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ACCEPTANCE TESTING LUNAR AND PLANETARY VEHICLES (A CONCEPT)

by Fritz Kramer

George C. Marshall Space Flight Center
Huntsville, Ala.

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INTRODUCTION*

Although manned exploration of the planets in our solar system is not very likely to take place in the near future, a manned lunar landing is presently the goal of our national space program. The lunar landing is a great goal in itself. But when the astronaut steps out of his lunar landing craft onto the lunar surface for the first time, a new epoch will begin, the manned exploration of the moon. This event will also be recorded as the first stepping stone to the manned exploration of the planets, although there is presently no indication as to when either of these two events will be made an active part of our space program. Even so, occupation with the related theories and ways and means to accomplish these feats is necessary well in advance of the actual event so that solutions to the many problems involved do not have to be searched for later when the pressure of time schedules or the stress of crash programs prevails.

From the very beginning of manned exploration, the astronaut will need a transport vehicle that can provide him with ground mobility, carry his equipment and instrumentation for scientific assignments, and bring him safely back to his spacecraft. This vehicle will have to be of the highest dependability and reliability conceivable. To develop the vehicle is difficult, not so much because of the mission requirements, but more basically because of the environmental conditions to which the vehicle will be subjected. These conditions differ greatly from those on Earth. On the moon, for instance, there is no atmosphere but a hard vacuum instead; temperature extremes prevail on the day and night side, and all masses are subjected to a rather low gravitational acceleration amounting to only 16 percent of that on Earth. Conditions on the planets, to the extent that they are known, differ from those on Earth in a similar manner, although the difference in gravitational attraction is not as great as that of our moon.

Characteristics of the lunar soil are not known in final detail; however, it is believed that a lunar roving vehicle could be designed and built today on the basis of automotive technology valid for terrestrial application. But once a lunar vehicle has been built and is to be acceptance tested, we will be at a loss as to the proper test program and test procedures which would constitute an indisputable basis for demonstrating that the vehicle will operate according

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* The English foot-pound system of measures has been used in this report where numerical values are shown. These numerical values, however, are purely illustrative, and can, therefore, be used with any system of measures without losing their validity.

to design criteria and performance specifications. This problem will not arise at a time as late as vehicle delivery to and acceptance by the customer, but during the research and development phase. In both instances, it will be an indispensable requirement that the vehicle can be checked out on a test track to verify the validity of the approaches taken, and to make sure that the specific requirements for performance, durability, and reliability have been met.

Unfortunately, such test tracks on which all lunar conditions are present in their true magnitude do not exist. In particular, the duplication of the low lunar gravitational attraction meets with great difficulties, if not to say that it borders on the impossible. The effect of the small lunar gravitation is, however, of prime importance in the development of the lunar vehicle; some effort will have to be spent to provide facilities and techniques through which the effect of lunar or planetary gravitation can be demonstrated and measured in order to develop these vehicles with high reliability and dependability.

This report presents the least known of the two concepts which allow us to study the effects of lunar or planetary gravitation on the full-size prototype vehicle with respect to vehicle dynamics and driving characteristics, and to familiarize the astronauts with the behavior of surface vehicles under different gravitations.

The concept is explained and illustrated for lunar application because the moon exhibits relative to Earth the smallest gravitational attraction, and causes, therefore, the greatest deviation of the vehicle's behavior from its behavior on Earth. However, the principle and its implementation are applicable without restriction or degradation to any other magnitude of gravitational acceleration.

LUNAR GRAVITATION AND ITS EFFECT ON THE MOTION OF A POINT MASS

It is known from Newton's second law of motion that if a mass (m) is to be set in motion, a force (P) has to be applied to accelerate the mass in the direction of (P) at a magnitude (a) equal (P)/(m) as shown graphically in Figure 1. The magnitude of this acceleration is independent from and unaffected by the strength of the gravitational field in which the force (P) may act and the motion take place. The mass (m), however, responds not only to the acceleration (a) but also to the acceleration (g) of the gravitational field. In fact, the mass has no potential or ability to differentiate between the two accelerations (a) and (g), but responds to the resultant acceleration (b) as if acceleration (b) were the one and only acceleration acting upon it. Figure 2 shows the basic difference between an acceleration of the mass on Earth and on the moon. Because the gravitation on Earth is about six times as great as the gravitation on the moon, the resulting acceleration on Earth (b_E) differs significantly from the acceleration on the moon (b_M), even if the applied force (P) produces the same horizontal acceleration (a). Because of the different gravitational accelerations (g_E) and (g_M), the resultant acceleration vectors (b_E and b_M) are not only different in direction but also in magnitude, as shown on Figure 2. Consequently, the two ensuing motions, their respective velocities and their paths of travel will be different from one another. This is the reason why the observation of the motion of the mass on Earth does not give any clue to the motion the mass will execute on the moon.

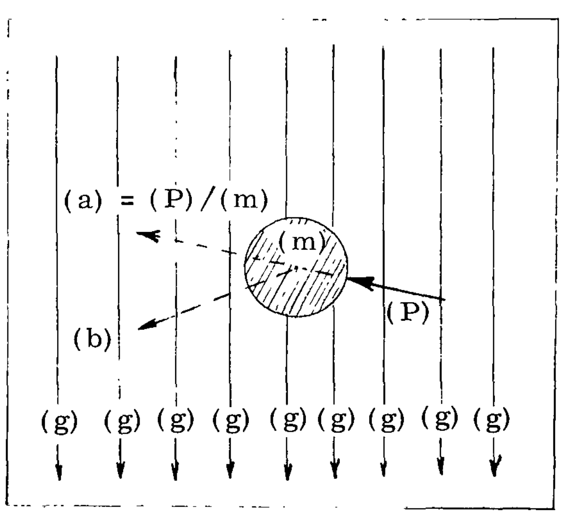


FIGURE 1. ACCELERATION OF MASS (m) BY FORCE (P) PRODUCING ACCELERATION (a) = (P)/(m)

