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DEVELOPMENT OF TECHNIQUES AND DATA FOR EVALUATING RIDE QUALITY
Volume I: Summary

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FINAL REPORT

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16. Abstract

Ride-quality models for city buses and intercity trains are presented and discussed in terms of their ability to predict passenger comfort and ride acceptability. These models were developed using passenger response data gathered under actual field conditions.

This, the first of three volumes, summarizes the results of the project. Volume II contains a technical discussion of the ride-quality models developed during the research effort. Volume III contains procedural guidelines to be employed by transportation specialists in developing ride-quality models and in using them to evaluate passenger comfort in existing or future systems.

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PREFACE

This study of ride quality, which developed predictive models of passenger comfort and ride acceptability, was conducted by Dunlap and Associates, Inc., under Contract No. DOT-TSC-1090 in close cooperation with the University of Virginia as subcontractor. The project was under the direction of Dr. Richard D. Pepler, Vice President of Dunlap and Associates, Inc. The design and conduct of the field data collection was the prime responsibility of Mr. Leroy L. Vallerie, Principal Associate of Dunlap and Associates, Inc., and the data analysis and model development was the responsibility of Dr. Ira D. Jacobson, Associate Professor, Department of Engineering Science and Systems, University of Virginia. Mr. Vallerie was supported by Ms. Joan M. Edwards, and Messrs. Charles A. Goransson and John J. Henschel of Dunlap's professional staff. Dr. Jacobson was assisted by Drs. Richard W. Barber and Larry G. Richards and by Messrs. Steven Troester, Steven Schaedel and George Cushnie of the University of Virginia.

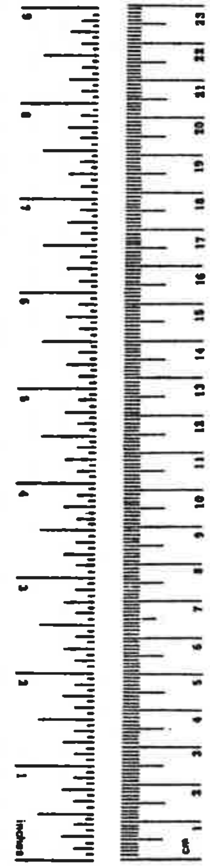
The success of the project depended on help of many kinds from many people. In particular, we would like to acknowledge the cooperation and assistance received from Mr. Charles Abell, Mr. Raymond Binheimer and the bus drivers of Connecticut Transit in arranging for and collecting data on city buses during experimental trials and on regular scheduled services. Similarly, we thank Mr. Joseph Schmidt, Mr. Ross Higginbotham and Mr. Robert Breese in Washington and Mr. Thomas Fortier and Mr. Tim Salveson in the Hartford office of the National Railroad Passenger Corporation (AMTRAK) for their assistance in arranging our use of selected passenger rail cars and in contacting AMTRAK passengers. We are especially grateful to those men and women who volunteered to participate in our experiments and to those groups of passengers on scheduled services who had agreed in advance to provide additional ride quality data.

Finally, we would like to express appreciation for the support, guidance and encouragement that we received from Dr. E. Donald Sussman, Technical Monitor and Ride Quality Project Manager, and Mr. Edward A. Sands, Contracting Officer, Transportation Systems Center, U.S. Department of Transportation; and from Dr. Robert J. Ravera, Transportation Advanced Research Program (TARP) Manager, Office of Systems Engineering, Office of Secretary, U.S. Department of Transportation, Washington, D.C.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

CONTENTS

ILLUSTRATIONS

SYMBOLS AND ABBREVIATIONS

a_T = RMS transverse acceleration of vehicle

a_V = RMS vertical acceleration of vehicle

a_L = RMS longitudinal acceleration of vehicle

ω_R = RMS roll rate (rotation around longitudinal axis)

ω_P = RMS pitch rate (rotation around transverse axis)

ω_Y = RMS yaw rate (rotation around vertical axis)

m_T = mean transverse acceleration (sustained component)

m_Y = mean yaw rate (sustained component)

g = gravities, or 9.8 meters per second squared

$^\circ C$ = degrees Celsius
$^\circ F$ = degrees Fahrenheit
R^2 = the proportion of variance in comfort judgments "explained" by regression equation; the square of the multiple correlation coefficient

dB(A) = decibels measured using the A-weighting system

deg/sec = degrees per second, a measure of angular velocity

RMS = root mean square; the data are processed to remove the long time constant (the mean)

$\bar{C}$ = mean comfort rating (empirically derived)
C' = mean comfort response predicted by a model

CPR = predicted comfort responses

α = the level of significance for a hypothesis test

σ = standard error of the coefficient

E_β = that value of a variable (say roll, ω_R) such that some percent in the sample lies within the range $\bar{\omega}_R \pm E_\beta$, that is within E_β units from $\bar{\omega}_R$.

