A “Super Bowl” Approach to Mars Rover Touchdown Loads Analysis

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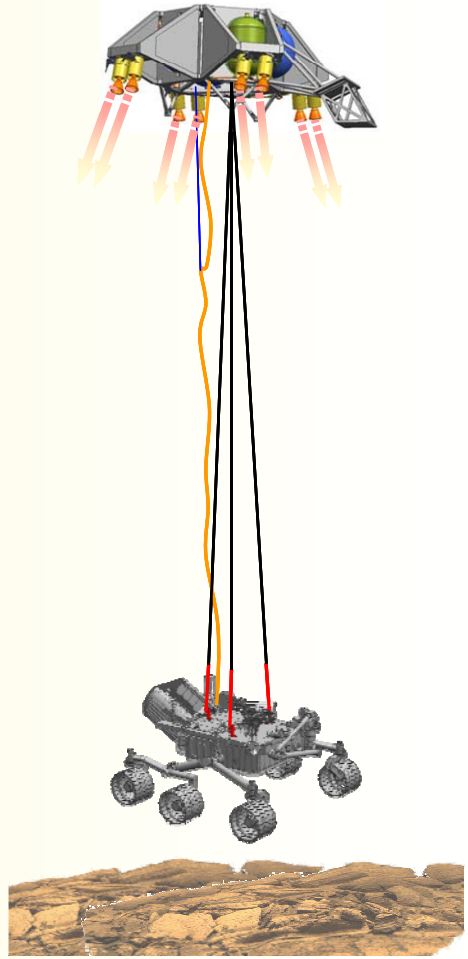
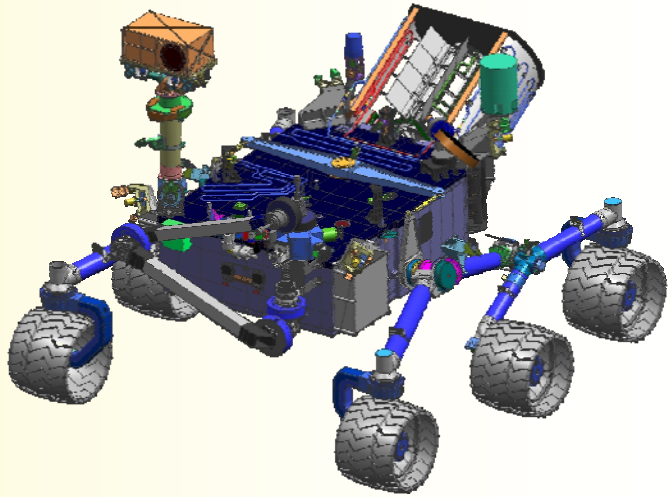
Jet Propulsion Laboratory

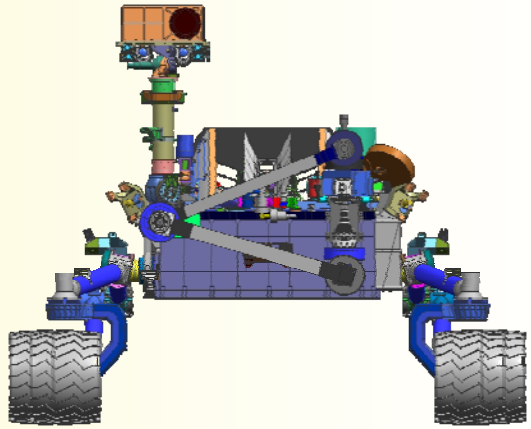


June 27-29, 2006

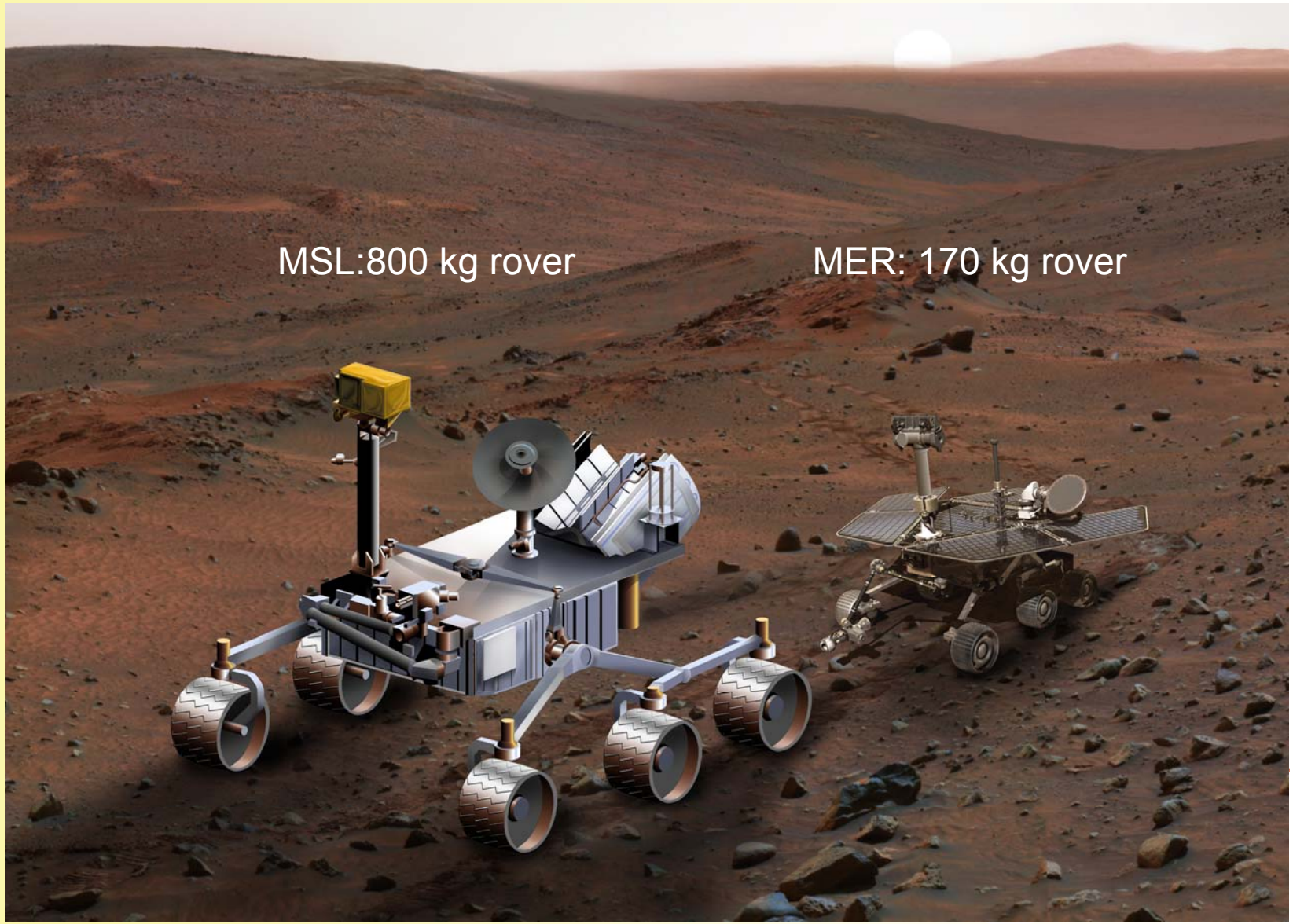
Introduction

- Mars Science Laboratory (MSL) scheduled to be launched in ’09
  - Mobile Science Laboratory
  - One Mars year surface operational lifetime (687 days)
  - Discovery responsive over wide range of latitudes and altitudes
  - Precision landing via guided entry
  - Controlled propulsive landing: Skycrane Touchdown Maneuver
  - Mission science will focus on Mars habitability
  - Next generation analytical laboratory science investigations



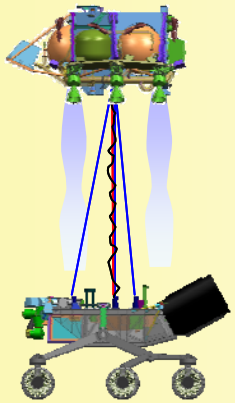


Mars Science Laboratory vs Mars Exploration Rover

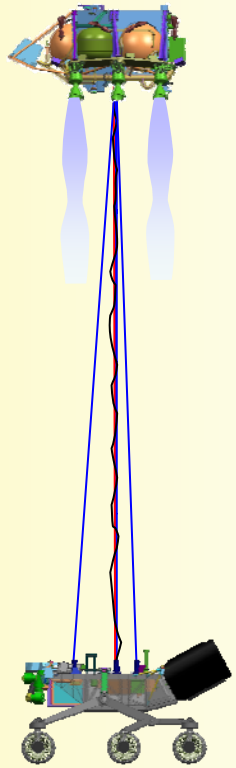


Skycrane Touchdown Maneuver

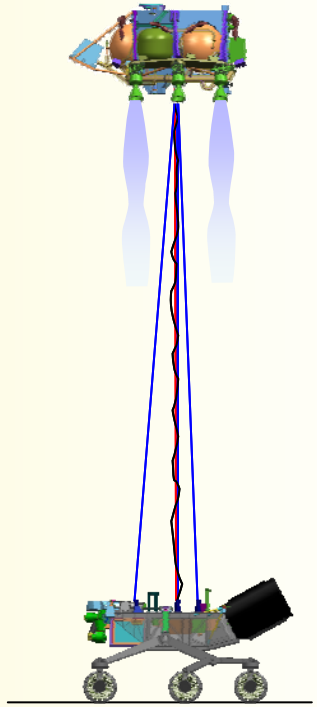
One Body Phase
(Vertical Descent)



