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REVIEW OF RIDE QUALITY TECHNOLOGY NEEDS OF
INDUSTRY AND USER GROUPS*

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SUMMARY

A broad survey of ride quality technology state-of-the-art and a review of user evaluation of this technology have been conducted. During the study so far, 17 users of ride quality technology in 10 organizations representing land, marine and air passenger transportation modes have been interviewed. Interim results and conclusions of this effort are reported in this paper.

INTRODUCTION

The quality of vehicle ride can be a significant factor in determining passenger acceptance and use of various modes of public transportation. Technology pertaining to the subjective aspects of ride quality is therefore needed to aid design and operation of vehicles and to achieve acceptance of existing and planned transport vehicle systems.

During the past few years significant efforts have been initiated to gain a better understanding of ride quality factors and to build a technology base adequate for supporting design of viable transport vehicle systems. Many of these ride quality technology programs (not including ride smoothing) have been conducted by research organizations rather than user organizations. Significant research has been accomplished to identify crew tolerance of acceleration in a military environment and has culminated in a portion of the military specification of Reference 1. Although this research is pertinent, it has resulted in identification of safety and proficiency levels rather than comfort levels as needed for evaluation of passenger response. This paper is confined to passenger ride response to commercial vehicles and its purpose is to present interim results of a critique of ride quality technology research activities from the viewpoint of user organizations.

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Ride quality is important in the design of public transportation vehicles due to the influence of several factors. The primary factor that has been studied is the effect of vibrations on passenger response. The effect of vibrations has received the greatest amount of attention because it has an obvious influence on passenger comfort and is not as easily quantified as other factors such as temperature, humidity, etc.

It is easy to predict that the general increase in vehicular operational speed (except automobiles) which has occurred over the past several years presents a potential ride problem to the designer. This potential problem is common to different transportation modes.

In the case of aircraft, this potential problem results from the fact that vehicle (and passenger) vertical and lateral acceleration responses are approximately proportional to speed for a given turbulence environment. Short haul carriers tend to operate at lower altitudes where the probability of turbulence encounter is greater, and typical vehicles tend to operate at a comparatively low wing loading which in turn increases gust sensitivity. In addition, very large vehicles tend toward increased airframe flexibility and studies have shown that structural response to turbulence becomes significant in ride evaluation. Inputs such as these cannot be controlled directly but undesired vehicle response may be reduced by the application of automatic control concepts as demonstrated by the results presented in Reference 2.

In some cases, helicopters which were designed primarily for military missions have been used to provide taxi type service. Passengers are subjected to ride considerations for which they may not be prepared, such as noise, blade flicker or unaccustomed maneuvers.

Marine transportation systems face similar adverse environments including atmospheric turbulence as well as a varying sea state. As in aircraft, not much can be done to control the inputs short of avoiding the worst of them.

High speed ground transportation vehicles are also subject to the effects of turbulence and cross winds. The smoothness of rails, surfaces or guideways also directly affects the ride quality of such vehicles. Unlike atmospheric turbulence, this input can be controlled to a certain extent by original manufacturing requirements and by continuing maintenance.

Ride quality criteria in use for existing transportation modes primarily focus on vibration effects, although in most cases secondary attention is paid to other amenities such as seating, temperature, humidity, noise and decor. The user is sometimes faced with applying inadequate criteria or adapting criteria formulated for other vehicles to his purposes. He has encountered this situation because sufficient technology has not been developed or because existing data have not been transformed into a design format useful to him. This is the case for ride parameters such as exposure time, vehicle attitude, combined axis motion and multiple frequency effects.

The problem for today's user is the transformation of available ride quality knowledge or data where it is available into the proper format for his application. Subsequent sections will point out areas of technology weakness which impede the user in performing this task.

DEFINITIONS

Definitions of key words and phrases used throughout the paper are provided to establish a common basis for understanding and interpreting the results.

Ride Quality Technology and Criteria

Ride quality technology is defined as that body of knowledge which provides performance and cost data for the development of vehicle or system ride quality criteria. Ride quality criteria are defined as the performance standards for system design and development. The inter-relationship of technology and criteria implies that a lack or weakness of criteria is a result of an insufficient technology data base and there is a need for additional research.

Ride Quality/Passenger Acceptance

Ride quality means different things to different people. Traditionally, the term "ride quality" refers to the effects of vehicle motions such as acceleration response to inputs from equipment or maneuvers, or inputs from turbulence or guideway roughness. For the purpose of this paper ride quality is defined as shown in Figure 1. This definition is an extension of the traditional definition of ride quality in that the passenger's subjective response to the perceived vehicle motion is only one of many relevant factors.

The passenger's age, background, ride experience, motivation, physical and psychological condition also have a direct effect on his subjective rating of the ride experienced during his trip. For instance, at one time there was a monorail system serving one of the major airports from a remote parking facility. One could drive directly to the monorail station, leave his car to be parked by an attendant and board the monorail directly. The monorail system itself was rather jerky, noisy, and suffered from excessive roll conditions, but the alternative was to park in a crowded lot nearer the terminal and carry luggage a long distance. This monorail system probably would not have been able to achieve a quality of ride which would meet the criteria levied on rail systems today, but motivation dictated that this system was used and appreciated. Other examples of motivation dictating choice of transportation mode may be found in the "park and ride" rail or bus systems to be found in many large metropolitan areas. These examples do not indicate that ride quality is subordinate to motivation in the passenger's choice of transportation mode but simply indicate that there are trades that the passenger will make.

Vehicle response parameters such as motion, noise, and effects of other amenities such as seat geometry, temperature and odor, have been quantified to some degree but the varying effects of each or combinations of these parameters on passenger response have not been well defined.

Figure 1 is completed by the addition of a passenger acceptance transfer function. This term includes such things as passenger evaluation of cost, schedule convenience, mode prejudice and onboard services. The effect of these concepts on the passenger's choice of transportation mode is beyond the scope of this paper but is shown in the diagram to complete the perspective of passenger evaluations.

User of Ride Quality Technology and Criteria

Users of transportation vehicles and systems relate to ride quality technology and criteria in two distinctly different ways. Users may be governmental agencies responsible for procuring and/or operating a transportation system or a private company developing a vehicle which it hopes to sell to other companies or to the government. In this case the procurement organizations and company technology groups need an adequate technology base to develop criteria for a system specification or for an internal product development program. On the other hand, a user, such as a manufacturer, responding to a customer's requirements, is concerned with satisfying the specified criteria and has little need for the technology data from which the criteria were derived. This paper discusses both ride quality criteria and technology from the appropriate user point of view.

Personal interviews of typical users of ride quality criteria and technology were conducted to expedite the gathering of data for this paper. The type and number of users contacted to date are listed in Table 1.

