NASA
SPACE VEHICLE
DESIGN CRITERIA
(STRUCTURES)

NASA SP-8077

TRANSPORTATION AND HANDLING LOADS

SEPTEMBER 1971

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

NASA experience has indicated a need for uniform criteria for the design of space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment
Structures
Guidance and Control
Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. A list of all published monographs in this series can be found at the end of this document.

These monographs are to be regarded as *guides* to the formulation of design requirements and specifications by NASA Centers and project offices.

This monograph was prepared under the cognizance of the Langley Research Center. The Task Manager was G. W. Jones, Jr. The author was F. E. Ostrem of General American Transportation Corporation/Research Division. A number of other individuals assisted in developing the material and reviewing the drafts. In particular, the significant contributions made by the following are hereby acknowledged: C. P. Berry, H. C. Bjornlie, L. D. Mutchler, and E. F. Winter of McDonnell Douglas Corporation; E. Y. W. Chow of Jet Propulsion Laboratory, California Institute of Technology; H. K. Blomseth of Hughes Aircraft Company; J. T. Foley of Sandia Corporation; J. F. Fowler of TRW Systems Group/TRW Incorporated; R. Kennedy of U. S. Army Transporation Engineering Agency; W. R. Mills of The Boeing Company; C. F. Warner of North American Rockwell Corporation; and E. J. Wolff of NASA Langley Research Center.

NASA plans to update this monograph periodically as appropriate. Comments and recommended changes in the technical content are invited and should be forwarded to the attention of the Design Criteria Office, Langley Research Center, Hampton, Virginia 23365.

September 1971

For sale by the National Technical Information Service, Springfield, Virginia 22151 – Price $3.00

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to provide a uniform basis for design of flightworthy structure. It summarizes for use in space vehicle development the significant experience and knowledge accumulated in research, development, and operational programs to date. It can be used to improve consistency in design, efficiency of the design effort, and confidence in the structure. All monographs in this series employ the same basic format – three major sections preceded by a brief INTRODUCTION, Section 1, and complemented by a list of REFERENCES.

The STATE OF THE ART, Section 2, reviews and assesses current design practices and identifies important aspects of the present state of technology. Selected references are cited to supply supporting information. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the CRITERIA and RECOMMENDED PRACTICES.

The CRITERIA, Section 3, state *what* rules, guides, or limitations must be imposed to ensure flightworthiness. The criteria can serve as a checklist for guiding a design or assessing its adequacy.

The RECOMMENDED PRACTICES, Section 4, state *how* to satisfy the criteria. Whenever possible, the best procedure is described; when this cannot be done, appropriate references are suggested. These practices, in conjunction with the criteria, provide guidance to the formulation of requirements for vehicle design and evaluation.

CONTENTS

TRANSPORTATION AND HANDLING LOADS

1. INTRODUCTION

Most space vehicles and their major segments, such as stages, motors, or spacecraft, are moved several times during their service life by a variety of handling and transportation systems. During these movements, the space vehicle or its segments are subjected to loads which may be different from those of flight or other mission requirements. It is a desired design goal that allowable loads for a space vehicle be governed by flight loads and mission requirements rather than by transportation and handling. Therefore, transportation and handling loads must be predicted during design and, if necessary, attenuated to ensure that the design goal is met where feasible and that space vehicle structural damage does not occur.

Inadequate assessment of transportation and handling loads can lead to local damage to the space vehicle caused by insufficient load-bearing on the handling fixture or it can lead to fatigue failure in flight caused by accumulated damage from cyclic loads.

This monograph is concerned with the generation and presentation of criteria and recommended practices for the prediction and verification of transportation and handling loads for space vehicle structure and for monitoring these loads during transportation and handling of the vehicle or major vehicle segments. Elements of the transportation and handling systems and the forcing functions and associated loads are described. The forcing functions for common carriers and typical handling devices are assessed throughout the monograph and references for descriptions of the functions are cited from the limited amount of available literature.

The monograph is particularly concerned with the assessment of loads at the points where the space vehicle is supported during transportation and handling.

The magnitude of transportation and handling loads is influenced by such factors as the transportation and handling medium; type of handling fixture; transport vehicle speed; types of terrain; weather (changes in pressure or temperature, winds, etc.); and dynamics of the transportation modes or handling devices (accelerations, decelerations, and rotations of the transporter or handling device). Thus, these factors must be considered when predicting the loads for each proposed transportation and handling system and its operation.

When estimates of allowable loads are available, an initial selection is made of a transportation and handling system which it is roughly estimated does not generate loads that exceed the allowable loads nor appreciably affect the vehicle's fatigue life. After this initial selection, the loads imposed on the space vehicle by the selected transportation and handling system are predicted by one or more of the following analytical methods:

- Limit load factors (constant "g") based on accumulated experience in transportation and handling of many types of fragile cargo are used as input to support points of the space vehicle.
- Composite loads, synthesized from loads measured at the cargo loadbed of the appropriate type of transport vehicle during previous shipments with many types of cargo, are used as forcing-function inputs to a mathematical model of the space vehicle and that portion of the transportation or handling system between the space vehicle and the transport vehicle cargo loadbed.
- Loads measured on a similar space vehicle during shipment or handling with the same or similar transportation or handling system are scaled or extrapolated to the space vehicle of interest by an analysis using mathematical models of both systems.
- Loads from the environment external to the transportation or handling system are used as forcing-function inputs to a mathematical model of the space vehicle and its entire transportation or handling systems.

When the space vehicle and handling fixtures are designed and built, the estimated transportation and handling loads are often verified by test. In addition, the load histories of critical areas are often monitored during each handling and transportation period of the production vehicles to ascertain if the levels and cycles of loads have exceeded vehicle flightworthiness limits.

This monograph is closely related to other planned and published monographs in this series. In particular, a monograph is being prepared on the interaction of space vehicle structure with transportation and handling systems. It describes how the limitations of the transportation and handling systems and the effects of transportation and handling loads influence the design of space vehicle structure. Other monographs on the subjects of natural vibration modal analysis (ref. 1) and structural vibration prediction (ref. 2) are concerned with the response of structure to a variety of loads, including those caused by handling and transportation.

2. STATE OF THE ART

Transportation and handling loads encountered by space vehicles during shipment are extremely difficult to predict accurately because of the complex nature of the loadings and the lack of documented studies or recommended practices for their prediction. In spite of these shortcomings, safe shipments of space vehicles have been made with few reported structural failures or damage. Much of this success can be attributed to elaborate load-attenuation systems and the many restrictions that have been imposed to limit the induced loads. For some vehicles, special transporters have been developed to act as the load attenuation system. Also, detailed restrictions have been specified on speed and the condition of the medium through or on which the system travels. In many cases an observer or an escort has been required to accompany the space vehicle to ensure that these restrictions were observed. These measures are justified because of the highly specialized nature of the cargo and the cost of its replacement. In addition to the major goal of determining that transportation and handling loads do not cause structural damage, and, where feasible, do not affect design of the structure, the determination of transportation and handling loads is essential to the design of space vehicles for the following reasons:

- To aid in the selection of appropriate handling and transporting devices and their operational procedures
- To establish load-attenuation requirements for the design of transportation and handling devices or fixtures
- To provide necessary load inputs to compute space vehicle response and internal stresses at critical locations within the vehicle during transportation or handling

Transportation and handling loads that can affect space-vehicle design include dynamic (transient, periodic, random, or combinations thereof), quasi-static, and static loads resulting from the interactions shown in figure 1. Various combinations of the elements shown in figure 1 are possible. For example, the handling fixture and transportation device may be combined to form a transport trailer or transporter. The transporter itself may be loaded on a ship or airplane and thus serve as an elaborate handling fixture. Some transporters may transport the vehicle in a vertical position and become an integral part of the launching system as in the case of the Saturn V Apollo space vehicle. The loads are usually defined and assessed at the vehicle attachment points to facilitate comparisons between various transportation and handling systems and to ensure useful inputs for related analyses of structural vibration and structural response to mechanical shock.

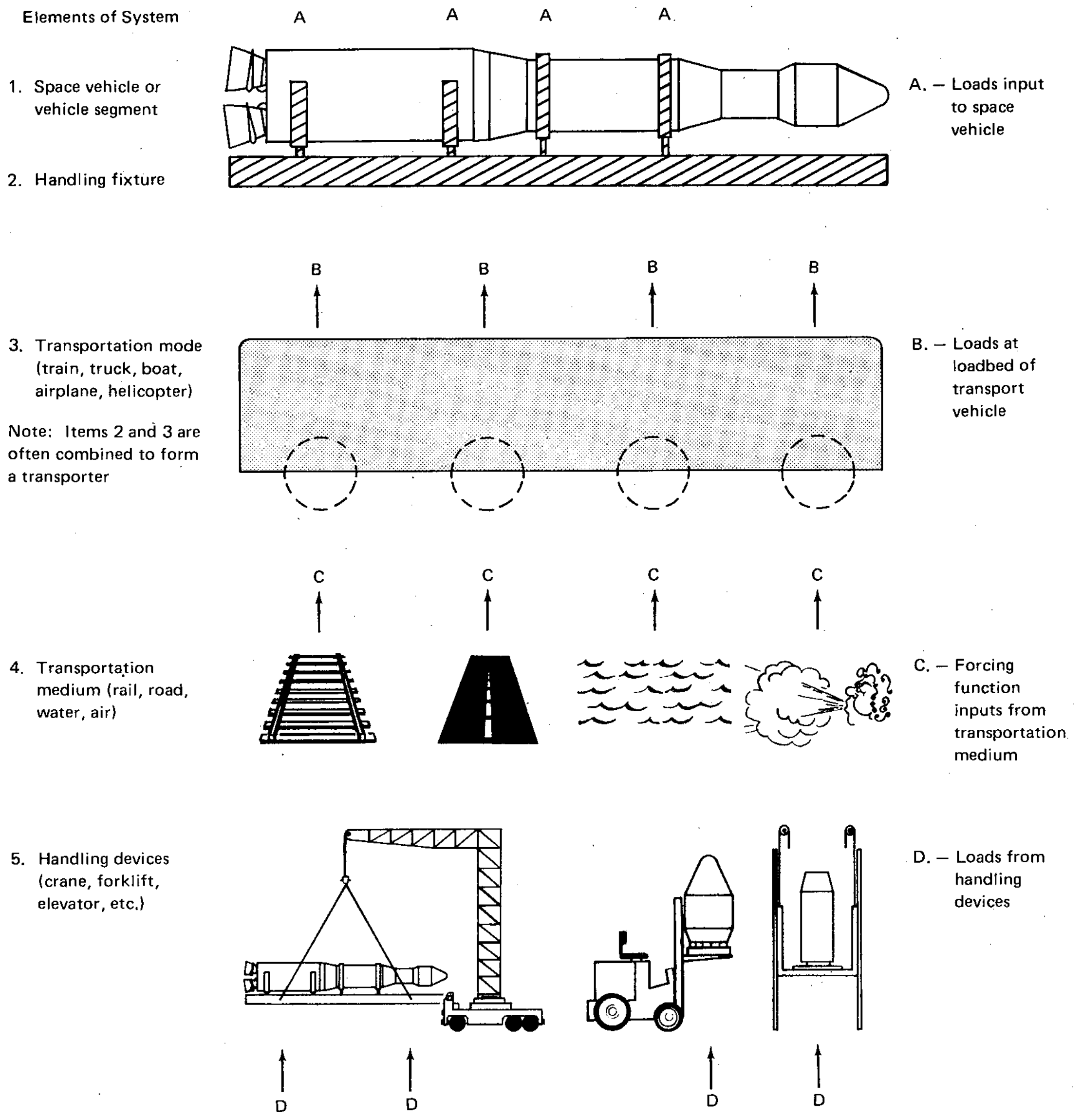

Figure 1. – Schematic of transportation and handling systems and loads.