GLOSSARY

ACCEPTABILITY: Degree to which a vehicle or system will be used by passengers.

BANDWIDTH: Range of frequencies contained in a given motion.

COMFORT: A subjective state of the passenger, assessed in the present research with a seven-point rating scale.

DECIBEL: A unit of measurement of sound intensity or power level.

EXCEDANCE COUNTS: Number of times a variable exceeds some chosen level in some unit of time.

FACTOR ANALYSIS: A set of techniques for determining the dimensionality of a set of variables, usually by finding the rank of the matrix of intercorrelations among the variables.

g-LEVEL: Amount of acceleration referred to the acceleration of gravity.

JERK: Rate of change of acceleration, usually pertains to the longitudinal direction.

LATERAL DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, the y axis represents the lateral direction.

LONGITUDINAL DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, the x axis represents the longitudinal direction.

MODEL: A mathematical (abstract) representation of some object, event or process.

PEAK VALUE: The maximum value of a variable.

PITCH: Rotation about the lateral axis (see lateral direction).

POINT OF PERCUSSION: Point about which vehicle can be considered to be in pure rotation giving rise to equivalent motion.

ROLL: Angular motion about an axis in the direction of travel, i.e., the x axis in the coordinate system adopted in this report (see longitudinal direction).

RMS: Root mean square of a variable.

SPECTRUM: The distribution of the values of any quantity.

TRANSVERSE DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, a transverse direction would be somewhere in the yz plane.

VEHICLE INPUT: The inputs to the vehicle from external sources, e.g., road roughness, track irregularities, winds, turbulence, sea state, etc.

VERTICAL DIRECTION: In an x, y, z coordinate system, with x oriented in the direction of travel of the vehicle, and z oriented perpendicular to the plane of the vehicle and directed into the supporting surface, the z axis represents the vertical direction.

YAW: Rotation about the vertical axis (see vertical direction).

SUMMARY

Introduction

For many years, transportation specialists have recognized the need to develop a quantitative tool for measuring and evaluating the ride quality of existing and proposed vehicles. Such a tool would permit them to compare the relative merits of two competing systems, to write vehicle specifications and to initiate cost effective design changes. Currently, designers and planners of transportation systems must rely on the use of comparative "as good as" criteria, subjective rating methods and ISO[1] guidelines established for human tolerance to vibration, none of which can reliably be employed to assess or predict passenger comfort or acceptability of ride.

Until recently, the problem has been investigated primarily in the laboratory with paid or volunteer subjects using simulation facilities to study the response of humans to vibration. In other studies, panels of experts have been employed to evaluate specific vehicles. A detailed review of the literature is contained in Volume II, Section I. A. Evaluation criteria, drawn from laboratory work, have several drawbacks: first, they are generally based on a limited number of degrees of freedom, usually vertical and lateral; second, they generally deal with a very selective sample of the population, young males; and third, they lack corroborating evidence that the test results correlate with those from commercial passengers.

The objective of this project has been to develop a quantitative model of subjective reaction to the ride environment of city buses and inter-city trains using field data for both paid subjects as well as regular passengers. The goal has been to develop a model which can be used for a variety of purposes. Among these are:

- Provide a quantitative basis for ride quality specifications.
- Evaluate ride environments on current transportation vehicles.
- Provide tradeoff data on alternative design approaches.
- Evaluate relative effectiveness of roadbed (guideway) vs. vehicle specifications in providing acceptable ride quality.

To meet these aims, the study was designed to have several distinct phases, each with its own specific objectives. These objectives were:

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[1] International Standards Organization

- Obtain field data on passenger comfort responses to bus/train ride environments.