VEHICLE RIDE QUALITY PROBLEMS - PRESENT AND FUTURE

Selected present and future vehicle ride quality problems are outlined in Table 2. Problems identified are those assumed to have greatest priority in terms of requirements for ride improvement for existing or future modes of transportation. Contents of this table are preliminary since much data bearing on this subject have not been received.

Vibration and noise environments account for a majority of user concerns with vehicle ride quality, both for existing and near-future transportation systems. Vibration sources presenting ride quality problems generally occur at the interface of the vehicle with the medium on or through which it is traveling. Noise sources exist in ground transportation systems at this same interface while a major contributor to noise level in water or airborne vehicles arises from the propulsion system.

There are sources of vibration and noise, however, that create unique ride quality problems for different transportation modes. Examples of these more unique problems are switch crossings, wheel squeal during turns (rail), transition from foilborne to hullborne status (marine), vibrations and noise associated with blade passage (helicopters) and effects of maneuvers (short haul aircraft).

This initial effort to anticipate ride quality problems associated with transportation vehicles of the near future did not identify many new areas of concern. Vibration and noise problems still appear to be primary and are aggravated due to higher speeds and more powerful propulsion systems. In the air transport mode, quiet short haul aircraft may have degraded ride due to low wing loading and runway roughness may be more of a problem as aircraft get larger and more flexible. These trends do not necessarily project a bleak picture for the future passenger, however, since application of vibration control and noise alleviation technology will likely solve the problems. These technologies will presumably be guided by more sophisticated and accepted ride quality criteria.

AN OVERVIEW OF THE EXISTING RIDE QUALITY DATA BASE

Persons responsible for specifying vehicle ride environment need an adequate data base to support this activity. The existing data base is given a cursory review here to establish a basis for discussion in the following section, the User View of Ride Quality Criteria. Elements of the ride environment addressed are temperature, humidity, airflow, barometric pressure, leg room, seat width, noise and vibration. An excellent starting point for persons interested in a more detailed review of the relevant literature is Reference 3, which develops initial environmental criteria for motion, noise, temperature, humidity and pressure.

This overview considers only those potential sources of criteria which are published in the general literature or which have been presented at technical meetings covering a specific area of ride quality data. This restriction excludes consideration of criteria based on passenger vehicle manufacturers' or passenger carriers' experience with consumer acceptance of their product, unless these criteria are in published form. Appropriate reference is made to ongoing ride quality related studies for which interim results have been presented.

Temperature, Humidity and Rate of Air Flow

These three components of the vehicle ride environment are commonly discussed jointly. It appears that there is general agreement among the handbooks regarding comfortable ranges although there may be minor differences. A comprehensive review of relevant data is found in References 4, 5 and 6.

Barometric Pressure

Primary concern in this area has been the rate of change of pressure that is acceptable to air travelers. References 6 and 7 present acceptable limits.

Leg Room and Seat Width

Space available to the seated commercial passenger is an important factor affecting assessment of vehicle ride quality, particularly if the trip is extended and if movement within the vehicle is restricted. Anthropometric data are available in standard design handbooks to establish these space requirements. In addition, Reference 6 proposes seat pitch and width to provide acceptable passenger comfort.

Noise

The data base from which ride quality noise criteria may be drawn is more fragmented than those for the elements of the ride environment discussed above for a number of reasons. Most of the literature relating subjective reactions of persons to noise levels deals with the problem of community reactions to noise sources such as road or rail traffic and airplane fly-overs. There is also disagreement on the most appropriate scale of noise measurement and the best means of measuring or evaluating the passenger noise environment. There are also problems in reaching a consensus on the level of subjective response that defines an unacceptable noise environment. References 3 and 8 contain relevant discussions of different approaches taken to define a noise exposure criterion.

Motion

There is a large amount of data available describing the human reaction to motion. References 3 and 9 provide results of literature searches that include most of the relevant reports. Reference 10 contains results of a survey of vibration research being conducted in Great Britain; final circulation of the survey was to 57 organizations, 27 of which reported ongoing research or research capabilities relating to human response to motion.

Most of the literature deals with human response to single frequency, single axis vibration (generally vertical or lateral). The most widely recognized criteria in this area are the ISO standards of Reference 11, which address human comfort response to vertical, lateral and longitudinal vibration in the frequency range above 1.0 Hertz. Other data sources available are contained in References 12 and 13. These two references are based on ground simulator and flight research experiments, respectively.

There is a lack of motion ride quality data for vibration frequencies below 1.0 Hertz and efforts are underway to fill this gap. An extension of

the ISO standards to include the 0.1 to 1.0 Hertz range was proposed in 1974 as reported in Reference 14. An alternative frequency response weighting curve was proposed for ISO consideration by U.S. members of the ISO committee. An amendment or an appendix to the ISO standards to include human response to vibration frequencies below 1.0 Hertz is nearing completion although the added criteria may not be viewed as an extension of existing standards because of qualitative differences in human response to vibration frequencies above and below 1.0 Hertz. Further developments relating to the ISO standard will be presented during this conference.

Data describing passenger response to vertical and lateral vibration at frequencies below 1.0 Hertz were obtained in a research flight test program conducted at NASA FRC. These data are reported in Reference 13. Results of a study to link incidence of motion sickness with frequencies and acceleration of vertical motion are reported in Reference 15. Equal subjective intensity curves for the frequency region 0.25 to 4.0 Hertz (vertical vibration) are reported in Reference 16.

The data base relating human response to angular motions is very limited. Little data have been generated to investigate human subjective response to multiple frequency or multiple axis vibration. Some starts have been made to explore this general area as shown in References 13 and 17.

Combined Elements of the Ride Environment

Little research has been conducted to investigate effects of combinations of ride quality variables on passenger ride comfort. Research reported in Reference 18 indicates that combinations of heat, noise and vibration were judged more stressful than any component variable alone.

USER VIEW OF RIDE QUALITY TECHNOLOGY

The user's view of ride quality technology seems to be focused through the lens of the criteria he has available or can foresee developing from the existing data base. Consequently, discussions with ride quality technology users always center on the adequacy of ride quality criteria. In this section the user view of ride quality technology is discussed.

As previously mentioned, interviews were conducted with representatives of various facets of distinct public transportation modes to expedite collection of opinions and data. During this study it was determined that the user typically assigns a large weight to the effect of accelerations on passenger ride response compared to other influences. Due to this fact criteria relating to passenger acceptance of vehicle motion are emphasized in the following discussion.

