



Astronaut Risk Levels During Crew Module (CM) Land Landing

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Summary

The NASA Engineering Safety Center (NESC) is investigating the merits of water and land landings for the crew exploration vehicle (CEV). The merits of these two options are being studied in terms of cost and risk to the astronauts, vehicle, support personnel, and general public. The objective of the present work is to determine the astronaut dynamic response index (DRI), which measures injury risks. Risks are determined for a range of vertical and horizontal landing velocities. A structural model of the crew module (CM) is developed and computational simulations are performed using a transient dynamic simulation analysis code (LS-DYNA) to determine acceleration profiles. Landing acceleration profiles are input in a human factors model that determines astronaut risk levels. Details of the modeling approach, the resulting accelerations, and astronaut risk levels are provided.

Introduction

An assessment of the merits and risks of a land landing system for the crew module requires the determination of landing acceleration profiles that result from a range of landing conditions that are defined in terms of horizontal and vertical landing velocities and vehicle orientation. These conditions are determined by variables such as wind speeds, parachute conditions, and the performance of landing attenuation systems. For each set of landing conditions, a transient dynamic simulation is performed, and the resulting acceleration profiles are extracted and employed to determine astronaut injury risk levels using a human body injury model. Ideally, a detailed structural model of the crew module and an accurate model of the landing medium would be used to simulate each of the land landing scenarios. The detailed model of the vehicle would include the elastic and nonlinear behavior of all the structural components, including the contribution of damping and energy-absorbing components, such as crushable materials on the bottom vehicle outer shell and shock absorbers used to mount the pallet where the astronaut seats are mounted. Additionally, the model would (a) include any landing attenuation system such as retrorockets or airbags; (b) be capable of accurately predicting transient accelerations throughout the vehicle including where the astronauts are seated; (c) be able to predict stress levels throughout the vehicle structure. The model of the landing medium would fully characterize the actual landing soil behavior, including the actual deformation of the soil and the contribution of the soil to absorbing energy from the incoming vehicle in the vertical and horizontal directions. For the present study, a simplified structural model of the vehicle and landing surface was employed because a higher fidelity model was not available at the time of this study. The simplified model consists of an astronaut pallet supported by energy-absorbing struts attached to a rigid structural model of the vehicle. The landing medium is modeled as a simple elastic plastic material with energy-absorbing behavior. Further details of the model are provided later in this report.

Before proceeding with a discussion of the crew module vehicle model and landing results, it is useful to point out a fundamental constraint behind vehicle landings: regardless of the landing vehicle, it requires a minimum stopping distance to be able to slow down without exceeding a specified acceleration limit. For retrorockets, this distance is measured from the point where the rockets fire and begin slowing the vehicle to the point where it comes to a stop. For the other landing attenuation concepts, the distance is measured from the point where the attenuation system first incurs loading and begins absorbing energy to where the vehicle stops. The point to emphasize with this behavior is that acceleration limits equate directly to a minimum stopping distance regardless of the vehicle design and attenuation system employed. If the vehicle needs, for example, 12 in. of space to decelerate from some initial velocity, it will need this space regardless of whether airbags, deployable legs, or crushable material is used (refs. 1 to 6).

Figure 1 depicts the best-case scenarios for limiting accelerations to astronauts aboard the CEV. The curves in this figure are computed using simple basic principles of physics. Using the relationships between acceleration, velocity, and displacement, the resulting acceleration is computed given the maximum available displacement that the crew module has to decelerate from an initial landing velocity to a stationary resting position. The curves in the figure show, as expected, that the acceleration levels increase as the landing velocity increases. Conversely, as the distance that the capsule has to come to a complete rest is increased, the resulting acceleration decreases. As an example, if the goal is to not exceed 15 g's and the initial velocity is 20 ft/s, then at least 8 in. of displacement are needed regardless of the type of attenuation system used.