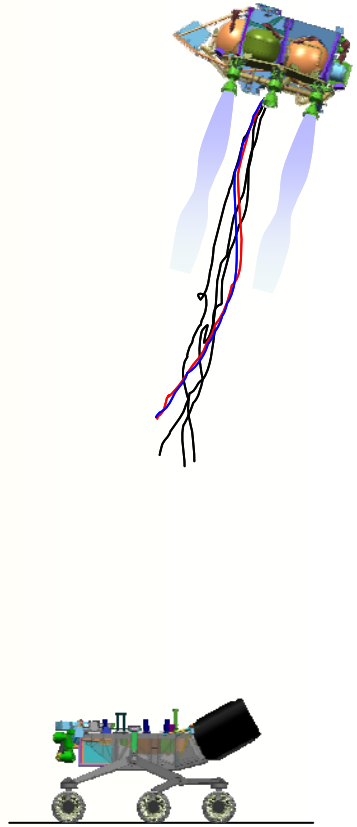
Two Body Phase
(DRL/Bridle Deployment)



Two Body Phase
(Constant Velocity)



Two Body Phase
(Touchdown Event)



Fly-Away Phase

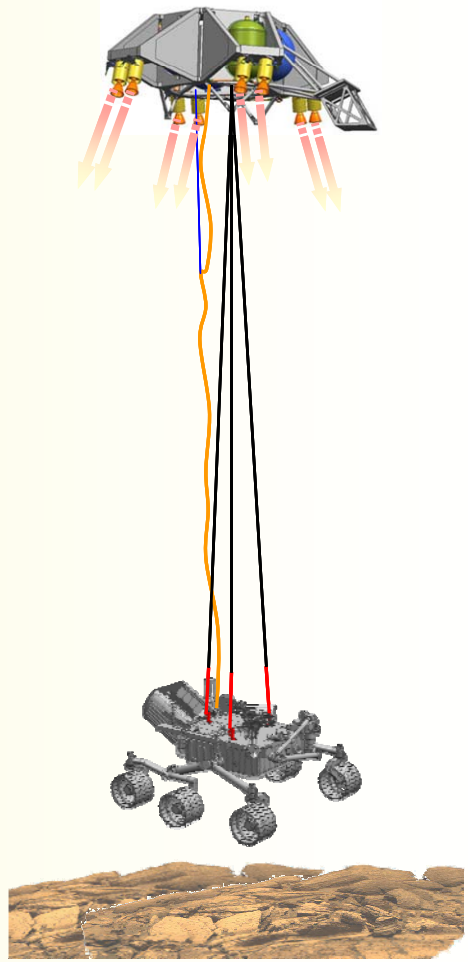
Requirement & Loads Development

- Touchdown Driving Requirement

  The mechanical system surface element shall be capable of facilitating a safe, stable landing at terrain angles up to 15 degrees, given an initial vertical velocity of 1 m/sec, horizontal velocity of 0.5 m/sec, and Z-axis spin rate of [4] deg/sec.

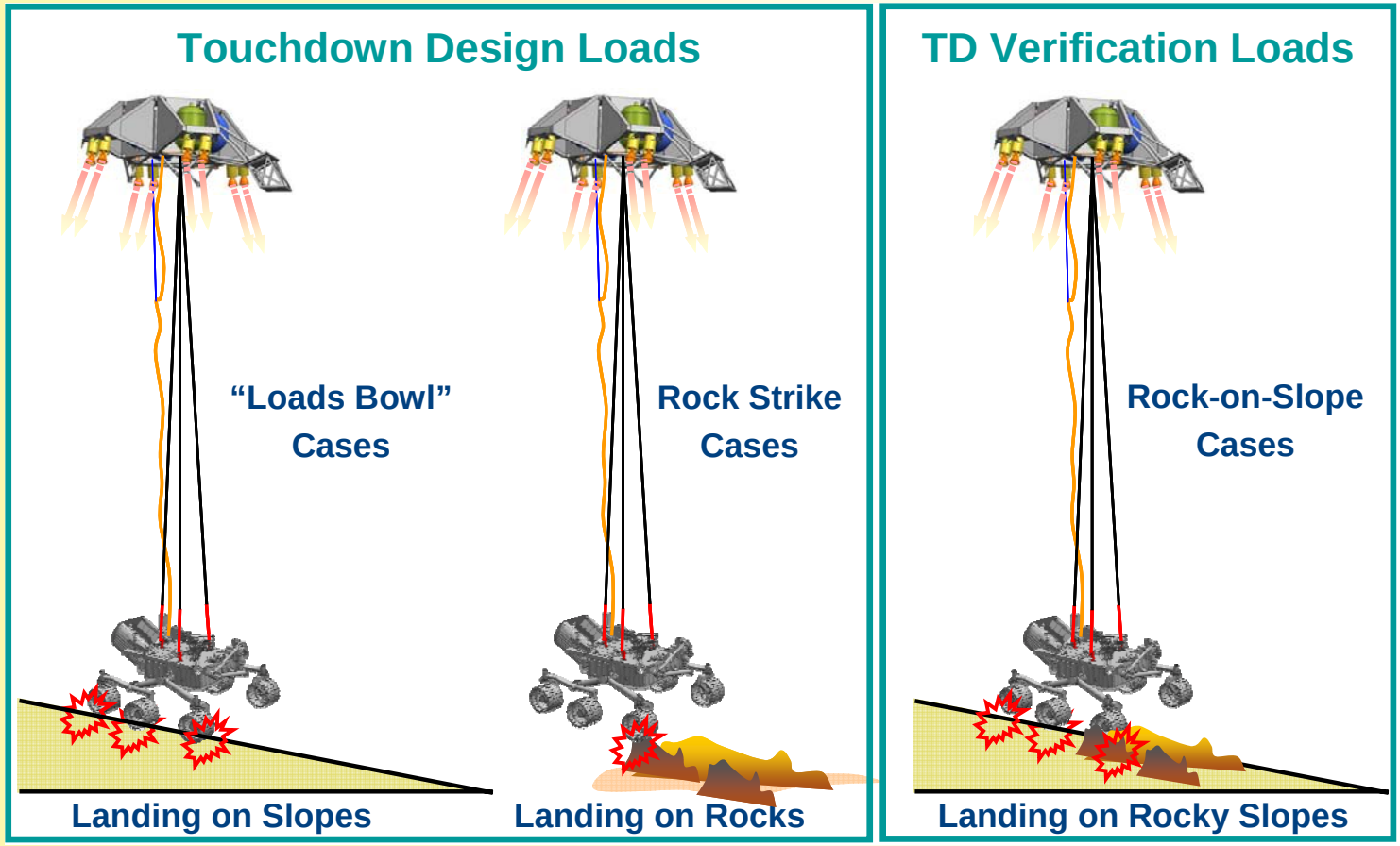
- Touchdown Loads Development

  A multi-year development effort has been successfully conducted leading to an innovative analytical methodology for the prediction of rover touchdown design loads and the assessment of rover touchdown stability.



Touchdown Loads Analysis Overview

- A systematic methodology developed for all TD loads analyses.