In most instances, however, the loads at the attachment points are not readily available and must be determined from inputs at other interfaces of the transportation or handling system, such as (1) the inputs (B in fig. 1) from the loadbed of the common carrier (a train, truck, barge, airplane, or helicopter), (2) the forcing inputs (C in fig. 1) from the medium on or through which the vehicle is transported (rail, road, water, or air) or (3) the inputs (D in fig. 1) from handling devices (cranes, forklifts, elevators, etc.).

The state of the art for predicting and verifying the transportation and handling loads on a space vehicle is presented in the following outline: (1) current methods for predicting transportation and handling loads are summarized and appraised and the elements of these prediction methods are discussed; (2) the forcing function inputs from the various transportation and handling mediums are described and the sources and descriptions of forcing function inputs from the transport vehicle cargo loadbeds are given; and (3) the procedures utilized and measurements needed to verify transportation and handling loads and to monitor these loads on shipments of production space vehicles are discussed.

2.1 Prediction Methods for Transportation and Handling Loads

An early approach was to design the space vehicle without regard to the transportation and handling loads and then design a protective system to limit the induced loads to desired levels. A prototype of the space vehicle was fabricated and submitted to tests which simulated operations with the transportation vehicles and handling systems under consideration and the loads were monitored. Suitable load-attenuation systems were then designed and/or operating restrictions imposed to limit the loads to specified levels. Although this approach has proven adequate, it is costly and time consuming. Another disadvantage of this approach is that the space vehicle structure cannot be readily modified if the transportation and handling loads cannot be adequately attenuated.

Several methods for predicting and estimating the loads to be encountered by space vehicles or their major segments during transportation and handling are in general use and have proven adequate when supported by test measurements on a prototype system. Generally, the simplest available approach is employed. The selection of a particular analytical method depends on such factors as the nature of the space vehicle and the transportation system chosen, and whether they are a new design or are similar to other vehicles and transportation systems for which measured loads data are available. These factors are discussed in the following sections.

Each of these analytical methods for predicting transportation and handling loads requires the formulation of a mathematical model. The formulation of this model is influenced by the desired accuracy and frequency range of the computed loads, the nature of the input loading, and the available knowledge of the space vehicle structure and the transportation or handling system. For successful mathematical modeling, the structural stiffness and mass distributions and the boundary conditions of the space vehicle and transportation and handling devices are given careful attention.

The basic methods for formulating mathematical models of the space vehicle and transportation systems are the same as those for natural vibration modal analysis or for vibration response prediction. These methods are discussed in detail in references 1, 2, and 3 and are particularly applicable for modeling the space vehicle. Experience with modeling transportation systems, however, has usually shown that certain components in the system are difficult to model (e.g., tires, shock absorbers, mechanisms with friction, leaf springs, coupling devices on rail cars, and oleo struts). Because these components must be modeled successfully to obtain valid answers, tests must often be run as part of the model development. Further, these components are often nonlinear; for example, tires leave the ground, and the resistance of dampers is different in extension and in compression.

Models of complete systems using road transport are given in references 4 and 5. More simple models of the road transport vehicles are given in references 6 and 7. Mathematical models of rail vehicles are given in references 8 and 9. Similarly, mathematical models for ships are given in references 10 and 11. An example of a mathematical model of an airplane that could be used to calculate the acceleration loads at the cargo floor is given in reference 12. Mathematical models of missile handling systems are given in references 13 and 14.

In each of the analytical prediction techniques for transportation and handling loads, the model of the system and the input forcing functions are both incorporated in the equations of motion which describe the dynamics of the system during transportation or handling. These equations of motion can be solved to obtain the transportation or handling loads in terms of input acceleration at the space vehicle attachment points. From such accelerations the response of the vehicle to its transportation or handling environment may be obtained. Examples of equations of motion formulated for a number of transportation and handling systems can be found in the references of the preceding paragraph.

2.1.1 Analysis Using Limit Load Factors

The simplest approach for predicting transportation and handling loads is to specify the loads in terms of constant "g" or peak, limit load factors. The limit load factors used are based largely on the accumulated experience in transporting and handling many types of fragile cargo. A summary of typical limit load factors (ref. 15) is shown in table I. Limit load factors for handling operations are also given in reference 15.

A disadvantage of the limit load factor technique is that it does not provide a basis for evaluating the accumulative effect of repeated loads of varying magnitudes and frequencies. The major advantage of this technique is that transportation and handling loads may be considered in the early stages of space vehicle design when the structure is not well defined. Although this approach may still be used for missiles and small space vehicles, it would be used only for the preliminary design of most of NASA's unique and expensive space vehicles.

TABLE 1. – TRANSPORTATION LIMIT LOAD FACTORS

[From ref. 15]

Medium/mode	Longitudinal load factors, g	Lateral load factors, g	Vertical load factors, g
Water	±0.5	±2.5	+2.5
Air	±3.0	±1.5	±3.0
Ground			
Truck	±3.5	±2.0	+6.0
Rail (humping shocks)	±6.0 to ±30.0	±2.0 to ±5.0	+4.0 to +15.0
Rail (rolling)	±0.25 to ±3.0	±0.25 to ±0.75	+0.2 to +3.0
Slow-moving dolly	±1.0	±0.75	+2.0

2.1.2 Analysis of Partial System with Composite Loadbed Inputs

Another method for predicting transportation and handling loads on a space vehicle imposes the forcing functions caused by the motions of the cargo floor or loadbed of the transport vehicle or handling device on a partial system consisting of the space vehicle and its handling fixture. Such forcing functions are composites of the loadbed inputs measured during the travel of a transportation or handling device such as a common carrier, crane, forklift, or elevator. The measured load values are compiled and used as forcing-function inputs to a mathematical model of the space vehicle and its handling fixture; the desired responses and loads on the space vehicle are calculated from this model. The portion of the transport vehicle or handling device that lies below the cargo loadbed may also be represented in the mathematical model if the space vehicle and its handling fixture significantly affect the motion of the loadbed.

Under ideal conditions, composite loadbed data would be generated from measurements at the desired locations during the travel of the system under consideration through actual operating environments. In practice, such specific information is seldom available and it becomes necessary to estimate loadbed effects by grouping a large amount of data obtained from the loadbeds of systems operating under a variety of loading and operating conditions. This approach tends to yield conservative estimates because the magnitude of the loadings is overestimated. This approach is also limited because few data are available for loads measured on transport vehicle loadbeds during the transportation and handling of space vehicles or their major components.

Some of the reasons for this scarcity of data are that (1) the primary interest has been in monitoring loads and responses at the space vehicle rather than loads at the loadbed; (2) the purpose of monitoring and surveillance of transportation and handling operations has been to limit load levels imposed on a specific system rather than to generate typical data; (3) data that are generated are usually considered proprietary; and (4) the systems that have been monitored are unique so that generalization of data has been difficult.

In spite of these obstacles, measurements on several systems have been reported. Moreover, loadbed data are available from extensive measurement programs which have been conducted to determine the shock and vibration loads for general cargo during transportation by commercial type vehicles and for typical handling operations. Although not directly applicable to the shipment of space vehicles, such information can be useful.

References 16 and 17 summarize the data available in 1967. Data reduction techniques and instrumentation are also described in these references. A review of transportation and handling data employed by missile manufacturers prior to 1962 is presented in reference 18.

Acceleration frequency spectrum curves for the four major modes of transportation are shown in figure 2. These curves envelop the maximum reported vertical accelerations measured on the cargo floor for all types of commercial vehicles traveling normal routes. The curves represent a composite of a great number of loads, systems, and operating conditions. For a particular system, the levels shown will only exist for discrete frequencies and for a specific condition, as discussed in detail in references 16 and 17.

The composite loadbed data method is a convenient, moderate-effort method for preliminary estimates of transportation and handling loads. Conservative results are usually obtained from composite loadbed curves like figure 2, but less conservative estimates are obtained from curves restricted to data generated from the particular type of transportation system under consideration for a given vehicle design. Also, when the transportation vehicle or handling system is large compared to the space vehicle, the transported vehicle usually has little effect on cargo floor motion, and the composite loadbed method of prediction results in very accurate estimates of the transportation and handling loads.

In any case, estimates obtained by the composite loadbed method will generally provide guidance on the need for further load definition. If, for example, the loads predicted by this method are less than the space vehicle allowable loads, further evaluation of the transportation and handling loads is generally unnecessary. However,