Two basic types of ride quality criteria are in use today in the transportation field. First, there are specific criteria based on results of experiments performed with subjects placed in a pseudo-real passenger environ-

ment using moving base simulators. These criteria are usually expressed as limits on some expression of vehicle acceleration versus frequency as shown in Figure 2. Most experiments of the type generating motion response data have used a small number of subjects with professional or semi-professional backgrounds. Habitability variables are most often fixed and vibrational inputs including noise are varied to observe effects. Also, the vibrational inputs representing vehicle motion are often of a single frequency, single axis nature. Criteria derived from empirical studies of this type often do not agree in interpretations of acceptable limits of acceleration as revealed in references such as 6 and 19. An attempt has been made to resolve these differences as shown in Reference 11, but agreement on criteria specification among transportation modes is still not universal.

It should be pointed out that a passenger's ride response will probably be influenced by his expectations rather than an absolute basis. This means that an acceptable ride for a train where sway or lateral acceleration may be expected may not be an acceptable ride for an airplane. When different modes of transportation are considered, there may be variable requirements for acceptable levels of acceleration. This argues against the use of a single standard for all types of passenger vehicles. From another point of view, such a universal application of criteria could cause additional and unwarranted cost of design and manufacture if requirements leading to overdesign were established.

The second type of ride quality criteria is called in this paper the "As Good As" or AGA criteria. These criteria are usually more related to passenger response than to vehicle response although generally there is some attempt to characterize acceptability in terms of acceleration versus frequency. For instance, a potential customer may require that a new vehicle shall ride "as good as" vehicles with which he has had previous experience and confidence of good passenger acceptance. This method has occasionally been taken a step farther by requiring that the new vehicle exhibit accelerations "less than" those encountered with some previous vehicle.

The primary problem with the use of AGA ride quality criteria is that the vehicle manufacturer must first determine the ride quality of the vehicle being used as the goal and then devise a method to demonstrate compliance which meets the customer's agreement.

In some industries, criteria such as these have been the traditional means of stating desired ride quality and the method has worked well within a manufacturing company that has previous experience to rely upon. A major difficulty with this approach occurs when a new type or family of vehicles is to be developed.

Air Transportation Mode

Public air transportation may be divided into three basic categories; trunk lines, feeder lines and commuter lines. Of the three, the commuter and feeder lines encounter the more significant ride quality problems because

they generally operate at lower altitudes where turbulence is more likely to be encountered and with small, light wing loading aircraft which are more responsive to turbulence than the large jets. In addition, their frequency of takeoff and landing and the accompanying degree of maneuvering motion is greater.

Air transportation is the clearest example of the use of AGA ride quality criteria. Typically, the airplane manufacturer relies heavily on past experience to determine what produces favorable passenger response to ride and designs to the dictates of this experience. During the preliminary design stage of an airplane, the vertical gust acceleration response sensitivity is evaluated in terms of its change in lift coefficient due to variation of angle of attack, $C_{L\alpha}$, or wing loading, lift per unit of wing area. A typical survey is shown in Figure 3 for comparison purposes. Here, vertical accelerations of several aircraft classes are characterized by their change in lift coefficient due to variation of angle of attack and compared to a baseline which is known to have good passenger ride response.

The situation is not as clear in the design of larger more flexible airframes where structural mode dynamics may have a significant role in passenger ride acceptance. Again the AGA criteria are used but a lack of definitive passenger subjective reaction models may lead to problems. The design goal of a recent large flexible airplane in the area of dynamic turbulence response was to be "as good as" a previous acceptable design. During the preliminary design stage it was known that aft body lateral acceleration response to turbulence was slightly greater than that exhibited by the baseline, but a review of passenger subjective response data and consideration of other factors resulted in a decision not to attempt a reduction. Subsequent service operations have revealed inadequate passenger response to aft body lateral ride in certain situations and an active control system has been designed for the airplane to alleviate this situation.

When the manufacturer begins the design of a new generation of aircraft not similar to previous designs, he is obliged to consider the ride quality situation in greater depth. For instance, during the conceptual design phase of the American Supersonic Transport, Boeing-Wichita conducted a broad range of studies to determine human reactions to vibrations ranging in frequency from 0.10 to 7.0 Hertz, as reported in Reference 17. These studies were undertaken because the slender, flexible fuselage of the design exhibited lower frequency larger amplitude response to turbulence than had previously been the case with conventional aircraft. This additional study was deemed necessary since passenger reaction to accelerations due to both turbulence and runway inputs was not clearly defined.

Contributory factors to the passenger ride response other than accelerations are listed in Table 3. The specific effect of each of these quantities as a modifier to ride response is not normally evaluated, but each factor has an effect on passenger comfort and apprehension, which in turn modifies the level of ride response.

Customer specifications or FAA egress regulations will normally determine basic seating factors as well as air conditioning, lighting and ventilation requirements. Noise and unusual odors are kept to a minimum and decor is specified by the customer but is designed to provide the passenger with an overall feeling of safety. Interior noise measurement techniques within the industry should be standardized and additional understanding of subjective reaction is necessary.

In the design of an aircraft, the cost of providing acceptable ride must be ranked in the overall economic equation and this rank will vary depending on the type service considered. Initial cost and return on investment are the two most important factors in the design of a commercial aircraft. A passenger must have a ride that will cause him to accept that airplane as a candidate for future flights but beyond that the benefit from increased cost to be devoted to comfort is difficult to ascertain. Normally if the ride is adequate in competition with similar services, costs associated with ride improvement will not be accepted by the airplane operator.

Helicopters present some unique facets of the same problems previously discussed. Noise, acceleration impulses due to blade passages and unaccustomed maneuvers are the primary adverse ride quality factors. Interior noise levels are generally required to be similar to existing conventional jet aircraft. Each noise source has its own characteristic frequency with engine noise being highest and least bothersome. Noise criteria are based on hearing loss, fatigue and on speech or communication requirements and are measured in several ways as shown in Reference 18. One serious deficiency in noise measurement is the inability to measure low frequency impulsive noise accurately using current techniques. The methods and units of noise measurement need to be standardized so that existing criteria can be evaluated.

In summary, the weak ride technology areas discovered relating to air transportation modes are:

- Passenger subjective reaction must be quantified and correlated with an easily measured vehicle parameter such as acceleration.
- Criteria need to be presented in terms that allow easy verification of compliance. This is a problem since the normal vehicle input is random but most criteria are based on single frequency inputs.
- Similarly, criteria need to take into account combined axis and multifrequency inputs.
- Noise measurement variables and techniques need to be standardized.
- Vehicle mission and type need to be recognized by criteria.
- Best criteria format needs to be established.

Rail Transportation Mode

The rail industry appears to divide naturally into three classes based on weight, size and number of cars per train. Light rail refers to street-cars and one or two car rapid transit trains operating at moderate speeds on elevated, grade level or subway type track. A middle ground is occupied by the regular subway trains such as used in New York that are larger, heavier, and operate in multicar trains. The third type is the heavier intercity type passenger train.

