gineering Science and Systems, Univ. of Virginia, Charlottesville, UVA/528060/ESS77/109, 1976.
11. L. G. Richards. Time Dependence and Temporal Information Integration for Human Reaction to Motion. Ergonomics, Vol. 21, No. 11, 1978, pp. 913-923.
12. S. A. Clevenson, T. K. Dempsey, and J. D. Leatherwood. Effect of Vibration Duration on Human Discomfort. NASA, Tech. Paper 1283, 1978.
13. G. R. Allen. Progress on a Specification for Human Tolerance of Repeated Mechanical Shock. Speech at Ergonomics Society Annual Conference, 1977.
14. G. R. Allen. Human Tolerance of Repeated Shock. Proc., European Symposium on Life Sciences Research in Space, Cologne, Germany, May 22-24, 1977, ESAP-130, pp. 343-349.
15. D. R. Stark. Hydrofoil Design Criteria and Specification--Volume III: Hydrofoil Ship Controls and Dynamics. Boeing Marine Systems, Seattle, WA, D321-51313-1, 1977.
16. D. R. Stark. Ride Quality Characterization and Evaluation in the Low Frequency Regime with Applications to Marine Vehicle. Conference on Ergonomics and Transport, Swansea, United Kingdom, 1980.
17. I. D. Jacobson, A. R. Kuhlthau, L. G. Richards, and D. W. Connors. Passenger Ride Quality in Transport Aircraft. Journal of Aircraft, Vol. 15, No. 11, 1978, pp. 724-730.

Ride-Quality Evaluation and Technology in Intercity Rail Passenger Car Specifications

R. HIGGINBOTHAM

Four factors—thermal comfort, noise, lighting, and vibration—that affect passenger comfort in rail passenger cars are reviewed. The effects of passenger seating and vehicle layout are also considered.

From the early 1950s until 1970 no new developments were made by American railroads or car builders in either state-of-the-art designs or passenger comfort for long-distance passenger cars. Therefore, ride-quality specification requirements for passenger cars must be addressed in light of the history of the U.S. long-distance passenger car industry.

Since 1970, Amtrak has operated almost all of the intercity passenger trains within the United States. When first formed, Amtrak owned neither rails nor rolling stock of any kind; it began to run passenger service in 1971 through contracts with private railroads using rolling stock acquired from those railroads. This rolling stock averaged between 20 and 30 years of age: all the cars with the exception of the Metroliners were built either before World War II or in the late 1940s and early 1950s. These cars were heated by steam and had electric power provided from axle-driven generators. Most of this old equipment was unreliable because of its age and because sufficient power could not be generated at the average slow passenger train speeds. Some of the most unreliable items were the air conditioning, lighting, and truck systems of the cars--three items that are of major importance to overall passenger comfort.

RIDE COMFORT SPECIFICATIONS

The process of buying rolling stock from the user's standpoint consists of writing the specification, selecting the car builder, and negotiating the final contract. The specification and contract cover the design parameters of the equipment as well as testing requirements. They also cover the program management terms and conditions. As far as passenger ride comfort is concerned, there are four major factors that must be addressed in all equipment specifications for passenger cars: (a) thermal comfort, (b) noise, (c) lighting, and (d) ride quality. In addition, there are several minor factors that are of secondary importance to passenger comfort: seating, space allocation, car interior color and material, toilets, food service, and the passenger's ability to see outside.

Of the four major factors mentioned above, the first three are relatively easy to specify, measure, enforce, test, and acquire reasonably accurate data based on the public's response. The fourth factor, ride quality, is the subject of much debate among scientists, car builders, and the public, as well as the operating railroads. The ride quality of long-distance rail equipment is difficult, if not impossible, to specify, test, measure, or analyze. It is also difficult to gather public response and reaction to the effects of ride quality.

