countermeasures are identified by increments—e.g., widen lane from 33.3 m to 36.3 m (10-11 ft), add left-turn lane, right-turn lane, and signalization—with each incremental change being cost estimated. This is accomplished by having the outlier float through a decision tree. The resistance to each change (moving from one mode to another) is measured by an estimated cost. The expected change in accidents is estimated for each countermeasure, including the do-nothing alternative. The cost of each countermeasure is divided by the anticipated reduction in accidents, producing a cost-effectiveness index for each proposal. The status of stage 2 is a preliminary working program for identifying and estimating the cost of countermeasures. Present accident predictive procedures are not satisfactory, and more comprehensive accident predictive algorithms are being developed.

Stage 3 is the model optimization process. The objective is to maximize expected returns within budget and management policy constraints. Theoretical procedures have been explored but will not be implemented until the completion of stage 2. Action is under way to accelerate the completion of the model, its validation, and expansion to access sources of data heretofore unobtainable.

ACKNOWLEDGMENTS

Several engineers and technicians, who labored in developing and editing the base data and subsequent software, deserve much credit. Special consideration is due Donald E. Orne, Traffic and Safety Division, for his substantial contribution in formulating the concepts and processes of the model.

Publication of this paper sponsored by Committee on Traffic Records.

Accident Characteristics Before, During, and After Safety Upgrading Projects on Ohio's Rural Interstate System

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In 1973, minor safety upgrading projects were conducted at 21 locations on the rural Interstate system of Ohio, involving 618 km (384 miles) of freeways. In 1972, the accident rate per million vehicle kilometers (MVKM) on these 618 km was 112.9 accidents/161 MVKM (112.9/100 million vehicle miles). In 1974, the accident rate dropped to 77.9 accidents/161 MVKM. To account for the possible effect of the introduction of the reduced speed limit in 1974, accident rates were also compared on 246 km (153 miles) of the rural Interstate system not subjected to safety improvement. The difference in proportional reduction in accident rates is statistically significant and favors the 21 study sites. The accident rates increased to 120.8 accidents/161 MVKM during the 1973 safety upgrading construction program. However, only 151 accidents were positively identified from traffic crash reports and construction diaries as construction related. These 151 accidents were studied in detail. Observed patterns included: (a) rear-end (61) and single vehicle, fixed-object (56) accidents were the most frequent; (b) 34 accidents occurred in the relatively short taper area; (c) the proportion of the lane taper accidents at night and at dawn or dusk was high; (d) the proportion of construction object accidents at night was high; (e) the proportion of tractor-trailer and bus accidents at night was high; (f) excess speed was listed in 88 cases as a contributing factor, while road defects or construction or traffic control were listed only in 15 cases. Some suggestions are being made regarding traffic control at work zones.

INTRODUCTION

The implementation of the Interstate highway system began in 1956 with the passage of the historic Highway Revenue Act and Federal-Aid Highway Act. The Interstate system is now about 90 percent completed. However, once a facility is constructed, it requires continuing attention to operation and maintenance.

Naturally, all highways will deteriorate in time at a rate determined by the traffic and environmental conditions. Resurfacing and other corrective measures are required to maintain the original design standards and the corresponding efficiency and level of safety.

Since the original design standards for freeways were developed, research, as well as experience gained from operating freeways, has taught us much about the relationship between design standards and performance. To eliminate safety hazards unwittingly built into our freeways, a 90 percent federally-supported Interstate Highway Safety Upgrading Program was begun.

For administrative purposes, safety improvement projects on the Interstate highways are classified as either major or minor upgrading. Major improvements are cost-intensive projects that are usually expected to reduce accidents. Minor improvements are low-cost projects and are usually expected to reduce the severity of accidents, mostly through reduction of roadside hazards.

Ohio's Interstate Highway Safety Upgrading Program was implemented in the early 1970s. It was rather puzzling to find, therefore, in the course of a previous study, that accident rates in Ohio actually exceeded projected trends during the first few years of the 1970s.