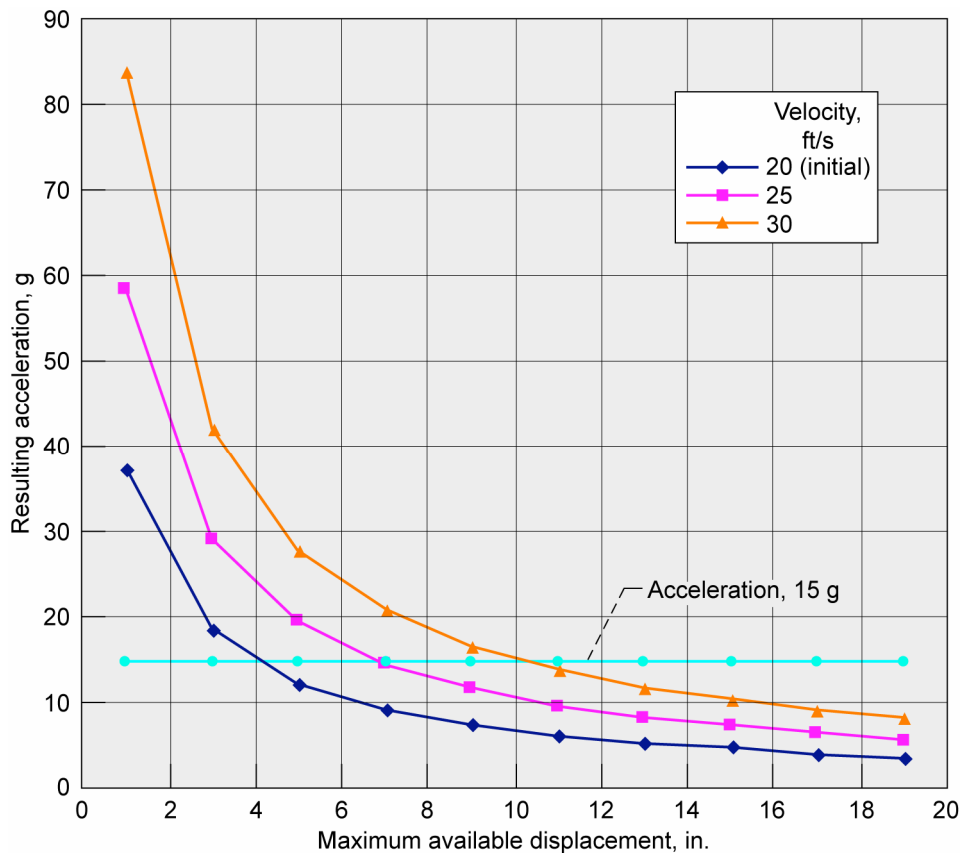


Figure 1.—Best-case scenario for acceleration.

