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Ride Quality Evaluation in Transport Aircraft

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A complete procedure is described for obtaining an estimate by transport aircraft passengers for the vehicle's comfort rating and its effect on overall acceptance of the flight. Passenger comfort is shown to depend on the state of the air through which the vehicle moves, the design characteristics of the vehicle, and the flight maneuvers involved. The comfort ratings are stated in terms of the percentage of passengers who have a certain probability of being sufficiently satisfied with their experience so as not to object to repeating it. Analytic expressions are included for the factors contributing to a passenger comfort evaluation. An interactive FORTRAN program is presented that will allow repeated computations of acceptance to be easily made. The procedure thus becomes a valuable tool for designers and operators to use in the study of the effects of vehicle configurations and flight maneuvers on passenger satisfaction.

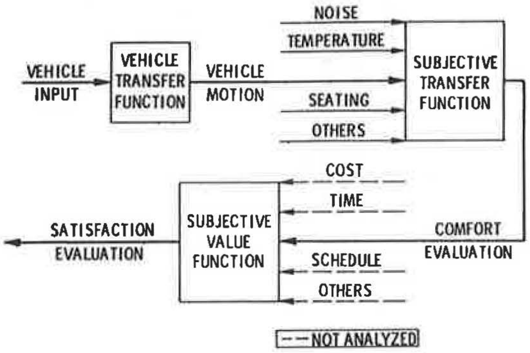
The quality of the ride as experienced and assessed by the passengers has a significant influence on the use and acceptance of a particular vehicle to achieve a particular transport mission. In this context ride quality is defined as the impact on the passenger of all aspects of the physical environment of the vehicle that have been found to influence acceptance. This paper presents a summary of a systematic quantitative procedure for evaluating the quality of a ride in a transport aircraft and of determining the effects of this ride quality on the passenger's satisfaction with the ride. It should be mentioned that the basic approach of the process is general and applicable to all modes of transportation. It is the specification of quantitative values that is peculiar to the air transport mode.

The evaluative procedure is not directly dependent on the choice of aircraft or the specific characteristics of the passengers, although these factors are accounted for indirectly, as they do indeed influence the results. Those aspects of the vehicle environment that influence acceptance can be grouped into three general categories: inputs to the vehicle from its surroundings, flight operations, and inherent vehicle design configurations. Inputs from the surroundings depend on characterization of the state of the air through which the vehicle moves. This results in a set of six degree-of-freedom motions caused by the normal response of the vehicle in flight. Flight operations consist of motions induced by maneuvers of the aircraft such as turns, climbs, descents, etc., and of resulting pressure changes that might occur in the cabin. The aircraft design inputs include such things as seating and passenger space limitations, noise caused by aircraft engines or control motors, and cabin temperature extremes caused by inadequate or improperly adjusted air conditioning equipment.

BACKGROUND

A general description of the evaluative procedure can be found in the literature (1,2) and is illustrated conceptually in Figure 1 (25). It requires

Figure 1. Analysis method used to assess ride comfort.



the use of three transfer functions as well as specification of the arbitrary inputs. The input due to the air environment can be represented by selection of appropriate statistical models of atmospheric turbulence, several of which have been published (3,4). Since these models depend on factors such as type of terrain, altitude, season of the year, etc., it may be necessary to divide a given evaluation into a number of trip segments. Vehicle transfer functions are definable (5) and are usually documented by the major aircraft manufacturers as part of their vehicle development programs. However, such is not always the case with all of the smaller aircraft used by commuter air carriers. In this respect it should be pointed out that the procedure can bypass the vehicle transfer function by using measured values of motion inputs, or by postulating a reasonable range of arbitrary inputs.

The development of the subjective transfer function has evolved over a period of many years and reflects the contributions of many investigators. In the early period of this research most of the work was focused on motion, but, as the importance of other vehicle parameters such as pressure, temperature, noise, and seating became evident, these parameters also began to command attention. However, it is not within the scope of this paper to refer directly to all of this work, although the reader may wish to note that a state-of-the-art evaluation of the field was made in 1974 by Jacobson (6), and since that time a series of symposia and workshops conducted with the cooperation of the U.S. Department of Transportation, NASA, and the Transportation Research Board Committee A3C11 update current research problems and issues in the field (7-10).