It is clear that safety upgrading projects differ from most new construction projects in that traffic must flow uninterrupted while work is in progress. This, of course, presents potential hazards to construction workers and through traffic alike. This realization led to the theory that safety upgrading projects may be responsible, at

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least partially, for the apparent increase in accident rates. That is, although these projects can be expected to ultimately decrease the accident rates on a roadway, they might be responsible for some increase of accidents during construction. If this is true, efforts should be taken to minimize the problem, since major emphasis has now shifted from new construction to maintenance and safety upgrading of the existing road network.

Study Objectives and Scope

This research project had three objectives:

1. Determine if accident rates in fact increased significantly during safety upgrading construction;
2. Determine if safety upgrading projects were successful in ultimately reducing the severity of accidents; and
3. Analyze construction-related accidents to determine if accident patterns can be related to elements usually present in work zones, and, based on the results, make suggestions which may reduce potential hazards in work zones.

A total of 21 minor safety upgrading projects on the rural Interstate highway system of Ohio were investigated. They mainly involved sign and lighting supports, guardrails, energy absorption barriers, drainage, and improved skid resistance. The 21 projects involved upgrading of some 618 km (384 miles) at a cost of $20 million, and most were completed during 1973. This study was conducted between November 1975 and May 1977.

Special Problem

The 55-mph speed limit, aimed at conserving fuel, was signed into law on January 2, 1974, and became effective nationwide on March 3, 1974. On Ohio's rural Interstate highways, the 1973 mean speeds and 85th percentile speeds were 102.9 km/h (63.9 mph) and 114.8 km/h (71.3 mph), respectively. The corresponding speeds in 1974 were 92.3 km/h (57.3 mph) and 99.4 km/h (61.7 mph). It is generally accepted that the reduced speed limit favorably affected accident rates. The implication for this project is that the routine comparison of accident statistics for the Before-Construction, During-Construction, and After-Construction time periods would be nonconclusive, since speed characteristics changed significantly in 1974.

It was, therefore, necessary to select 13 control sites, totaling 246 km (153 miles). These control sites were similar to the 21 study sites in terms of design standards and traffic volumes, but, of course, no safety upgradings were performed during the study period.

Sources of Accident Data

From the Ohio Department of Transportation's computerized data storage system, the number of fatal, nonfatal, and property-damage-only accidents could be obtained for any segment of the roadway for a given time period. Traffic crash reports prepared by the Ohio State Highway Patrol are stored on 16-mm microfilm by accident case number and were also available for review.

Records of the 2948 accidents that occurred on the 21 study sites during safety upgrading were investigated. Construction-related accidents were identified by reviewing the sketches and reading the accident descriptions prepared by the highway patrol. In construction-related accidents, the diagrams usually included sketches of temporary traffic control devices and location of construction equipment and construction material. The narrative description mentioned the construction zone. A total of 151 accidents were thus identified as definitely construction related.

Traffic volumes were also available for the 21 projects and for the 13 control sites. It was, therefore, possible to compute accident rates, expressed as accidents per million vehicle kilometers. Table 1 lists accidents, travel, and accident rates. For the during-construction period, accident statistics are given in two ways: by excluding construction-related accidents, denoted (w.o.), and by including construction-related accidents, denoted (with).

The field districts of the Ohio Department of Transportation, which conducted safety upgrading construction projects, were asked by operation and traffic engineers to submit the following information:

1. Date work started,
2. Day-by-day description of work in progress,
3. Location of work in progress,
4. Lane or shoulder closure for work in progress,
5. Any material or equipment stored within 9 m (30 ft) of pavement,
6. Any accidents involving contractor's equipment,
7. Any evidence of accidents occurring during the night that were not on state highway patrol reports,
8. Any evidence that accidents were related to contractor's traffic control (any complaints about unsafe traffic control method), and
9. Date work zone opened to traffic.

Responses were received for all 21 projects. Many of the responses also contained suggestions for improving traffic control procedures. These suggestions provided the rationale for the recommendations presented in this paper.

BEFORE- VERSUS DURING-CONSTRUCTION ACCIDENT RATES

The first objective of this study was to determine if accident rates in fact increased significantly during safety upgrading construction. For each of the 21 study sites, the number of accidents and the vehicle kilometers were determined for the construction period (X_D, M_B).