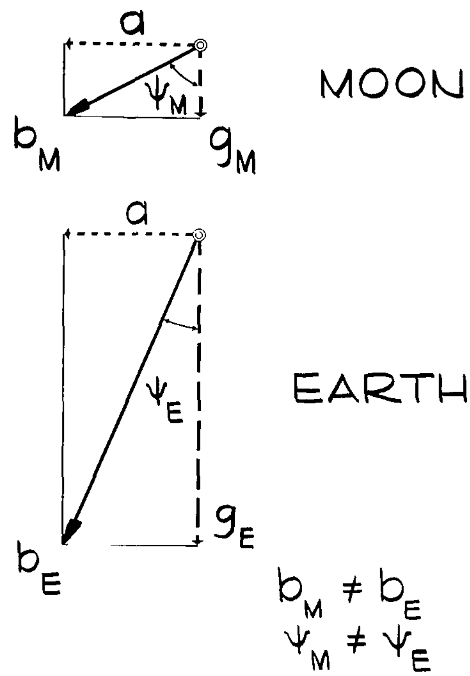


FIGURE 2. EFFECT OF DIFFERENT GRAVITATIONAL ACCELERATION ON TOTAL ACCELERATION OF A POINT MASS (Although the point mass is subjected to the same horizontal acceleration (a), the motion on the moon is different from the motion on earth because of different total accelerations b_M and b_E, respectively.)

SIMULATED LUNAR GRAVITY AND ITS APPLICATION TO VEHICLE TESTING

The literature pertaining to the simulation of lunar gravity deals primarily with scale models through the principles of similitude or dimensional analvsis. It is evident, however, that tests with scale models cannot be used as a substitute for the acceptance testing of a prototype; the full-size prototype itself has to be subjected to the tests.

There exist only two possibilities of testing a prototype under different gravitation in which the prototype is used as a scale model with a scale factor of unity. These two possibilities are illustrated in Figures 3 and 4. The principle shown in Figure 3 is generally known because it has been proposed elsewhere; for completeness, it will be described in some detail in the appendix.

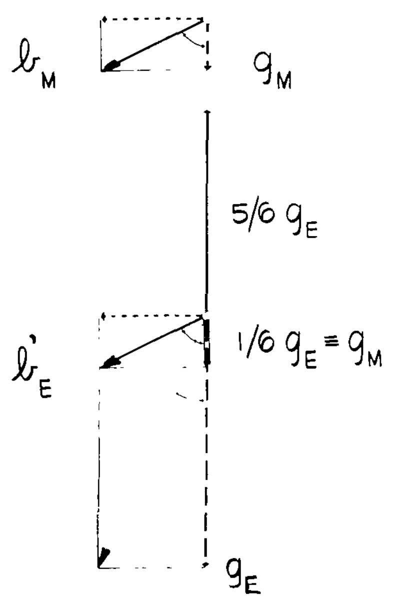


FIGURE 3. SIMULATION OF LUNAR GRAVITY ON EARTH (A vertical force of proper magnitude produces an upward acceleration of $5/6\ g_E$, leaving a downward acceleration of $1/6\ g_E$ which is of the same magnitude as g_M on the moon.)

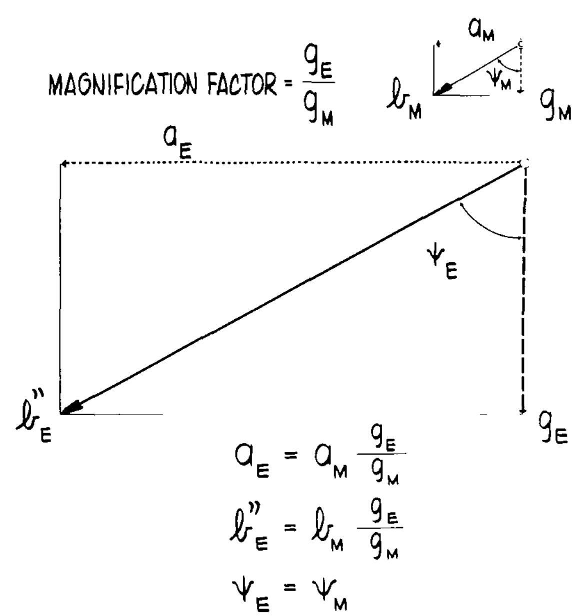


FIGURE 4. SIMULATION OF LUNAR GRAVITY THROUGH MAGNIFICATION. (Geometrically similar vector diagrams of total acceleration on Earth and on the moon are obtained if the external forces on Earth are larger at the same proportion as the gravitational forces, g_E/g_M.)

It centers around the partial compensation of Earth's gravitational acceleration (g_E) by a vertical counterforce; that is, it tries to superimpose a man-made mechanical force field upon the natural gravitational force field of Earth. The resulting force field is expected to again be a force field of constant but reduced magnitude, independent of the motion of the vehicle within this field. The conclusion is reached in the appendix that the useful application of this principle to testing of lunar and planetary vehicles may be rather limited because of its own limitations in producing the resultant force field of constant magnitude.