In rail transport vehicle procurements, both the specific criteria (usually accelerations) and the AGA criteria are used. For instance, the San Francisco Bay Area Rapid Transit (BART) system specifications incorporated specific criteria based on measured accelerations as shown in Figure 4. Another specific criterion is that for the State of the Art Car (SOAC) shown in Figure 5. On the other hand the AGA criteria used in the specification for new Chicago transit cars stated that ride quality should be equal to or better than that of certain serial number cars already in service. as determined by measuring vertical, lateral and longitudinal accelerations. Competitors for this contract had to determine how to measure the ride of the existing cars and then how to compare the ride of their proposed vehicle to show compliance. One complicating factor was that of track inputs. In order to keep inputs regulated, a track with known dynamic characteristics or a particular section of track must be specified. Power spectral density (PSD) must be specified and then, when compliance is to be demonstrated, a track with similar PSD must be used. If track dynamics were specified along with required accelerations, the manufacturer could analytically determine the adequacy of ride in his vehicle with respect to the criteria.

Here again the lack of quantified passenger subjective response is apparent. Either criteria are presented in terms of accelerations, or the ride is required to be as good as existing equipment known to have acceptable ride.

In the ride quality specifications for intercity railroad cars the National Railroad Passenger Corporation (AMTRAK) has taken the more sophisticated approach of specifying a particular track PSD and requiring that the resultant vehicle accelerations meet a certain rms level on one type car and, on another car, that measured acceleration PSD's of the new vehicle and an existing vehicle be analytically transformed to a perceived comfort level for comparison. A data base is being developed from actual measurements of track PSD, vehicle accelerations and passenger subjective reactions using experienced "raters".

The two main facets of ride quality in rail transportation are the vehicle dynamics and the rail dynamics. Rail construction specifications are always in terms of allowable static deflections per unit of distance traveled. This type criterion puts very little restraint on the resultant track dynamics at higher frequencies although the trend from jointed to welded rails has moved primary input frequencies away from those most objectionable to the passenger. The impact of track smoothness criteria on construction costs

should be considered in selecting applicable criteria since the cost of building a dedicated rail system may be a large percentage of the total cost of the system.

As in aircraft, passenger amenities are specified separately from allowable acceleration with no attempt to show modifying influences. Noise measurements in dB(A) seem to be standard but the acceptable levels are open to question. A minimum level should also be specified in order to provide speech privacy.

In summary, the weak ride technology areas discovered relating to the rail transportation mode are:

- There is a proliferation of ride quality criteria.
- There is not much correlation of criteria with track dynamics.
- Track and car dynamic models are generally not adequate for extensive analysis.
- Cost impact of ride criteria needs to be carefully assessed.
- The data base must be expanded in track dynamics.
- Passenger subjective reaction must be quantified.
- It must be confirmed that criteria specified are applicable to the vehicle.

Marine Transportation Mode

One of the newest modes of marine commercial transportation is the submerged hydrofoil, hereafter referred to as the Jetfoil. The unique feature of this vehicle is that its lift is derived from submerged hydrofoil surfaces. This provides a ride impervious to sea state up to the capability of the system to keep the hull above wave crests. Ride quality criteria developed by the manufacturer for this system are similar in form to criteria used for aircraft and have been described in Reference 20.

The primary deficiency in ride quality technology for this transportation mode is for motions in the frequency range below 1 Hertz. Since this is the frequency range in which motion sickness is predominant, criteria in the range below 1 Hertz are of utmost interest in the design of marine vehicles. Information is lacking on the effects of motion and the effects of the duration of the motion. It is possible that different criteria might be required for passengers and crew due to the effects of duration in this low frequency range.

Another related deficiency is the effect of combined axis inputs on the passenger reaction to motions in this frequency range. As in other transportation modes investigated, habitability variables such as temperature, seating,

etc., are specified but effects are not assessed to determine impact on ride. In the case of the Jetfoil, the goal was to provide passenger amenities "as good as" a current jet aircraft.

Another weak criteria area is in the specification of a sea model. Models similar to those used to define atmospheric turbulence have been developed to aid in marine vehicle analysis and synthesis, but work in this area is by no means complete or adequate. Once again the passenger subjective reaction needs to be quantified so that the manufacturer can predict passenger reaction to proposed marine vehicle ride. The manufacturer could then predict the percent of passengers that would be satisfied with ride in a particular customer's operating environment and more easily reach adequate contract agreements. This capability would also allow overdesign to be identified and reduced, thereby reducing cost.

In summary, the weak ride technology areas identified in the marine transportation mode are:

- Inadequate criteria in the frequency range below 1 Hertz.
- Inadequate definition of the effects of duration in this frequency range.
- Inadequate knowledge of multi-input axis effects.
- Lack of passenger subjective reaction quantification.
- Lack of adequate sea models.

Surface Transport Mode

In surface transport, as in rail transport, there is a proliferation of ride quality criteria as well as possible inappropriate application of these criteria. For instance, acceleration versus frequency criteria have been used to define acceptable ride for some recent rubber-tired automatic people-mover systems. There has also been some disagreement about correlation between these criteria and the passenger subjective reaction to the ride actually perceived. The need here is to provide the necessary subjective passenger reaction evaluation so that appropriate criteria may be determined and adjustments made if necessary.

Another facet of the ride criteria situation that is a candidate for close inspection is the required interior noise level. The ability to achieve required levels is affected by many factors. For instance, the fact that maintenance requirements may severely impact the noise level illustrates the need to consider the effects of all inputs. Maintenance requirements that dictate ease of cleaning and low susceptibility to vandalism can cause difficulty in achieving required noise levels. The conclusion then is that all factors affecting ride should be considered simultaneously, weights for each input established, and trade studies conducted to define costs.

The AGA criteria are also used in the surface transport mode. One such case is found in the TRANSBUS program sponsored by the UMTA where prototype transit buses were developed to a ride criteria goal of "as good as a 1973 Ford LTD". In order to apply this criterion, quantitative data had to be generated. This involved building a test track with simulated roadway anomalies and evaluating two automobiles of the type specified as well as an urban bus to serve as a baseline. Results are reported in Reference 21. Here again, as in other transportation modes, we find the AGA criteria being used with the result that these criteria must be quantified before they can be applied.

In some cases of commercial manufacture, this quantification step is bypassed by the use of subjective evaluations by experienced raters and management personnel. This approach has apparently worked well in the past in lieu of quantitative acceleration criteria.

The surface transportation modes face problems similar to those described for the rail transportation modes in the area of guideway surface criteria. Again the usual specification relates to static deflections and very little dynamic modeling information is available to the investigator so that he can realistically predict vehicle response to random inputs. Some work is being done in this area as shown in Reference 22 to try to quantify guideway surface dynamics and produce criteria other than the familiar acceleration criteria. The approach taken has been to generate a figure of merit based on a particular weighting of vehicle response variables. This approach has been investigated by the British Railways Board and is also being investigated at the University of Texas where an ISO weighted ride index has been developed that exhibits good agreement with passenger subjective reaction to automobile ride. Some results are presented in Reference 23.