Touchdown Design Loads

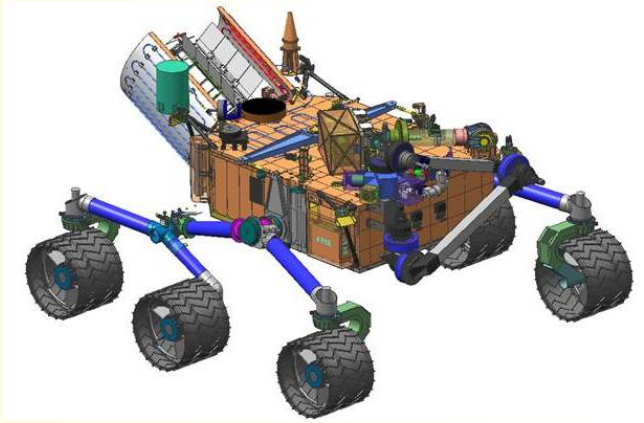
- Explore worst case limit loads from a reasonably bounding set of ADAMS simulations:
  - 1,752 Loads Bowl Cases + 618 Rock Strike Cases
- Simulate conservative touchdown conditions
  - 3-sigma landing velocity (V_v = 1 m/sec, V_h = 0.5 m/sec)
  - High friction of coefficient (μ_{fr} = 1)
  - Rigid terrain stiffness
- Compute case-consistent but not time-consistent loads, assumed to peak simultaneously
- Apply a Load Uncertainty Factor (LUF) of 1.3 to account for:
  - Changes in mass, geometry and stiffness (wheel, differential, suspension)
  - Uncertainty in damping, rover z-spin and unanticipated load cases
  - Not overly conservative for convergence of loads and structure sizing

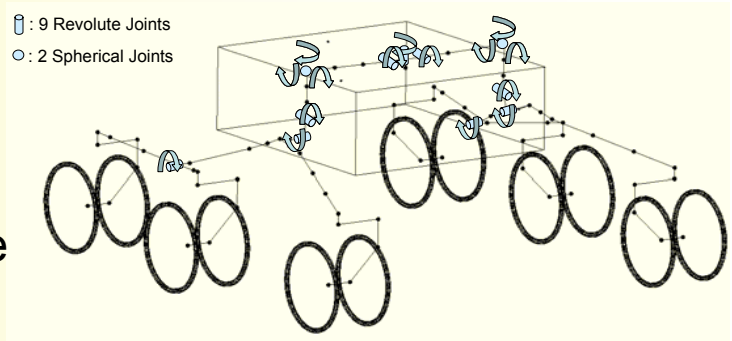
Touchdown Verification Loads

- Develop less conservative limit loads for final margin assessment
- Explore worse case by running large no. of ADAMS simulations
  - 2,000 to 5,000 of Rock-on-Slope Cases
- Perform probabilistic assessment by dispersing key touchdown performance parameters with known statistical distributions
  - Vertical and horizontal landing velocities
  - Rover z-spin rate prior to touchdown
  - Representative rock and slope field or probabilistic model
- Compute time-consistent loads for items with negative margins
- Reduce Load Uncertainty Factor (LUF) based on:
  - Exploration of a comprehensive set of load cases
  - Design maturity in mass, geometry and stiffness
  - Model correlation & damping verification by component, subassembly, subsystem and drop tests

Touchdown Dynamics Model

- A high-fidelity rover model with "proper" level of idealization developed in ADAMS:
  - Flexible suspension idealized with beam elements
  - Vehicle chassis modeled as a rigid body with its CBE mass properties scaled to allocations
  - Wheel compliance modeled by a 6-DOF bushing
  - Wheel/ground impact modeled by a robust torus-to-surface contact model with $\mu_{fr} = 1$
  - Mobility joints idealized by revolute and spherical constraints

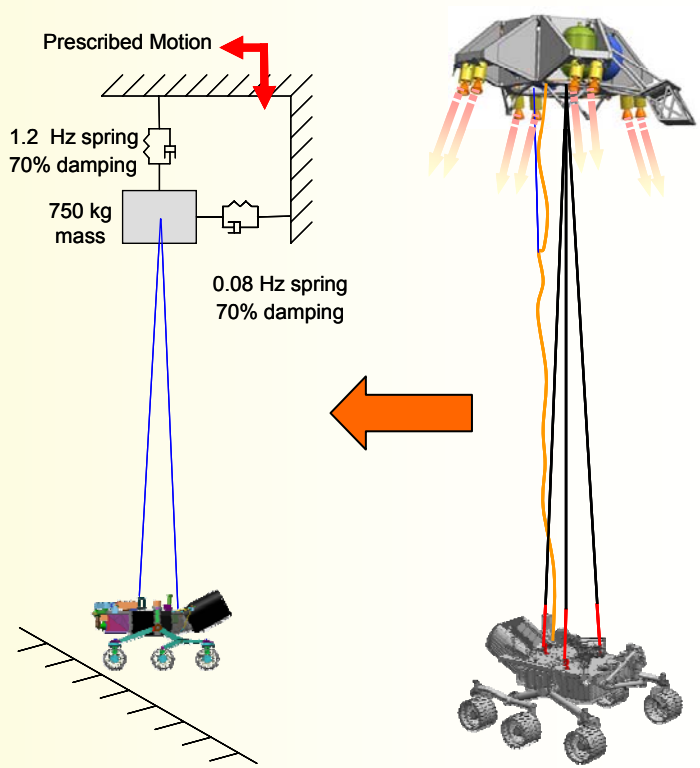




Touchdown Dynamics Model (cont.)

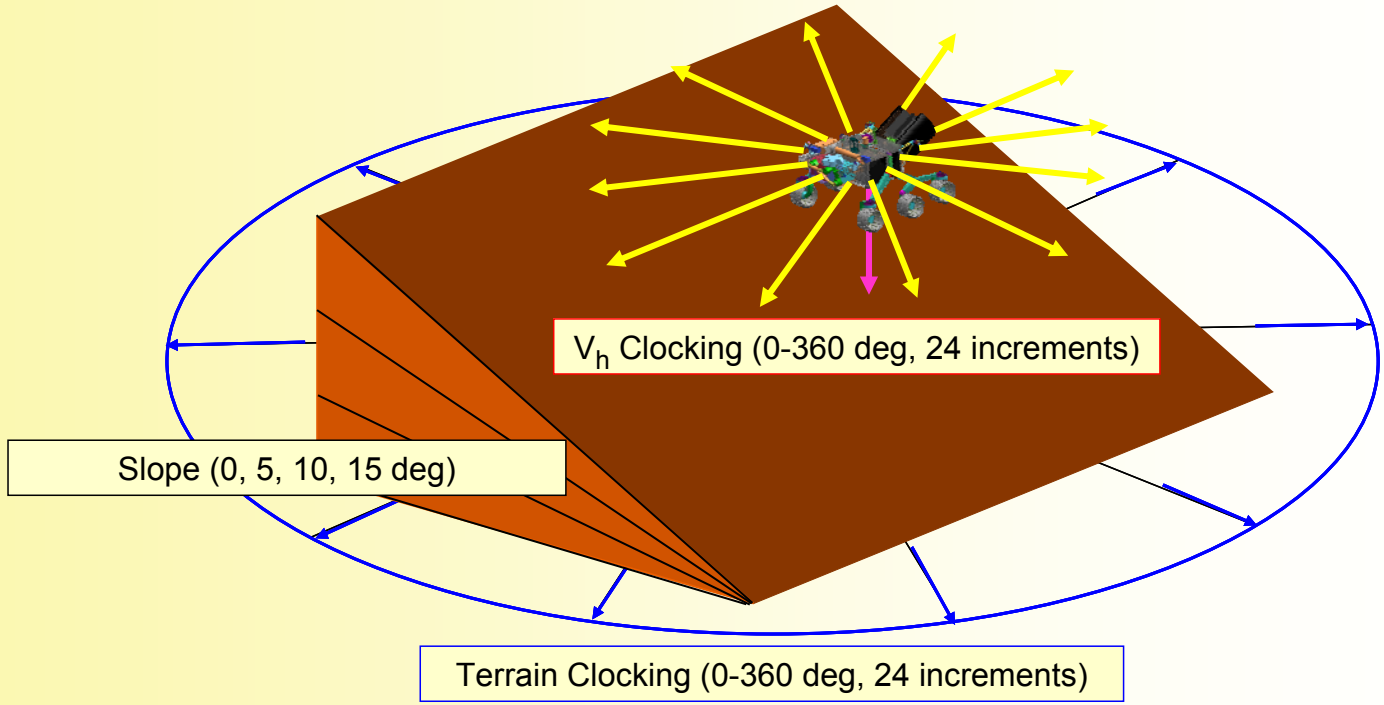
- Descent stage modeled as a rigid body with its CBE mass properties scaled to allocations
- Each bridle modeled as a tension-only spring-damper element
  - 40 kN/m per bridle, 1% damping
- Descent stage control system modeled by a mechanical analog:
  - Control compliance simulated by an equivalent spring-damper system.
  - Maximum touchdown velocities prescribed:

    V_v = 1.0 m/sec, V_h = 0.5 m/sec



Loads Analysis of "Loads Bowl" Cases

- A "Super Bowl" of 1,752 load cases are developed to cover all the possible combinations of slope angles (0°,5°,10°,15°), slope orientations (0°-360°, 24 increments), and the clocking of horizontal landing velocity (0.5 m/sec, 0°-360°, 24 increments).