The second approach, which forms the basis of this report, is based on the premise that the testing has to be performed in Earth's gravitational field but that the motion as it would occur in a gravitational field of a different magnitude should be obtained on a different force and time scale. This different time scale is obtained by selecting a new scale for the accelerating forces; it is related to the gravitational acceleration which prevails on the celestial body under consideration. Through this principle, the very same motion can be created as it would occur on another planet, but it will be compressed or expanded into our terrestrial time frame, depending on whether the gravitational acceleration of the planet is smaller or larger than Earth's gravitational field. Figure 4 shows the basic principle applied to the force system acting on the lunar vehicle; the force (P) on Earth is to be increased by a factor of g_E/g_M, which has a numerical value of 6.25. Accordingly, the acceleration (a_E) on Earth is increased by the same factor because the mass of the vehicle is not changed. In this way, the external acceleration forces are at the same ratio as the gravitational accelerations, and the two vector diagrams pertaining to the forces on the moon and on Earth, respectively, become now geometrically similar, as shown in Figure 4. The resultant acceleration vectors (b''_E) and (b_M) now have the same direction but differ in magnitude by a factor of g_E/g_M.

What happens now to the ensuing motion in this case? The answer is that the two motions will be absolutely identical in space; that is, the traces of the paths of travel of the two masses in an x, y-coordinate system are identical. However, the motion of the mass on Earth takes place at a greater speed than the motion of the mass on the moon. The two velocities relate to one another as the square root of the force ratio, or as $\sqrt{g_E/g_M}$, the numerical value of which is 2.5. Accordingly, the times required for the two masses to travel in an identical fashion the same distance on Earth and on the moon are inversely proportional to the velocity or proportional to $\sqrt{g_M/g_E}$, which has a numerical value of 0.4. For example, if a motion on the moon would require five seconds for its completion, the very same motion would be executed on Earth in only two seconds; the magnitude of the forces on Earth, however, would be 6.25 times as great as those on the moon. This rather interesting result can be derived from Newton's second law of motion, as is shown in Figure 5. Froude's law also shows that the two motions which have to take place under the influence of different gravities are similar if the velocities relate to one another as the square root of the ratio of the two gravities. This relation is shown in Figure 6. It is to be noted that this relation holds true, of course, only if the two masses and the terrain features are of the same physical size, which means that the vehicle used on the Earth track is not a "model" of the moon vehicle but is the real flight or "moon" hardware. The lunar surface features are, of course, modeled at full scale.

At this point, the question may be asked why one should go to the proposed extreme and subject the moon vehicle to forces 6.25 times as large as the actual forces on the moon, and to run it in this way at a speed 2.5 times as fast as its design speed for the moon, just to demonstrate on Earth the motion which the vehicle would execute on the moon. Why shouldn't it be sufficient to go to some desert area or some hilly terrain, and determine the vehicle's capability of climbing and traversing such formation? If it can run across some sand dunes in the desert, it can certainly climb

$$P_E = m_E \left(\frac{d^2s}{dt^2}\right)_E$$

$$P_M = m_M \left(\frac{d^2s}{dt^2}\right)_M$$

$$P_E/P_M = K = \frac{g_E}{g_M}$$

$$m_E/m_M = \mu = 1$$

$$ds_E/ds_M = \lambda = 1$$

$$dt_E/dt_M = \tau = ?$$

$$K = \mu\,\frac{\lambda}{\tau^2};\quad \frac{g_E}{g_M} = 1/\tau^2$$

$$\tau = \frac{t_E}{t_M} = \sqrt{\frac{g_M}{g_E}}$$

$$\frac{t_E}{t_M} = \sqrt{\frac{g_M}{g_E}} = \sqrt{\frac{1}{6.25}};$$

$$\boxed{t_E = \frac{1}{2.5}\,t_M}$$

$$ds_E = ds_M$$

$$V_E = \frac{ds_E}{dt_E} = \frac{ds_M}{dt_M/2.5} = 2.5\,V_M$$

$$\boxed{V_E = 2.5\,V_M}$$

$$ds = v \cdot dt$$

$$ds_E = V_E \cdot dt_E = 2.5\,V_M \cdot \frac{1}{2.5} \cdot dt_M = ds_M$$

$$\boxed{S_E = S_M}$$

FIGURE 5. NEWTON'S SECOND LAW OF MOTION. (Law shows that velocity on Earth will be larger by a factor of $\sqrt{g_E/g_M}$ if forces on Earth are larger by a factor of g_E/g_M, and the scale as well as the masses are not changed.)

FROUDE'S LAW

Motion under influence of gravity

$$Fr = \frac{V^2}{\ell \cdot g}$$

$$\frac{V_E^2}{\ell_E \cdot g_E} = \frac{V_M^2}{\ell_M \cdot g_M};$$

$$\frac{\ell_E}{\ell_M} = \lambda = 1$$

$$V_E = V_M \cdot \sqrt{\frac{g_E}{g_M}};$$

FIGURE 6. FROUDE'S LAW OF MOTION UNDER INFLUENCE OF DIFFERENT GRAVITY. (Law shows that velocities have to be proportioned to $\sqrt{g_E/g_M}$ in order to produce similar motion under influence of two different gravities g_E and g_M, respectively.)

similar dunes on the moon, the more so because the "weight" of the vehicle on the moon is only one-sixth of its weight on Earth, but the power of the vehicle's most likely electric motor does not diminish. It could, therefore, climb even steeper grades on the moon because there we would have power to spare. This seems to be a valid argument. But we have to ask ourselves what we can really find or prove when we drive the vehicle across a sand dune in the desert. Figure 7 illustrates what such a drive would reveal. Under the conventional terrestrial conditions of air drag and frictional resistance of the rolling wheels, the vehicle shown has a potential maximum speed of 37.5 mph on level, horizontal ground, which reduces to 17.5 and 9 mph, respectively, on grades of 5 and 10 percent inclination. According to Froude's law, the dynamic behavior of the vehicle at these speeds would be identical to that at speeds on the moon of 15, 7, and 3.6 mph, respectively.

