily assess EDL design decisions and implications. It is intended for pre-phase A mission studies and Mars program planning and systems engineering activities. Therefore, it is not intended for us in later detailed design studies. More specifically, the current pork chop plots were generated based on an MSL-type entry configuration and are dependent on MSL-type mass properties for the results. There are also approximations in the specific disciplinary codes, particularly in the trajectory code. The calculated trajectories represent three degree-of-freedom trajectories and can only propagate single-body trajectories. Additionally, TPS sizing is done off-line, so there is no closure between TPS sizing, entry mass, and peak heat rate and total heat load. As explained above, there is no hypersonic guidance algorithm incorporated, so the contour plot represent lofted trajectories with vertical L/D. Finally, the terminal descent phase is based on a simple gravity turn algorithm, and therefore does not include pinpoint landing or other more complicated algorithms that may improve landed accuracy but at the cost of other performance metrics. If these limitations and the above assumptions are kept in mind, however, these contour plots still provide a useful tool for early exploration of the Mars EDL design space, without the need to run time-consuming analysis.

V. Conclusions

This work has successfully demonstrated that the Mars EDL design space can be visualized as a set of contour plots as a function of a limited number of variables. The addition of the sensitivity plots allows the user of the mission design handbook to understand the consequence of having fixed certain variables, in terms of their effect on the output metrics of interest. The mission design handbook will prove to be a useful tool for pre-phase A Mars mission studies and for technology planning, as long as the assumptions behind the plots are kept in mind. Additional planned functionality will further improve the usefulness of the contour plots. This includes adding a hypersonic guidance for the lifting cases, adding pinpoint landing descent guidance, and integrating a radiative heating and 1-D TPS thickness calculation.

VI. References

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