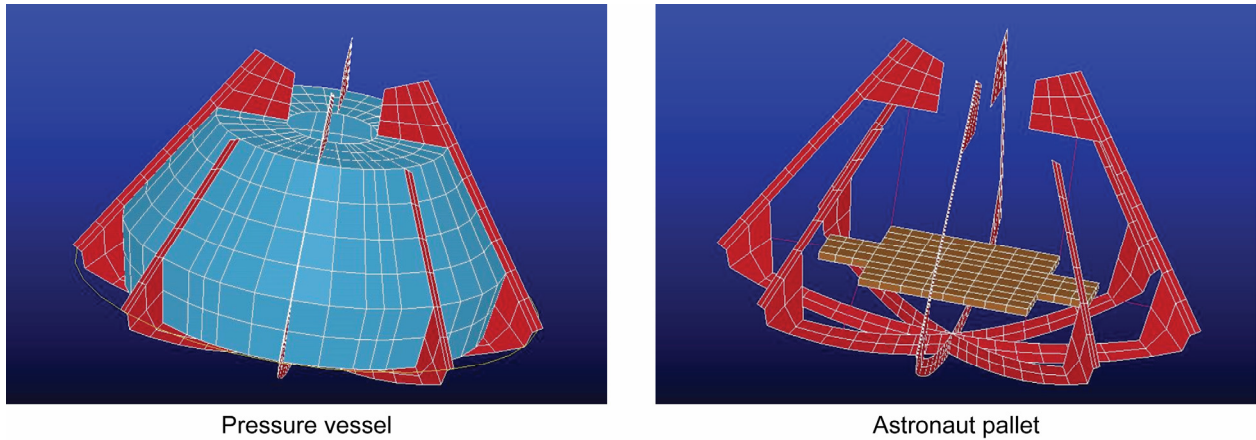


Figure 2.—Crew module land landing model showing rigid structures.

Crew Exploration Vehicle Model

The finite-element program LS-DYNA (ref. 7) was used to perform the analysis of crew module land landings. This commercially available program was selected because of its ability to simulate the complex transient dynamic behavior of the crew module impacting a landing surface. The crew module model is a collection of structural parts (fig. 2). The main portion of the vehicle, which consists of the pressure vessel, associated structure, and internal components, was modeled as a rigid part having inertia properties equivalent to those of the design analysis cycle II (DAC-II) crew module design (table 1). Since this part is modeled as rigid, it will act as a rigid mass and will exhibit no structural deformation; hence, no structural loadings will be computed.

TABLE 1.—CREW MODULE INERTIA PROPERTIES

Mass, lbm (lb).....	32.608 (12 600)
Moment of inertia, lbm-in. ²	
I_{xx}	101 904
I_{yy}	3296.9
I_{zz}	-4196
I_{xy}	79 725.6
I_{yz}	0
I_{zx}	73 731.2
Center of gravity, cg, orientation at	
$x = 134, y = 0, z = -11.5$ from theoretical CM apex (positive x from apex to heat shield, positive z from feet to head, right-hand rule denotes y)	

Inside the crew module pressure vessel is the astronaut pallet (fig. 3), which supports the astronaut seats and is held up by eight energy-absorbing landing struts. A portion of the vehicle inertia properties is allocated to the pallet (modeled as a rigid part) to account for the astronaut and seat weights. Although the pressure vessel and pallet are modeled as structurally rigid and nonenergy-absorbing, the pallet struts are modeled as energy absorbing because they provide the primary source of landing load attenuation. Four pallet struts attenuate vertical landing loads; two sideways struts and two diagonal struts contribute to vertical support and horizontal landing loads.

At the time of the present study, a structural model of the crew module, astronaut pallet, and pallet struts was not available. This lack of information led to the pressure vessel and pallet being modeled as rigid parts. Furthermore, although the preliminary location of the pallet struts was available, the design and properties of the struts had not yet been determined. To circumvent this limitation, a preliminary design of the struts was performed and the resulting strut properties were used for the present model.