Techniques

The literature shows that experimental research in ride quality (this term is used synonomously with ride comfort) has involved four basic techniques. The first of these techniques has been the laboratory study of the effect on motion on humans; the great majority of these studies use motion tables, limited to sinusoidal motions in one or two degrees of freedom, and are often conducted at or near the discomfort level. The basic objective of such studies is to understand the physiological effects of motion, or the effect on ability to perform tasks; hence, little attention has been paid to psychological factors inherent in any association with a true passenger vehicle environment.

A second technique is the use of vehicle simulation devices in the laboratory. This attempts to provide an element of realism and relationship to the particular type of vehicle involved. However, it is unable to address the possible differences in the response of a test subject to a series of events taking place while actually airborne, and similar events re-created on the ground, at best in a mock-up of an aircraft cabin. Nevertheless, this technique does provide considerable sophistication in adding three or more degrees-of-freedom in motion; in addition, other simulation devices could be added to provide the effects of noise, temperature, seating, and visual cues. It is also a relatively inexpensive technique and is readily adaptable for use with a large number of test subjects. In general, however, motion combinations that can be produced on laboratory simulators are not necessarily faithful reproductions of what is experienced in an actual vehicle. In fact, attempts to drive such simulators with input spectra taped during actual flights clearly demonstrate this deficiency.

Another evaluative approach is the use of a special purpose airborne vehicle. Such vehicles are limited in number, but during the 1970s several aircraft capable of generating prescribed motion in all degrees of freedom did exist. These vehicles provided appropriate motion combinations with all the realism of actual flight, but were also extremely expensive and inconvenient to use. Scheduling problems essentially restricted the experimenter to a limited group of test subjects who were used primarily to obtain data on motions near the extremes of those usually encountered in regular air carrier vehicles.

The final technique used is the collection of data during regularly scheduled flights of air carriers. This turns out to be relatively inexpensive and provides all of the desired realism. Most airlines are cooperative when properly approached, and data can be obtained from special test subjects on board the flight, as well as from all of the passengers. The basic shortcoming of this method, however, is that the flight environment (e.g., motion and temperature) cannot be prescribed in advance. The experimenter must therefore use whatever exists. Also, extreme data points are difficult to obtain as the airline and crew do everything possible to avoid such occurrences.

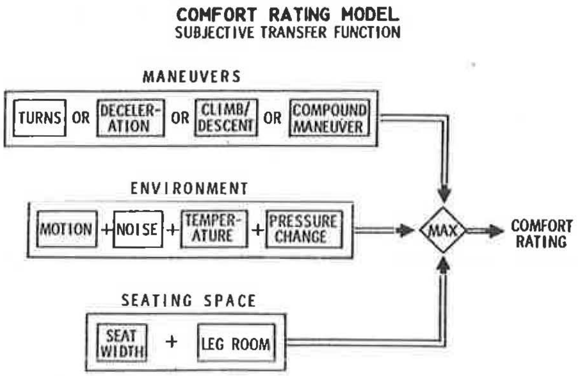
The next section of this paper presents the details of a model for measuring the subjective reaction of airline passengers. The model was developed at the University of Virginia (with the financial support of the NASA/Langley Research Center) from a series of experiments performed between 1970 and 1976. Most of the data were obtained from regularly scheduled airline flights, although they were supplemented by experiments in both laboratory and flight simulators. The Passenger Ride Quality Apparatus (PRQA) at NASA/Langley was the laboratory simulator used, while flight simulations were made with the General Purpose Airborne Simulator (GPAS) operated by the NASA/Dryden Research Center, and the Total In-Flight Simulator (TIFS) operated by Calspan Inc., under contract with NASA/Langley.

Some comments on the process of relating comfort evaluation to overall passenger satisfaction, as well as some general comments on the overall subject of ride quality modeling are then presented. The validity of using the model as a predictive tool will be demonstrated by comparing it with results obtained in actual field tests. Finally, the interested user will be introduced to SEGMENT, a FORTRAN program developed to implement easy application of the model under a variety of circumstances.