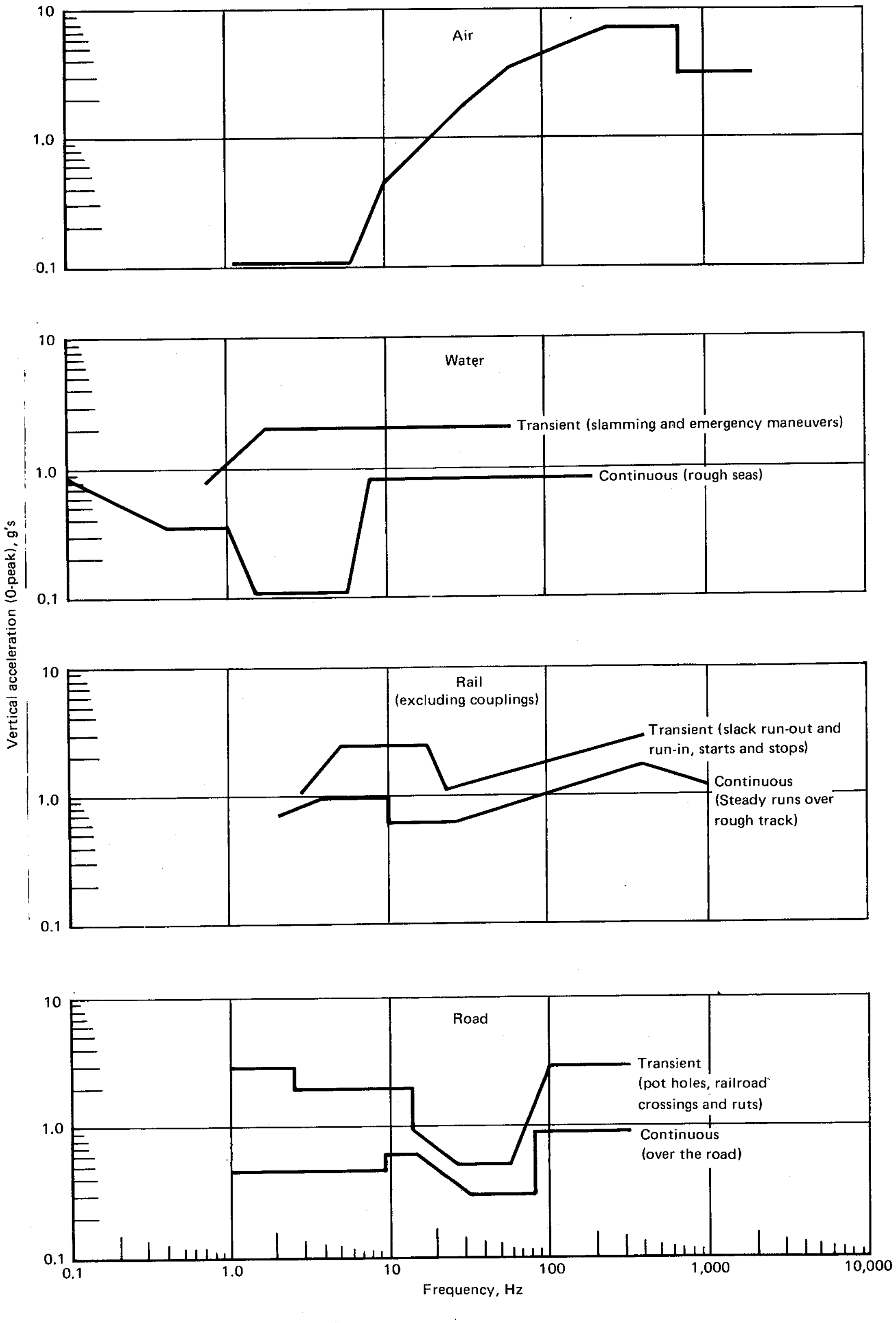

Figure 2. – Transport vehicle composite loadbed data.

predictions of loads in excess of allowable loads by this method are usually substantiated by a more comprehensive prediction approach, such as the dynamic full-system analysis discussed in Section 2.1.4.

2.1.3 Scaling and Extrapolation from Similar System Experience

A third method of predicting the transportation and/or handling loads is based on the use of previously measured data from an analogous system, usually a similar space vehicle and the same transportation or handling system. In addition to the measured loads, a knowledge of the structural characteristics of the system for which the measurements were recorded is required. The source of excitation is assumed to be the same for both the previous and the new system, and the measured data are adjusted to account for any change in the structural characteristics of the new system. This technique is particularly useful in estimating loads for a system developed with only size, or capacity, and/or minor structural changes from a previous design.

In this approach, the previous system is analyzed using the actual data measured on the space vehicle as the system response and working backward into the transportation system to compute the basic forcing function. Depending upon the degree of similarity between the previous and the new systems, the forcing function may be defined at the points where the space vehicle is attached to its handling fixture, at the points where the handling fixture is attached to the transport vehicle, or even at the interface between the system and the transportation medium (see fig. 1). The computed basic forcing function is then used as the forcing function input to a mathematical dynamic model of the new system which is usually the model of the previously developed system. The extent of the modeling and analyses depends upon the degree of similarity between the systems and the detail of load definition required. Methods of applying data recorded on one transport vehicle/load combination to other loads which might be carried on the same transport vehicle are discussed in references 19 and 20.

Of the four approaches, this method provides the most accurate predictions of the transportation and handling loads but requires very detailed information. Data useful for this technique have not been published in generally available literature. Information such as the detailed description of the mathematical model of the previous similar system must be sought in internal company reports or through the users of the previous system.

2.1.4 Analysis of Full System with Transportation Medium Inputs

The fourth prediction method emphasizes the dynamic load response and transfer characteristics of the entire moving system – the space vehicle, the handling fixture, and the transport vehicle or handling device. The inputs to the mathematical dynamic model used in this approach are primarily the forcing functions generated by the transportation or handling medium (e.g., the road or rail profile) coupled with the velocity of the moving system. The development of the mathematical model requires detailed information on the mass and stiffness distributions of each element of the system so that the model and the attendant equations of motion acceptably approximate the dynamics of the actual system. The system is subjected to known input forcing functions and the input loads at the vehicle attachment points are computed.

The approach of full-system analysis with transportation-medium inputs is particularly applicable to new or extensively modified systems for which no applicable data are available. It is also employed when transportation and handling loads have been judged critical by preliminary analysis and detailed load definition is required. If the load inputs are distributed over several points, this method of analysis will provide the time and phase relationship of the loads. A disadvantage of this analysis is that it may require the development of a complex mathematical model.

A major part of this method of estimating transportation and handling loads is an accurate determination of the input forcing function or excitation to the model from the transportation medium (C in fig. 1). Unfortunately, there is little published information on these inputs. The sources of excitations to the various types of transport vehicles and handling devices and the means for determining these inputs are discussed in the following section.

2.2 Inputs from Excitation Sources

The accuracy with which the transportation and handling loads on the vehicle are predicted by any of the preceding methods depends on the accuracy of specification of inputs from excitation sources. Published data giving the input loadings from various excitation sources are quite limited. In the following subsections, various excitation sources are discussed, their input loads are summarized and assessed, and references to input loads data are given.

2.2.1 Inputs from Transportation Mediums or Handling Devices

Each of the transportation mediums – road, rail, air, and water – is a source of input forcing function loads to transport vehicles moving over or through the medium. These inputs exist simultaneously with other inputs and together become the input load sources for transport vehicles and handling devices.

2.2.1.1 Inputs to Road Transport Vehicles

The sources of excitation for road transporters can be categorized as both internal and external. However, internal excitations, the vibrations caused by the engine, transmission and drive assembly, wheel unbalance, and shimmy, can be limited to low levels by careful design and maintenance of the transport vehicle and therefore do not contribute significantly to the system load environment; in fact many transporters are towed and therefore do not have engine and drive assemblies as sources of excitation. The principal external excitation results from road irregularities. Other external excitations result from starting, stopping, turning, docking, and wind loadings. Starting and stopping excitation inputs to the system can be determined from the braking and starting characteristics of the vehicle. The maximum speed and minimum turning radius establish maximum inputs during turning. Docking inputs are determined by the force of impact with the dock, which can be controlled to a large degree by the vehicle operator. Local weather conditions and the drag coefficient of the exposed system establish wind inputs.

By means of operating restrictions and special handling instructions that can be given to the equipment operators, excitations from starting, stopping, turning, and docking can be controlled to acceptable levels. Criteria for wind and thermal environments during transportation and handling are discussed in reference 21.

The determination of excitations caused by road irregularities is more complex than those due to the other sources and therefore of more concern. Numerous systems have been developed to measure road roughness (refs. 22 to 24) but very few detailed data have been published. A description of some road profile measuring systems, their operating principles and procedures, and methods for reducing measured data for use in vehicle response analyses is given in reference 24.

Descriptions of road-profile measurements of concrete and bituminous roads in West Germany and Arizona are presented in reference 4. Typical data (ref. 4) on power spectral density or displacement density given in m^2/rad/m (ft^2/rad/ft) versus the reduced frequency given in rad/m (rad/ft) derived from road measurements are presented in figure 3. These results were obtained with a slope integrating system that measured the generated angle between a vertical line and the perpendicular to a line between the points at which two wheels, some distance apart, touched the road surface. The curves can be converted to displacement spectral density m^2/Hz (ft^2/Hz) versus frequency (Hz) by multiplying the ordinate and abscissa by the speed of the vehicle and dividing by 2π. Application of these data to a dynamic model of a missile transportation vehicle is also described in reference 4. Power-spectral density was used as the forcing function to determine the root-mean-square (rms) response. For transient response analyses, the actual road profile was used as an input to determine maximum payload response. The two analyses correlated well with field measurements.

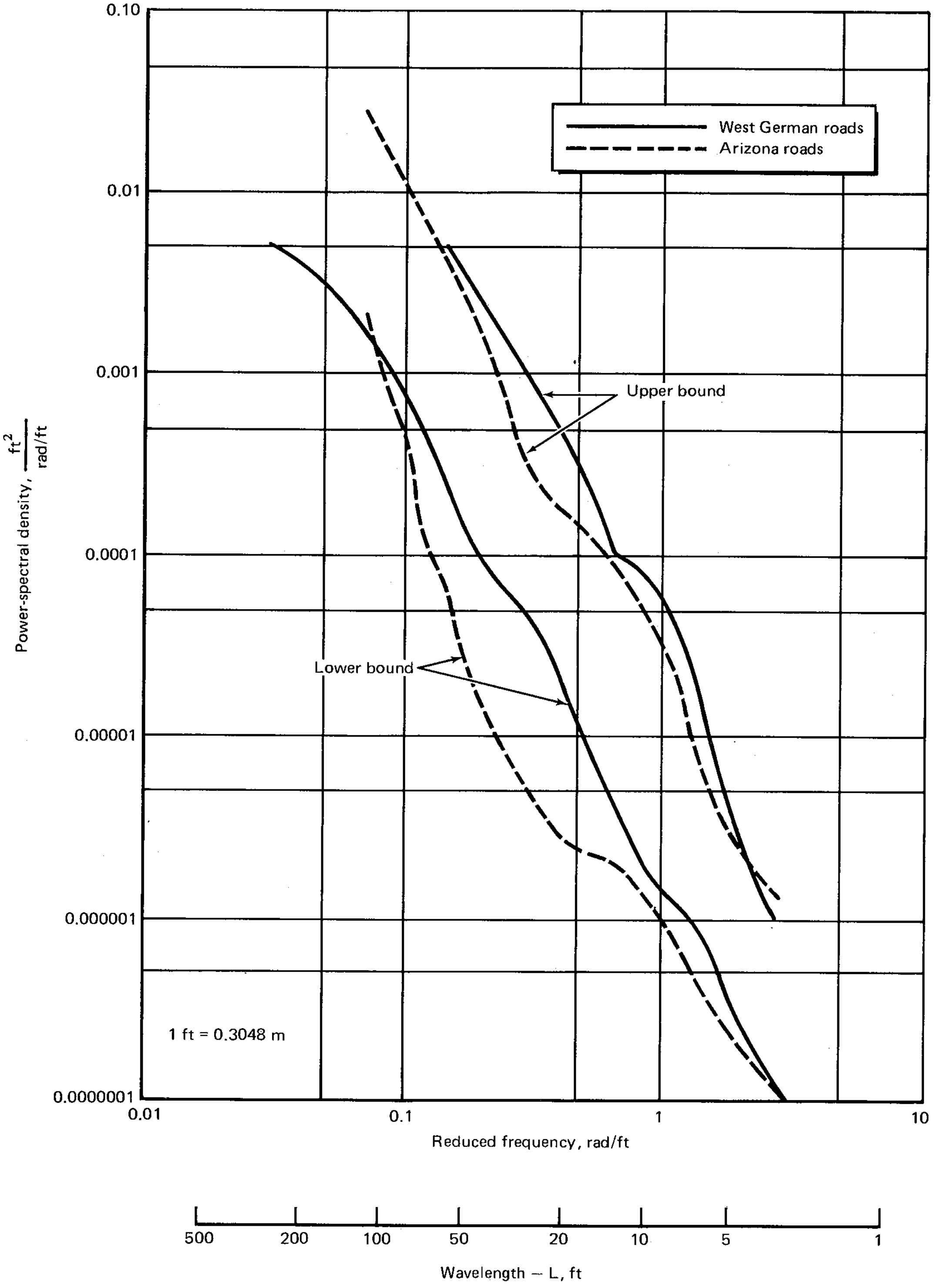

Figure 3. — Road power-spectral densities

To compensate for the lack of measured data of road surface profiles, one investigator developed (ref. 5) the generalized classification of road roughness shown in table II. The road profile is assumed to consist of a washboard course and individual bumps. The washboard course is set at the critical wavelength – the wave length that gives the greatest input into the vehicle. The washboards are usually spaced so that all or most of the axles reach the top of the boards at the same time. The critical frequencies are then obtained by moving a vehicle over the course at various speeds. The course is sufficiently long to develop maximum response in the lowest system mode. The heights of the washboard and bumps are given in the table in terms of probability of occurrence. Use of this road-roughness classification has given conservative estimates of cargo response.