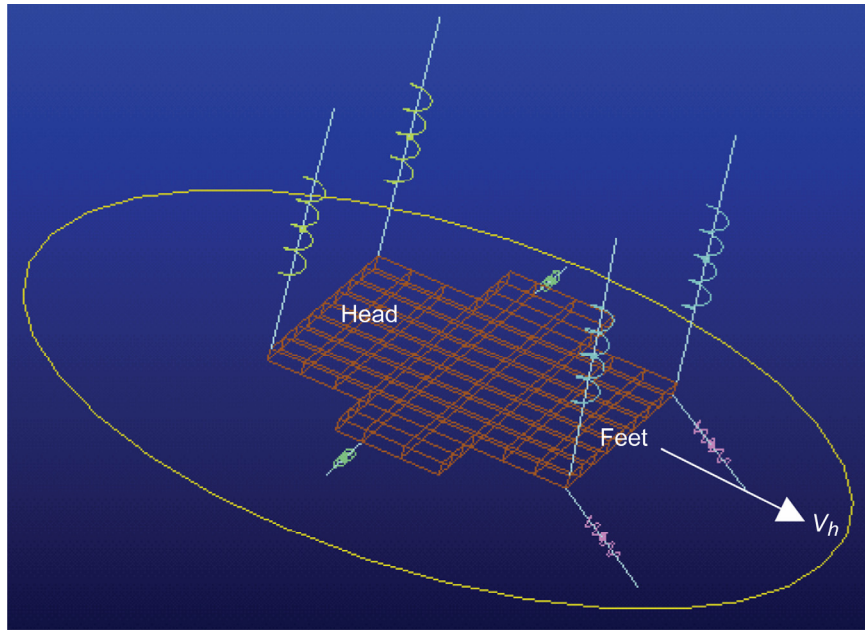


Figure 3.—Crew module land landing model showing astronaut pallet and landing struts. Horizontal velocity, V_h .

The strut design was accomplished by assuming maximum allowable accelerations in the three directions corresponding to the astronaut’s eyes in/out (into the chest/into the back), spine, and sideways directions (table 2). For each of these directions, maximum accelerations were established based on the level of acceleration that a healthy astronaut can incur without exceeding a low level of injury risk. Then, based on these allowables, the geometric orientation of the struts, and the pallet weight, an allowable strut force was computed. The pallet struts were modeled in LS-DYNA using a discrete (one-dimensional) element that carries an axial load and is characterized with a nonlinear material property equal to the calculated design strut force. The strut force was held constant throughout the entire strut displacement profile. After 16 in. of displacement, the struts were designed to bottom out and a very stiff spring to be activated.

TABLE 2.—MODIFIED STRUT DESIGN
[Pallet weight, 2000 lb.]

Global direction	Design acceleration of gravity, ^a g	Number of struts	Strut force, lb
Side/side, x	8	2	$2000 \times 8/2 = 8000$
Spine, ^b y	15	↓	$2000 \times 15/2 \cos 30 = 17\ 000$
Eye in/out (front struts), z	20		$(1000 \times 20 - 2 \times 17\ 000 \sin 30)/2 = 1500$
Eye in/out (rear struts), z	20		$1000 \times 20/2 = 10\ 000$

^aBased on approx. human allowance.

^bStruts in y-direction sloped at 30°.

It is important to note that the acceleration predictions resulting from the present model are dependent on the assumption of a rigid pressure vessel and pallet model and on the assumptions used for the pallet strut designs. Since the struts are designed for a specific acceleration limit and are modeled with a constant force behavior, they are in fact designed to perform optimally for a single design point and will perform less than optimally for off-design conditions. A tradeoff in the strut design was made since the struts could be designed to accommodate a worse-case condition or nominal conditions, but not both. It should also be noted that the actual pallet support system may employ another type of attenuation system

Soil type	Density, ρ , lb/in. ³	Modulus, E , lb/in. ²	Yield stress, σ_y , lb/in. ²	Tangent modulus, E_H , lb/in. ²
Soft	2.06	0.000580×10^6	9.99	116
Medium	2.06	0.0058	9.99	1160
Hard	2.06	0.019	323	3812
Rigid	2.25	2.5	3000	-----

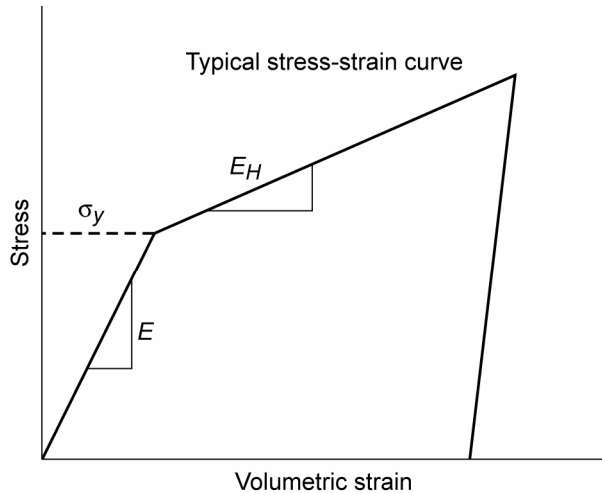


Figure 4.—LS–DYNA soil material model.

that performs differently from the present design. For example, an active attenuation system could be used, in which case a feedback loop would enable the struts to perform optimally for a broader range of landing conditions.