“The Da Vinci Code” of Loads Bowl Cases

- Example: Cases #1177 to #1752 (touching down on 15° slope)

Vh Clocking from Rover +X (deg)

Slope Clocking from Rover +X (deg)	0	15	30	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255	270	285	300	315	330	345
180	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200
195	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224
210	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248
225	1249	1250	1251	1252	1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264	1265	1266	1267	1268	1269	1270	1271	1272
240	1273	1274	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296
255	1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318	1319	1320
270	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	1334	1335	1336	1337	1338	1339	1340	1341	1342	1343	1344
285	1345	1346	1347	1348	1349	1350	1351	1352	1353	1354	1355	1356	1357	1358	1359	1360	1361	1362	1363	1364	1365	1366	1367	1368
300	1369	1370	1371	1372	1373	1374	1375	1376	1377	1378	1379	1380	1381	1382	1383	1384	1385	1386	1387	1388	1389	1390	1391	1392
315	1393	1394	1395	1396	1397	1398	1399	1400	1401	1402	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	1414	1415	1416
330	1417	1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428	1429	1430	1431	1432	1433	1434	1435	1436	1437	1438	1439	1440
345	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450	1451	1452	1453	1454	1455	1456	1457	1458	1459	1460	1461	1462	1463	1464
0	1465	1466	1467	1468	1469	1470	1471	1472	1473	1474	1475	1476	1477	1478	1479	1480	1481	1482	1483	1484	1485	1486	1487	1488
15	1489	1490	1491	1492	1493	1494	1495	1496	1497	1498	1499	1500	1501	1502	1503	1504	1505	1506	1507	1508	1509	1510	1511	1512
30	1513	1514	1515	1516	1517	1518	1519	1520	1521	1522	1523	1524	1525	1526	1527	1528	1529	1530	1531	1532	1533	1534	1535	1536
45	1537	1538	1539	1540	1541	1542	1543	1544	1545	1546	1547	1548	1549	1550	1551	1552	1553	1554	1555	1556	1557	1558	1559	1560
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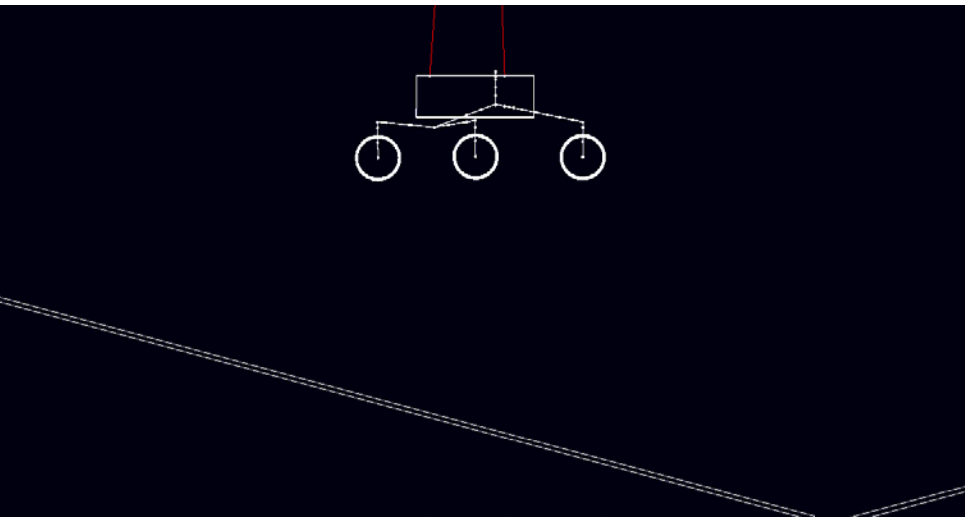
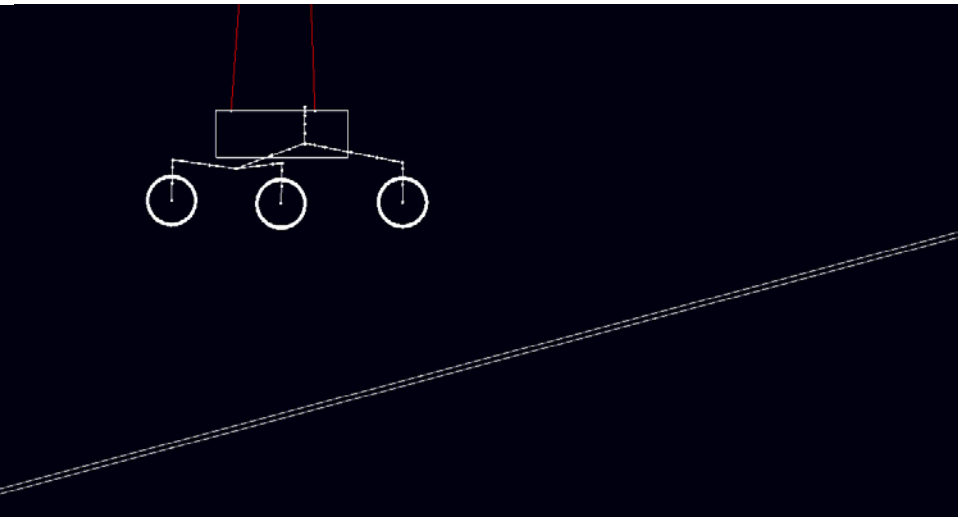
90	1609	1610	1611	1612	1613	1614	1615	1616	1617	1618	1619	1620	1621	1622	1623	1624	1625	1626	1627	1628	1629	1630	1631	1632
105	1633	1634	1635	1636	1637	1638	1639	1640	1641	1642	1643	1644	1645	1646	1647	1648	1649	1650	1651	1652	1653	1654	1655	1656
120	1657	1658	1659	1660	1661	1662	1663	1664	1665	1666	1667	1668	1669	1670	1671	1672	1673	1674	1675	1676	1677	1678	1679	1680
135	1681	1682	1683	1684	1685	1686	1687	1688	1689	1690	1691	1692	1693	1694	1695	1696	1697	1698	1699	1700	1701	1702	1703	1704
150	1705	1706	1707	1708	1709	1710	1711	1712	1713	1714	1715	1716	1717	1718	1719	1720	1721	1722	1723	1724	1725	1726	1727	1728
165	1729	1730	1731	1732	1733	1734	1735	1736	1737	1738	1739	1740	1741	1742	1743	1744	1745	1746	1747	1748	1749	1750	1751	1752