The Comfort Model

As shown by a schematic representation of the model in Figure 2 (25), the mean subjective comfort rating

Figure 2. Procedure for determining the subjective transfer function for comfort.



is controlled by three factors essentially independent in their influence on the passenger. Thus, the passenger will make the rating judgment on the basis of the maximum number provided by any of these groups. The remaining groups do not contribute to the quantitative rating. If two or all three groups give the same maximum number, then that will be the rating value. The model is calibrated to provide a numerical value of subjective comfort rating, C_E, on a seven-point scale, where low values are "most comfortable" and a value of 4 is the neutral point. Analytically, the model may be expressed in the form:

$$C_E = \max(C_{env}, C_{man}, C_{seat}) \quad (1)$$

where

C_E = comfort rating value for a unique ride event,
C_{env} = Comfort rating value due to environmental factors for that event = f(motion, noise, temperature, rate of altitude change),
C_{man} = Comfort rating value due to vehicle manuevers during that event = f(motions induced by particular maneuver performed, noise, temperature, rate of altitude change), and
C_{seat} = Comfort rating value due to seat and seating space during that event = f(seat width, seat leg room).

The detailed relations for each of these factor groups are presented in Appendix A, while Appendix B defines the many symbols used.

The reader should note that the acceleration terms describing motion in the vertical, transverse, and longitudinal modes are expressed in terms of σ, the standard deviation of acceleration. This has the effect of removing steady changes in acceleration, which are then treated in the maneuver factor. The relationship between a_x and $\sigma_{a,x}$ is given by Equation 2:

$$\sigma_{a,x} = [(1/T) \int_0^T (a_x - \mu_x)^2 dt]^{1/2} \quad (2)$$

where

T = period of the motion,
μ_x = mean of the x component,
a_x = acceleration at any instant of time in the x direction, and
t = time.

For large T and in the absence of maneuvers, $\mu_x \cong 0$.

These expressions are used to calculate the contribution of any of the factors present during a unique flight event. When the group rating with the maximum value for that event is determined, it becomes the comfort rating for that event in accordance with Equation 1. The manner in which these event ratings are combined by the passenger to provide an overall comfort rating, C, for the entire trip, remains to be determined. The data indicate that a memory decay does indeed occur during the final rating and that passengers generally attach less significance to events occurring at the beginning of the flight than to those occurring near the end. A 3/4 power decay was found such that C is related to C_E by the expression contained in Equation 3:

$$\left(\sum_{E=1}^{n} E^{3/4} C_E\right) / \left(\sum_{E=1}^{n} E^{3/4}\right) \quad (3)$$

The derivation of this relationship is explained in more detail by Jacobson and Richards (11).

Relationship of Comfort to Overall Satisfaction

Knowledge of the ratings assigned by passengers for the ride quality (or comfort) of a given vehicle is not without value. If these ratings are low (i.e., "very comfortable"), then the manufacturer or the operator can rest assured that the comfort of the vehicle is a positive factor in the service being offered. However, this gives no information about the cost/benefit trade-off between what might be saved in vehicle costs by sacrificing a little comfort, nor whether this money might be better invested in improving other operating parameters as far as influencing the overall satisfaction of the passenger is concerned.

Likewise, if comfort ratings are high (i.e., "uncomfortable"), then, although the model will indicate where improvements should be made to have the most effect on passenger comfort, there is still no basis for judging the relative importance of making these improvements. Some of the other factors that must be considered in making such a decision are shown in Figure 1.

We addressed this question in 1972 using a factor analysis of a large number of returns of questionnaires from the general traveling public (12,13). It was found that the variables associated with the passenger's degree of satisfaction with air travel experience could be distinguished on the basis of four principal dimensions: (a) Dimension 1 (A safety dimension)--this includes reliability of the vehicle; (b) Dimension 2 (A cost/benefit dimension)--Cost alone is not the prime quantity involved; convenience and time saving must be considered in a trade-off with cost; (c) Dimension 3 (A "luxury" dimension)--This dimension includes a mix of comfort, convenience, on-board services, and aesthetics; and (d) Dimension 4 (An in-flight dimension)--This characterizes the passenger's preference for how flight time will be spent, and is influenced strongly by comfort.

Thus, if comfort information is to be used to determine the market attractiveness of a given vehicle, then it must be combined with other service attributes. However, even in those cases where an evaluation of comfort is the primary objective, it is important to take the process one step further and translate this information into terms of passenger satisfaction. A diverse group of individuals providing subjective interpretations of comfort in the absence of other service attributes can be expected to have a variety of interpretations of how comfort affects their willingness to use the vehicle on a regular basis. Also, when the above model is used, the comfort rating obtained represents a mean of the judgments of a group of individuals. Certainly there are some individuals in this group who were not comfortable. On the other hand, some who are comfortable may not be willing to continue to use this vehicle. Richards and Jacobson have examined this problem in detail, and they have compiled a transfer function [see Figure 3 (25)] relating mean comfort rating as obtained from the model and the percentage of passengers satisfied (14). This particular function is determined by using data obtained from commuter and local service air carrier flights.