TABLE II. – ROAD ROUGHNESS CLASSIFICATION

[From ref. 5]

Type of road encountered	Low probability of occurrence (a)		High probability of occurrence (b)	
	Sinusoidal washboard amplitude, cm (c) (d)	Single bump amplitude, cm (c) (d)	Sinusoidal washboard amplitude, cm (c) (d)	Single bump amplitude, cm (d)
Primary and secondary roads with rigid or flexible pavement that are well constructed and maintained	1.91	3.81	0.95	2.54
Paved primary and secondary roads with average maintenance; or well constructed unpaved roads with good maintenance	2.54	5.08	1.29	3.81
Secondary roads that are flexibly paved and poorly maintained, and unpaved roads	5.08	10.16 (chuckhole)	3.81	7.62 (chuckhole)

[a] Low probability of occurrence indicates levels will be encountered only for a long service life (> 160 934 Km or 100 000 miles).

[b] High probability of occurrence indicates levels will be encountered even in a short service life (<16 093 Km or 10 000 miles).

[c] Washboard will be of critical wavelength and of sufficient length to develop maximum response of lowest mode in the system. Vehicles will be designed for these road roughness criteria at all speeds within the vehicle normal operating range.

[d] 1 cm = 0.3937 in.

2.2.1.2 Inputs to Rail Transport Vehicles

The major sources of vertical excitation to railroad transport vehicles are rail roughness (or rail profile), discontinuities at the rail joints, and elasticity of the rail roadbed. Lateral excitation is induced by the tapered wheel treads which cause the trucks to hunt or oscillate between the rails and by the wheel flanges striking the rail head. Lateral and vertical sources of excitation are discussed in detail in references 25 and 26. Longitudinal excitation is caused by railroad-car switching or coupling operations and by slack run-outs and run-ins which occur when there is a take-up of slack in the couplers on starting, stopping, or varying speed. Very few data on rail profiles have been published. Reference 25 discusses some unpublished statistical studies which show that the frequency spectra of irregularities in typical tracks exhibit some predictable relationships between frequency and amplitude; for example, the displacement amplitude decreases as spatial frequency increases.

Instrumentation has been developed to measure the vertical, lateral, and cross-elevation characteristics of rail profiles. Two of these rail-profile measuring systems are described in references 27 and 28. Measurements of the rail profiles, however, are generally complicated by the elasticity of the rail and road bed. Because the inputs required for the mathematical model of a transportation system using a rail transport vehicle are the undisturbed track profile, plus the characteristics of the road bed, the deflection of the rail caused by the weight of the vehicle containing the measuring system must be accounted for. If the measuring system vehicle is similar to the transportation system vehicle under consideration, the dynamic track profile can be used as the input to the model. The dynamic characteristics of the rail and roadbed combination are also required inputs for the model. Measurement of these parameters is discussed in reference 27.

A measurement technique in which the rail measurements include the response of the rail tie and soil to the traversing rail car is described in reference 8. Since the information relevant to load evaluation is the absolute vertical and lateral motion of the contact point between the rail car and the rail, this technique calls for measurement of axle accelerations. Frequency components, acceleration levels, and the time histories generated from measurements of this type remained essentially constant for differing test sites and rail cars. Acceleration envelopes were derived from data measured on rail cars having individual wheel loads ranging from 7575 to 11 885 kg (16 700 to 26 200 pounds). The variation in the wheel load did not affect the system load environment and, accordingly, it appears that the developed data are applicable to other rail cars having wheel loads within or near this range. Measured response showed good correlation with response predicted on the basis of data developed using this measurement technique.

Application of axle-acceleration-measurement data to a dynamic model of a missile/transporter system is described in reference 8. Dynamic modeling of rail-car systems to determine lateral stability caused by track discontinuities (joints) is described in reference 9.

The longitudinal excitation caused by slack run-out or run-in depends on the length of the train and the position of the car in the train. Cars in short trains, or cars close to the locomotive in long trains, encounter the lowest shocks. Run-out and run-in effects are discussed in reference 29.

A major reason for the infrequent use of rail cars for transporting space vehicles is the severe loadings which can occur during coupling operations. The excitation occurring during rail-car coupling is a transient phenomena and depends upon the speed of impact, the configuration of cars impacted, and the undercarriage design of the car in the system being evaluated. Evaluation of this excitation is based on establishing a reasonable speed for actual impacts (a summary of measured impact speeds is presented in reference 16). A dynamic model of the Minuteman missile/transporter used for longitudinal-impact analyses is described in reference 30. Analytical results for various impact velocities showed good correlation with measured loads.

2.2.1.3 Inputs to Air Transport Vehicles

Sources of excitation to aircraft can be local or distributed; they are discussed in detail in reference 31. Local excitations include the forces applied by the ground during taxi, take-off, and landing as well as those caused by the power plants at their attachment points. Significant local excitation of the fuselage occurs at the blade passage frequency on propeller-driven aircraft, whereas excitation on jet-powered aircraft is random in nature. Distributed excitations are those which are spatially distributed over the surface of the aircraft and include the aerodynamic forces applied to the structure by the surrounding air, such as acoustic, aerodynamic (flutter and buffeting), and gust excitations.

Gust excitation has received considerable attention in evaluating air-transport loads on a space vehicle. Indirect measurements of gusts have been made by recording the accelerations of aircraft during flights in turbulent air (ref. 32). The measured data are converted to a derived gust velocity by an empirical formula relating rigid-body accelerations of the aircraft to gust velocity. The formula includes an arbitrary factor to account for differences in wing chord and pitching effects among aircraft. Thus, the derived gust velocity obtained for one aircraft can be used to compute accelerations for other aircraft. Statistics on derived gust velocity are presented in reference 32. Reference 33 documents an attempt to include dynamic effects and extend this concept of gust evaluation from rigid bodies to flexible bodies by mathematically flying the flexible aircraft through gusts of different duration and velocity profiles.

A method to account for atmospheric turbulence on a continuous rather than a discrete-gust basis is given in reference 34. This reference also presents data on atmospheric-turbulence measurements in clear air, cumulus clouds, and thunderstorms; calculated and experimentally determined airplane transfer functions; and analytical procedures for determining aircraft response based on power-spectral techniques.

Local excitations during taxi and take-off can be determined from runway and taxi-surface profile measurements made with the same instrumentation systems used in measuring road profiles. A bibliography of runway roughness studies is given in reference 34. Reference 35 presents data for several airport runways. The response of several turbojet airplanes to runway roughness is presented in reference 36.

Landing forces can be determined by measurement of the vertical rate of descent or sinking speed at the time of impact. Sinking speeds measured on cargo aircraft are presented in reference 31.

2.2.1.4 Inputs to Water Transport Vehicles

Major ship excitations result from rough seas and "slamming" which occurs when the bow rises out of the water and subsequently impacts it again. Other dynamic excitations of a ship include (1) the simple harmonic excitations resulting from unbalanced propellers and shafting or by reciprocating engines, (2) the varying hydrodynamic excitations caused by rotation of the propellers in a nonuniform wake, and (3) the varying wave forces in heavy seas. These sources of excitation are discussed in detail in reference 10.

The excitations caused by machinery and propellers are generally much lower than slamming or wave excitations. Excitation caused by waves is determined by measurements of the form, height, and length of the waves. Statistical data describing ocean waves can be found in reference 37.

The development of a dynamic model for describing ship response to waves and impulsive loads is discussed in references 11 and 38. In the analysis of the dynamic model, the buoyancy and added-mass effects which vary with the motions of the ship must be considered in evaluating forces applied by the water. The inertia and viscosity effects of the water are accounted for by the added mass, which can be calculated for various ship profiles by a procedure presented in reference 10.

2.2.1.5 Inputs to Handling Devices

The excitations caused by handling are difficult to predict primarily because they are largely caused by the human element. A system can receive a sudden push or pull or be dropped as a result of human error, accident, or expediency. Thus, the significant handling loads that can occur during operations such as hoisting, jacking, and assembly are apt to be accidental. The magnitude of such loads depends largely on the training and skill of the personnel involved and the equipment being used. Special handling instructions and procedures and an observer can help to limit these loads.

The normal handling excitations can usually be determined from the performance (e.g., torque, acceleration, lifting and lowering speeds, and braking. characteristics) of the handling equipment under consideration. Predictions of significant excitations from the human element must be based on some assumed height of possible vertical drop and/or on some assumed lateral and longitudinal impact velocity. Typical accidental drop heights for various containers are presented in references 17 and 18. Space vehicles, however, are not usually designed for accidents and therefore the experience accumulated in handling them is used in estimating handling load inputs.

References 13 and 14, describe models of missile handling systems for the Polaris missiles and also give some realistic values of inputs from handling devices to the system. The handling equipment consisted of a missile container, a shock-isolation system, a cable, and a crane. The models were analyzed to determine missile response and to establish impact forces for various lowering velocities and inertia forces for various cable accelerations.

In many of the current space vehicle handling systems, the space vehicle is loaded on or off the transporter by means of a roll-on/roll-off mechanism with the transporter itself providing the lowering or elevating capability (refs. 39 and 40). This procedure effectively eliminates the possibility of the system being dropped or handled roughly during this type of transfer.

2.2.2 Inputs from Loadbed Measurements

2.2.2.1 Inputs Road Transport Loadbed Inputs

Loadbed measurements have been reported for several road transporters. Reference 39 presents data recorded on two special land transporters developed for the Saturn S-IV stage. On one of the transporters, vibrations occurred at a frequency of 1.6 Hz with a maximum vertical acceleration level of 0.6 g. The other transporter had a characteristic frequency of 1.8 Hz at the same acceleration level. The frequency of occurrence of the vibration levels for both transporters is presented in reference 39. The transporters were towed at low speeds (approximately 10 miles per hour) to minimize the induced loads. These transporters are typical of most space vehicle transporters because they produce relatively low-level accelerations and low-frequency inputs. Because of the relatively large amplitude of motion at these low frequencies, an observer accompanying the system estimated visually whether the space vehicle response was excessive, and if so, requested a reduction in speed until the motion had attenuated.