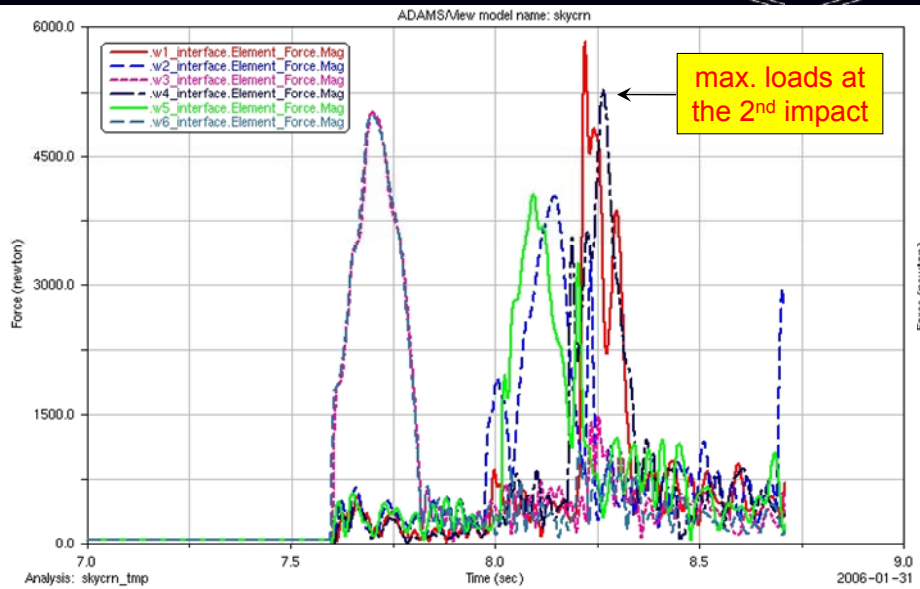
Touchdown Loads of Loads Bowl Cases

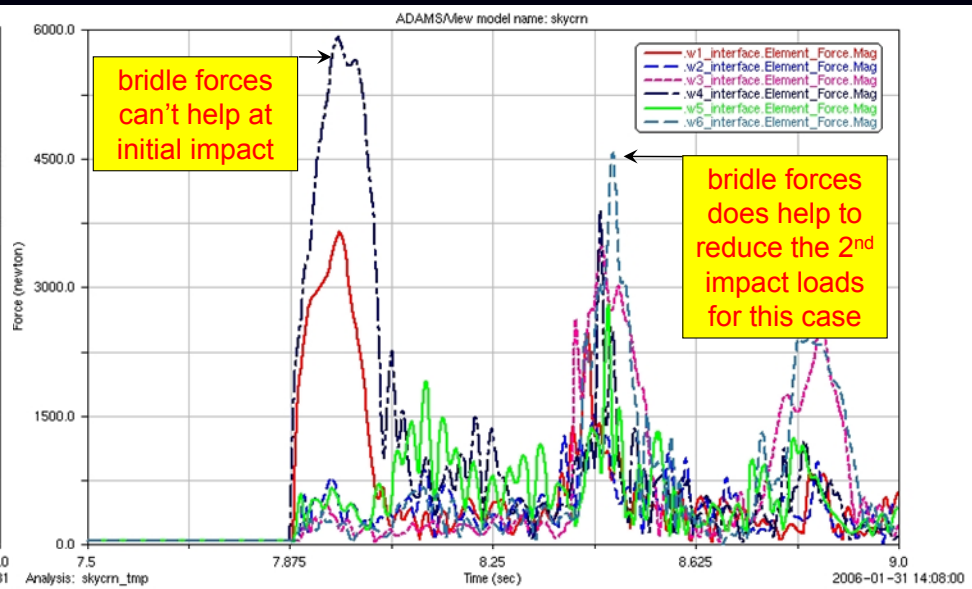
Cases #1189 – 15° slope, 180° clocking, (Vx, Vy, Vz) = (-0.5, 0, 1) m/sec

Cases #1486 – 15° slope, 0° clocking, (Vx, Vy, Vz) = (0.5, 0, 1) m/sec



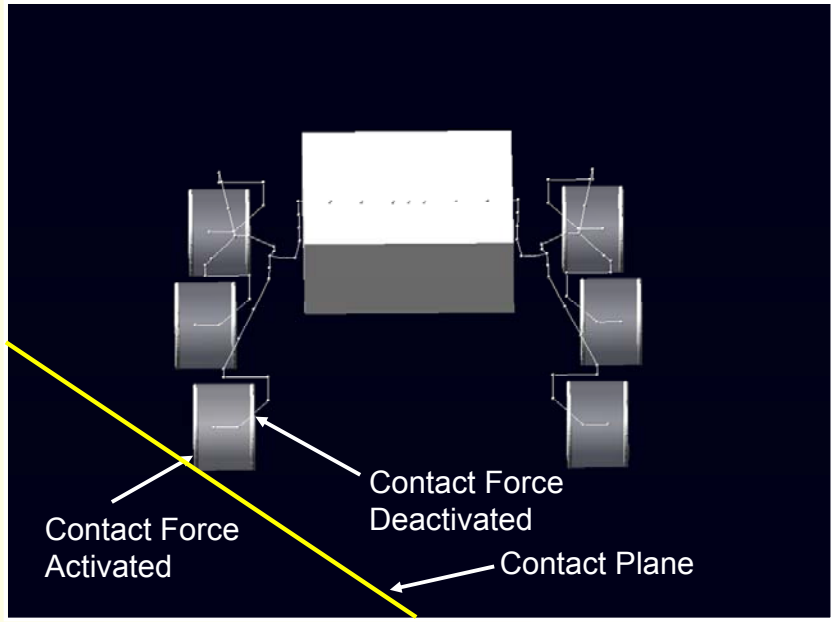


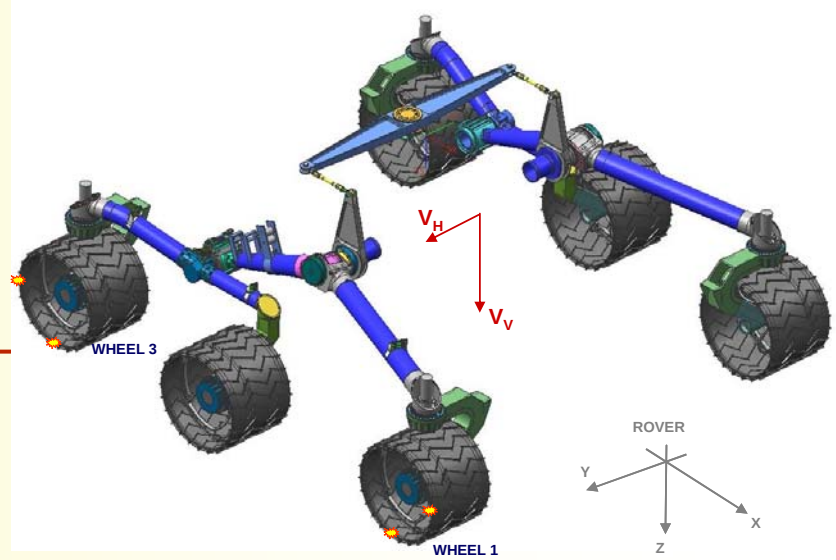




Loads Analysis of Rock Strike Cases

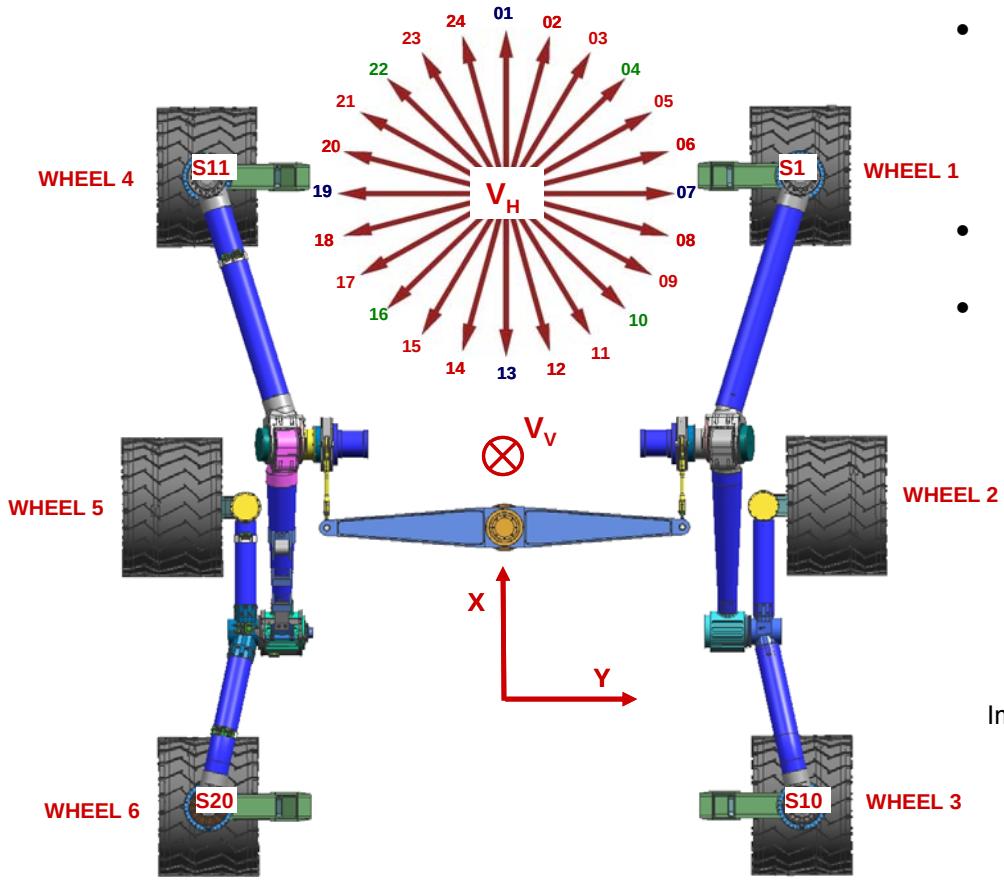
- To explore "worst" loads, 618 rock strike cases have been simulated:
  - Normal of local rock impact surface is aligned with impact velocity vector.
  - Normal of local rock impact surface is aimed at the rover c.g.
  - Normal of local rock impact surface is aimed at the stiffest suspension direction.
  - Specific wheel impact cases suggested by the MSL rover mobility team.
  - The local rock impact surface is a vertical one.
  - The local rock impact surface is a horizontal one.