- Generate quantitative model(s) able to predict comfort responses from motion data inputs.

- Validate model(s) using data from passengers on commercial services.

The model(s) developed in this program are not meant to apply to all transportation vehicles--past, present and future; rather, they are specific to the city bus and inter-city train. There has been some attempt, as discussed below, to develop a composite model for hybrid types of transportation systems that might be applied more broadly than any of the vehicle specific models. More work is needed, however, on combining the data for many transportation modes (e.g., air, high speed train, automobile, ship, etc.) to evolve a general model for predicting the reactions of passengers to future systems.

Ride-Quality Models For Buses

Data were collected on city buses over a wide range of terrain conditions. Two separate tests were conducted using paid subjects driven over a variety of preselected road surfaces, both on straight and level roads, and also on hills and curves. In addition, a third test was conducted using preselected volunteers who regularly use the service over scheduled routes. Figure I-1 shows subjects on board one of the buses in the test. Paid subjects and volunteer passengers were asked to rate the ride over selected segments of road on a seven-point comfort scale as follows:

1 - Very Comfortable

2 - Comfortable

3 - Somewhat Comfortable

4 - Neutral

5 - Somewhat Uncomfortable

6 - Uncomfortable

7 - Very Uncomfortable

The motions of the bus in six degrees of freedom were recorded over each road segment. These data were analyzed as described in Volumes II and III to arrive at suitable "best fit" models to describe the subjective reactions to the ride. The experimental design and details on the numbers of subjects and data can also be found in Volumes II and III.

FIGURE I-1. PASSENGERS ON BOARD ONE OF THE BUSES DURING EXPERIMENT.

Two separate models were generated from these data; one for straight/level roads and hills, and one for curves. The model for travel on straight roads has been validated using the data from regular passengers (see Volume II, Section III. B.). Insufficient data were available to validate the model for travel around curves.

The models giving the "best fit" predictions of comfort to the mean subjective response to the ride environment are:

Straight/Level Roads and Hills

$$C' = 0.87 + 1.05\,\omega_R \qquad (1)$$

Curves

$$C' = 1.4 + 7.7m_T + 8.25a_T \quad (2)$$

where C' is the subjective response to the ride environment ranging in value from 1 to 7 as per the above list, ω_R is the angular rate of motion about the vehicle roll axis in degrees/sec, m_T is the transverse mean acceleration in g's, and a_T is the rms transverse acceleration in g's. There is some variation in these coefficients with subpopulations; however, the above models are adequate for the riding public in general. It should be remembered that these models represent the mean subjective response for a ride segment with given values for the motion variables indicated.

The correlation coefficients between the comfort ratings and motion data for the "straight/levels roads and hills" and "curves" models are R = .76 and .72, respectively. These are not improved significantly by adding any additional terms to the equations. This is not to say that no other terms are important, only that some of the variation in the subjective response has already been accounted for due to the intercorrelation between variables and the remainder is negligible (see Volume II, Sections III.A. and III.C.

Train Ride-Quality Model

As in the bus ride quality models, the independent variable is the mean subjective response to the vehicle's ride environment. The details of the experimental design and the data used in arriving at the model shown below are described in Volumes II and III. A picture taken during the train experiment is shown in Figure I-2. The train model involves two terms: one is motion and the other is overall noise level in dB(A), and is expressed as:

Train Model

$$C = 1.0 + 0.96\,\omega_R + 0.10\,[\mathrm{dB(A)} - 63] \quad (3)$$

The correlation coefficient between the comfort ratings and motion data for this model is R = .72. The validation of this model using data from regular passengers can be found in Volume II, Section IV.B.

Composite Ride-Quality Model

The above models are "best fit" models for the data obtained in bus and train field experiments. They should, in general, give reasonable estimates of the ride quality in vehicles of the same type for which they were generated.

FIGURE I-2. PASSENGERS BOARDING AMTRAK RAIL CAR DURING EXPERIMENT.

However, for future modes of transportation which exhibit characteristics shared by more than one existing mode or system, the application of these mode specific equations is questionable. In order to give the user a method to evaluate the potential problems of future designs and to provide a quantitative tool for tradeoff analyses, a composite, or combined model, has been formulated.