Data recorded during transportation of the Ranger 8 and Surveyor spacecraft by air-suspension trailer vans are presented in references 41 and 42. Shock spectra and power-spectral densities of the measured data are presented for rough and smooth highways for three different locations in the van. Only measurements in the vertical direction are given. The report states that values in the longitudinal and transverse directions were as much as 40-percent less than the vertical measurements; however, these levels may still be important. The vertical acceleration at the van floor rarely exceeded 1-g peak. A significant variation in acceleration levels recorded between two supposedly identical vans indicated that each transporter must be qualified individually.

Reference 43 presents data measured during road transportation of a 3.05-m (120-in.) diameter solid-propellant vehicle segment. The transportation vehicle was a low-bed trailer 3.35-m (11-ft) wide, with a 6×10^4 kg (60-ton) capacity. The reference gives representative acceleration data and forcing frequencies for each part of the trip, including a sudden stop on an incline. The vertical acceleration levels ranged from 0.2 to 0.4 g at frequencies from 2 to 6 Hz.

Reference 40 presents loadbed measurements made during shipment of Polaris motors, including measurements of maximum vertical accelerations for various road conditions and speeds. Vibrations occurred at frequencies of 1 and 10 Hz. The transporter was a semitrailer van with an inner structural-support box suspended on air springs.

Additional data describing measured loads on commercial road carriers are presented in references 16 to 18. References 16 and 17 summarize the data available up to the time of publication (1967). The documents present the maximum load levels likely to be encountered on commercial carriers and discuss the state of the art in data-reduction techniques.

An extensive program for measuring the loads encountered on a flatbed tractor-trailer combination is described in reference 19. Representative samples of loads measured on the cargo floor of the vehicle are presented for various road conditions, vehicle speeds, and locations. Typical tractor-trailer loadbed data are presented in table III in terms of the probability distribution of acceleration as a function of narrow bands of frequency. The composite plots account for the probabilities of encountering various road types and road speeds in a typical transcontinental trip. The data showed that the environment over most roads consists of a low-level complex vibration upon which a great number of repetitive shock pulses are superimposed. Similar data are presented in reference 44 for a 2-1/2 ton flatbed truck.

TABLE III. – LOADBED DATA FOR A SEMI-TRAILER TRUCK COMBINATION

[From ref. 19]

O-Peak acceleration, g	Probability of occurrence in percent												
3.2	3.85						- - -	- - -	- - -	- - -	0.20	0.19	0.90
2.3	- - -												
1.65	- - -						- - -	- - -					- - -
1.2	0.52		- - -	- - -	- - -		- - -		- - -	- - -	- - -		
0.86	0.82	- - -	- - -	- - -	- - -	- - -	- - -	- - -		0.12	- - -	- - -	- - -
0.62	19.06	- - -	- - -	0.11	- - -	- - -	- - -	- - -	- - -	0.91	0.10	- - -	0.17
0.45	3.11	- - -	- - -	0.70	0.15	- - -	- - -	- - -	- - -	3.58	0.83	1.36	1.60
0.32	7.16	0.21	0.26	1.99	0.71	0.32	- - -	- - -	- - -	6.71	3.12	5.51	4.92
0.23	18.14	1.35	2.05	5.66	3.33	2.12	0.66	0.53	- - -	10.59	8.92	16.48	11.86
0.17	15.24	3.24	4.87	7.71	6.85	4.54	2.47	1.24	0.19	8.89	11.28	15.97	13.51
0.12	7.24	7.02	10.27	10.01	12.82	7.52	6.88	2.86	0.95	9.17	12.87	17.65	16.12
0.1	23.33	88.11	82.50	73.78	76.09	85.42	89.90	95.25	98.65	59.96	62.63	42.71	50.66
Frequency band, Hz	0-2½	2½-5	5-10	10-15	15-23	23-30	30-44	44-63	63-88	88-125	125-175	175-238	238-313

Notes: This summary accounts for probability of occurrence of road speeds and road types encountered in a typical transcontinental trip.

The circled values are those which may be considered to be shocks. The uncircled values are those considered to be vibration.

Total peak accelerations used in this summary: 2 253 493

(- - -) (Probability less than 0.1% is not reported)

Overall trip composite amplitude distribution for a loaded truck, vertical axis (front, center and aft locations)

2.2.2.2 Rail Transport Loadbed Inputs

Loadbed measurements have been made on rail transporters for both over-the-road operation and coupling. All phenomena except the shock motions caused by coupling are considered to be occurring during the over-the-road operations.

Over-The-Road Load Measurements. Results of tests conducted during shipment of a solid-rocket-motor segment are reported in reference 43, including data on maximum accelerations and frequencies imposed on the transporter and the rocket segment for each phase of the trip. The highest accelerations were caused by the inherent slack built into each coupler. Track and roadbed inputs did not produce any maximum-load parameter values because of speed restrictions imposed by the carriers when traveling over adverse road conditions. The fundamental frequency recorded for the lateral axis was 2 to 7 Hz, 5 to 10 Hz for the longitudinal axis, and 5 to 20 Hz for the vertical axis with a frequency of 40 to 100 Hz superimposed on the basic frequencies. The maximum vertical acceleration recorded on the transporter was 1.8 g; it was produced by a slack run-in. Although the loads were applied in the longitudinal direction, the highest accelerations were recorded in the vertical direction.

Reference 8 presents data recorded during rail movement of the Minuteman missile in a special soft-ride car, the Minuteman Rail Transporter. The truck suspension system of this transporter consists of a combination air and coil spring for shock isolation in the vertical direction and a pendulum system with snubbers for shock isolation in the lateral direction. Shock isolation is provided in the longitudinal direction by a sliding center sill and a hydraulic cushioning device. Because the Minuteman train was short, longitudinal levels were low (shocks during coupling were considered the only significant longitudinal loads). The Minuteman Rail Transporter provided an order-of-magnitude reduction in load levels on the missile.

Reference 40 presents data on measurements made during rail shipment of Polaris motors, including accelerations recorded on the floor of the transporter and at various locations on the motors. Maximum levels for various events are described. The maximum vertical acceleration (1.7 g on the transporter and 1.4 g on the motors) occurred during a slack take-up. The maximum longitudinal acceleration (2.0 g on the transporter and 1.6 g on one of the motors) occurred during the same event.

References 16 and 17 present additional data describing over-the-roadbed operations including (1) envelope curves which show the maximum levels reported for all types of suspension systems, road conditions, and speeds in terms of zero-to-peak acceleration versus frequency and (2) envelope curves which show the effect of train speed and direction of measurement (longitudinal, vertical, and lateral). Statistical data describing the rail-transport vibration environment are presented in reference 45. Data similar to that presented in table III are given for load measurements in the vertical, transverse, and longitudinal axes. The loadbed environment (ref. 45) consists of random low-amplitude vibrations with a number of repetitive transients superimposed in the low-frequency ranges. The very low frequencies were composed almost entirely of transients. In the longitudinal and transverse axes, 50 percent or more of the peaks were below 0.01 g; in the vertical direction the mean acceleration was less than 0.05 g.

Coupling Load Measurements. A major source of shock in railroad transporters is the coupling operation. Although very low impact speeds 0.9 m/sec (2 mph) are necessary for automatic coupling operations, speeds greater than 4.5 m/sec (10 mph) have been observed. Data on impact speeds observed during switching operations are presented in reference 16 in the form of probabilities of exceeding a given impact speed.
Data recorded during impact tests with a 10^5 kg (100-ton) capacity hydrocushion car carrying a solid-rocket-motor segment are presented in reference 43. Tests were conducted with systems weighing from 31 475 to 112 000 kg (69 400 to 247 000 lb) and with a car having a 50.8-cm (20-in.) travel hydrocushion. Measured accelerations

on the transporter ranged up to 2.27 g in the longitudinal direction, 2.90 g in the vertical direction, and 0.59 g in the lateral direction for impact speeds up to 4.5 m/sec (10 mph).

Data recorded during rail-coupling impact tests of a system for transporting Polaris motors is reported in reference 40. The system tested consisted of a refrigerated van containing first- and second-stage motors mounted in an internal container that was supported and restrained by an air flotation system. The maximum longitudinal acceleration (3.95 g on the van and 1.12 g on one of the motors) occurred during a 4.32 m/sec (9.67 mph) impact. Data for other impact speeds, measurement locations, and directions are also given.

Reference 16 presents additional rail-coupling impact data in terms of shock spectra of the cargo floor for various impact speeds and directions (longitudinal, lateral, and vertical) and for both a standard and high-capacity (cushioned) coupling device. Shock spectra for the traditional worst case, the 4.92 m/sec (11 mph) impact, are presented in reference 45 and compared to shock spectra for other events such as a nominal 0.9 to 2.25 m/sec (2 to 5 mph) coupling and the crossing of railroad tracks and switches. It is shown that at some frequencies, the 4.92 m/sec coupling is as much as two orders of magnitude higher than the usual or normal events.

2.2.2.3 Air Transport Loadbed Inputs

Measurements recorded during air transport of the Saturn S-IV stage are presented in references 16 and 39. The loads were measured on the Pregnant Guppy, a conversion of the 4-engine Boeing 377 Stratocruiser that was modified specifically for transporting large space vehicles. Measured loads are reported for the forward and aft stations where the space vehicle is supported in the aircraft. Statistical distribution of the composite acceleration records are presented for take-off, climb, and cruise conditions. The fundamental frequencies reported for each of these conditions are 67, 60, and 51 Hz, respectively. These frequencies correspond to the blade passage frequencies. The results of harmonic analysis of data recorded during take-off are also given in the references. Landing loads were found to be extremely low unless prop reversal was used for braking. Data describing vehicle response to loads are also presented.

Summaries of loads recorded on the cargo decks of various aircraft commonly used for transporting space vehicles or vehicle segments are presented in reference 16. Composite curves are presented for propeller (turbine- and reciprocating-engine driven), helicopter, and jet aircraft. Vertical, lateral, and longitudinal components of loads are given for the C-123, C-130, C-133, 377PG, KC-135, and H-37 aircraft. The curves presented are composites of data for all operating conditions and therefore represent the maximum levels likely to be encountered.

Reference 46 presents measurements of the environment on the cargo deck and on the outer skin near the cargo hook of the HH43 helicopter. It gives the probability distribution of the acceleration amplitude peaks as a function of narrow bands of frequency. The HH43 helicopter is powered by a turboshaft engine which drives two contrarotating rotors. Motor starts, rotor engagement, and straight and level cruise were of little significance in inducing loads when compared to hover, climb, and high-speed events. Data showed both random and damped sinusoidal characteristics. Rotation of one rotor blade causes a sinusoidal excitation which begins to decay but is reinforced by the next blade. The engine and air movement generate random excitations.

2.2.2.4 Water Transport Loadbed Inputs

Measurements of the loads encountered during shipment of the Saturn S-IV stage by ship and barge are presented in reference 39. For the ship, the only loads of significance occurred during rough weather. The periods of measured accelerations ranged from 4 to 10 seconds per cycle. Composite accelerations were less than 0.35-g vertical, 0.22-g lateral, and 0.15-g longitudinal. For the ocean-going barge, the primary environment consisted of gentle swells causing low-level accelerations, with periods ranging from 4 seconds to 12 seconds. During one shipment, strong winds produced an 8 to 10 foot wave; the draft of the barge slammed the water and induced responses in the barge and transporter at 9 Hz. The acceleration levels reached 0.8 g in the vertical direction.