In summary, weak ride technology areas identified in the surface transport mode are:

- Proliferation of criteria.
- Inappropriate application of criteria (criteria developed for one class of vehicle applied to a different class).
- Lack of correlation between acceleration criteria and passenger subjective reaction.
- Criteria weight (noise, etc.).
- Trade studies to identify undetermined criteria effects.
- Criteria cost impact (related to weight).
- Lack of ability to correlate acceleration response to random inputs with criteria based on single frequency inputs.

- Lack of adequate statistical definition of guideway surface.
- Methods of providing specification compliance.

DISCUSSION OF FINDINGS

The preliminary results of an effort to determine representative views of ride quality technology users in four distinct public transportation modes were presented in the previous section. A review of the findings reported discloses that there are many similarities among the needs presented. In fact, it appears that one list of user needs can be constructed that will suffice for all transportation modes. Such a list is presented in Table 4.

One of the first things necessary to satisfy user needs is standardization. This applies to both acceleration and noise technology. For instance, there is the question of applicability of acceleration criteria developed from technology based on the use of single frequency inputs in the evaluation of vehicle response to random inputs. The user wants to know how to reconcile any possible differences and how to evaluate realism effects such as passenger apprehension not present in moving base simulators. Also, information is limited on effects of motion below 1 Hertz. Another factor that generally lowers the user's evaluation of the available technology is the minimal knowledge of effects of combined axis inputs and multiple frequency inputs.

Standardization does not mean the application of one criterion to all vehicles. In fact, it is quite possible that criteria magnitudes should be adjusted for applicability to different modes and to different vehicles within each mode. Different criteria formats might be desirable. Such a format might be the figure of merit type discussed previously instead of the more familiar acceleration versus frequency format.

Agreement on standard units and methods of noise measurement is desired. Typical noise measurement locations, vehicle configuration and passenger loading should be defined.

The situation that allows a proliferation of criteria without sufficient guidance for application places an unacceptable burden on the contractor trying to demonstrate specification compliance. If compliance is to be demonstrated analytically, proper mathematical models of vehicle input such as a PSD of rail or guideway surface smoothness should be developed for use and standard methods of determining vehicle response should be agreed upon. In addition, standard methods of vehicle response measurement should be defined so that demonstration of specification compliance is adequate.

Second, passenger subjective reaction must be quantified and correlated with an easily measured vehicle response parameter, probably acceleration. This would allow the user to more precisely determine passenger ride response analytically. Benefits beyond preliminary assurance of specification

compliance would include more intelligent marketing and the ability to eliminate some overdesign with subsequent lowering of manufacturing cost. In line with this quantification, the combined effects of varying other passenger comfort quantities such as noise, temperature, humidity, etc., should be determined.

Thirdly, the cost of applying ride quality criteria should be determined. Some vehicles within a transport mode may need more sophisticated criteria than others, depending on the job to be performed, but applying criteria without first determining the impact on system cost may penalize a particular transport mode by escalating initial cost. The percent of passengers satisfied with the ride versus the cost of providing the ride should be quantified so that the desired cost effectiveness can be determined. A plot typical of such a quantification is shown in Figure 6. Point A on the figure is representative of a ride that would satisfy only a small percent of passengers although the cost is lowest. Point B represents some optimum or desired trade between percent of passengers satisfied and cost of providing that satisfaction. Point C is included to demonstrate the cost of satisfying the last 5 or 10 percent of passengers can be quite high and it is probably true that not everyone can be satisfied no matter how much is spent.

CONCLUDING REMARKS

The interim results of this study show that ride quality technology users perceive technology weaknesses through the ride quality criteria that are subsequently developed. Technology weaknesses identified during this study were discussed in detail in the previous section and are concentrated in four areas.

Ride technology results need to be standardized so that standard criteria may be developed. In conjunction with this, units and methods of measurement should be standardized. Passenger subjective reaction to vehicle ride must be quantified so that the user can accurately predict the percent of passengers satisfied. Costs of applying technology to improve ride must be assessed so that the user can determine the level of ride he can afford. Finally, advanced techniques for specifying and evaluating guideway construction should be investigated.

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TABLE 1
RIDE QUALITY TECHNOLOGY USERS
PERSONAL CONTACTS

VEHICLE CLASSIFICATION	NUMBER OF ORGANIZATIONS	TYPE OF ORGANIZATION
MARINE	1	MANUFACTURER
BUS	2	MANUFACTURER GOVERNMENT AGENCY
HELICOPTER	1	MANUFACTURER
LIGHT RAIL	3	MANUFACTURER GOVERNMENT AGENCY
HEAVY RAIL	1	OPERATING AUTHORITY
LARGE AIRCRAFT	1	MANUFACTURER
MEDIUM AIRCRAFT	1	OPERATOR

TABLE 2
VEHICLE RIDE QUALITY PROBLEMS
PRESENT AND FUTURE

VEHICLE CLASS	PRESENT PROBLEMS	FUTURE PROBLEMS
LIGHT RAIL	<ul style="list-style-type: none"> ● RAIL/GUIDEWAY SMOOTHNESS AND INTERACTIONS WITH VEHICLE CARRIAGE SYSTEM <ul style="list-style-type: none"> – VERTICAL AND LATERAL MOTION ● NOISE, INCLUDING WHEEL SQUEAL WITH TURNS ● LONGITUDINAL ACCELERATION ● ROLL LIMITS (MONORAIL) 	<ul style="list-style-type: none"> ● RAIL/GUIDEWAY SMOOTHNESS AND INTERACTIONS WITH VEHICLE CARRIAGE SYSTEM
HEAVY RAIL	<ul style="list-style-type: none"> ● RAIL/GUIDEWAY SMOOTHNESS AND INTERACTIONS WITH VEHICLE CARRIAGE SYSTEM <ul style="list-style-type: none"> – VERTICAL AND LATERAL MOTION 	<ul style="list-style-type: none"> ● RAIL/GUIDEWAY SMOOTHNESS AND INTERACTIONS WITH VEHICLE CARRIAGE SYSTEM ● OUT-THE-WINDOW VIEW DURING HIGH-SPEED TRAVEL ● MOTION CAUSED BY HIGH-SPEED TRAVEL
BUS	<ul style="list-style-type: none"> ● VERTICAL AND LATERAL MOTION ● NOISE 	
MARINE	<ul style="list-style-type: none"> ● LOW FREQUENCY MOTION, SHORT AND EXTENDED DURATIONS OF EXPOSURE ● PEAK ENCOUNTER ● TRANSITION FROM FOILBORNE TO HULLBORNE 	
HELICOPTER	<ul style="list-style-type: none"> ● NOISE ● VERTICAL AND LATERAL MOTION 	
AIRPLANE – SHORT TO MEDIUM RANGE	<ul style="list-style-type: none"> ● VERTICAL AND LATERAL MOTION ● MANEUVERS ● LOW FREQUENCY MOTION ● NOISE 	<ul style="list-style-type: none"> ● MORE CRITICAL MANEUVERS (STOL) ● TERMINAL CONFIGURED VEHICLE MANEUVERS
AIRPLANE – MEDIUM TO LONG RANGE	<ul style="list-style-type: none"> ● VERTICAL AND LATERAL MOTION ● LOW FREQUENCY MOTION ● TAXI (EFFECTS ON CREW) 	<ul style="list-style-type: none"> ● HIGHER LEVELS OF MOTION OF FREE A/P (HIGHER SPEED AND MORE FLEXIBLE AIRFRAMES) ● LONGER DURATION FLIGHTS AND LOWER WING LOADINGS (FUEL CONSERVATIVE TRANSPORTS) ● TERMINAL CONFIGURED VEHICLE MANEUVERS