GENERAL COMMENTS

There are several issues in the study of passenger ride comfort that deserve brief comment. The first relates to the form of the model selected to express the contribution of the motion terms. The model presented in this paper turns out to be a simple linear relationship between comfort rating and rms accelerations. However, it was developed on the basis of determining a general power law involving all six degrees-of-freedom and their cross correlations. This is essentially an extension of the approach originally used by Van Deusen (15). A statistical analysis of the results does not justify retaining any additional terms or using other exponents. Many experimenters have favored a model based on the power spectral density of the accelerations, an example of which is presented by Rustenberg (16). A model was developed from the same data set using this approach, and still another model was based on a power law approach recommended by Stevens (17). For a comparison of the models, see Jacobson and Richards (11); essentially there was an insignificant improvement in correlation when using any of the models rather than the simple linear approach, despite the greater complexity of the former. The simplicity of the linear approach seems to justify its use when it has been determined that there is little sacrifice in accuracy.

The physical location of the motion sensors in the aircraft during the data-collection phases is another issue frequently encountered in motion measurements. The measurements used in developing the models presented earlier were made with the instrument located on the floor directly in front of the seat occupied by the seat subject. The instrument made hard contact with the structural members of the floor. Whether this motion is representative of that experienced by the passenger after transmission through the seat cushions has been questioned by some investigators. Leatherwood examined the transmissability of aircraft seats in some detail (18). He determined that at frequencies at which most of the energy associated with aircraft motion is concentrated, the seat has no appreciable effect on motion. That is, the seat is essentially a pass-through device at these low frequencies. Since the power spectral densities do not vary appreciably among types of aircraft, a floor location for motion sensors within airborne vehicles seems reasonable.

The subjective value function is based on the relationship between data obtained during discrete events as provided by test subjects and a final overall subjective judgment made by both test subjects and regular airline passengers. The question then arises as to the manner in which information provided by these two sources should be handled. This was studied in detail and reported by Jacobson and Rudrapatna (19), who found a direct relationship (neither linear nor a one-to-one correspondence) between the overall response of passengers and test subjects (see Figure 4).

The possibility of using laboratory simulation was established by the fact that the test subject responses had been shown to be transferrable to passengers, but the validity of combining the quantitative values obtained by simulation with those obtained in flight still remained to be examined. The results obtained from a carefully executed set of experiments on an in-flight simulator were compared with those obtained from the same set of test subjects experiencing the same set of motions in the laboratory simulator. In this manner, it was possible to identify a transfer function to rotate the two sets of values and define the key aspects of the experimental procedure that should be followed (20,21).

Recently, an extensive piece of work using the NASA/Langley PRQA laboratory simulator was reported by Leatherwood, Dempsey, and Clevenson (22). Models were developed from extensive use of the PRQA with a large group of test subjects. A unipolar scale was used expressed in terms of discomfort only. The general trends of the results seem to agree qualitatively with the results of the model presented ear-

Figure 3. Relationship between mean comfort rating and passenger satisfaction.

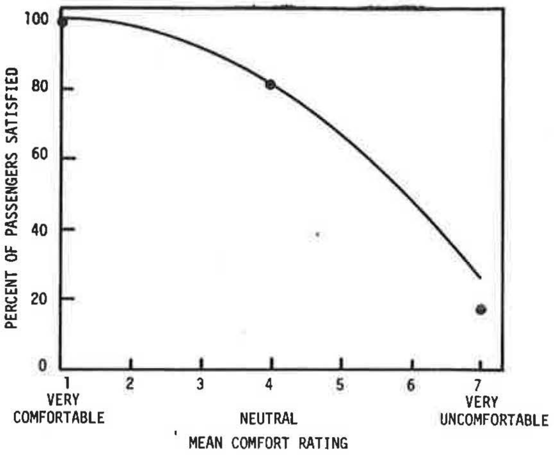
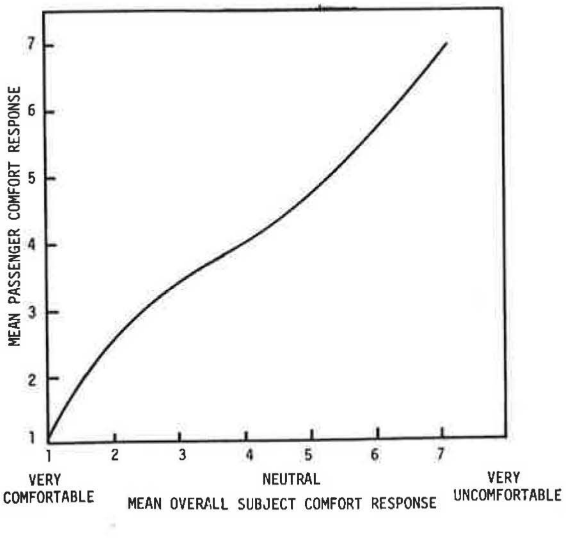