Reference 16 summarizes data on transient and continuous vibrations from numerous measurements on various types of ships. The transient vibrations include those which occur during emergency maneuvers and slamming. Measurements recorded in the cargo area of ships are generally too few to define the cargo-area load environment adequately. Extensive measurements have been made on the fantail, where the severest load environment exists on a ship. These measurements are used to establish upper bounds for loads. Envelope curves in reference 16 show the maximum reported acceleration levels as a function of frequency. Data are also presented in this reference to show the effect of sea state for two different ship lengths. Also shown are the acceleration levels measured in the various directions (longitudinal, lateral, and vertical) and the effect of maneuvers on loadings.

Rolling and pitching of a transport ship result in quasi-static loads parallel to the ship's deck. Transport ships may roll up to 30 degrees from the vertical (ref. 47); at this angle significant lateral loading can be imposed on the space vehicle. Angular acceleration, and consequently rotational load factors, of ships are extremely low because of the long roll and pitch periods of approximately 15 to 30 seconds in roll and 6 to 9 seconds in pitch. In addition to the lateral load component during severe rolling or pitching, water may wash over the ship's deck and produce severe loads on cargo located on the deck.

2.2.2.5 Handling Devices Loadbed Inputs

Loads imposed on the space vehicle or vehicle segments during handling operations such as transfers, loading, and unloading are generally very low because these operations are preplanned and closely monitored, and the equipment operators exercise extreme caution. Special handling systems, e.g., roll-on and roll-off systems, also contribute to low load levels. For these reasons little data on handling loads have been reported. Only when an accident occurs are handling-system loads significant. However, space vehicles are not normally designed for this contingency.

Reference 40 reports the loads encountered during the transfer of a flexi-van containing Polaris motors from a truck to a railroad car. The transfer consisted of the removal of the rear wheels from a container van and the transfer of the van onto a hydraulic platform of the freight car. During the transfer operation, the maximum loads recorded on the van were a 1.3 g vertical shock with a duration of 40 milliseconds and a 1.3 g vertical vibration at a frequency of 10 Hz.

Maximum vertical acceleration recorded during handling and transfer operation of the Saturn S-IV stage with a crane and cable system was 0.60 g. During one of the transfers, however, the forward end of the vehicle was dropped 7.62 cm (3 in.) because the crane operator thought the vehicle was already firmly on the ground. The severest vertical acceleration level induced by this drop was 0.94 g at the forward attachment-point cradle. Reference 17 presents a shock-spectra envelope for this event covering the shock spectra computed from measurements recorded at various critical locations on the space vehicle.

Loads developed during several simulated handling operations of a 3.05-m (120-in.) diameter solid-rocket-motor segment are described in reference 43. Maximum accelerations occurred while lowering the segment onto a highway trailer. The levels were 0.22-g longitudinal, 0.10-g vertical, and 0.20-g lateral.

Reference 17 presents additional data on commercial handling operations, including the probabilities of packages receiving a drop from a given height for given handling systems or operations. Data are also presented to show the effect of size and weight of the package on drop height. Various methods of monitoring and reporting the data are also discussed in reference 17.

2.3 Verifying and Monitoring Transportation and Handling Loads

The actual transportation and handling loads are usually measured to verify the accuracy of the estimated loads, and they are monitored on selected vehicles to ensure that the vehicle's flightworthiness is not affected. Measurements are made at the points where the loads have been estimated and at other critical locations, as required, to define the input loads to the vehicle and the vehicle response.

Initially, the loads are usually measured during trial runs of instrumented transportation and handling systems both with and without an instrumented simulated space vehicle. Later, as the program develops, qualification tests are performed to measure these loads on an instrumented transport vehicle and an updated engineering model of the space vehicle. Frequently, during shipment of production flight vehicles from the factory to the launch pad, the transportation and handling loads are monitored to record unexpected occurrences that may produce load levels in excess of specifications.

Instrumentation and data analysis techniques vary, depending upon the type of information being sought. Instrumentation may consist of strain gages, load cells, and/or accelerometers. References 16 and 17 discuss the various instrumentation and recording systems used in transportation and handling studies. Methods used for analyzing the data are also discussed. Descriptions of instrumentation systems used specifically for acquiring spacecraft transportation and handling data are presented in references 39, 40, 42, and 43. The development of a special instrumentation package for measuring and recording the transportation environment is described in reference 48. This system, called the Transportation Environmental Measurement and Recording System (TEMARS), can operate continuously and unattended for over two weeks. The recorded data include direction, magnitude, and time of occurrence of transient vibration or shock forces above preset threshold levels, as well as periodic measurements of quasi-static phenomena.

3. CRITERIA

The transportation and handling loads acting on a space vehicle shall be determined as needed for space vehicle design. Transportation and handling loads shall be predicted by appropriate state-of-the-art analyses, verified by experimental measurements, and, to the extent necessary, monitored during transportation and handling to ensure that space vehicle allowable loads have not been exceeded.

3.1 Determination of Transportation and Handling Loads

The transportation and handling loads shall be determined, as necessary, for all phases of space vehicle movements, including at least the following:

- Loading on transporter or transportation vehicle
- Transporting to assembly, test, and launch sites
- Transferring from one transportation vehicle to another
- Unloading at assembly, test, and launch sites
- Moving (locally) by special ground handling equipment, dollies, or lift trucks
- Assembling and integrating with other space vehicle elements
- Erecting on the launch pad
- Recovering the space vehicle and returning to base (if applicable)

For each of the transportation and handling phases, the loads to be accounted for shall include all dynamic (shock and vibration), quasi-static, and static loads resulting from at least the following:

- Normal interaction with the transport medium (air, water, rail, road)
- Acceleration, deceleration, rotation, and impact of the handling device
- Starts, stops, and maneuvers of the transport vehicle
- Restraint at tiedowns and reaction points

All appropriate combinations of the above load sources in all directions of load application (vertical, longitudinal, lateral) shall be accounted for.

The transportation and handling loads shall be determined by suitable state-of-the-art methods of analyses. The analyses used shall predict the transportation and handling loads to the accuracy needed to permit adequate design.

3.2 Verification of Transportation and Handling Loads

Experimental measurements on engineering, prototype, or production models of space vehicles and transportation and handling systems shall be performed, as required, to verify the predicted transportation and handling loads.

3.3 Monitoring of Transportation and Handling Loads

Transportation and handling loads shall be monitored on shipments of production space vehicles to the extent necessary to ensure that the loads actually incurred are less than the allowable loads.

4. RECOMMENDED PRACTICES

To ensure that transportation and handling loads are adequately determined and accounted for in space vehicle design, close cooperation should be maintained between environmental specialists, dynamicists, structural designers, ground support equipment designers, packaging specialists, and instrumentation engineers. As a general rule, it is recommended that transportation and handling loads do not exceed the space vehicle allowable loads established by flight or other mission requirements. If the estimated loads exceed the allowable loads, the transportation or handling systems should be modified to provide sufficient attenuation to reduce these estimated loads to values less than the allowable loads. The space vehicle structure should be modified to withstand transportation or handling loads only if the transportation or handling system cannot be feasibly modified to attenuate these loads.

An initial selection of the transportation and handling systems should be made during the conceptual design phase because the basic structural configuration of the space vehicle, i.e., the size and weight of the stages, is constrained to some extent by the cargo volume, weight capacity, and other limitation of feasible transportation modes. When the space vehicle allowable load estimates first become available, an initial estimate of the transportation and handling loads should be made. This initial estimate and subsequent estimates of the transportation and handling loads should use an appropriate method of analysis based on the type of transportation and handling input data available and the nature of the space vehicle and transportation or handling system selected. The initial transportation and handling load estimates should be used to (1) provide guidance in evaluating and selecting appropriate transportation modes and handling devices, (2) establish load attenuation requirements for the design of transportation and handling fixtures, and (3) act as source inputs for the strength and fatigue analyses of the space vehicle.

The transportation and handling loads should be defined at the points where the space vehicle is supported during transportation and handling operations to facilitate comparison of loads for several transportation and handling systems and for use in subsequent analyses (e.g., natural vibration modal analyses, structural vibration prediction, structural response to mechanical shock). Because information on loads at attachment points is generally not available, loads measured at other locations should be used in suitable analyses to compute the loads at the attachment points.

The mathematical models used in the analyses of transportation and handling loads should contain enough degrees of freedom to represent the desired response of the system. No single type of analytical model representation can be recommended for all systems. It should be kept in mind that the accuracy of the computed response will vary with the complexity of the structure as represented by its mathematical model and with the number of the modes responding, as discussed in reference 2. References 1, 2, and 3 should be consulted for guidance on modeling techniques for space vehicles.

For predicted transportation and handling loads, the analytical models should simulate, individually, each significant loading direction for the transportation or handling operation under consideration. Actual loads and structures are complex and multidirectional and difficult to analyze; however, adequate results may often be obtained by analyzing 2-dimensional (planar) lumped-mass parameter models.

4.1 Determination of Transportation and Handling Loads

Transportation and handling loads should be estimated by one or more of the following prediction methods (see Section 2.1):

1. Analysis using limit load factors
2. Analysis of partial system with composite loadbed inputs
3. Scaling and extrapolation from similar system experience
4. Analysis of full system with transportation medium inputs

The particular method used to estimate the loads should be based on a number of considerations including the availability and applicability of pertinent data for the transportation and handling system under consideration, the detail of load definition required (which will depend on the severity of the load relative to space vehicle design loads), and the time and resources available. Applicable limit load factors from table I [method (1)] are recommended for use during preliminary design to determine whether a transportation and handling loads problem exists (Sec. 2.1.1). Note: This method of analysis results in very conservative estimates of the loads.

If the transport vehicles for the system under consideration are common carriers or special carriers on which loadbed loads have been measured, then composite load data should be used with a mathematical model of the partial system [method (2)] to estimate the loads (Sec. 2.1.2). The data used should cover a wide range of systems, operating conditions, and loads, to ensure that they encompass all conditions and factors likely to occur during transportation and handling of the new system. Load estimates resulting from this approach will also usually be conservative. The loadbed data should be closely examined to determine where the data were measured and their applicability to the proposed system. If, for example, the data have been measured on the cargo floor of all types of commercial vehicles and loads, they can then serve as input loads to the handling or vehicle support mechanism attached to the floor of the transport vehicle. Applicable composite data of this type for the four major modes of transportation are shown in figure 2. Other valid sources of composite data are discussed in Section 2.2.2. Mathematical modeling of the system above the cargo floor in an analysis that uses the cargo floor loads as inputs should be used to determine input loads to the space vehicle and vehicle response to these loads (Sec. 2.1.2).

When available, loadbed data for the specific transportation vehicle or handling system, rather than the data of figure 2, should be used to provide a more accurate estimate of the loads. However, care should be taken that the data cover the range of conditions likely to be encountered with the actual system. This approach is particularly applicable to transportation and handling systems which are large compared to the space vehicle, i.e., the space vehicle has little effect on the cargo-floor motions. Aircraft, ship, and some rail cars fall into this category. Sources for loadbed data are discussed in Section 2.2.2.