Before- and During-Construction accident rates (λ_B, λ_D) were computed from the ratio of the total number of accidents and total vehicle kilometers on the 618 km (384 miles) of rural Interstate highways included in this study, and expressed as accidents per 161 million vehicle kilometers (accidents per 100 million vehicle miles).

It is assumed that X has a Poisson distribution with parameter $\lambda M = \mu$. The F-test was then applied to the null hypothesis: $\lambda_B = \lambda_D$. The test statistics, $F^* = [X_D/(X_B + 1)]\,(M_B/M_D)$, are compared with $F_{1-\alpha}$ where the

Table 1. Accident statistics for construction and control projects.

	No. of Accidents				Accident Rates/161 MVKM		
Project	Total	Fatal	Non-fatal	Per 161 MVKM	Total	Fatal	Non-fatal
Construction							
Before	2551	34	1345	22.604	112.9	1.5	59.5
During (without)[a]	2797	36	1438	24.399	114.6	1.5	58.9
During (with)[b]	2948	39	1487	24.399	120.8	1.6	60.9
After	1819	14	734	23.347	77.9	0.6	31.4
Control							
Before	1031	15	369	10.271	100.4	1.5	35.9
After	823	5	259	9.905	83.1	0.5	26.1

[a] Construction-related accidents excluded.

[b] Construction-related accidents included.

degrees of freedom are $\nu_1 = 2(X_B + 1)$ and $\nu_2 = 2X_D$ and α is the significance level. For the one-sided, upper-tail test, the $F_{1-\alpha}$ was computed from $\log_{10} F_{1-\alpha}(\nu_1, \nu_2) \cong a/(h - b)^{1/2} - cg$

where

$$h = 2\nu_1\nu_2/(\nu_1 + \nu_2),$$
$$g = (\nu_2 - \nu_1)/\nu_1\nu_2,$$

and a, b, and c are constants obtained from statistical tables. The null hypothesis is to be rejected in favor of the alternative, $\lambda_D > \lambda_B$, if $F^* > F_{1-\alpha}$.

The α significance level represents the probability of rejecting a true hypothesis. No specific α was preselected in this study; rather, the statistic $\underline{\alpha}$ was determined for each test. The $\underline{\alpha}$ is the lowest significance level that would lead to the rejection of the null hypothesis. It is customary in traffic engineering studies to work with $\alpha = 0.05$ or $\alpha = 0.10$.

Total accidents, fatal accidents, and injury accident rates were compared. The results of the test are as follows:

Time Period and Factor	Total	Fatal	Injury
During			
λ_D	120.8	1.6	60.9
Before			
λ_B	112.9	1.5	59.5
F^*	1.070	1.032	1.024
ν_1	5104	70	2692
ν_2	5896	78	2974
$\underline{\alpha}$	$0.005 < \underline{\alpha} < 0.01$	$0.25 < \underline{\alpha} < 0.50$	$0.25 < \underline{\alpha} < 0.50$

The test indicates we can reject the null hypothesis that the total accident rates before and during construction were the same, with a 0.5 to 1 percent chance that we are rejecting a true hypothesis. The test on the fatal and injury accidents, however, does not result in a convincing argument against rejecting the null hypothesis. We interpreted the results of the statistical tests to mean that, although accidents during the construction period increased, the increase in the more serious (fatal and injury) accidents is not statistically significant.

BEFORE- VERSUS AFTER-CONSTRUCTION ACCIDENT RATES

The second objective of this study was to determine if safety upgrading projects were successful in ultimately reducing the severity of accidents.

Minor safety upgrading projects, investigated in this study, are typically designed to reduce the severity of accidents. But their effectiveness is difficult to test because of the reduced 55-mph speed limit introduced in March 1974. To bypass the problem, 13 control sites were selected, and proportional changes in before and after accident rates were compared with changes on the 21 improved roadways.

Table 2. Details of statistical tests, before versus after accidents.