If this vehicle is taken to the moon, its weight will be only 1000 lb but the power available at its wheels will still be 20 hp. There is no air drag, and because of the lower weight, the vehicle now has a speed potential of 140 mph on horizontal ground, 90 mph on a 5 percent grade, and 60 mph on a 10 percent grade. Its dynamic behavior in the speed range from 15 to 140 mph, however, is unknown; it cannot be determined on Earth and remains unknown until the vehicle is driven on the moon. This basic relationship does not change regardless of the numerical values which may be chosen for the mass and the power of the vehicle. The basic behavior of the vehicle (that is, all aspects of its dynamic response) cannot be unveiled on Earth. This may illustrate that information not too useful will be gained from driving the vehicle across the California desert or any other typical terrestrial terrain. Such a drive would reveal only some performance data in the very low speed bracket,

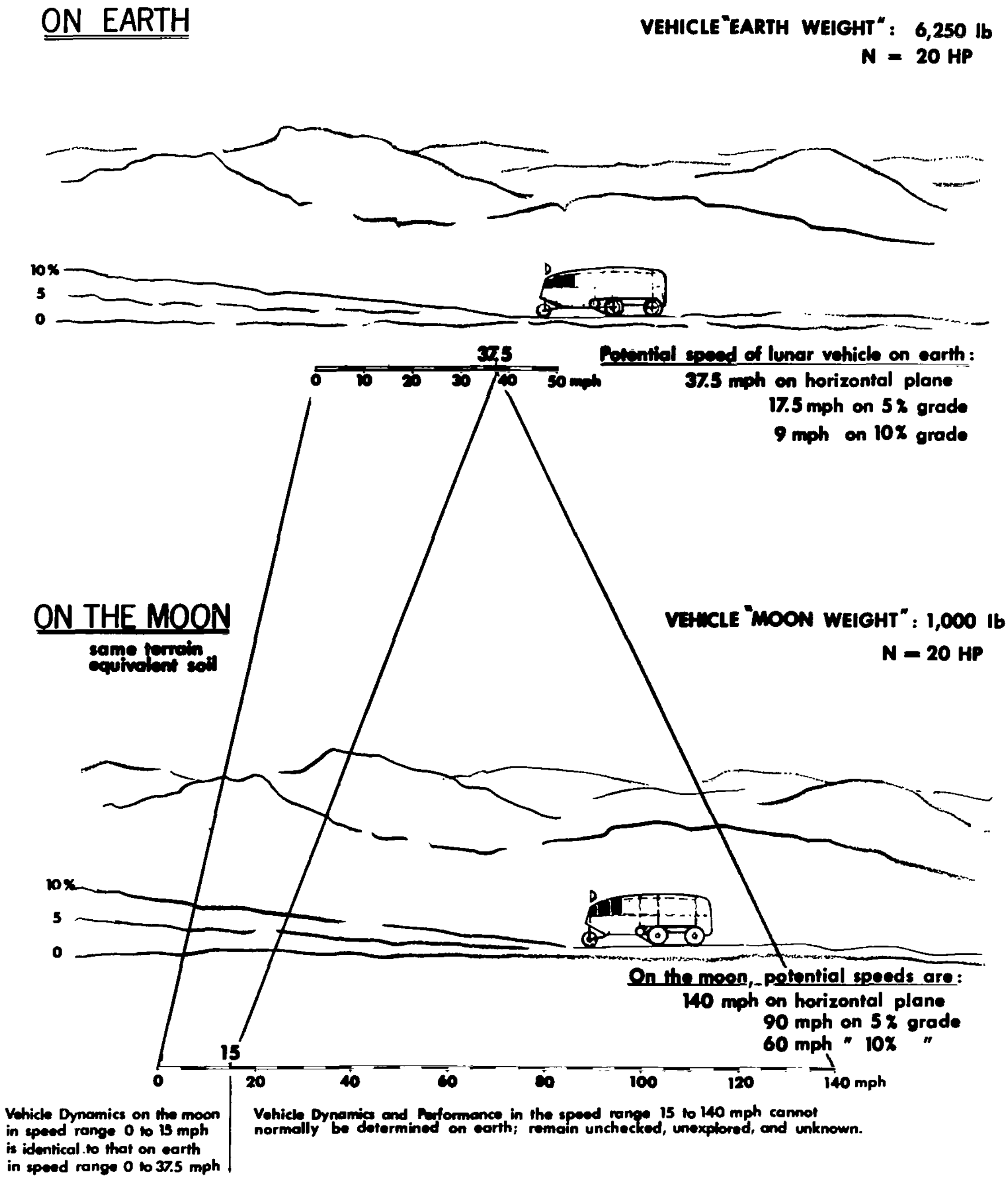


FIGURE 7. VELOCITY POTENTIAL OF LUNAR VEHICLE ON EARTH AND ON MOON

but no dynamic characteristics, such as stability or controllability over the remainder of the speed range.

The value of the proposed testing concept may become more apparent when it is demonstrated in its application to a special event, such as the overturning of the vehicle because of too high a speed in a turn. Figure 8 shows the two forces acting at the vehicle's center of mass: the weight (W) and the centrifugal force (C). On the moon, the magnitudes of these two forces are $W_M = m \cdot g_M$ and $C_M = m \cdot v_M^2/r$, respectively; on Earth, they would be $W_E = m \cdot g_E$ and $C_E = m \cdot v_E^2/r$. They form a resultant (T) that makes an angle α with the vertical. It is known that the vehicle will take the turn in a stable fashion at speed (v) as long as the resultant (T) intersects the ground plane between the wheels, but that the vehicle will overturn when the resultant (T) falls outside the wheels. The critical angle α_{cr} is fixed through the distance between the wheels and the location of the center of mass above the ground. These two values are a matter of design, and their ratio C/W which equals the tangent of the critical angle α_{cr} determines the vehicle stability. It follows that the overturning velocities on the moon and on Earth are different, according to the equality