Figure 4. Relationship of subject comfort response to passenger comfort response.



lier in this paper. However, it is doubtful whether quantitative agreement would necessarily occur. Generally, straightforward transmissions need to be applied in order to make the results indicative of how ride quality would be judged by passengers in aircraft. Incidentally, the choice or rating scales should not influence the results, as was shown by Dempsey and others (23).

MODEL VALIDATION

The Canadian Airtransit Short Take-Off and Landing (STOL) Demonstration Program was used to validate the model. This was an experimental city-to-city operation between Montreal and Ottawa. DeHaviland DHC-6-300 aircraft (Twin Otters) were used, but they were specially modified to present a luxury image to the business traveler by using larger, more comfortable seats, reducing the density of seating from 18 to 11, and increasing the air-conditioning capacity. Ride environment measurements and responses from the passengers were obtained from 61 flights (24). As can be seen from Figure 5, the model did a reasonable job of predicting the passenger response on comfort rating. However, it should be noted that the model was conservative in predicting the percentage of passengers who would rate the ride quality in the very comfortable range. From the point of view of the designer or the operator of this vehicle, this is the preferred result. Perhaps the difference between the two ratings is attributable to the many other passenger acceptance improvements that were inherent in the Airtransit program. These included improved airport access, time savings, and good scheduling--factors that might have preconditioned the passengers to the extent that they found it difficult to acknowledge small discomforts in ride quality.

MODEL APPLICATION

In order to make the rather complex procedures for analyzing aircraft ride quality (as shown by Figures 1 and 2) easy to use for vehicle or system designers and operators, a simple interactive computer program named SEGMENT was written in FORTRAN to accomplish the process (see Jacobson and McPherson) (25). The program uses user inputs to construct a flight profile consisting of up to 200 straight and level flight segments, and up to 50 maneuver segments. Variables such as temperature, pressure, noise, and seating can be included as desired. If a rating is requested by the user, the inputs must consist of the measured values of the variables in each segment used to make the comfort determination. When ratings distributions are desired, the user is asked to input the terrain, altitude, and season for straight and level flight segments, the type and characteristics of the maneuvers performed in each of these segments, and levels for the non-motion environmental variables. The ratings or distributions of either comfort or satisfaction, or both, can be computed for each travel segment, or for the entire flight as desired.

The program is composed of a mainline and many subroutines to perform the various functions. This modular form makes it simple for the user to change any or all of the subroutines to suit special needs. For example, a designer may wish to alter both the aerodynamic parameters used and the vehicle transfer function while monitoring passenger acceptance as the vehicle performance/cost trade-offs are optimized. This approach would be extremely valuable during the design of a new ride smoothing system.

A simple example of the program's output is shown in Figure 6 (25). It shows probable comfort and satisfaction distributions during a single flight segment of a longitudinal deceleration and with a pitchover maneuver (the maximum aircraft pitch angle is -10 degrees). The program produces these points automatically, using a CALCOMP or similar plotter. The results show that if the operator is interested in a 60 percent probability level, the comfort can be expected to be 5.5, and 55 percent of the passengers will be satisfied. Alternatively, there is only about a 5 percent chance of obtaining a neutral

Figure 5. Total trip ride comfort for Airtransit STOL demonstration.