The first Amtrak rolling stock specifications were prepared by consultants familiar with commuter equipment, federal government procurement practices, and test requirements as specified by the Urban Mass Transportation Administration. These specifications, although valuable, were hard to interpret and enforce.

Two types of specifications can be used to specify rolling stock equipment. The first and most lenient specification is called a hardware specification, wherein the buyer specifies to the builder only that he wishes a piece of equipment such as one that already exists (somewhat like purchasing a refrigerator or washer for the home). The second and most restrictive specification is called a requirements specification, wherein only the required parameters such as construction material dimensions, operating criteria, testing criteria, etc., are specified.

There are obvious problems with both types of these specifications. First, the builder can manufacture almost anything to satisfy the general hardware specification, whereas the buyer must have, or have access to, a large technical staff to ensure that the builder complies with the requirement spec-

Figure 1. ASHRAE proposed standards for thermal comfort.

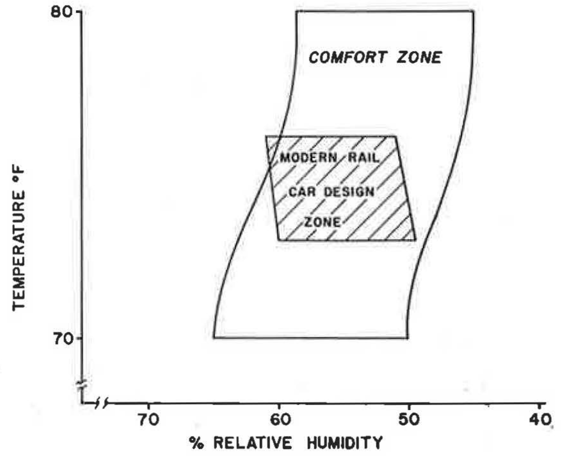
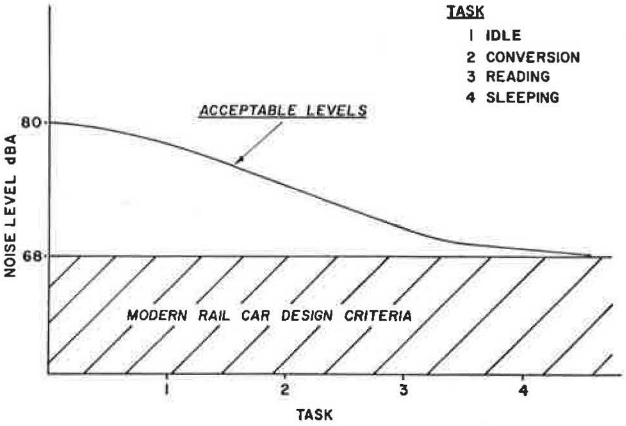


Figure 2. Amtrak noise limit specifications.



ification. In addition, equipment purchased by the requirement specification almost always costs a great deal more than the hardware specification.

Through experience, I conclude that a compromise between the hardware specification and the requirements specification is the best course for Amtrak to follow in purchasing new rolling stock. I also conclude that to specify a requirement, for example, a noise requirement of 68 dB(A) in the passenger area of a moving passenger car, without also specifying construction details, which, if followed, would yield the proper noise level, does not usually yield a satisfactory product. For instance, a buyer would be under great pressure to accept a less than desirable product if the only method available for the builder to meet a noise specification meant complete disassembly of a passenger car costing approximately $1 million.

In conclusion, the four major factors that determine passenger ride comfort must be specified in absolute quantities to the extent practicable. Construction details and testing requirements must also be specified: all of this information is controlled by the cognizant program manager.

Thermal Comfort

In this discussion of thermal comfort, I use a diagram (Figure 1) based on standards of the American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE).

Humidity and air velocities within the passenger car are important in determining passenger comfort. A total lack of air movement gives passengers a feeling of stuffiness and leads to stratification and poor temperature distribution. A low temperature coupled with a high relative humidity can also give passengers a feeling of "clamminess".