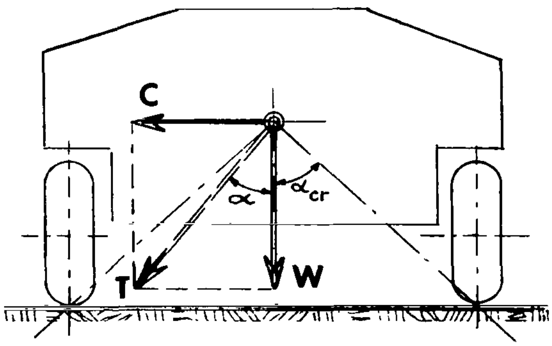


FIGURE 8. FORCES ON VEHICLE IN A TURN

$$\frac{m \cdot v_E^2}{m \cdot r \cdot g_E} = \frac{m \cdot v_M^2}{m \cdot r \cdot g_M} = \tan \alpha_{cr}$$

The two velocities relate to one another as $v_E = v_M \cdot \sqrt{g_E/g_M}$, as follows immediately from the above equation. Thus, the magnitude of the overturning velocity on the moon can be determined on Earth experimentally by driving the vehicle through a turn of radius (r) at a speed at which it will be close to overturning; dividing this speed by $\sqrt{g_E/g_M}$ or by a value of 2.5 yields the overturning speed on the moon. For example, if the vehicle is found to be close to overturning on Earth at a speed of 50 mph, the vehicle will be close to overturning on the moon at a speed of 20 mph. However, if the stability against overturning is to be made the same for the moon vehicle as it is found for a comparable Earth vehicle — that is, for the same turning radius at the same speed — the track of the lunar vehicle has to be 6.25 times as wide as that of the terrestrial vehicle, as Figure 9 shows. This is true if the center of mass of either vehicle is located at the same height above ground.

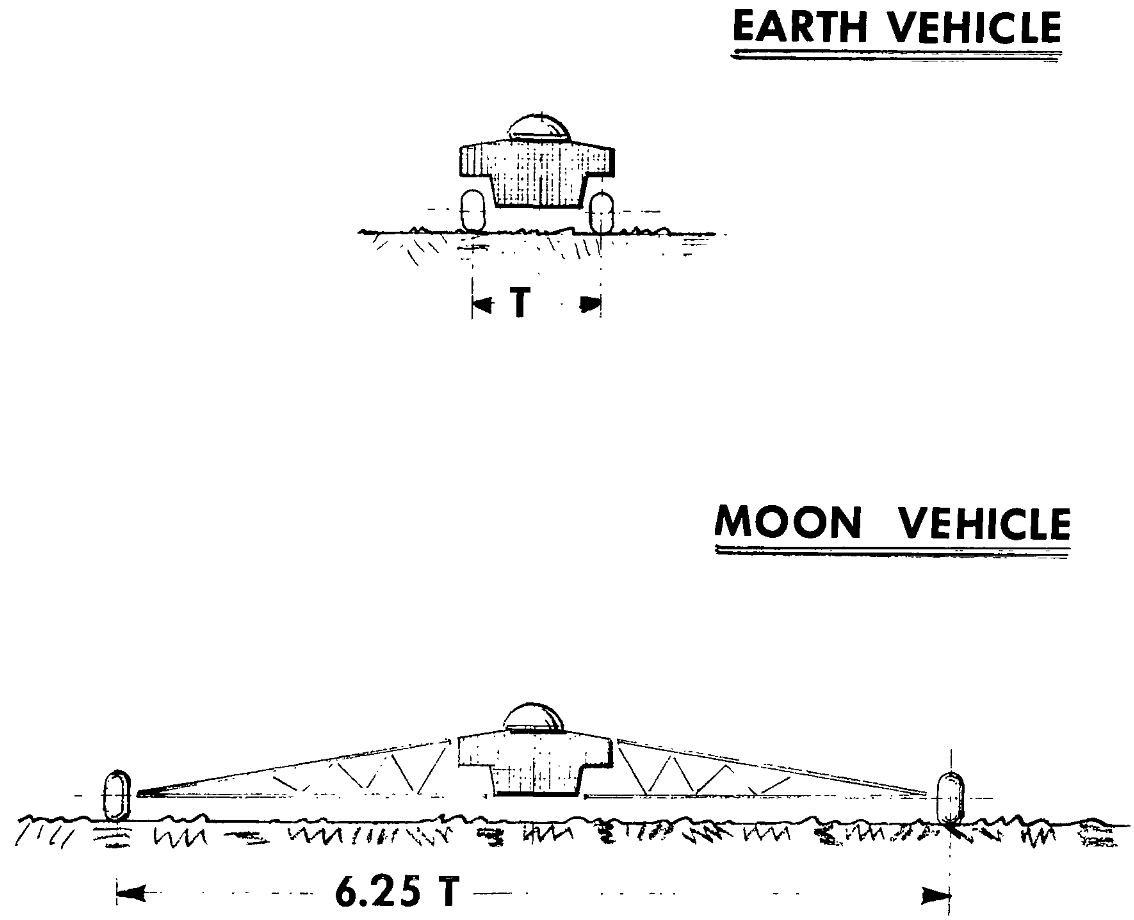


FIGURE 9. TRACK WIDTH REQUIREMENT FOR EQUAL LATERAL STABILITY OF VEHICLE ON EARTH AND ON MOON

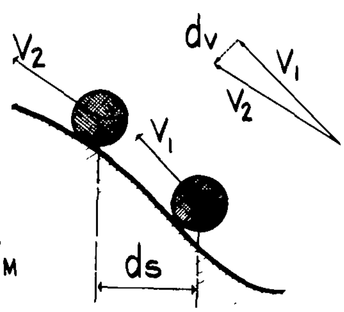
A similar relation can be derived for the condition under which the vehicle will skid sideways. Skidding may occur because of insufficient friction between the wheels and the ground, or because of insufficient shear strength of the soil against side forces exerted by the wheels. The same relation is found as before if skidding takes place because of insufficient friction. If the vehicle skids on Earth at a speed of 45 mph, it will skid at 18 mph on the moon, provided the soil on the moon would exhibit the very same friction and strength characteristics as the soil used in the test on Earth. If sideways slippage takes place because of insufficient shear strength of the soil, the same relation holds again provided the shear strength of the soil used in the Earth test is 6.25 times as great as the shear strength of the soil on the moon. The latter is, of course, not yet known.