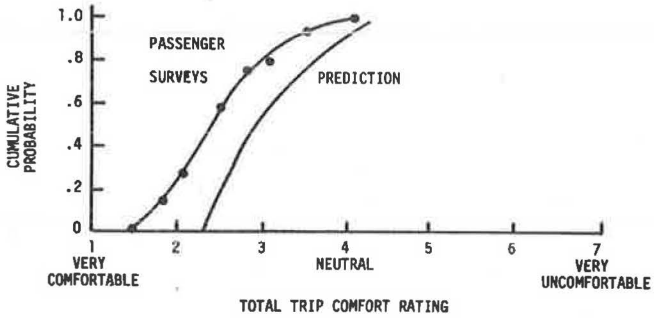
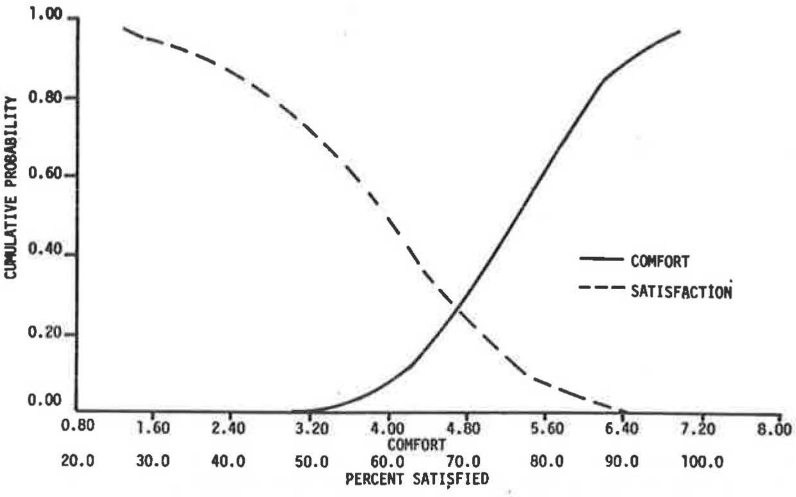


Figure 6. Probable comfort and satisfaction distribution for a single flight segment.



comfort rating (4). Likewise, if the operator would like to have 80 percent of his or her customers satisfied, the likelihood of achieving this is only a little better than 5 percent.

A more detailed example illustrating the interactive nature of the program is included in Appendix C of this paper.

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Appendix A: Model for Rating Mean Subjective Comfort (based on cited research)

Environmental Factors Group

$$C_{env} = 2 + C_{mot} + C_{no} + C_{\dot{h}} + C_T \qquad \text{(A)}$$

where

$$\begin{aligned}
C_{mot} &= 18.9\sigma_{a,v} + 12.1\sigma_{a,t} \ (\sigma_{a,v} \geq 1.6\sigma_{a,t}) = \\
&\quad 1.62\sigma_{a,v} + 38.9\sigma_{a,t} \ (\sigma_{a,v} \geq 1.6\sigma_{a,t}) \\
C_{no} &= 0.19[\mathrm{dB(A)} - 85] \\
C_{\dot{h}} &= 0.005(\dot{h} - 90)\delta_{\dot{h}} \\
&\qquad \sigma_{\dot{h}} = 1 \text{ for } \dot{h} > 90 \text{ m/min} \\
&\qquad \sigma_{\dot{h}} = 0 \text{ for } \dot{h} \leq 90 \text{ m/min} \\
C_T &= 0.054\ (T - 20.5)\delta_T \\
&\qquad \delta_T = 1 \text{ for } 2 + C_{mot} + C_{no} + C_{\dot{h}} > 3.4 \\
&\qquad \delta_T = 0 \text{ for } 2 + C_{mot} + C_{no} + C_{\dot{h}} \leq 3.4
\end{aligned}$$

Maneuvers Factors Group

$$C_{man} = C_{turn} \text{ or } C_{po} \text{ or } C_{dc} \text{ or } C_{cm} \text{ (depending on type of maneuver)} \qquad \text{(B)}$$

where

$$\begin{aligned}
C_{turn} &= 0.293 + 0.0665|\sigma_{max}| + 0.07|p_{max}| + C_{no} \\
&\quad + C_{\dot{h}} + C_T \\
C_{po} &= 1.75 + 22.1\ a_{z,rms} + C_{no} + C_{\dot{h}} + C_T \\
C_{dc} &= 0.151 + 0.098|\theta_{max}| - 0.118\ \gamma_{max} + 0.019 \\
&\quad V_{max} + C_{no} + C_{\dot{h}} + C_T \\
C_{cm} &= 1.48 + 12.3\sigma_{a,1} + 32.8\sigma_{a,t} + 11.6\sigma_{a,v} \\
&\quad + 0.22\ \dot{h}_{rms} + C_{no} + C_{\dot{h}} + C_T
\end{aligned}$$