If the space vehicle transportation or handling system under consideration is similar to a system for which load measurement data and either a mathematical model or the physical characteristics required for the model are available, then the data should be scaled or extrapolated (Sec. 2.1.3) to the new system using method (3). The dynamicist should have a knowledge of the structure on which the data were recorded to determine the effect of the load. The approach is best suited to systems in which there is only a small change in the structure or weight of the new space vehicle, compared with the structure and weight of the vehicle on which the load measurements were made. The data used, however, should cover all the conditions likely to be encountered by the system under consideration. Data should be sought through internal reports or records since very little data of this type are available in the general literature.

For entirely new transportation and handling systems or extensively modified systems for which applicable data are unavailable or inadequate, the loads should be determined by method (4), dynamic modeling and analysis of the entire system with transportation medium inputs (Sec. 2.1.4). This method should also be used when the time and phase relationships of the loads must be known, i.e., when such information would significantly affect the results, or when the loading is judged critical from preliminary analyses and detailed load definition is required. This method should also be used in predicting loads for systems whose response will be significantly influenced by the mass distribution and stiffness distribution of the space vehicle. Where transportation vehicles such as aircraft, ships, and in some instances railroad cars are large in comparison to the new space vehicle, the space vehicle will generally have little influence on the response of the transportation vehicle. Prediction for such systems should be based on composite loadbed data.

For this method of analysis, in which the entire system is modeled and analyzed, the environmental specialist should seek data describing the basic source of excitation of the transportation medium, i.e., road profile, rail profile, air turbulence or gusts, and wave height and frequency. A summary of the limited data available in the literature is given by reference and discussion in Section 2.2.1.

Of the four basic sources of excitation, the road profile is the input medium which, where feasible, should be determined by measurements along the actual route. For road transport, the measuring equipment described in reference 4 should be used to provide data describing the road profile. Road profiles should be monitored over the roughest section of the actual route. If time or circumstances do not allow this, previously measured data (ref. 4) or estimates (ref. 5) should be used. Use of estimates of the road profile such as those presented in reference 5 results in conservative predictions of the loads. Use of power-spectral-density data, such as those presented in reference 4, results in prediction of loads in terms of root-mean-square (rms) values. Maximum load values should be determined by multiplying the rms loads by a factor of 1.414 if the loads are sinusoidal and by a factor of 3 sigma if the loads are random.

For handling systems, the input to the system should be based on judgment and past experience. The significant loads that occur during handling operations are a result of human error, accident, or expediency in which the space vehicle receives a bump or sudden push or pull. These loads are chance phenomena and estimates of their magnitude and frequency of occurrence should be based on experience and described on a statistical basis. As discussed in Section 2.2.1.5, very few data of this type are available and it is necessary to establish arbitrary but reasonable inputs. For example, a step change in velocity may be considered reasonable for loads imposed by human error or expediency during raising and lowering handling operations. The velocities used should be related to the characteristics of the equipment being used. If accidents are to be considered, a reasonable drop height should be estimated for the equipment and operation being considered. Guidance to estimates of handling system inputs should be based on data discussed in Section 2.2.2.5. The inputs should be applied to a mathematical model of the system as described in references 13 and 14.

Conservative practices should be used in estimating the transportation and handling loads and appropriate safety factors should be used to account for any uncertainties in the data. Past experience and engineering judgment are required for assigning values to such factors because there are no relevant documented studies and recommended practices in this area. Reliability and applicability of the available data, validity and accuracy of the dynamic models, and possible combinations of load inputs to the system are recommended for consideration in applying safety factors. A discussion of safety factors and design load factors employed by various missile manufacturers is presented in reference 18.

If the space vehicle design loads from flight and sources other than transportation and handling are significantly greater than the loads induced by transportation and handling, only a limited analysis is required. If the induced transportation loads are close to the allowable loads, more extensive analyses should be performed. Although beyond the scope of this monograph, the analysis of vehicle response (ref. 2) should be considered as a logical extension of the analyses for predicting transportation and handling loads. This is particularly important in the design of a transporter or other special equipment where the transporter itself is designed to act as the load attenuation system.

Appropriate combinations of transportation and handling load inputs should be considered in arriving at the final estimated loads. For example, it is known that in actual ground transportation and handling operations, the loads can occur simultaneously along the three perpendicular axes. In addition, moments or torques can occur or tie-down loads, wind loads, and thermal expansion loads can occur at the same time. These combinations should be considered in arriving at the final predictions when such loads are known to act at the same time.

4.2 Verification of Transportation and Handling Loads

If the predicted values of transportation and handling loads are equal to, or more than, 50 percent of the values of allowable loads, then the predicted load values should be verified by load-measurement tests. Even if the predicted load values are less than 50 percent of the allowable values, load-measurement tests should be conducted if there are serious doubts concerning the accuracy or conservatism of the analyses used to predict the loads.

When it has been determined that load measurements are required, the recommended procedures for verification of transportation and handling loads are as follows. Prototypes of the transportation and handling systems should be instrumented to measure and record transportation and handling loads during trial runs of the systems. Trial runs should be conducted so that events occur in the same sequence and along the same route as the planned handling and transportation operations. A simulated space vehicle which has dynamic characteristics closely approximating the actual flight vehicle should be carried on the trial runs and be instrumented to measure its response to input loads from the prototype transportation and handling systems.

If the trial runs indicate the measured values of transportation and handling loads are close to the predicted loads, or are at least less than the allowable loads by a sufficient margin, then final verification of the loads should be made by tests of an instrumented prototype or production space vehicle with the instrumented prototype or production transportation and handling systems. These final load-verification tests should be integrated with the qualification test programs for the transportation and handling systems. If feasible, these tests should be conducted for all phases of movement of the space vehicle or its major segments and for all conditions likely to be encountered during actual shipment. If this is not practical, the tests should at least duplicate the severest intransit and handling conditions likely to be encountered during normal shipping operation. The loads should be measured at the points where they have been estimated, particularly at the space vehicle attachment points and the transport vehicle loadbed, and at all locations on the space vehicle that have been judged critical as a result of space vehicle response analyses. Results of these tests should provide the basis for qualifying the transportation and handling systems. The tests should also establish the need for restrictions on specific transportation or handling operations. For example, if the loads are excessive for a particular transport vehicle speed and road type, a speed restriction should be imposed to ensure protection of the space vehicle.

Instrumentation used for measurements to verify the transportation and handling loads should be appropriate to the information being sought and the location on the vehicle. Selection of the type of instrumentation and the location of the instrumentation on the transportation and handling system should be determined jointly by the instrumentation engineers, dynamicists, strength engineers, and test engineers. In all cases, the instrumentation should not influence the measured response and should be capable of accurately measuring and recording the induced loads and the space vehicle response.

Whenever a program is undertaken to verify transportation and handling loads through measurement, these measurements should be of value to designers and analysts on similar programs. Therefore, it is recommended that during the data measurement and documentation phases, consideration be given to acquiring and presenting sufficient structural and dynamic information to allow the data to be used in estimating the loads on new systems.

4.3 Monitoring of Transportation and Handling Loads

Monitoring the transportation and handling loads is recommended during all shipments of the space vehicle when the maximum predicted loads are greater than 50 percent of the allowable loads. The instrument locations and types should be determined from evaluation of data measured in the load-verification test phase.

The monitoring instrumentation should be carefully selected for the position where it is to be mounted and the critical frequency regime of the transported structure. The instrumentation and recording system should be portable and capable of recording unattended for long periods. It is recommended that the self-contained system described in reference 48 be used for monitoring these loads.

The measurements obtained during production shipments should be used to verify that the space vehicle allowable loads have not been exceeded. In the event of an accident or an abnormal loading condition not previously considered, this information should be used to determine whether the space vehicle's flightworthiness has been impaired.

REFERENCES

1. Anon.: Natural Vibration Modal Analysis. NASA Space Vehicle Design Criteria (Structures), NASA SP-8012, 1968.

2. Anon.: Structural Vibration Prediction. NASA Space Vehicle Design Criteria (Structures), NASA SP-8050, 1970.

3. McCormick, R. W., ed.: NASTRAN Users Manual. NASA SP-222, 1970.

4. Harvey, J. R.; and Wursche, R. A.: Roughness Measurement and System Response Evaluation for Highway Environment. The Shock and Vibration Bull. No. 35, Part 5, Feb. 1966.

5. Hager, R. W.; and Conner, E. R.: Road Transport Dynamics. The Shock and Vibration Bull. No. 31, Part 3, Apr. 1963.

6. Lever, S. A.: Shock and Vibration of Apache Trailer. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

7. Simun, R. R.; and Peterson, R. S.: Missile Transporter Vibration Analysis. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

8. Hager, R. W.; Partington, R. L.; and Leistikow, R. J.: Rail Transport Dynamic Environment. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

9. Manos, W. P.; and Shang, J. C.: Dynamic Analysis of Rolling Freight Cars. Paper No. 65-WA/RR55 presented at the Winter annual meeting of the Railroad Division, ASME at Chicago, Nov. 7-11, 1965.

10. McGoldrick, R. T.: Ship Vibration. David Taylor Model Basin. Rept. 1451, Dec. 1960. (Available from DDC as AD 259466)

11. Kaplan, P.: Development of Mathematical Models for Describing Ship Response in Waves. Rept. SSC-193, Ship Structure Committee, Natl. Res. Council, Natl. Academy Sci. U.S., Jan. 1968.

12. Bennett, F. V.; and Pratt, K. C.: Calculated Response of a Large Swept Wing Airplane to Continuous Turbulence with Flight Test Comparisons. NASA TR R-69, 1960.

13. Fischer, E. G.; Brown, C. R.; and Molnar, A. J.: Lateral Impact Shock During Ship Loading of the A3 Polaris Missile. The Shock and Vibration Bull. No. 37, Part 7, Jan. 1968.

14. Brown, C. R.; and Avis, A. J.: Missile Handling Analysis. The Shock and Vibration Bull. No. 36, Part 7, Feb. 1967.

15. Anon.: Structural Design Criteria Applicable to a Space Shuttle. NASA Space Vehicle Design Criteria (Structures), NASA SP-8057, 1971.

16. Ostrem, F. E.; and Rummerman, M. L.: Transportation Shock and Vibration Design Criteria Manual. Vol. I, Rept. No. MR-1262, General American Transportation Corporation, Sept. 1965.

17. Ostrem, F. E.; and Rummerman, M. L.: Transportation and Handling Shock and Vibration Design Criteria Manual. Report No. MR-1262-2, General American Transportation Corp., Apr. 1967.

18. Thompson, M. B.; Loser, J. B.; and Brown, R. S.: Research Study on Ground Environment Loads Criteria for Guided Missiles. Report No. WADC-TR-59-627, Wright-Patterson AFB, Ohio, August 1962. (Available from DDC as AD 285852)

19. Foley, J. T.: The Environment Experienced by Cargo on a Flatbed Tractor-Trailer Combination. Report SC-RR-66-677, Sandia Corp., Dec. 1966.