Although overturning and skidding are two important characteristics which need attention when designing a cross-country vehicle, the straightforward run across some uneven terrain will be of more direct interest from the viewpoint of forces involved and power required. In this forward motion across the lunar surface, the vehicle will have to negotiate the obstacles and irregularities of an unprepared roadway. Its dynamic characteristics, such as roadability, stability, and controllability, become just as important as the capability of its structural elements to withstand all stresses. With the proposed testing concept, the motion of the vehicle can be determined, measured, and recorded. It has only to be driven across the same typical terrain features on Earth at a speed 2.5 times the anticipated speed on the moon. Then, its motions resemble exactly those which will occur on the moon, only 2.5 times faster. Also, all forces involved will be larger by a factor of 6.25. If the vehicle can stand such an "abuse" on Earth, it will take all forces on the moon with a "safety factor" of 6.25, which may more descriptively be termed a "load factor." To design the vehicle for such a lunar load factor may be a very comforting thought to the designer in charge, but particularly so to the astronaut who has to trust his safety to it. If, in addition, the vehicle can stand these tests on Earth over a distance of 1000 miles without structural failure, it may be concluded that the vehicle can stand up on the moon over a distance of 6000 miles, provided that the fatigue endurance limit is inversely proportional to the stress level. However, because the stress level would be reduced to the very low value of 16 percent of that on Earth, the endurance limit on the moon may actually never be reached.

MAGNITUDE OF FORCES, POWER REQUIREMENTS, AND HARDWARE MODIFICATIONS

As mentioned before, the forces during the tests on Earth will have to be 6.25 times as large as the forces acting on the vehicle under lunar gravity. This is required of the initial forces which set the vehicle in motion, and also of those forces that sustain the motion, and those which are created as reactions between the ground and the vehicle. The latter ones evolve in this magnitude in a natural way, as the derivation in Figure 10 shows. The impulse-momentum law has been used to show that the reaction forces are amplified by a factor of g_E/g_M if the speed of the mass is increased by a factor of $\sqrt{g_E/g_M}$. A necessary condition is, of course, that the terrain contour remain unchanged, which means that the test track terrain features are full-size replicas of the expected lunar terrain. The deformation resistance of the replica material against the forces exerted by the wheels of the vehicle must be 6.25 times as high as the deformation resistance of the lunar soil. As long as there is no close information on this characteristic of the lunar soil, any requirement on the test track material will remain purely speculative.

$$P \cdot dt = m \cdot dv$$



$$dV_E = \sqrt{\frac{g_E}{g_M}} \cdot dV_M$$

$$dt_E = \sqrt{\frac{g_M}{g_E}}\ dt_M$$

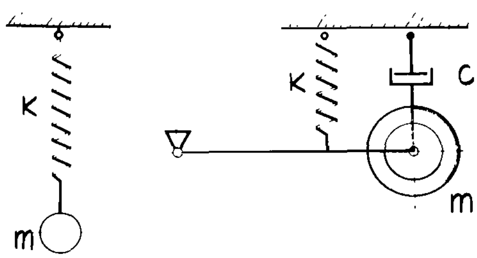
$$P_E = m \frac{dV_M \cdot \sqrt{g_E/g_M}}{dt_M \cdot \sqrt{g_M/g_E}} = m \cdot \left(\frac{d_V}{dt}\right)_M \cdot \frac{g_E}{g_M}$$

FIGURE 10. REACTION FORCES UNDER INCREASED VELOCITY. (The impulse-momentum law shows that the reaction forces from the ground are g_E/g_M times larger if velocity is increased by a factor of $\sqrt{g_E/g_M}$ in traversing the same size obstacle.)

As a consequence of the larger forces and the higher velocity, the power required to move the vehicle on the test track is also higher, since power is the product of force and velocity. It follows, therefore, that the power required on Earth is larger by a factor of $(g_E/g_M)^{1.5}$, which has a numerical value of 15.625 for a value of g_E/g_M

equal 6.25. For instance, if 2 hp would be necessary at the wheels to drive the vehicle across a lunar plane at 16 mph, a power source of 31 hp would be necessary on Earth to drive the vehicle across the test track at a speed of 40 mph, simply from similarity considerations. Air drag on Earth, as well as soil characteristics may increase the power ratio above the similarity value. A similar power ratio would apply for driving the vehicle on a grade. The same speed ratio as before would be required but the slope of the grade on the test range would have to be the same as that on the moon.