Project	Total	Fatal	Nonfatal
Construction			
Before accidents (X_{B1})	2551	34	1345
After accidents (X_{A1})	1819	14	734
Sum of accidents (N_1)	4370	48	2079
ΔP_1	0.168	0.417	0.294
Control			
Before accidents (X_{B2})	1031	15	369
After accidents (X_{A2})	823	5	259
Sum of accidents (N_2)	1854	20	628
ΔP_2	0.112	0.500	0.175
P	0.151 3	0.4414	0.266 4
Z^*	5.638 3	-0.6280	5.911 6
$\underline{\alpha}$	$\underline{\alpha} < 0.000\ 01$	$0.70 < \underline{\alpha} < 0.75$	$\underline{\alpha} < 0.000\ 01$

As can be expected, accident rates (λ_c) at the control sites were lower in 1972 than accident rates (λ_s) on the 21 sites scheduled for safety improvements. The difference is statistically significant for total accidents and injury accidents, as shown below by the results of the two-sided F-tests:

1972 Rates/ Factor	Total	Fatal	Injury
Study sites			
λ_s	112.9	1.5	59.5
Control sites			
λ_c	100.4	1.5	35.9
F^*	1.123		1.652
ν_1	2064		740
ν_2	5102		2690
$\underline{\alpha}$	$0.001 < \underline{\alpha} < 0.001$		$\underline{\alpha} < 0.001$

The years 1972 and 1974 were used as before and after periods, although some of the safety upgrading projects extended into 1974. The 1974 accident rates and the results of the two-sided F-test are shown below:

1974 Rates/ Factor	Total	Fatal	Injury
Study sites			
λ_s	77.9	0.6	31.4
Control sites			
λ_c	83.1	0.5	26.1
F^*	0.937	0.990	1.198
ν_1	1648	12	520
ν_2	3638	28	1468
$\underline{\alpha}$	$0.10 < \underline{\alpha} < 0.20$	$0.50 < \underline{\alpha}$	$0.01 < \underline{\alpha} < 0.02$

In 1974, on the study sections, where safety upgrading projects were completed before 1974 (or, in a few cases, during 1974), total accident rates were lower than on the control sites. The difference is small, however. Fatal accident rates are about the same, and injury accident rates are still higher on the study projects. It is clear that accident rates improved at the study sites, relative to the control roadways. It is also quite clear, however, that accident rates improved from 1972 to 1974 on the control sites, too, although no safety upgrading projects were conducted there. It is necessary, therefore, to test statistically the difference between the proportionate improvements.

The one-sided upper-tail test was based on the statistic, $Z^* = \Delta P_1 - \Delta P_2/\sqrt{P(1 - P)(1/N_1 + 1/N_2)}$. The null hypothesis $H_0{:}\Delta P_1 = \Delta P_2$ was rejected and $H_2{:}\Delta P_1 > \Delta P_2$ was accepted, if $Z^* > Z_{1-\alpha}$. Cumulative normal distribution tables provide the $Z_{1-\alpha}$ values. The details of the test are given in Table 2. The proportionate difference in the reduction of fatal accidents is not statistically significant, but the reduction in total accident rates and injury accident rates is significant at the $\underline{\alpha} > 0.000\ 01$ level.

Thus, it was concluded that safety upgrading projects were effective in reducing injury accidents as well as total accident rates.

ANALYSIS OF CONSTRUCTION-RELATED ACCIDENTS

The third objective of the study was to analyze construction-related accidents to determine if accident patterns can be related to elements usually present in work zones, and based on the results, to make suggestions which may reduce potential hazards in work zones.

Selected Categories

Fairly detailed information was available on the 151 construction accidents. The following 11 categories were selected with the expectation that they would provide the framework for the identification of some informative accident patterns.