The car heating and air-conditioning systems must perform at outside ambient temperatures that range between -30°F to +130°F while, at the same time, keep the inside passenger compartment temperatures constant for all ambients.

Special attention must be given to the first-class sleeping room spaces because of the vast differences in personal comfort criteria. In the sleeping rooms, therefore, the individual passenger should be able to control the room environment independently of the total car environment. All other cars are automatically controlled for thermal comfort.

The car heating systems are a combination of overhead blower-type heat and panel-type floor heat. It has been concluded that the greatest passenger comfort is achieved in those coach cars where the system is designed such that the floor panel heat takes care of the car body losses and the overhead heat is used to temper fresh and return air to a temperature of 75°F. Passengers are most comfortable when the floor heat is controlled between 71°F and 73°F.

In addition to heating and air conditioning, the ventilation and number of air changes in the passenger car (the number of times per hour the air is completely changed) are important design considerations. It has been determined that passengers are most comfortable when the mixture of recirculated air to fresh air is in the ratio of approximately 2.5-2.8 to 1 and when the total exhaust air is approximately 0.8 percent of the fresh air intake. This allows for approximately eight or nine air changes in the passenger compartment each hour for a typical passenger car with 1000 ft^3/min of fresh air intake.

The balance of fresh air intake to exhaust air is important because a positive pressure should be kept on the passenger car at all times to help eliminate noise and outside dust from the passenger compartments. A sublimating air purifier added to each evaporator blower will also enhance the passenger compartment environment.

Noise

The design criterion for noise is highly dependent on the passenger's actions at any one time and can vary from 68 dB(A) for sleeping to 80 dB(A) during idle time. The higher noise figures are of course unacceptable for long-distance passenger cars and therefore Amtrak noise limit specifications are based on 68 dB(A), as shown in Figure 2.

Separate consideration must be given to airborne and structure-borne noise transmission. As far as airborne noise in concerned, adequate superficial density in the car body sides and floor is necessary, whereas structure-borne noise can be reduced by a high acoustic impedance in all potential transmission paths. To reduce the noise level, attention must be paid to more predominant noise components especially if their respective levels differ by more than 5 dB(A).

In order to ensure that the final passenger car meets the noise requirements, there are specification requirements concerning the use of sound-deadening material, carpeting, car body insulation, vibration isolators, and resilient mounts, as well as requirements for the car builder to make tests and calculations to substantiate that noise levels of the vehicle will meet the specification.

Lighting

Under normal conditions, the lighting intensity in passenger car vestibules, aisles, toilet rooms, bedrooms, passageways, and stairwells for maximum passenger comfort and safety should be approximately 5 footcandles when measured at floor level.

However, food preparation areas, passenger reading lights, and toilet mirror lights require special consideration and lighting with high intensity. Food preparation areas, for instance, should have a lighting intensity of 20 footcandles measured at the working surface, whereas the best results for reading lights and mirror illumination can be obtained from lighting intensities of approximately 30 footcandles measured at the location and in the geometric plane of use.

General illumination is best provided by a warm (3200°-K color temperature) flourescent light that does not produce glare. The general background lighting is provided by cove lighting (lighting along the edge where roof meets sidewalls of car) arranged to indirectly illuminate the seating area. Reading lights, mirror lights, and bedroom lighting should be under the control of the passenger at all times.

Night illumination and emergency lighting require special consideration from a design standpoint in that sufficient illumination must be provided in both cases for the safety and comfort of passengers. Night illumination is provided only in the aisle areas by prefocused lights that provide the required illumination. This allows passengers to walk safely through the vehicle without disturbing sleeping passengers. Emergency lighting is achieved by requiring a sufficient number of the lights to be battery-powered with a high reliability.

Ride Quality

Many factors affect the ride quality of passenger car equipment, among which are track conditions, the design of the truck's suspension system, and the car body. One of these factors, track conditions, obviously cannot be controlled by Amtrak since some railroads are privately owned. Although private owners are required by federal law to maintain railroad conditions, many private railroad tracks are nonetheless poorly maintained.