Seating Space Group

$$C_{seat} = 1 + [0.0077\,(63 - w)^2 + 0.16\,(30 - l)^2]^{½} \quad (\text{for } 30 < w \leq 63 \text{ and } 18 < l \leq 30) \qquad \text{(C)}$$

Appendix B: Nomenclature

a = Acceleration
C = Comfort rating on a seven point scale
dB(A) = A-weighted noise level, dB
E = Event (a given ride situation)
g = Acceleration of gravity, 9.8 m/s²
h = Rate of change of altitude, m/min
l = Seat legroom, cm
p = Roll rate, deg/s
s = Satisfaction
T = Temperature, °C
V = Indicated air speed, knots
w = Seat width between armrests, cm
γ = Flight path angle, deg
δ = Kroneker delta
θ = Pitch angle, deg
σ = Standard deviation of acceleration, g
ϕ = Roll angle, deg

Subscripts

cm = Compound maneuver
dc = Descent or climb maneuver
E = Event
env = Environmental (factors other than maneuvers and seating)
h = Rate of change in altitude
l = Longitudinal direction
man = Maneuver
max = Maximum
mot = Motion
no = Noise
po = Pitchover
seat = Seating space
T = Temperature
t = Transverse direction
trip = Total trip
turn = Turning maneuver
v = Vertical direction
z = Normal direction to cabin floor

Appendix C: Flight Profile

An example of a more complex flight profile composed of maneuvers and straight/level flight can also be obtained from the SEGMENT program. As will be shown, there are 21 ride segments, 11 of which are straight/level flight. This profile represents a typical flight with maneuvers at the beginning and end for take-off and landing. There are also maneuvers in the middle of the profile for the altitude change. The flight profile is summarized below:

Segment	Segment Description
1	Maneuver--steady descent/climb
2	Maneuver--compound maneuver
3	Maneuver--longitudinal deceleration with pitchover
4	Maneuver--simple turn or S-turn
5-10	Straight-level flight--terrain flat; altitude = 5000 ft
11	Maneuver--steady descent/climb
12	Maneuver--steady descent/climb
13-17	Straight-level flight--terrain water; altitude = 5000 ft
18	Maneuver--simple turn or S-turn
19	Maneuver--longitudinal deceleration with pitchover
20	Maneuver--steady descent/climb
21	Manuever--steady descent/climb

Since all the segments must be of equal time duration, a common denominator for the time of a segment must be found. For example, the maneuver or straight/level flight with the shortest duration could be picked as the denominator if all other periods of flight characteristics are integer multiples of this segment.

Structural Models of Attitude-Behavior Relations for Intercity Rail Travelers

PETER M. ALLAMAN AND TIMOTHY J. TARDIFF

The interrelationship of various attitude and behavioral measures of intercity rail travel within a simultaneous equation, multiattribute formulation is examined. The overall structure of perception influencing preference, preference influencing activity, and activity influencing perception has been established, although not for all dimensions of user evaluation. Satisfaction with the schedule, cost, speed, and physical design of the train seems to be the most important determinant of an overall positive evaluation of train travel, although the social environment inside the car and pretrip experiences also have an impact. Overall evaluation of train travel has a positive relationship to frequency, and frequency in turn influences satisfaction with schedule, and (very slightly) perception of the physical dimension of train travel. Satisfaction with schedule is influenced not only by frequency of travel but also by travelers' general evaluation of the train regarding cost, schedule, and comfort. Satisfaction with design aspects of the train is influenced by perception of the physical qualities of the ride, as well as perception of the train's comfort. The image of the train tends to influence evaluation of the food and facilities available on the train. The major negative finding is the lack of significance of frequency in predicting more aspects of traveler perceptions or dimensions of satisfaction, in contrast to its pivotal role for urban travel. These results indicate the role of traveler style, demographics, and trip characteristics in the formation of perceptions, the translation of perceptions into specific dimensions of satisfaction, and the translation of these components of satisfaction into overall effect and frequency. The use of a methodology such as this can aid decisionmaking for service offerings, advertising campaigns, and design studies.

Over the past few years, transportation planners and researchers have been exploring ways to integrate consumer needs into the design process. A prime motivating factor behind these efforts has been the desire to make cost-effective trade-offs among system features. Implicit in this approach is the assumption that the quality of trade-off decisions required in designing these systems may be improved by a fuller understanding of which system features are important to users. There is a general consensus among researchers that it is necessary to obtain