The composite model incorporates features of three existing modes--buses, trains and aircraft. As such, it will not produce results which are as good as the mode specific models for any of the existing modes, but it has the potential for being a more useful predictor of the ride quality of future systems. In this composite model, the mean or average comfort rating is given as:

$$C' = 1.0 + .5\,\omega_R + 0.1\ [\mathrm{dB(A)} - 65] + 17a_T + 17a_V \qquad (4)$$

The model incorporates four environmental variables: vertical and lateral acceleration, roll rate, and acoustic noise in dB(A). The user is cautioned in using this model since it is only an estimate of the expected ride quality and is not based on data for the particular mode in question. Judgment and care, therefore, should be taken in establishing the appropriateness of the composite model. The composite model is described in more detail in Volume II, Section V.

Distributed Response Ride-Quality Model

The three previous ride quality models are useful in estimating the mean or average response of a group of passengers to vehicle motions and noise. However, they are incapable of describing the distribution of passenger responses. It is common to observe a wide disparity of responses to the same motion environment depending on the individual characteristics of the passengers. A model must allow the investigator to ascertain the distribution of responses about the mean. If this distribution can be estimated for a vehicle, then one may estimate the probability that, say, 90% of the passengers are "comfortable." Conversely, if it is desired that a stated percentage of the passengers is to be comfortable, the model will allow the estimation of the mean comfort level required and hence the allowable ride environment.

The binomial distribution is chosen to represent the approximating distribution. This model is an excellent representation of the actual distribution encountered in experiments as is discussed in Volume II, Section VI. The model is applicable to both bus and train data. Application of the model leads to the following equation for the probability P of a comfort level c occurring when the mean response for all passengers is $\bar{c}$.

$$P\,(\text{Comfort Rating} = c) = \binom{6}{c-1} \left[\frac{\bar{c}-1}{6}\right]^{c-1} \left[1 - \frac{\bar{c}-1}{6}\right]^{7-c} \qquad (5)$$

Where the leading terms is the binomial coefficient and can be expressed in terms of factorials as:

$$\binom{6}{c-1} = \frac{6\,!}{(7-c)\,!\;(c-1)\,!} \qquad (6)$$

Given any value of the average comfort rating $\bar{c}$, this equation allows the computation of the percentage of responses at each of the seven possible response categories. These values for mean responses from one through seven in increments of .1 can easily be computed and tabulated in advance for convenience of use.

Practical Applications and Use of Ride-Quality Models

The uses of the models described in the previous sections fall into three general categories. They are:

Writing Vehicle Specifications

Evaluating Existing Vehicle's Ride Quality

Evaluating Proposed New Vehicle Ride Quality.

Examples of each of these applications are given in Volume II, Section VIII and Volume III, Section V. Each involves selecting the appropriate model, restricting the analysis to those variables within the model, and utilizing the quantitative relationships to derive equal comfort zones. It is important to note that none of these applications presupposes the level of ride quality that is acceptable. The user must select the level of comfort deemed appropriate for the vehicle in question. Some guidance for doing this is provided by previous work that has indicated a relationship between mean comfort level and perceived willingness to take another trip.[1] Although this is not necessarily accurate for all modes, all subpopulations or for actual prediction of return trips, it does serve to indicate when a passenger might become reluctant to "take another trip" on the mode in question.

Further Research

This research project has resulted in the successful development of ride quality models for city buses and inter-city trains. These models have been validated using comfort ratings gathered from regular passengers in commercial services and may now be used as tools to evaluate existing or future bus and train systems of these general types. The techniques employed to carry out this research effort have proven to be both reliable and practical in terms of the time and cost expended to produce models of good quality. These same techniques should now be used to develop quantitative models for other transportation systems such as rapid rail, automated guideway transit, large and small automobiles, custom buses and hydrofoil ferries. With an expanded data base, it may also be possible to develop a composite model that can be applied more broadly, than any vehicle specific model, to transportation systems of the future.

The modeling techniques used in this research project may also be applied to other nonphysical aspects of transportation systems. Among these are economic and social factors which play such a large role in the public's decision to use a particular system or mode of transportation.

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[1] Jacobson, I. D. and Richards, L. G. Ride quality evaluation II: Modeling of airline passenger comfort. Ergonomics, 1976, 19(1), 1-10.

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