TABLE 3
CONTRIBUTING FACTORS
TO PASSENGER RIDE RESPONSE

- **BASIC SEAT ARRANGEMENT**
- **AISLE WIDTH**
- **SEAT WIDTH**
- **SEAT RECLINE**
- **SEAT SETBACK**
- **AIR CONDITIONING**
- **LIGHTING**
- **GENERAL NOISE**
- **VENTILATION**
- **ODORS**
- **DECOR**
- **UNEXPECTED EQUIPMENT NOISE**

**TABLE 4
FINDINGS**

USER NEEDS	BENEFITS
<p>STANDARDIZATION OF RIDE TECHNOLOGY</p> <ul style="list-style-type: none"> • ACCELERATION <ul style="list-style-type: none"> - UNITS - EXTEND BELOW 1 Hz - SINGLE FREQUENCY VERSUS RANDOM - COMBINED AXIS EFFECTS - MULTIPLE FREQUENCY EFFECTS - FIGURE OF MERIT • NOISE <ul style="list-style-type: none"> - UNITS - MEASUREMENT TECHNIQUES - MEASUREMENT LOCATIONS - PASSENGER LOADING • ANALYTICAL REPRESENTATION OF INPUTS 	<ul style="list-style-type: none"> • EASE OF COMMUNICATION BETWEEN CONTRACTING PARTIES • FIRM BASE FOR DEMONSTRATING SPECIFICATION COMPLIANCE • IMPROVED APPLICATION OF ANALYTICAL TECHNIQUES • INCREASED CONFIDENCE IN RESULTS
<p>QUANTIFY PASSENGER SUBJECTIVE REACTION</p> <ul style="list-style-type: none"> • CORRELATION WITH MEASURABLE RESPONSE PARAMETERS • DETERMINE COMBINED EFFECTS OF OTHER INPUTS 	<ul style="list-style-type: none"> • ELIMINATION OF POSSIBLE OVERDESIGN • ASSURANCE OF CERTAIN PROBABILITY OF PASSENGER RESPONSE • INCREASED EASE OF MARKETING
<p>DETERMINE COSTS OF IMPROVED RIDE</p> <ul style="list-style-type: none"> • CRITERIA WEIGHT • IMPACT ON SYSTEM COST • TRADE STUDIES 	<ul style="list-style-type: none"> • MORE INTELLIGENT APPLICATION OF CRITERIA • MINIMIZED SYSTEM COSTS
<p>ADVANCED SPECIFICATION FOR GUIDEWAY CONSTRUCTION</p> <ul style="list-style-type: none"> • DYNAMIC AS WELL AS STATIC 	<ul style="list-style-type: none"> • CONTROLLED VEHICLE INPUT

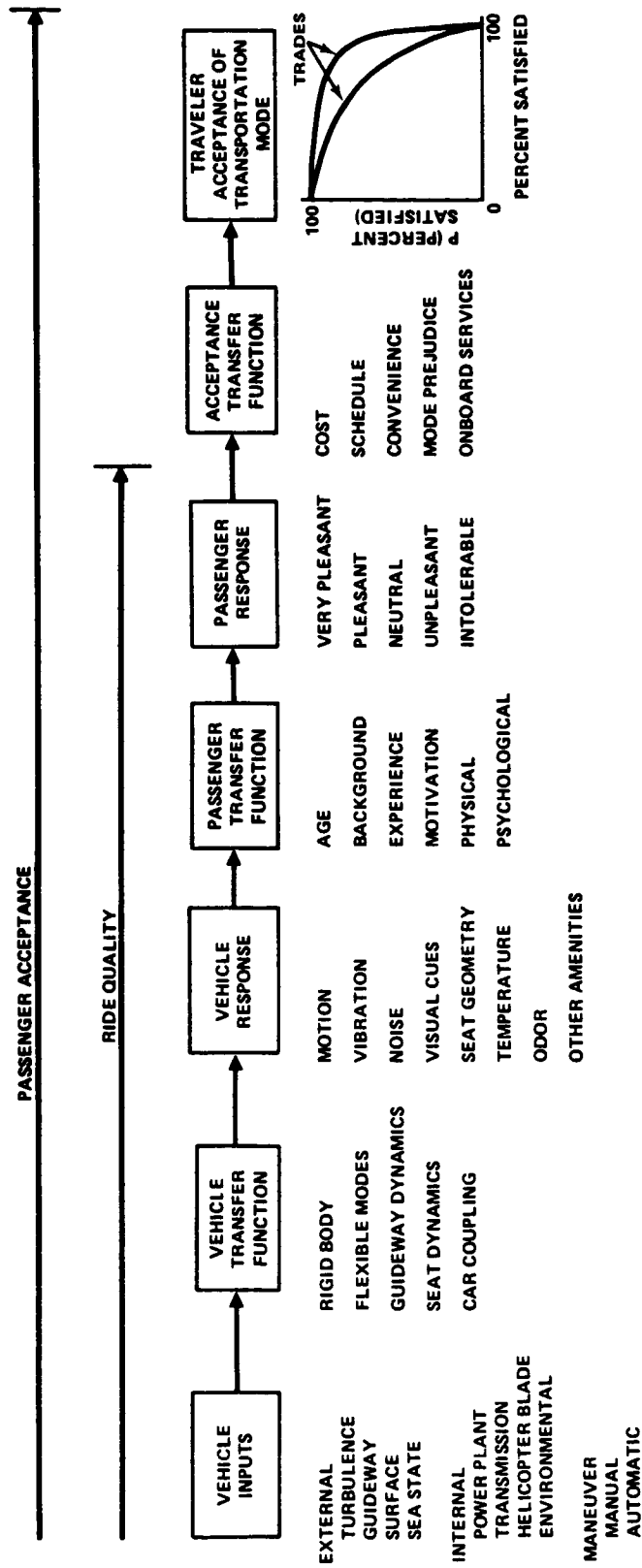


Figure 1.- Passenger acceptance diagram.