In reality, the vehicle landing surface will be some type of soil that will deform on impact and absorb energy. For the purpose of the present study, the landing surface was conservatively assumed to be a hard soil. A simple study was performed and it was determined that the hard soil does not absorb much more energy than a rigid surface but does eliminate many of the numerical difficulties associated with a rigid capsule model impacting a rigid ground surface. A simple elastic plastic model is employed in LS–DYNA to model the behavior of the hard soil (fig. 4). The landing surface is made large enough to capture the important portion of the vehicle response before it leaves the landing surface. A comparison between the hard soil and a softer soil was made for a subset of the landing conditions to determine the effect of the soil properties.

Simulation Results

Simulation results were generated for a variety of load cases (fig. 5) selected to encompass a range of landing conditions to provide a complete assessment of land landing. The four landing variables are vertical and horizontal velocity, center-of-gravity (cg) orientation, and pitch angle. For the present study, cg orientation and vertical velocity were held constant, and only horizontal velocity and pitch angle were varied. The vertical velocity was varied to correspond with different numbers of parachutes and landing attenuation systems working. Rollover of the vehicle was assessed in addition to acceleration levels and astronaut injury.

The results are reported in a body-fixed coordinate system that is fixed in the vehicle and rotates as the vehicle rotates (fig. 6). The axes of this coordinate system correspond to the directions that are used to assess injury risk levels to the astronauts. The body-fixed x -, y -, and z -axes correspond to the eyes in/out, sideways, and spine directions of the astronauts in the vehicle. The use of these axes allows the acceleration time histories to be directly input in the Brinkley model (refs. 8 and 9) employed to assess astronaut injury risk.

The first load case was run for a pitch angle of 0° and a cg oriented in the direction of the horizontal landing velocity. A hard soil model and a contact friction of 0.60 were used (fig. 7). The results depicted in this and subsequent figures are color coded according to levels of risk. Green indicates a low level of risk whereas orange and red are indicative of moderate and high levels of risk, respectively. The curved arrows indicate the level of risk associated with the vehicle's rolling over subsequent to impacting the ground.

Attenuation system	Vertical velocity, V_v , ft/s	Horizontal velocity, V_h , ft/s	Center-of-gravity orientation	Contact angle, deg
Chutes, all retrorockets	5	0	Forward (direction of V_h) +11.5	-15
All chutes out with retrorockets	9	30	Backward -11.5	0
All chutes, no retrorockets	25	60	Side (lateral) 11.5	+15
Two chutes, no retrorockets	29			

Figure 5.—Land landing simulation matrix.