One important aspect of vehicle testing on the proposed track has not been mentioned yet. It is the effect of the six-fold increase of the forces on the spring-supported parts of the vehicle, primarily the wheels and the axles of the chassis. Since all motions take place at a velocity which is higher by a factor of 2.5, the natural frequency of the spring-mass systems also has to be increased by the same factor, so that the superposition of the motion of the spring-mass system with the general motion of the vehicle chassis results in the same absolute motion as would occur on the moon. Figure 11 shows that this is possible by increasing the spring constant as well as the damping coefficient of the dashpot by a factor of g_E/g_M and $\sqrt{g_E/g_M}$, respectively. In this way, the natural frequency increases by a factor of $\sqrt{g_E/g_M}$ as desired, whereas the amplitudes remain of the same magnitude as before. This modification of the original flight vehicle— for test purposes only — is the only structural modification required to comply with the similarity requirements. This modification should be made possible through the addition of an auxiliary spring and damping device to each axle or individual wheel; in fact, the ease of installation of auxiliary springs and shock absorbers should be considered in the design of the vehicle, just as the possibility of attaching auxiliary power units.



$$\omega = \sqrt{\frac{K}{m}}$$

$$\omega_D = \sqrt{\frac{K}{m} - \left(\frac{c}{2m}\right)^2}$$

$$K_E = \frac{g_E}{g_M} K_M \quad C_E = \sqrt{\frac{g_E}{g_M}}\, C_M \quad \omega_E = \sqrt{\frac{g_E}{g_M}}\, \omega_M$$

$$\boxed{A_E = A_M}$$

FIGURE 11. NATURAL FREQUENCY OF DAMPED OR UNDAMPED SPRING-MASS SYSTEMS. (Frequency can be increased by increasing the spring constant and damping coefficient accordingly.)

When the vehicle has shown in these tests that it meets the requirements of structural strength and durability, additional, complementary tests in vacuum chambers should be the final step in the completion of the acceptance testing and thus of the vehicle development. For this purpose, the vacuum chamber should be equipped with a rotary platform, or a conveyor-belt-type roadway, on which the vehicle can move under its own power at its lunar design speed. No auxiliary springs or power units would be attached. In the chamber, while in motion, the vehicle would be subjected to vacuum, solar radiation, and the cold of the lunar night. These tests would be continued until there is sufficient evidence that the vehicle components also have the capability to withstand these particular lunar environmental conditions.

TEST FACILITY POTENTIAL

The testing concept has been described in terms of lunar application; however, it is applicable to any other celestial body without changes. Table I shows in ascending order the gravitational acceleration of the planets relative to Earth, and derives therefrom the relative velocities required for the reproduction of the dynamic behavior, and the power factors required to drive the vehicles on a terrestrial test range. The moon data have been inserted to separate the values smaller than unity from those larger than unity.

TABLE I. VELOCITY RATIOS AND POWER FACTORS FOR TESTING PLANETARY VEHICLES ACCORDING TO GRAVITATIONAL ACCELERATION OF THE PLANETS

Planet	Relative Gravity (Earth = 1)	Velocity Ratio	Power Factor
Mercury	0.38	1.62	4.26
Mars	0.39	1.60	4.10
Pluto	0.5	1.41	2.82
Venus	0.87	1.07	1.23
MOON	0.16	2.5	15.625
Uranus	1.05	0.975	0.930
Saturn	1.17	0.925	0.790
Neptune	1.23	0.90	0.740
Jupiter	2.65	0.615	0.232

The reproduction of the dynamic motion of vehicles on the planets with higher gravity than the Earth does not meet with any difficulty because the corresponding velocities on Earth are all smaller than the design speed on those planets. Correspondingly, the power required is less, and the speed potential of those vehicles on Earth is actually higher than the planetary design speed. The probability of building and testing vehicles for the planets Jupiter, Saturn, Uranus and Neptune is, however, rather remote.

Venus and Mars, as the two planets closest to Earth, have been considered the most likely candidates for manned exploration after the moon. They possess smaller gravitational attraction than Earth, and fall, therefore, into the same principal category as the moon, as far as the concept of testing vehicle dynamics is concerned. The data show that if a test facility were to be designed and built to accomodate the projected lunar vehicles for testing, it would possess the capacity to also cover all speed and power requirements for testing of vehicles for the planets Venus and Mars.

IMPLEMENTATION OF TEST CONCEPT

Implementation of the developed concept requires design engineering and feasibility studies before firm engineering solutions can be offered. However, there are three basic lines of approach which suggest themselves almost immediately. The first one is, of course, to disregard the concept as delineated in this report and to subject the vehicle only to the test speeds within its terrestrial speed capability, and to restrict operation of the vehicle on the moon to that low speed bracket which is equivalent to the terrestrial range according to Froude's law. Although this may seem to be a sensible and economical approach for the very first lunar application of such vehicles, it actually transposes only the proving ground to the moon, which in the final end may prove to be a very uneconomical way to discover undesirable characteristics of the vehicle.

The second approach would consider testing of the vehicle at moderately increased speeds, attainable through lightweight, auxiliary powerplants, the use of which was already considered during the design phase of the vehicle. The higher speed at the proving ground may allow primarily the study of vehicle performance and stability in turns and on slopes. However, aerodynamic forces may begin to show their influence on test results; moderate test speed may, therefore, be considered to be 40 mph which would correspond to 16 mph lunar velocity.

The ultimate approach would lead to a facility at which the required maximum test velocities can be attained, emphasis of testing turning toward component life expectancy, fatigue limits, wear and tear, vehicle reliability, and the recordings of forces necessary for astronaut familiarization. Because power requirements would be rather high in the vehicle, and aerodynamic forces predominant at the high vehicle speeds required, the ultimate facility appears to comprise a moving roadway for captive testing of the vehicle. The undesired aerodynamic forces on the vehicle during testing would thus be eliminated, measuring and recording systems could be designed as permanent installations, and many other advantages are evident. At least, such a facility would have the potential of attaining the very high test velocities required for proper simulation of the lunar speed range and its effect on the vehicle.