1. Accident severity: fatal, nonfatal, property damage only;
2. Type of accident: head-on, rear-end, sideswipe, improper merge, single-vehicle fixed-object, single vehicle run off road, pedestrian, construction only, other;
3. Location of accident: beginning of construction zone, lane taper, lane closure, construction area, median opening, ramp;
4. Construction object involved: construction machinery, drums, other traffic control devices, none;
5. Time of day: daylight, dawn or dusk, night;
6. Weather: no adverse weather conditions, rain, snow, fog, other;
7. Road conditions: dry, wet, snow or ice, mud or sand, other;
8. Vehicle type at fault: passenger car, pickup or recreational vehicle, tractor-trailer or bus, motorcycle;
9. Probable cause of accident: traffic control, driver, vehicle;
10. Contributing circumstances: excess speed, failure to yield, following too closely, drinking, driver preoccupation, improper passing, drove off roadway, defective vehicle, road defects, construction, traffic control, other, none; and
11. Traffic control procedures: traffic officer only, single-lane closure, multiple-lane closure, all lanes closed, shoulder closure, no closure, officer and single-lane closure, officer and multiple-lane closure, officer and all lanes closed, officer and shoulder closure, flagman.

The size of the data set did not permit any complex statistical analysis. Instead, 21 pair combinations were tested by means of difference-in-proportion tests. The comparisons and the results are presented next.

Combinations of Accident Categories

The following combinations were used in this study:

1. Accident severity versus type of accident, location of accident, construction objects involved, time of day, vehicle type at fault, traffic control procedures;
2. Type of accident versus location of accident, construction objects involved, time of day, vehicle type at fault, traffic control procedures;
3. Location of accident versus construction objects involved, time of day, vehicle type at fault;
4. Construction object involved versus time of day, vehicle type at fault, traffic control procedures;
5. Time of day versus vehicle type at fault, traffic control procedures;
6. Weather versus road conditions; and
7. Vehicle type at fault versus traffic control procedures.

The highlights of conclusions based on the tests are summarized here, organized by the 11 categories listed earlier in this paper. Detailed results of all tests are available from the authors.

Accident Severity

Accident severity was measured by the proportion of accidents resulting in injury or fatality. The proportions were as follows:

Type	Construction Accidents	All Accidents
Fatal accidents	3 (1.99%)	39 (1.32%)
Injury accidents	49 (32.45%)	1487 (50.44%)
Property damage only	99 (64.56%)	1422 (48.24%)

At the 21 study sites, construction-related accidents were less severe than all accidents. Of the 25 accidents that occurred in construction activity areas (where work was actually performed), one was fatal and 12 others resulted in injuries. This is significantly higher than the corresponding proportion of all accidents. Accidents involving construction objects (67) were less severe than other construction-related accidents. Accidents involving construction machinery (11) were more severe than accidents involving other construction objects, such as drums (45) or other traffic control devices (11). Accidents during the daylight hours (102) were more severe than those occurring at night (39) or at dawn and dusk (5). (Time of day information was not available for 5 accidents.) Accidents where pickup and recreational vehicles were at fault (16) were more severe than other accidents. Accident severity could not be related to traffic control procedures, e.g., lane closure or shoulder closure.

Type of Accident

The following types of accidents were observed: rear-end, 61 (40.40 percent); sideswipe, 15 (9.93 percent); improper merge, 7 (4.64 percent); single-vehicle fixed-object, 56 (37.09 percent); single vehicle run off road, 10 (6.62 percent); and other, 2 (1.32 percent). There was a difference in distribution of accident types at different locations within the work zone (see Table 3). Most of the single-vehicle, fixed-object accidents involved construction objects (see Table 4). There was a difference in the distribution of accident types during different times of the day: While most rear-end (53) and sideswipe (13) accidents occurred during daylight, all other types of accidents were evenly distributed between day and night. There was no difference in the distribution of accident types when vehicle types at fault or traffic control procedures were considered.

Location of Accidents

The construction zone, which might be several kilometers long, consists of specific sections, as listed under category 3 (see Selected Categories). The beginning of a construction area starts with the first set of advance warning signs. The lane taper area is the transition area where the normal roadway is altered laterally by channelizing devices. The lane closure area starts at the end of the taper and continues through the marked construction zone, but does not include the next category, the construction area. This is the actual site of the activities, which may move during the day within the lane closure area. The distribution of the accidents by location is as follows: beginning of zone, 24 (15.9 percent); lane taper, 34 (22.5 percent); lane closure, 59 (39.1 percent); construction area, 25 (16.6 percent); median opening, 4 (2.6 percent); and ramp, 5 (3.3 percent). Of the 11 construction machinery accidents, 6 occurred at the construction area and 3 at median openings. Of the 45 drum and 11 other traffic control de-

Table 3. Type of accident versus location of accident.