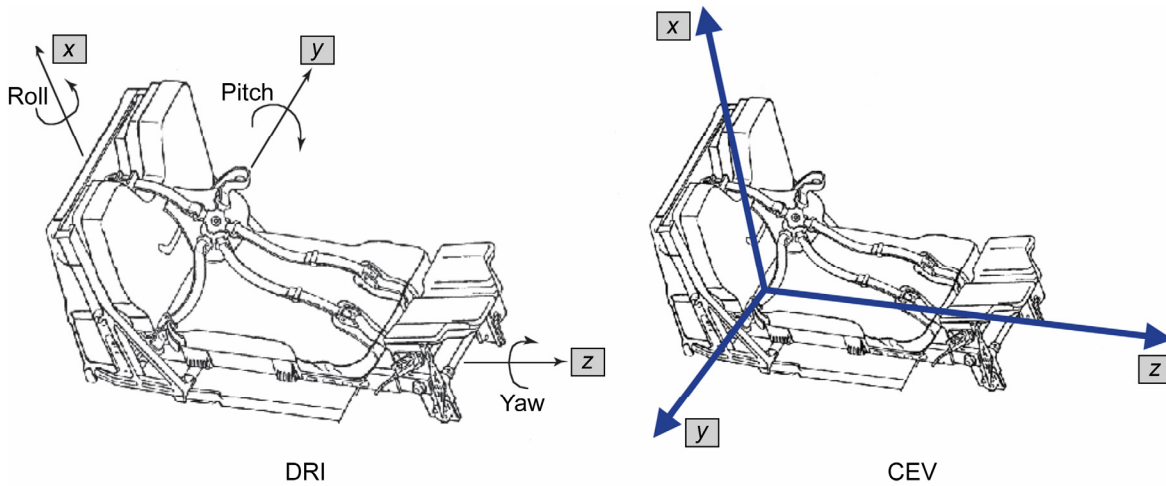


Figure 6.—Coordinate systems for dynamic response index (DRI) and crew exploration vehicle (CEV).

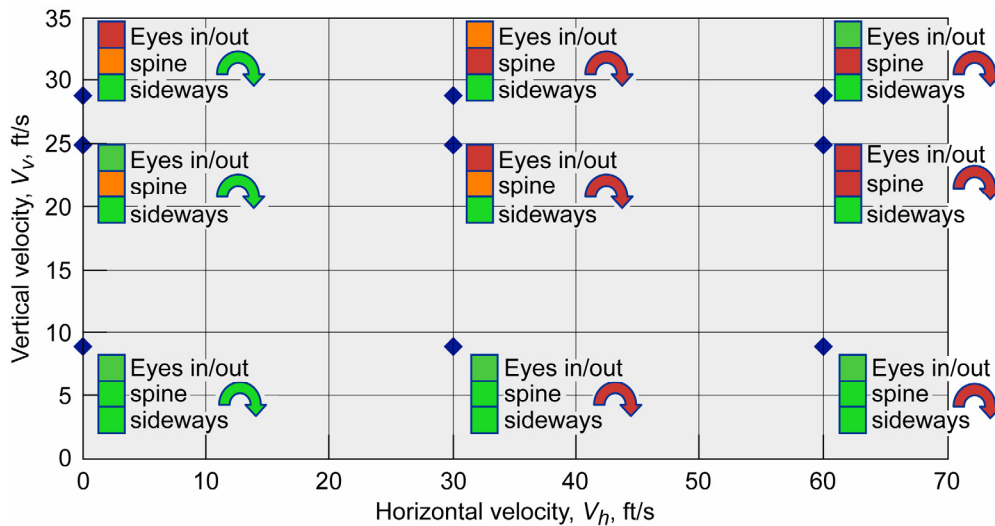


Figure 7.—Center of gravity, forward; pitch, 0°; soil, hard; contact friction, 0.60.

The harder soil provides negligible landing load attenuation, thus leading to higher predictions of the landing accelerations than would be predicted with a softer landing surface and an inclusion of the vehicle's complete structural flexibilities. The contact friction, although not having a strong influence on the landing accelerations, does significantly influence the vehicle rollover. Lower values of contact friction allow the vehicle to slide as a result of horizontal landing velocities whereas high contact frictions cause the vehicle to "grab" the landing surface, leading to rollover. The contact friction of 0.60 used for the present study was considered to be on the higher side and probably led to an overprediction and therefore conservative prediction of rollover. In general, the risk of injury increases as the horizontal and vertical landing velocities increase. For vertical landings of 9 ft/s and all levels of horizontal landing velocities, the injury risk is low whereas for the higher horizontal velocities, the rollover potential is high. As the vertical landing velocity increases, the risk levels change from low to moderate and high, depending on the directions of the accelerations. For all cases, the sideways risk is low, which is to be expected because the cg and landing velocities are symmetric to the landing and there are no accelerations in the sideways directions. The spine direction produces the largest number of higher risk situations. This direction is particularly problematic because the positioning of the pallet struts is not best suited for attenuating landing loads in this direction.