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When the vehicle has been developed to the desired degree of overall dynamic behavior, the astronaut's familiarization with the vehicle's driving characteristics can be considered. It may begin with a visual demonstration of the vehicle's movements through the motion-picture coverage of the final test runs. Because the motion of the vehicle on the test track is a true duplication of the vehicle's motion on the moon but takes place at a higher velocity, it is only required to also record the motion picture at a higher frame rate (e.g., 64 fps) and to replay it at a slower rate (e.g., 24 fps). Through this simple procedure, the vehicle motions are made to appear in real moon time, that is at a speed which is reduced by a factor of 2. 5 (approx 64/24). The speed at which the vehicle then appears to move on the screen, corresponds to the actual velocity on the moon.

The essential measuring equipment may be calibrated, or the recorders provided with a different gradation so that they will indicate the measured forces on a scale reduced by a factor of 6. 25, while the time scale would be increased by a factor of 2. 5. The trace of the forces thus recorded, represents the one to be expected on the moon ride, in true time. This type of recording will be particularly useful for all forces which act directly upon the astronuat's body, his trunk and limbs, through the seat, cushion, the foot rests, and the steering wheel. It will be a requirement in all tests that masses of appropriate size are attached to the vehicle at these points which support the astronaut's body. These points will also have to be equipped with load cells or accelerometers to identify the loads exerted on these parts by the mass of the driver.

These recorded force measurements can then be used to recreate these forces through electronic systems similar to "flight trainers" for instrument flight. The astronaut, being exposed to these forces will simultaneously see the film of the scenery passing by the moving vehicle as seen from the driver's seat in real moon time. He will thereby experience the sensation of the vehicle accelerations as if he were actually riding the vehicle on the moon. In this trainer, the trunk and the limbs of the astronaut will also have to be gravity-relieved by a simple mechanical spring system, in order to simulate lunar or planetary gravity on the astronaut's body. Because the forces involved are relatively small, and the displacement will amount to only a few inches, a mechanical spring system will not only be feasible but will also be very attractive because of its simplicity.

The astronaut's familiarization and training could be described more elaborately and the capabilities of the proposed method could be delineated in greater detail. However, it may suffice here to have this capability uncovered as an inherent characteristic feature of the proposed testing technique.

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
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APPENDIX

SIMULATION OF LUNAR GRAVITATION BY CONSTANT COUNTERFORCE

The concept of simulating lunar gravitation (Fig. 3) is generally known because it has been proposed several times. The effect of the gravitational acceleration on Earth can be reduced to that of the lunar gravitation by simply having a force act on the mass in the upward direction and of such magnitude that it produces on the mass an upward acceleration of 5/6 (g_E). The balance between the natural gravitation (g_E) and this artificial upward acceleration of 5/6 (g_E) leaves a downward acceleration of 1/6 (g_E), which is equal to the magnitude of the lunar gravity (g_M), as Figure 3 shows. Figure 3 also shows that the two acceleration vectors (b'_E) and (b_M), resulting from this procedure, are now equal in both magnitude and direction. The two motions, resulting from (b_M) on the moon, and from (b'_E) on Earth, will, therefore, be identical.

This simulation concept is thus based on the assumption that a constant, vertical force can be provided at all times and under all operating conditions with a magnitude of 84 percent (or 5/6) of the vehicle weight on earth. The magnitude of this force would have to be maintained constant regardless of the motion of the vehicle. If the vehicle motion is rather steady — as it can be expected to be in a lunar landing simulator — a constant force can be produced within close limits. However, if the vehicle is to travel over a rough and uneven test range which would represent the original and "unimproved" lunar surface, the implementation of this principle meets with formidable difficulties. An elementary calculation shows that it is not feasible to provide the 5000 lb suspension force for a 6000 lb vehicle, for example, by a sufficiently soft mechanical spring. It has, therefore, been proposed to use a hoisting system on a bridge-crane type structure from which the vehicle is suspended by a cable which carries five-sixths of the vehicle weight. The remaining weight is, of course, supported by the ground. The hoisting winch moves the suspension cable up and down, synchronized with the vertical movements of the vehicle as it travels over the irregularities of the test track. The synchronization will have to be almost ideally perfect so that the suspension force in the cable remains constant at all times, regardless of the forces exerted on the vehicle from the ground. The steel suspension cable will most likely be 25 to 30 feet long. According to

Hooke's law, this cable will elongate under the 5000 lb load and the corresponding stress σ in the cable by an increment $e/L = \sigma/E$. For steel with $E = 30 \times 10^6$ psi, and an allowable stress of $\sigma = 30 \times 10^3$ psi, the relative elongation will be 0.1 percent of the overall cable length, or 0.36 inch for a 30 foot long cable. This means that if the synchronization of the winch movement with the vehicle's vertical movements is out of phase by only 0.36 inch, the force exerted by the cable on the vehicle will either be reduced to zero or increased to twice the suspension force of 5000 lb, which would lift the vehicle clear off the ground. To avoid these large force variations, it may be required to produce the lunar gravitation with no greater deviation than ± 20 percent. This would mean that the free weight component of 1000 lb should not vary by more than ± 200 lb. For the load carried in the suspension cable, this means only a variation of ± 4 percent and requires a phase lag in synchronization of less than $\pm 0.04 \times 0.36$ inch $= \pm 0.0144$ inch. The difficulty of meeting this requirement is aggravated by the required power of approximately 20 hp in the drive system which moves the cable under a 5000 lb load at a speed of up to one foot per second, and by the necessity to reverse the direction of motion in a fraction of a second (0.39 second from 1 fps up to 1 fps down velocity). In this consideration of the cable deflection under a static load, it has been disregarded that oscillatory movements of the winch (because of the elasticity of the support structure) will be superimposed to the phase lag between the cable movement and the vehicle movement, rendering it even more difficult to meet the requirements for a resultant force field of constant magnitude. In conjunction with the restriction in length of the test track of such a system, and because it will be practically impossible to execute turns on this track, it appears that the useful application of such a system to the acceptance testing of lunar and planetary vehicles can be debated.

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