Type	Location						
	Construction Zone (beginning)	Lane Taper	Lane Closure	Construction Area	Median Opening	Ramp	Total
Rear end	14	8	30	6	3	0	61
Sideswipe	2	6	3	3	0	1	15
Improper merge	0	5	0	2	0	0	7
Single vehicle, fixed-object	7	15	22	9	1	2	56
Single vehicle, run off road	1	0	3	4	0	2	10
Other	0	0	1	1	0	0	2
Total	24	34	59	25	4	5	151
% of total	15.9	22.5	39.1	16.5	2.6	3.3	100

Table 4. Type of accident versus construction equipment involved.

Type	Construction Equipment				
	Construction Machinery	Drums	Other Traffic Control Devices	None	Total
Rear end	5	3	0	53	61
Sideswipe	3	1	2	9	15
Improper merge	1	5	0	1	7
Single vehicle, fixed-object	2	34	8	12	56
Single vehicle, run off road	0	2	1	7	10
Other	0	0	0	2	2
Total	11	45	11	84	151
% of total	7.3	29.8	7.3	55.6	100

vice accidents, 21 occurred in the relatively short taper area, 26 in the lane closure area, and only 3 in the construction area. The proportion of the 34 lane taper accidents occurring at night and at dusk (20) was significantly greater than the proportion of all other accidents occurring at the same time. The proportion of the tractor-trailer and bus accidents at the taper was significantly greater than accidents at all other locations involving the same type of vehicles.

Construction Equipment Involvement

The proportion of construction object (drum) accidents at night was significantly greater than the proportion of daylight construction object accidents. However, no construction machinery was hit at night or at dawn or dusk.

Time of Day

The distribution of accidents by time of day differed for different vehicle types at fault. The proportion of tractor-trailer and bus-caused accidents at night and dawn or dusk was greater than the proportion for other vehicles.

Weather

Accidents during adverse weather conditions included 15 during rain, 5 during fog, and 3 other. There were no snow-related accidents. No statistically significant patterns were discovered.

Road Condition

A total of 21 accidents occurred on wet roadway, matching closely the weather category. No other patterns related to pavement condition were discovered.

Vehicle Type at Fault

Vehicle type at fault categories were tested against traffic control procedures. No differences in distribution were found.

Probable Cause of Accident

The state highway patrol reports listed the driver as the probable cause of accident in 130 cases, the vehicle in 12 cases, and traffic control on 5 occasions.

Contributing Circumstances

The data obtained from the accident reports are given here. No statistical tests were performed. Excess speed was the most significant of the contributing circumstances noted. The contributing circumstances were excess speed, 88; failure to yield, 10; following too closely, 15; drinking, 5; driver preoccupation, 16; improper passing, 7; drove off roadway, 9; defective vehicle, 12; road defects, 4; construction, 8; traffic control, 3; other, 24; and none, 6.

Traffic Control Procedures

Only a few accident reports noted the presence of traffic officers or flagmen. Single-lane closure accounted for 124 of the reported accidents. There were 21 accidents where no part of the roadway was closed, and 6 accidents occurred when the shoulder was closed. No attempt was made to perform statistical analysis.

SUGGESTIONS REGARDING TRAFFIC CONTROL AT WORK ZONES

The procedures listed below and prescribed in the Manual of Uniform Traffic Control Devices are recommended given careful consideration of specific local conditions:

1. Expected proportions of large vehicles seem to be involved in more severe accidents and in more nighttime accidents.
2. Nighttime accidents are especially concentrated in the taper area. The review of channelizing devices for effectiveness at night is suggested. Signs should be well illuminated by headlights of all types of vehicles.
3. Excess speed was identified as the one single dominating contributing circumstance in accidents. The effectiveness of speed reduction signs should not be assumed.
4. Accidents are more severe in the construction activity area. Screening should be considered, if high speeds are to be maintained.
5. If traffic is expected to back up occasionally be-

yond the usual warning signs, additional warning signs should inform drivers about the cause of the problem.