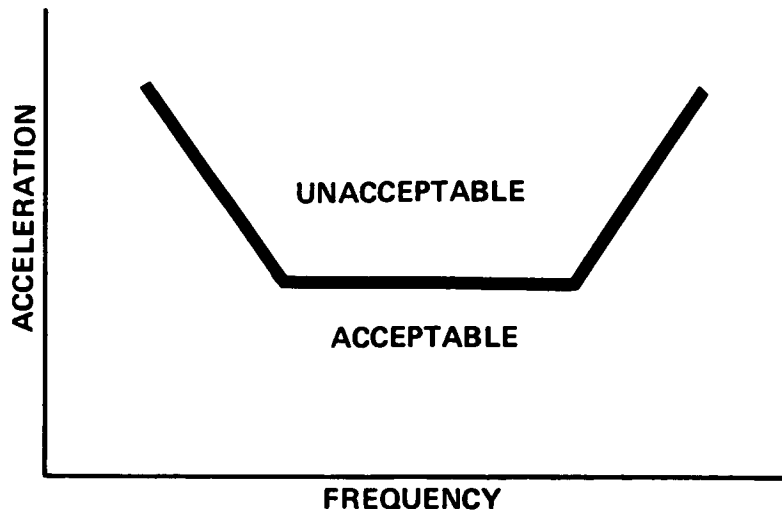


Figure 2.- Typical ride quality criteria format.

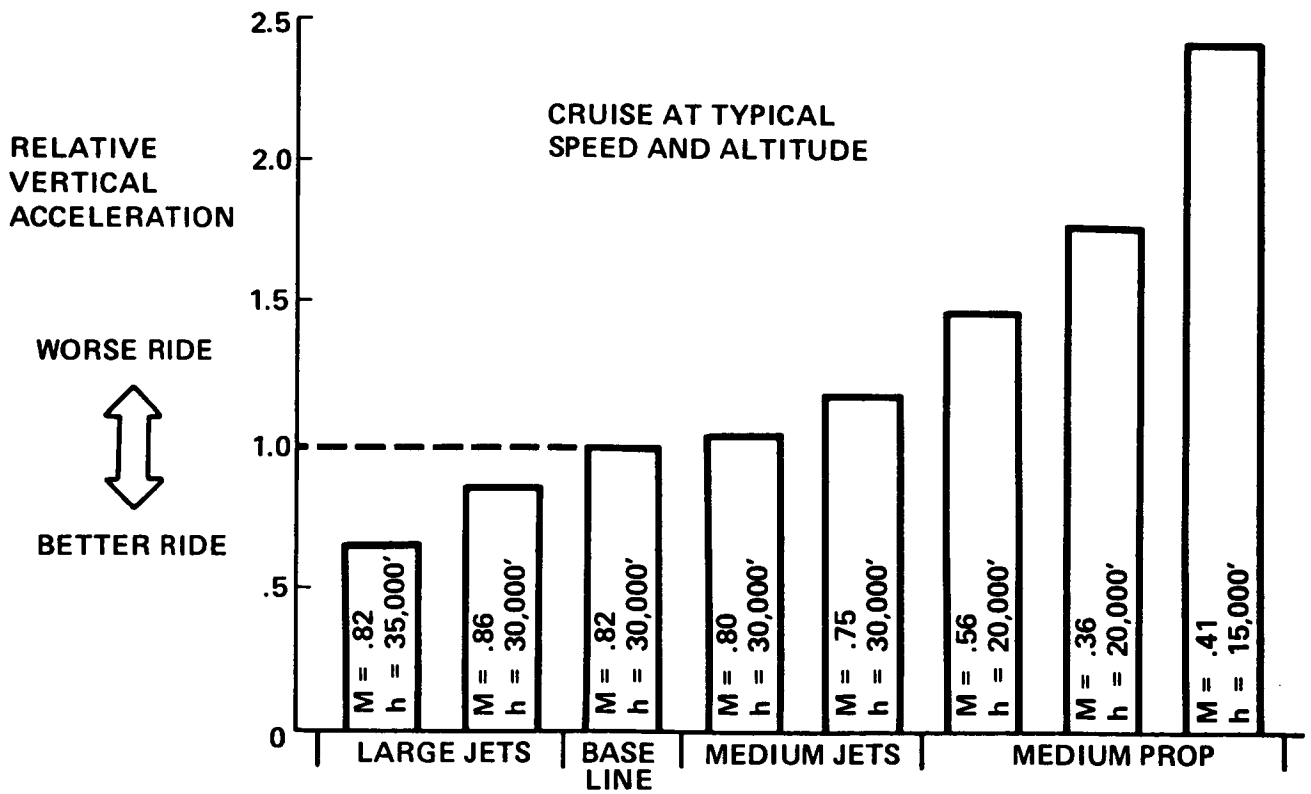


Figure 3.- Relative ride quality. M denotes Mach number and h denotes altitude. 1 ft = 0.3048 m.