The above landing cases were re-run with the soft soil model to assess the effect of soil properties (fig. 8). When the softer soil model was used, all the eyes in/out risk levels that were moderate and high changed to low risk. This result reaffirms the sensitivity of the risk levels to the landing surface and its ability to deform and absorb landing loads. The spine direction risk levels remained high for the most part, except for one case where the risk increased to high and another case where it decreased from moderate to low. These last results are not intuitively easy to explain; however, they were probably caused by the coupling that occurs between the vertical and horizontal accelerations as a result of the sloped pallet struts.

Figure 9 presents the next set of landing cases, which were generated using a pitch angle of +15° (toe up). For this landing configuration, accelerations and resulting risk levels are generally lower than when the vehicle lands at a 0° pitch. In fact, although many of the landing conditions for a 0° pitch resulted in a spine direction high risk, none of the results under these conditions exceeds a low risk when the pitch angle is at +15°. There are, however, a few cases where the eyes in/out risk elevated to high and rollover is just as much a problem with a +15° pitch as it is for a 0° pitch.

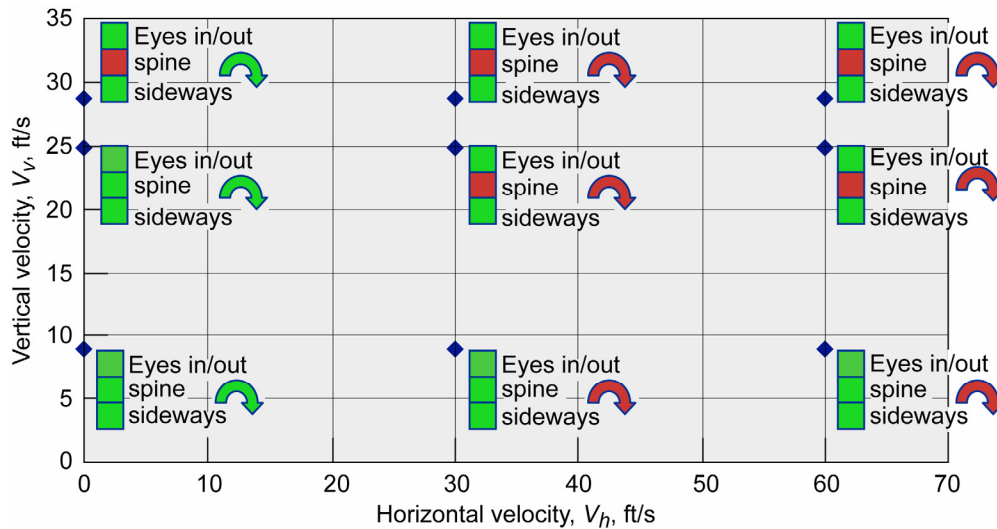


Figure 8.—Center of gravity, forward; pitch, 0°; soil, soft; displacement, ~6 in.