"The Da Vinci Code" of Rock Strike Cases

- Example: Cases #1101 to #2624 (rock normal aligned with velocity)



- Normal vector of impact surface parallel to impact velocity vector
- 288 cases total
- Case mnxy

m = 1, Impact at outer wheel rim

m = 2, Impact at inner wheel rim

n = 1 to 6, wheel ID

(xy-1)*15 = clocking angle of V_H from rover +X axis in degrees

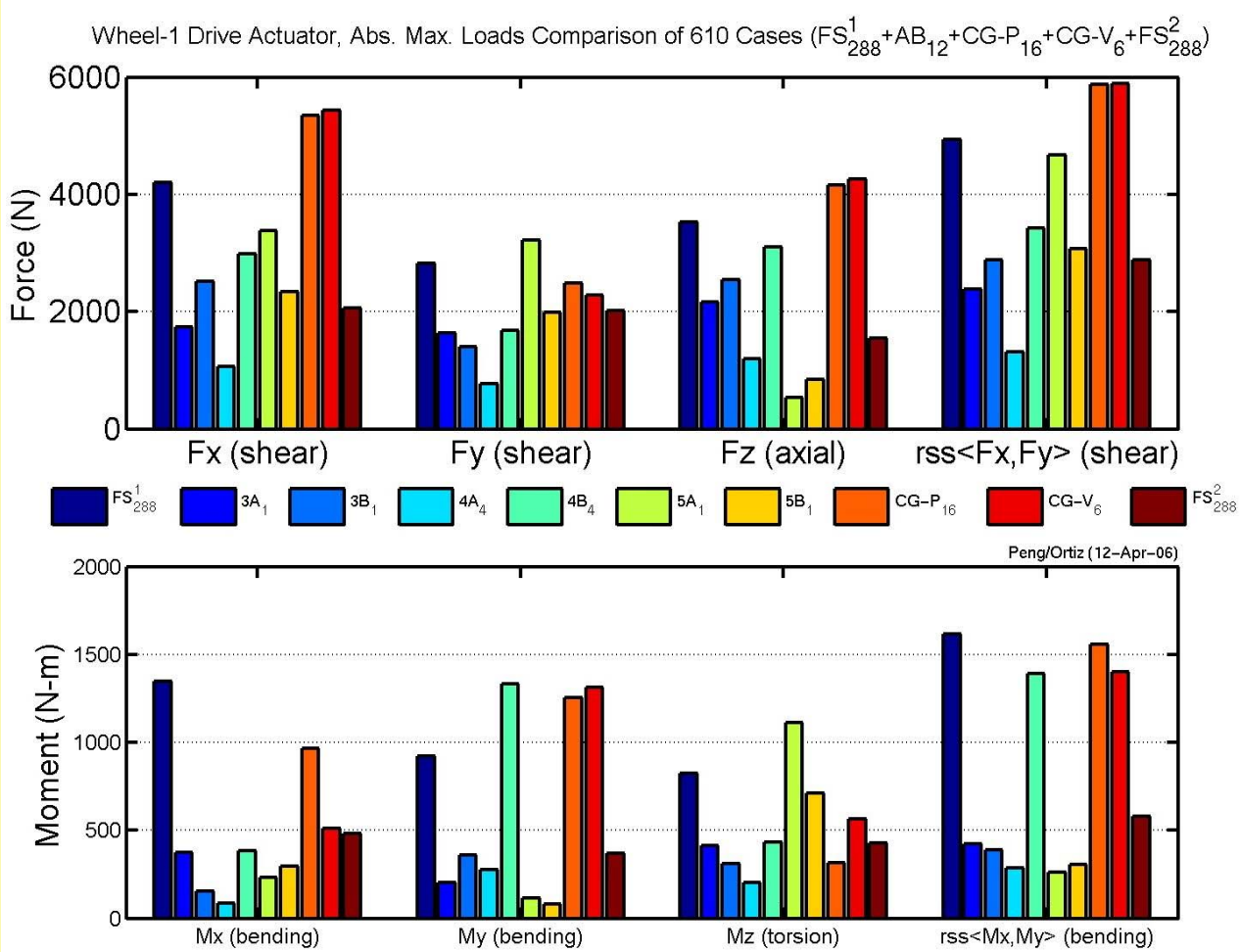
Example: Case 2104

Impact at inner wheel rim

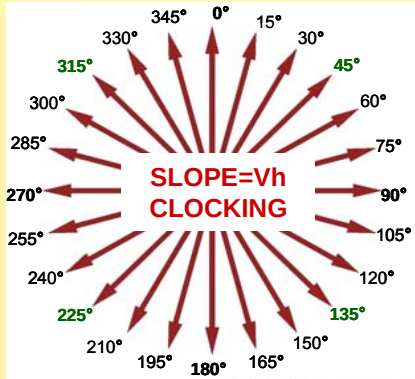
Impact at wheel 1

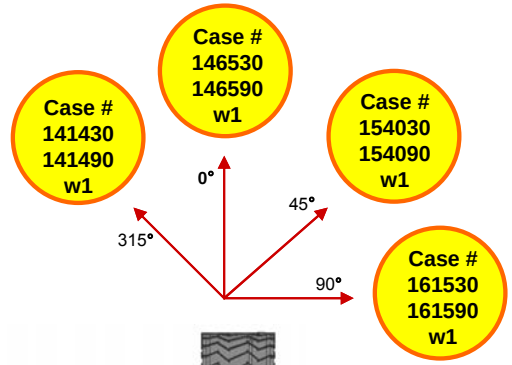
V_H @ 45° from rover +X

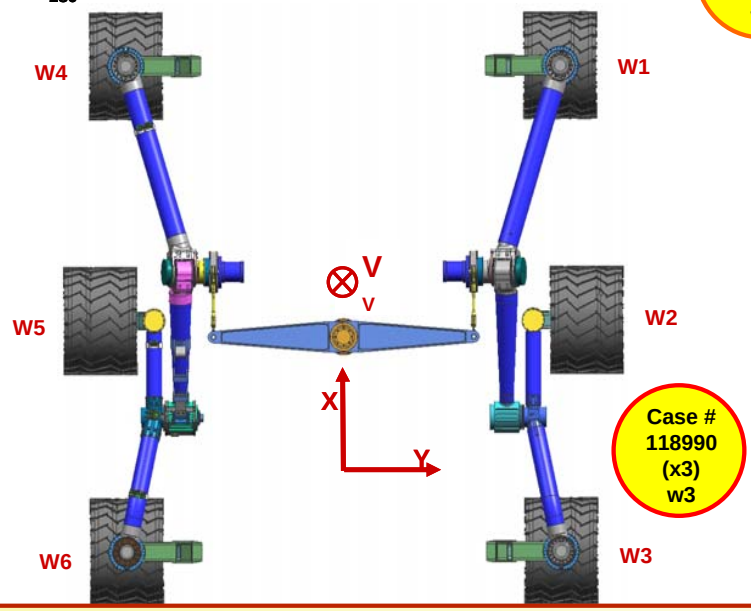
Touchdown Loads of Rock Strike Cases



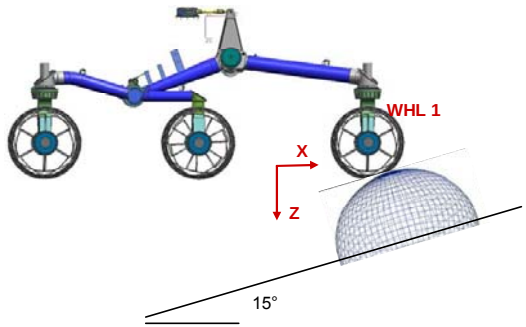