The specifications necessary to achieve good vehicle ride quality consist basically of detailing the permissible natural frequencies of the car body, the suspension system, and the trucks. Therefore, achieving good ride quality depends not so much on the ability to write good specification numbers, but on the ability to ensure that the final designs will meet the specification numbers and yield a satisfactory ride quality prior to reaching an irreversible point in the passenger car design.

To ensure that the above condition is met, Amtrak requires that detailed analysis be submitted by the car builder and reviewed by a design review team prior to making final engineering drawings. Consideration of the controllable parameters involved leads to the following specification values:

1. Ideal "base shell" passenger car frequency, 19 Hz;
2. Minimum acceptable passenger car frequency, 16 Hz;
3. Ideal "fully equipped" passenger car frequency, -15 Hz;
4. Minimum acceptable frequency, -12 Hz; and
5. Structural damping at resonance, -5 to 10 percent.

These figures apply to all possible low-frequency modes such as lateral bending, vertical bending, torsion, and cross-section distortion. The difference between the base shell and fully-equipped frequencies represents an educated guess at the effect of added equipment and trim mass on the car body itself. the addition of seated passengers will undoubtedly raise both the frequency and the damping slightly, and, therefore, the term fully equipped is used to specify an unoccupied vehicle.

The above specifications are based on the following observations: (a) the minimum structural frequency should be substantially above any natural frequencies present in the suspension, and (b) structural damping should be as high as possible to prevent undesirable peaks in body response at resonance. A structural damping value of 10 percent represents close to the maximum value practically attainable even with the use of vibration absorbers, whereas 5 percent is the minimum value necessary to prevent noticeable peaks occurring in the response. Adherence to the specification should ensure a good ride, provided that truck performance is also adequate. Falling short of the specification will make the vehicle sensitive to the high-frequency (10-30 Hz) transmissability through the suspension and will likely result in noticeable vibrations in the car body.

Track conditions are important to ride quality. Even though track conditions cannot be controlled by a user organization, some mention of how track conditions affect passenger car ride quality should be included, at least in gross terms. Vertical geometric irregularities in track conditions, when kept to a minimum, do not seriously affect the riding properties of a passenger car because most truck systems have a low natural frequency. Even if a passenger car speed were to be increased, it has been found that a comparative modest reduction in the natural frequency of the trucks can easily eliminate the effect of vertical irregularities. Therefore, maintenance work to improve vertical track irregularity is not cost-effective for improving ride quality. Lateral track layout defects, however, must be considered in ride quality as it has been concluded that an increase in these defects brings about a decrease in the critical hunting speed of the trucks, along with a decrease in the damping of these hunting oscillations.

Clearance diagrams for unrestricted passenger car use will allow a vehicle to be designed 15 ft x 10.5 ft wide x 85 ft long, with trucks placed on 59.5-ft centers. These design parameter values for the length and height are generous; however, the 10.5-ft width (130 in) represents a formidable design task when one considers that seating arrangements must allow four passengers abreast for minimum passenger comfort and maximum revenue, or about 92 in of space (assuming a seat width of 23 in). The car body sides take up an additional 10-12 in and the aisle must be 30 in wide to accommodate the handicapped traveler. The simple addition of these figures shows that 134 in of car body are therefore necessary, although only 130 in are actually available.

To gain comfort and maximum use of car body size, passenger cars are built out to the clearance line in width (10.5 ft), and hard stops are installed in the lateral suspension to keep the vehicle within the lateral clearance envelope.

Thus, it appears that the only method to increase ride quality of the vehicle is to eliminate or control the lateral track defects.