6. Traffic control plans should be prepared by knowledgeable personnel. If geometric design standards or high volumes appear to indicate problems, past records of accident history should be studied for possible clues. The sites studied in this research did not have very bad accident problems, but all sites were on the rural Interstate system, which usually has low accident rates. On lower standard roads or in urban areas, the problems were more serious.

These suggestions are based on our interpretation of a relatively small set of accident data and on comments received from construction engineers during the data collection phase. More research is clearly needed.

ACKNOWLEDGMENTS

This research set out to investigate some questions, first raised by Tom Culp of the Ohio Department of Transportation. He provided valuable assistance throughout the study. The coauthor, Donald J. Migletz, received a Federal Highway Administration Safety Fellowship for the first year of his graduate study at Ohio State University.

Publication of this paper sponsored by Committee on Traffic Records.

Ride Quality Criteria of Multifactor Environments

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A comprehensive ride quality model that accounts for the effects of multifrequency and multiaxis vibration inputs as well as the interactive effects of noise and vibration upon passenger discomfort is under development. The model development has been based upon extensive experimental studies utilizing a realistic multi-degree-of-freedom laboratory simulator located at the Langley Research Center, Hampton, Virginia. This paper briefly describes the basic elements of the ride quality model; presents summary data relating to human discomfort response to vertical, lateral, and roll vibrations; and concludes with a description of the results of an initial study of human response to combined noise and vibration stimuli. Results of studies involving vibration stimuli alone are presented in terms of sets of equal discomfort curves for each of the previously mentioned axes of vibration. In addition, a set of noise-vibration criteria curves are included based upon the concept of additivity of the discomfort components due to noise and to vibration. This assumption is shown to be valid for the restricted range of stimuli used in this study.

Passenger comfort within existing as well as future transportation systems is strongly dependent on environmental factors such as vibration, noise, temperature, and pressure. These factors can act to degrade vehicle ride quality and hence passenger acceptance of a particular transportation system. For example, the introduction of advanced transportation systems such as short-takeoff and landing (STOL) aircraft, civil helicopters, and high-speed surface vehicles is expected to be accompanied by more severe levels of vibration and noise than most currently operating systems. The increased levels of these environmental factors are likely to produce additional decrements in ride quality and, therefore, further reductions in passenger acceptance. Consequently, a definite need exists for a valid ride quality model that can be readily used by system designers to estimate the trade-offs between passenger acceptance (or comfort) and the degree of complexity of vehicle ride control systems required to achieve a specified level of comfort. To be useful, such a model should be applicable to any transportation system and should account for both multiaxis and multifrequency vibratory inputs as well as the interactive effects, if any, of noise and vibration. The uses of such a model would be to predict passenger acceptance of any noise-vibration environment, to determine the specific components of the noise or vibration environment or both that most affect passenger discomfort, and to serve as a diagnostic tool in providing a "fix" to a ride quality problem by knowing how much reduction in noise or vibration characteristics or both is required to achieve acceptability.

Numerous studies in the area of human subjective response to whole-body vertical vibration have been conducted (see 1-5). An excellent summary and critical review of a larger number of studies conducted prior to 1970 is given in Hanes (6). Unfortunately, as Hanes points out, the results of these studies show very little agreement with one another. Many of the criteria curves or recommended levels of vibration proposed by various investigators differ by as much as one or two orders of magnitude. Many reasons have been offered for such disparities in results, and these reasons are summarized as being attributable to poor experimental design, the multifactor nature of actual ride environments, use of inadequate adjective rating scales, subject populations used, and a lack of a fundamental understanding of the empirical laws governing human discomfort response to vibration (7).

A systematic and comprehensive effort to develop a general predictive model of passenger discomfort to combined noise and vibration that is free of the above limitations has been under way at the Langley Research Center, Hampton, Virginia. The National Aeronautics and Space Administration (NASA) model (7) recognizes that passenger discomfort results from the interrelationships of many factors of which vibration and noise are the most important. The NASA model approach involves the experimental determination of the basic psychophysical relationships governing human discomfort response to complex vibration and noise stimuli