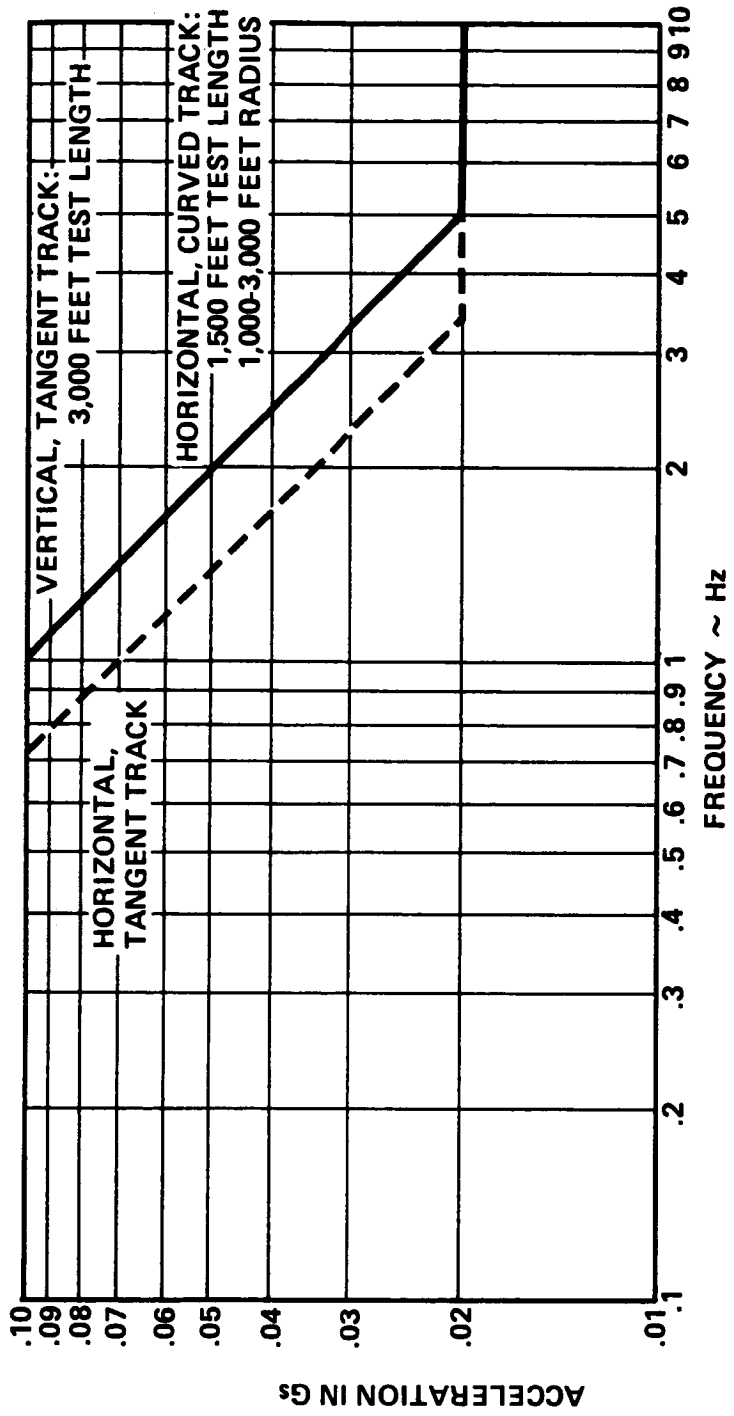


Figure 4.- BART ride quality goals. 1 ft = 0.3048 m.

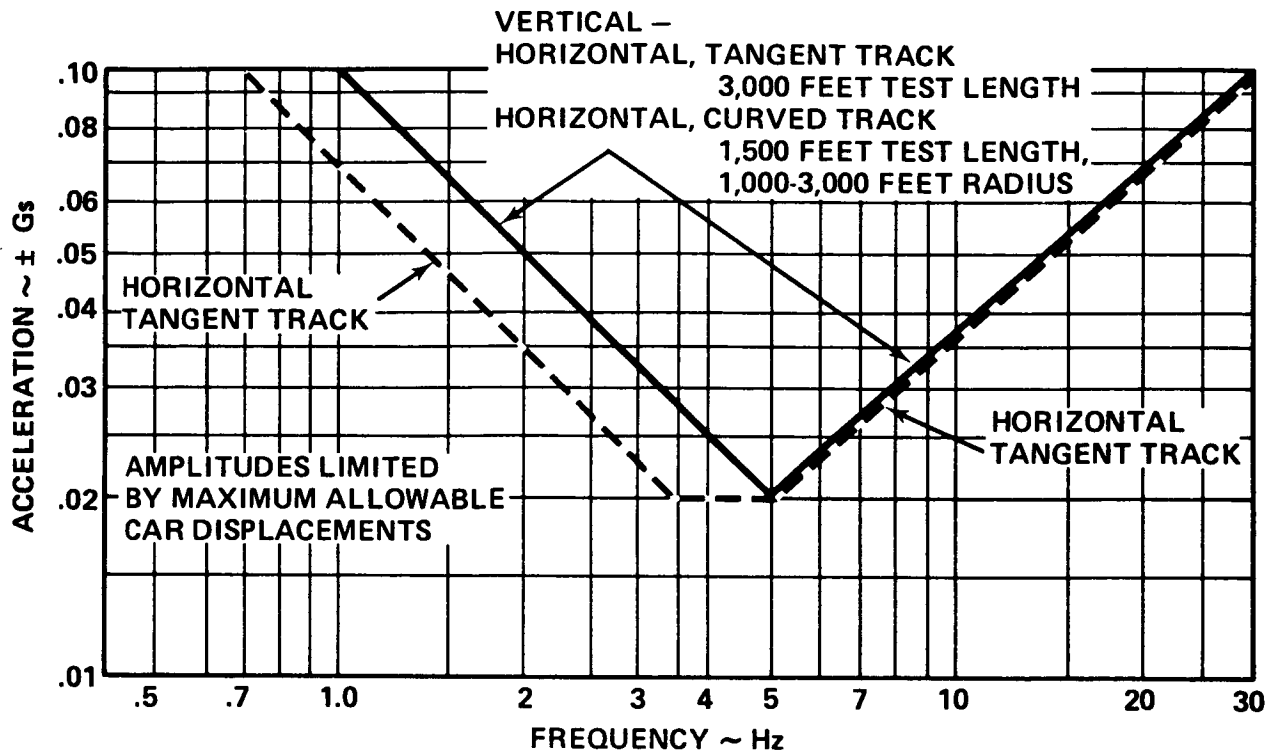


Figure 5.- SOAC ride quality goals. 1 ft = 0.3048 m.

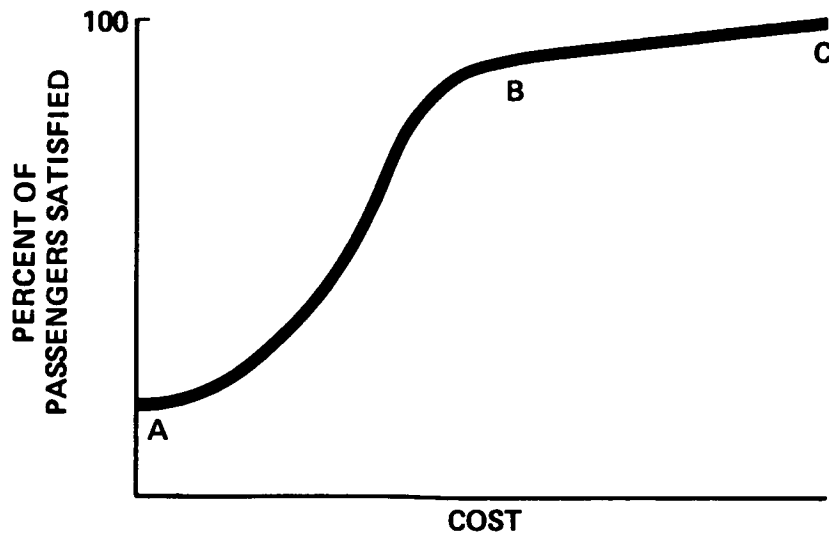


Figure 6.- Cost of satisfying passengers.