Other Factors That Affect Passenger Ride Comfort

In addition to the four major factors that affect passenger ride comfort, there are many other factors that are also worthy of mention, among which are seating and vehicle layout. For example, seats must be designed to avoid resonance of the passenger on the seat. Since passengers vary in weight, the resonant frequencies vary greatly, and, therefore, care must be taken to ensure adequate vibration isolation between the mountings and the passenger. The seat must be designed to be comfortable to a wide range of passenger sizes and shapes and must be adequately soft and damped so that dynamic characteristics remain essentially unchanged in all working deflections. The width of the seats and the pitch (distance between seats) also play an important part in passenger comfort and should be maximized to the extent possible. Amtrak is currently using a seat width of 23 in with a pitch of 50 in for long-distance passenger car specifications.

Vehicle layout is also a very important factor in passenger comfort. Luggage space, space per passenger, luggage racks, aisle width, clear window visibility, and dining atmosphere are all considerations that must be properly specified for each particular passenger car procurement.

TESTING REQUIREMENTS

Testing requirements for thermal comfort, noise, and lighting are fairly straightforward. Testing requirements for thermal comfort, for example, must be conducted in an environmental chamber that can be accurately controlled for temperature and relative humidity. The passenger car is placed in the environmental chamber and exposed to all the specified ambient conditions while accurate measurements are taken of all the inside and operational characteristics of the car. In much the same way, lighting and noise levels of the vehicles can be easily and accurately measured by meters to ensure agreement with performance specifications.

The measurement of ride quality, however, is not such an easy task; there are many methods for gathering data to ascertain the ride quality of vehicles. These methods all result in numbers that only verify the engineering description of the vibration of a vehicle and that usually are not highly correlated with either the passenger's perceptions of the vibration or evaluation of the ride. In fact, there is not enough agreement between vertical and lateral vibration to define a region of maximum passenger sensitivity. Passenger sensitivity has been shown to be largely dependent on procedural differences in operating conditions, and, thus, available data give no clear-cut basis for choosing any one vibration comfort criteria in preference to another.

The criteria Amtrak utilizes to judge quality of vehicles are generally referred to as the "as good as" criteria. (The "as good as" criteria require specific instrumentation and test condition details be specified and met.) It has been our experience that no one person is satisfied all the time; however, if one can demonstrate that the ride of a new vehicle is as good or better than the vehicle that passengers consider your most comfortable riding one, then there is no room for further arguments.

Future Areas for Development

There are many areas in passenger car ride comfort that will need future work. The following areas will need special consideration:

1. In terms of thermal environment, there should be an emphasis on system efficiency and a large utilization of outside ambient air over a wider range of temperatures for energy conservation.
2. Environmental considerations also require a substitute for refrigerant 12 in air-conditioning systems.
3. Active suspension systems need to be investigated toward solving comfort problems with lateral accelerations and high-speed curving.
4. Seat designs and window visibility need much study and improvement and more work needs to be done on passenger car interiors.

In light of the influence of passenger comfort on the rail business, it is clear that improvement must continue to be made not only to improve maintainability of components and to eliminate known weaknesses, but also to raise passenger car standards in line with the expectations of the traveling public.

Methods for Ride Quality Evaluation of Off-Road Machines

JAMES C. BARTON

This paper summarizes the state of the art of ride quality evaluation methods for off-road machines. The factors that affect ride quality for machine operators are identified. In addition, the application of vibration standards such as ISO 2631 and SAE J1013 is reviewed.

Off-road machines are machines that generally do not travel on public roads, streets, or highways, although they may operate on pavement (such as a lift truck in a warehouse) or on a prepared road (such as a haul road in a mine). Off-road machinery, therefore, includes agricultural, construction, industrial, forestry, underground, and earth-moving machinery, but excludes military and recreational vehicles (1). The term "machine" refers to a work tool with either a paid or self-employed operator and without passengers.

Ride quality is discussed only in terms of the dynamics of motion, in the sense of what is measured as vibration (including transients). The objective or criterion of interest for off-road machines is in terms of "operator preference" or "acceptability."