Loads Analysis of Rock-on-Slope Cases



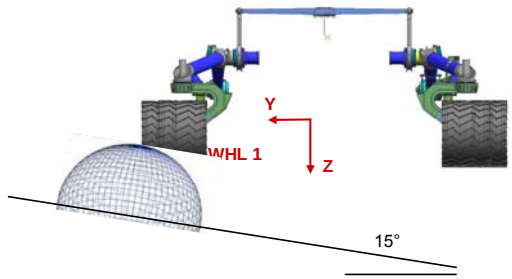




Rock/Slope Configuration



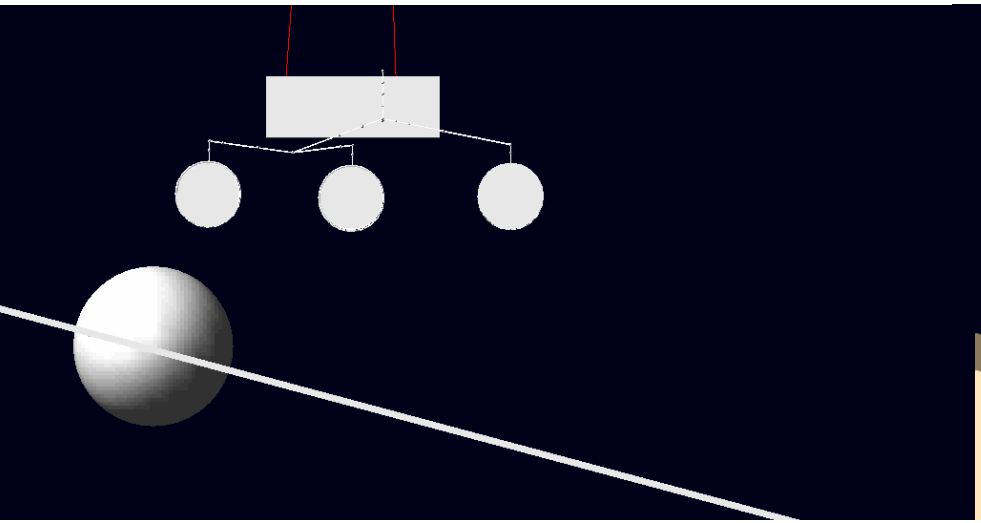
Case #146590 – 15° slope at 0° clocking



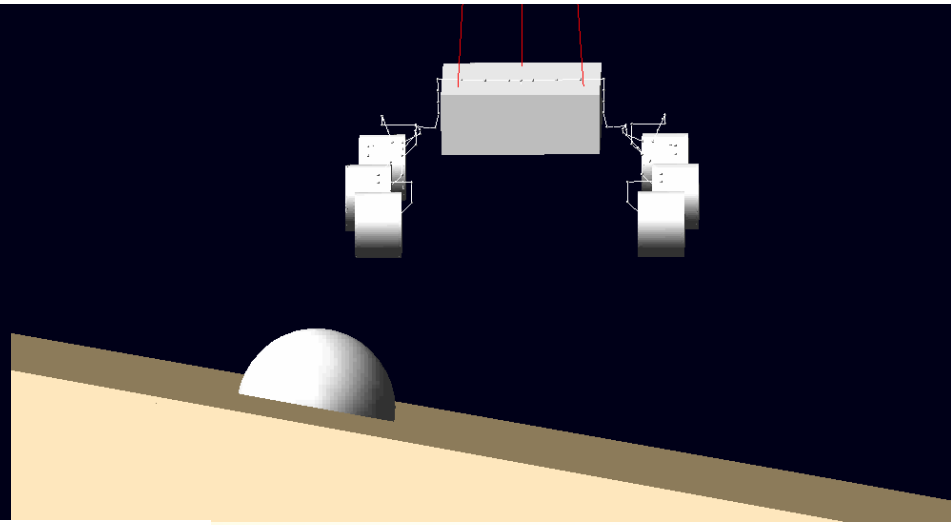
Case #161590 – 15° slope at 90° clocking

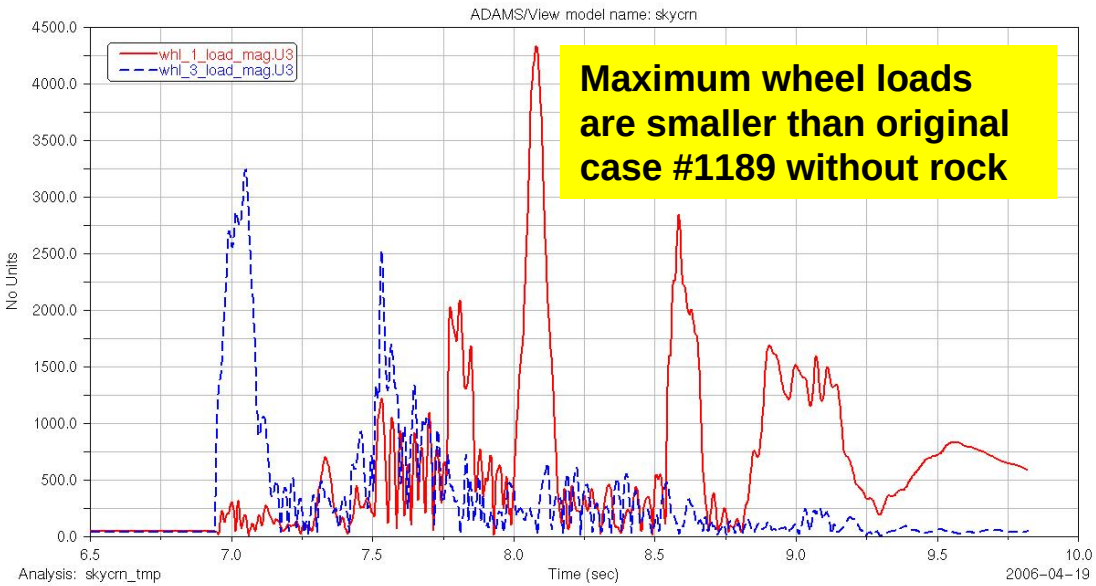
Touchdown Loads of Rock-on-Slope Cases

Loads Bowl Case #1189 with wheel #3 Impacting a rock



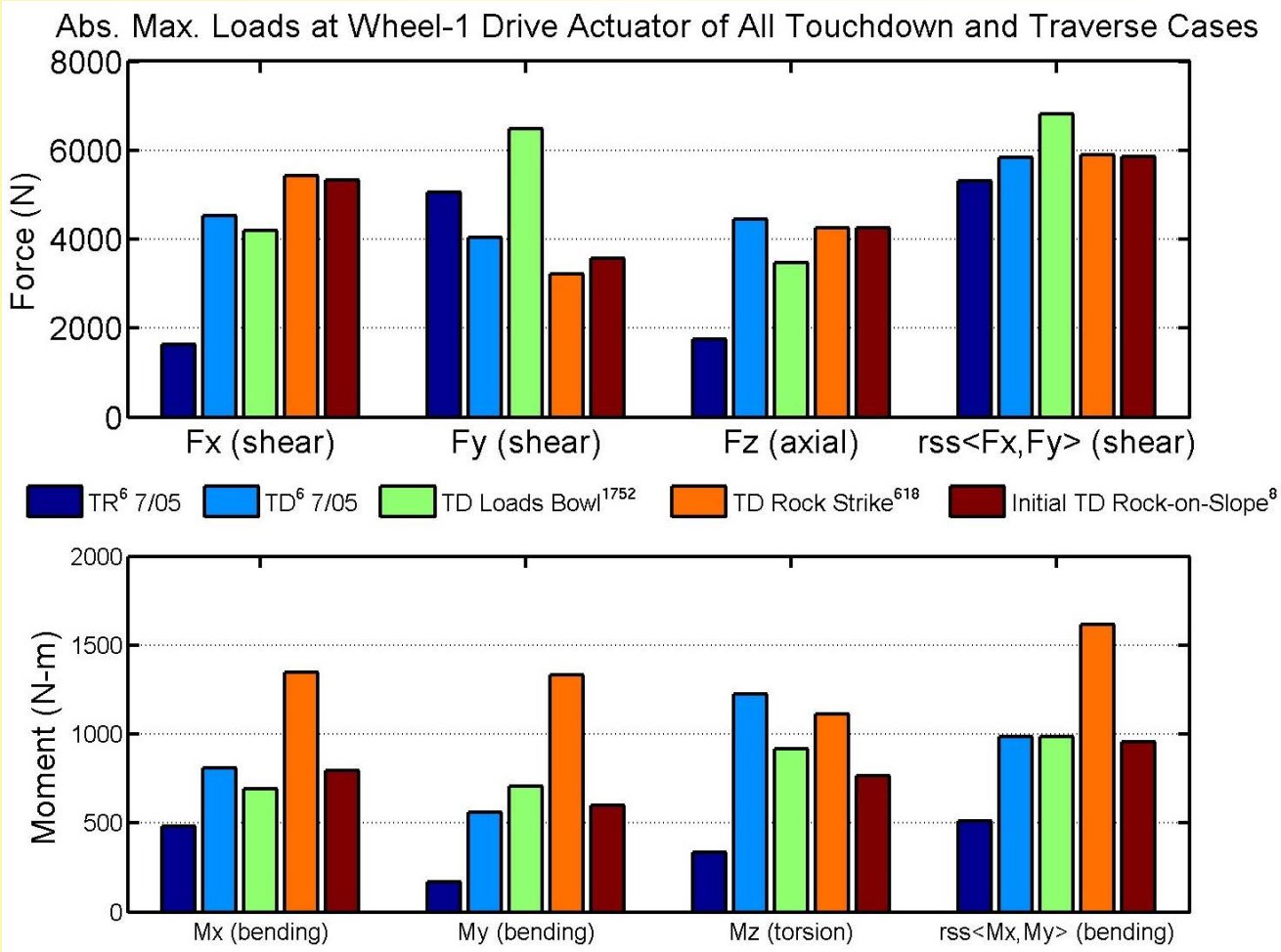
Loads Bowl Cases #1540 with wheel #1 Impacting a rock





- Based on a preliminary study, the touchdown loads of single-rock-on-slope cases will be bounded by the loads bowl cases and rock strike cases, as shown on next slide.