20. Mains, R. M.: What Should be Known to Evaluate Rail Shipping Damage. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

21. Daniel, G. E.: Terrestrial Environment (Climatic) Criteria Guidelines for Use in Space Vehicle Development – 1969 Revision. NASA TM X-53872, 1970. (ASC No. N70-16998)

22. Sattinger, J.; and Sternick, S.: An Instrumentation System for the Measurement of Terrain Profile. Tech. Rept. University of Michigan, Dec. 1961.

23. Hveem, F. N.: Devices for Recording and Evaluating Pavement Roughness. Bull. 264, Highway Research Board, Washington, D. C., 1960.

24. Simon, H. P.; and Roach, C. D.: Measurement of the Cross-Country Terrain Environment. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

25. Milenkovic, V.: Feasibility Study for a Wheel-Rail Dynamics Research Facility. Research Division, General American Transportation Corporation, Dec. 1968. (Available from NTIS as PB 182472)

26. Lindgren, P. W.: Dynamic Train Simulation. Preprint No. 23-2-TID-67, 22nd Annual Instrument Society of America Conference, Sept. 1967.

27. Law, C. W.: Instrumentation for High-Speed Railroad Research Project. Preprint No. 23-2-TID-67, 22nd Annual Instrument Society of America Conference, Sept. 1967.

28. O'Sullivan, W. B.: Boston and Maine Expand Role of Mechanical Track Inspection. Railway Track and Structures, Apr. 1965.

29. Lindner, F. J.: Engineering Approach to the Protection of a Fragile Item-Panel Session. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

30. Brown, W. H.; and Drydahl, R. L.: Simulation of Rail Car Coupling Environment. The Shock and Vibration Bull. No. 30, Part 3, Feb. 1962.

31. Harris, C. M.; and Crede, C. E.; eds.: The Shock and Vibration Handbook Vol. III. McGraw-Hill Book Co., Inc., 1961.

32. Pratt, K. G.; and Walker, W. G.: A Revised Gust-Load Formula on a Re-evaluation of V-G Data Taken on Civil Transport Airplanes from 1933 to 1950. NACA Rept. 1206, 1954.

33. Houbolt, J. C.; and Kordes, E. E.: Structural Response to Discrete and Continuous Gusts of an Airplane Having Wing-Bending Flexibility and a Correlation of Calculated and Flight Results. NACA Rept. 1181, 1954.

34. Houbolt, J. C.; Steiner, R.; and Pratt, K. G.: Dynamic Response of Airplanes to Atmospheric Turbulence Including Flight Data on Input and Response. NASA TR R-199, 1964.

35. Hall, A. W.: Three-Track Runway and Taxiway Profiles Measured at International Airports C and D. NASA TN D-5703, 1970.

36. Morris, G. J.: Response of Several Turbojet Airplanes to Runway Roughness. NASA TN-5740, 1970.

37. Jasper, N. H.: Statistical Distribution Patterns of Ocean Waves and of Wave Induced Ship Stresses and Motions, with Engineering Application. David Taylor Model Basin Rept. 92, Oct. 1957.

38. St. Denis, M.; and Fersht, S. N.: The Effect of Ship Stiffness upon the Structural Response of a Cargo Ship to an Impulsive Load. Rept. SSC-186, Ship Structure Committee, Natl. Res. Council, Natl. Acad. Sci. U.S., Sept. 1968. (Available from DDC as AD 675639)

39. Trudell, R. W.; and Elliott, K. E.: The Dynamic Environment of the S-IV Stage During Transportation. The Shock and Vibration Bull. No. 33, Part 4, Mar. 1964.

40. Anon.: Rail and Road Transportation Test. New York Central System. "Flexi-Van." LMSD 501917, Lockheed Missiles and Space Division, Aug. 1959.

41. Schlue, J. W.; and Phelps, W. D.: A New Look at Transportation Vibration Statistics. The Shock and Vibration Bull. No. 37, Part 7, Jan. 1968.

42. Schlue, J. W.: The Dynamic Environment of Spacecraft Surface Transportation. Jet Propulsion Lab., TR 32-876, Mar. 1966.

43. Molinari, L. A.; and Reynolds, J. R.: Program 624 A Titan III-C Transportation Tests. The Shock and Vibration Bull. No. 35, Part 5, Feb. 1966.

44. Foley, J. T.: Normal and Abnormal Environments Experienced By Cargo on a Flatbed Truck, Rept. SC-DR-67-3003, Sandia Labs., Feb. 1968.

45. Gens, M. B.: The Rail Transport Environment. The Journal of Environmental Sci., Vol. XIII, No. 4, July 1970, pp. 14-20.

46. Gens, M. G.: A Preliminary Observation of the Dynamic Environment of Helicopters. Pro. of the Inst. of Environmental Sci., 1968.

47. Anon.: Guidelines for Deck Stowage of Containers. Rept. MA-RD-71-4, Maritime Administration, Dept. of Commerce, July 1970.

48. Holley, F. J.: Transportation Environmental Measurement and Recording System. The Shock and Vibration Bull. No. 36, Part 6, Feb. 1967.

NASA SPACE VEHICLE DESIGN CRITERIA MONOGRAPHS ISSUED TO DATE

SP-8001	(Structures)	Buffeting During Atmospheric Ascent, May 1964 – Revised November 1970
SP-8002	(Structures)	Flight-Loads Measurements During Launch and Exit, December 1964
SP-8003	(Structures)	Flutter, Buzz, and Divergence, July 1964
SP-8004	(Structures)	Panel Flutter, July 1964
SP-8005	(Environment)	Solar Electromagnetic Radiation, June 1965 – Revised May 1971
SP-8006	(Structures)	Local Steady Aerodynamic Loads During Launch and Exit, May 1965
SP-8007	(Structures)	Buckling of Thin-Walled Circular Cylinders, September 1965 – Revised August 1968
SP-8008	(Structures)	Prelaunch Ground Wind Loads, November 1965
SP-8009	(Structures)	Propellant Slosh Loads, August 1968
SP-8010	(Environment)	Models of Mars Atmosphere (1967), May 1968
SP-8011	(Environment)	Models of Venus Atmosphere (1968), December 1968
SP-8012	(Structures)	Natural Vibration Modal Analysis, September 1968
SP-8013	(Environment)	Meteoroid Environment Model – 1969 [Near Earth to Lunar Surface], March 1969
SP-8014	(Structures)	Entry Thermal Protection, August 1968
SP-8015	(Guidance and Control)	Guidance and Navigation for Entry Vehicles, November 1968
SP-8016	(Guidance and Control)	Effects of Structural Flexibility on Spacecraft Control Systems, April 1969
SP-8017	(Environment)	Magnetic Fields – Earth and Extraterrestrial, March 1969
SP-8018	(Guidance and Control)	Spacecraft Magnetic Torques, March 1969
SP-8019	(Structures)	Buckling of Thin-Walled Truncated Cones, September 1968
SP-8020	(Environment)	Mars Surface Models (1968), May 1969
SP-8021	(Environment)	Models of Earth's Atmosphere (120 to 1000 km), May 1969

SP-8022	(Structures)	Staging Loads, February 1969
SP-8023	(Environment)	Lunar Surface Models, May 1969
SP-8024	(Guidance and Control)	Spacecraft Gravitational Torques, May 1969
SP-8025	(Chemical Propulsion)	Solid Rocket Motor Metal Cases, April 1970
SP-8026	(Guidance and Control)	Spacecraft Star Trackers, July 1970
SP-8027	(Guidance and Control)	Spacecraft Radiation Torques, October 1969
SP-8028	(Guidance and Control)	Entry Vehicle Control, November 1969
SP-8029	(Structures)	Aerodynamic and Rocket-Exhaust Heating During Launch and Ascent, May 1969
SP-8030	(Structures)	Transient Loads from Thrust Excitation, February 1969
SP-8031	(Structures)	Slosh Suppression, May 1969
SP-8032	(Structures)	Buckling of Thin-Walled Doubly Curved Shells, August 1969
SP-8033	(Guidance and Control)	Spacecraft Earth Horizon Sensors, December 1969
SP-8034	(Guidance and Control)	Spacecraft Mass Expulsion Torques, December 1969
SP-8035	(Structures)	Wind Loads During Ascent, June 1970
SP-8036	(Guidance and Control)	Effects of Structural Flexibility on Launch Vehicle Control Systems, February 1970
SP-8037	(Environment)	Assessment and Control of Spacecraft Magnetic Fields, September 1970
SP-8038	(Environment)	Meteoroid Environment Model – 1970 (Interplanetary and Planetary), October 1970
SP-8040	(Structures)	Fracture Control of Metallic Pressure Vessels, May 1970
SP-8041	(Chemical Propulsion)	Captive-Fired Testing of Solid Rocket Motors, March 1971
SP-8042	(Structures)	Meteoroid Damage Assessment, May 1970
SP-8043	(Structures)	Design-Development Testing, May 1970
SP-8044	(Structures)	Qualification Testing, May 1970
SP-8045	(Structures)	Acceptance Testing, April 1970
SP-8046	(Structures)	Landing Impact Attenuation for Non-Surface-Planing Landers, April 1970
SP-8047	(Guidance and Control)	Spacecraft Sun Sensors, June 1970

SP-8048	(Chemical Propulsion)	Liquid Rocket Engine Turbopump Bearings, March 1971
SP-8049	(Environment)	The Earth's Ionosphere, March 1971
SP-8050	(Structures)	Structural Vibration Prediction, June 1970
SP-8051	(Chemical Propulsion)	Solid Rocket Motor Igniters, March 1971
SP-8052	(Chemical Propulsion)	Liquid Rocket Engine Turbopump Inducers, May 1971
SP-8053	(Structures)	Nuclear and Space Radiation Effects on Materials, June 1970
SP-8054	(Structures)	Space Radiation Protection, June 1970
SP-8055	(Structures)	Prevention of Coupled Structure-Propulsion Instability (Pogo), October 1970
SP-8056	(Structures)	Flight Separation Mechanisms, October 1970
SP-8057	(Structures)	Structural Design Criteria Applicable to a Space Shuttle, January 1971
SP-8058	(Guidance and Control)	Spacecraft Aerodynamic Torques, January 1971
SP-8059	(Guidance and Control)	Spacecraft Attitude Control During Thrusting Maneuvers, February 1971
SP-8060	(Structures)	Compartment Venting, November 1970
SP-8061	(Structures)	Interaction with Umbilicals and Launch Stand, August 1970
SP-8062	(Structures)	Entry Gasdynamic Heating, January 1971
SP-8063	(Structures)	Lubrication, Friction, and Wear, June 1971
SP-8065	(Guidance and Control)	Tubular Spacecraft Booms (Extendible, Reel Stored), February 1971
SP-8066	(Structures)	Deployable Aerodynamic Deceleration Systems, June 1971
SP-8067	(Environment)	Earth Albedo and Emitted Radiation, July 1971
SP-8068	(Structures)	Buckling Strength of Structural Plates, June 1971
SP-8070	(Guidance and Control)	Spaceborne Digital Computer Systems, March 1971
SP-8071	(Guidance and Control)	Passive Gravity-Gradient Libration Dampers, February 1971
SP-8072	(Structures)	Acoustic Loads Generated by the Propulsion System, June 1971
SP-8077	(Structures)	Transportation and Handling Loads, September 1971

NASA-Langley, 1971