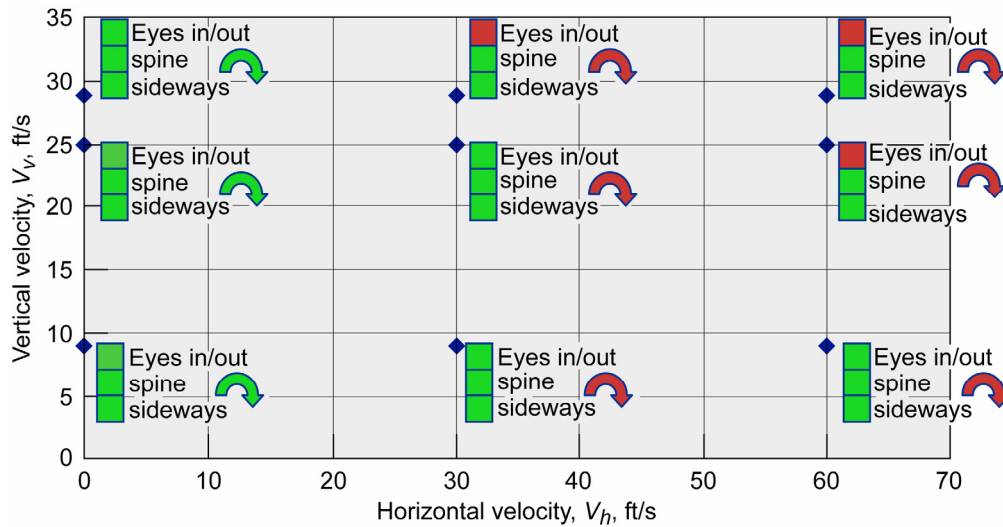


Figure 9.—Center of gravity, forward; pitch, +15°; soil, hard; contact friction, 0.60.

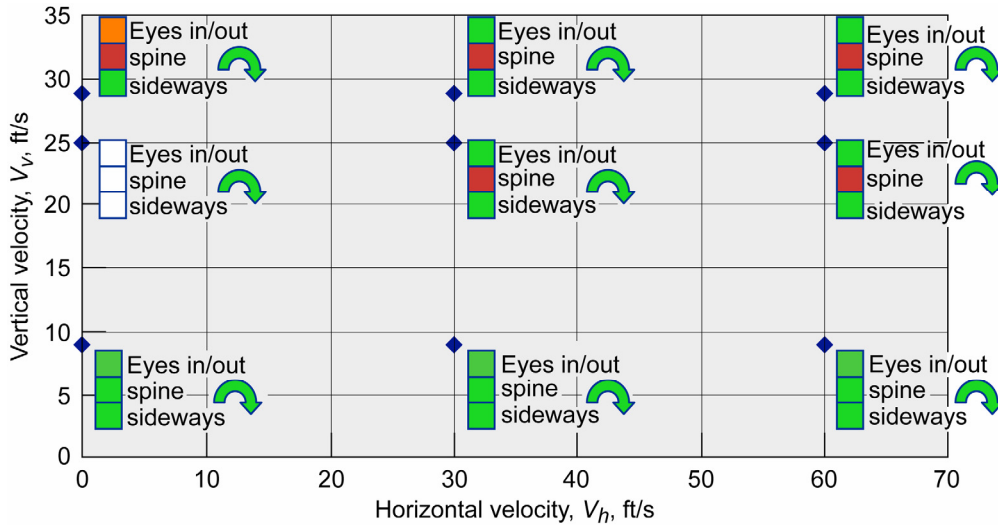


Figure 10.—Center of gravity, forward; pitch, -15°; soil, hard; contact friction, 0.60.

Figure 10 shows the final set of landing cases, which were generated using a pitch angle of -15° (heel up). For this set, there were slightly more high-risk situations than for the toe-down orientation. However, for this set, rollover is never a problem because the combination of heel-up orientation and horizontal landing velocity never produces a rollover condition.

Concluding Remarks

The results presented in this study are based on a crew module structural model that is rigid except for the pallet struts that attenuate landing loads and reduce the accelerations transferred to the astronauts. This model does not account for structural flexibility and, most important, does not account for any landing attenuation systems such as retrorockets or airbags. The effect of employing these landing attenuation systems can approximately be accounted for with the present model by estimating the landing velocity reductions that the attenuation system would attain and then using these velocities along with the present results to predict astronaut risks.

It should also be noted that the pallet strut design, including the strut properties and locations, is not optimal for all the landing cases considered. More detailed designs of the pallet struts and alternate strut mechanisms beyond a crushable design should be considered. Given the time constraints and the availability of a vehicle design, the present study provides predictions about the levels of risk that the astronauts may incur. Further fidelity in these predictions will occur as more refined designs become available.

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