Comparison of All Touchdown Loads

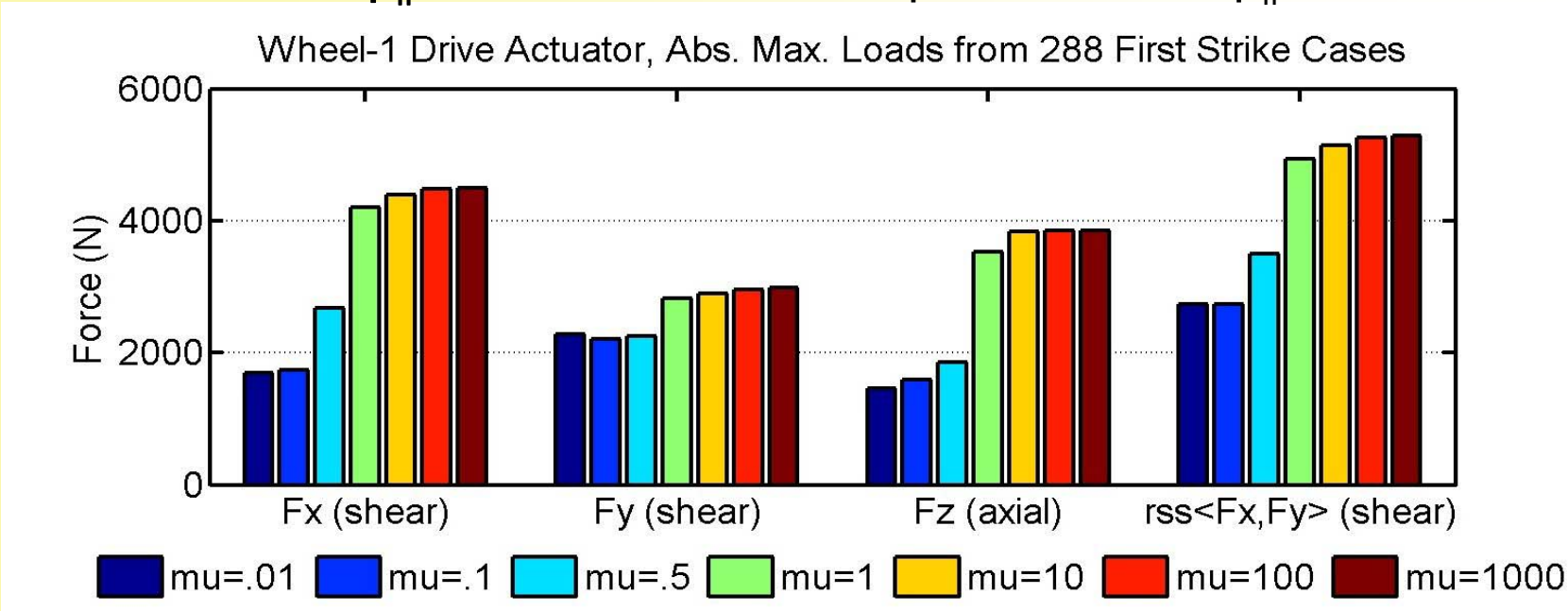


Sensitivity Study of Touchdown Loads

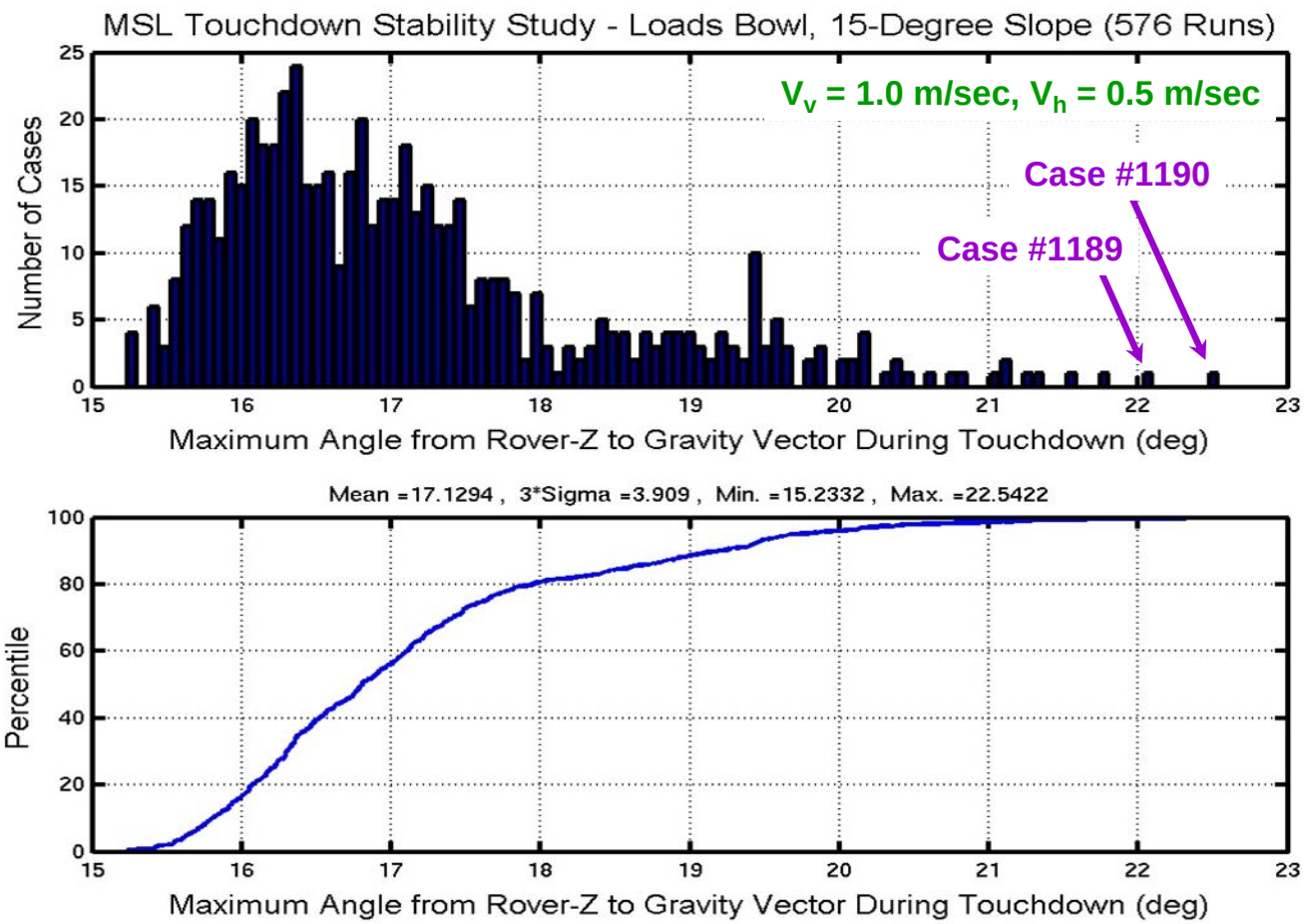
- **TD Loads vs. Landing Velocity** – Loads reductions approximately linear with landing velocity magnitude reductions.

Vv & Vh (m/sec)	1.00 (-0%)	0.75 (-25%)	0.5 (-50%)
0.50 (-0%)	-0%	-17%	-45%
0.25 (-50%)	-9%	-23%	-51%

- **TD Loads vs. μ_{fr}** – Conservative loads predicted with $\mu_{fr} = 1$



TD Stability Analysis – 15° Slope Cases



TD Stability Envelope – Loads Bowl Cases

- Four full sets of loads bowl runs (i.e. 4 x 3480 = 13,920 runs) were conducted to explore stability envelope with V_h = 0.5 m/s & μ_{fr} = 1.
- Max. angle from rover-z to gravity is used to check the TD stability.

Vv (m/sec)	0	5	10	15	20	25	30
1.25	9.7°	12.8°	17.3°	22.4°	32.8°	unstable	unstable
1.00	6.1°	8.9°	15.0°	22.5°	30.8°	46.7°	unstable
0.75 (nominal Vv)	3.1°	8.1°	13.6°	20.9°	25.8°	30.4°	45.4°
0.50	1.5°	12.1°	16.3°	21.7°	27.2°	32.2°	32.9°

Slope Angle (deg)

stable | marginal to unstable | unstable

Summary

- Innovative touchdown design loads development and intensive sensitivity studies successfully conducted leading to:
  - Significant understanding of touchdown loads and stability
  - Sufficient confidence to proceed to rover design and test
- Preliminary design loads delivered on schedule to support PDR's
  - 1,752 Loads Bowl Cases + 618 Rock Strike Cases + 1.3 LUF
- Passed 2 touchdown loads reviews with an important conclusion:
  - "… the design loads and loads uncertainty approach is acceptable, and the planning and execution of the verification loads testing and analysis should commence."
- Future Work
  - Model verification and loads validation by tests
  - Probabilistic touchdown loads assessment