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Maintenance Management Systems and Transportation Ride Quality

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Abridgment

Birmingham-Jefferson County Transit Authority Maintenance Management Information System

JERRY D. HAIGHT AND TIMOTHY B. COLLINS

The way in which a computerized maintenance management information system has made a notable and favorable financial impact on maintenance labor cost at the Birmingham-Jefferson County Transit Authority is discussed. The paper identifies the need to which the computerized system was directed and presents a system overview of the elements of the system. It also shows how each element works and describes the achievements in financial terms of the maintenance management information system.

In recent years the demand for urban public transportation has been increasing. Furthermore, as a result of current changes in the cost and supply of energy resources, it can be anticipated that public transportation networks will need to be expanded in the future. The labor intensity of public transit operations means, however, that operating costs are significantly influenced by prevailing economic inflation. Accordingly, the cost of public transportation service in the 1970s has increased substantially. Faced with limited and reasonably predictable financial resources, transit management must be vitally concerned with the most effective use of these resources, particularly with regard to labor compensation and productivity. Much attention is usually devoted to the examination of labor requirements in the administrative and operational departments of a transit organization. At the Birmingham-Jefferson County Transit Authority, however, an examination of work activities and personnel requirements in the maintenance department proved very interesting. Indeed, the maintenance management information system (MIS) produced as a result of this examination has been instrumental in controlling costs and in improving the performance of daily operations. This paper briefly examines this maintenance MIS and reviews its potential application in other transit environments.

Maintenance labor usually constitutes about 25 percent of the total labor cost of a transit system. This cost element has perplexed many transit operators because of the general unavailability of qualified data supporting the expenditure. Most transit operating budget and control reports provide lump-sum expenditure calculations without any specific accounting for the accomplishments associated with this cost. When analysis is directed at these statistics, most transit managers can only develop broad generalities about the actual maintenance situation, thus leaving many matters subject to question and concern.

Maintenance activities, however, are not unique to the transit industry. Labor-quantifying techniques that are used widely in other industries, particularly in aerospace, automotive, and trucking industries, just have not been employed to any great extent in the transit industry. To a certain extent this practice may be excused by the recent history of the transit industry. Data processing is largely an outgrowth of the 1960s and 1970s, a period in which transit-management capabilities were not progressing rapidly. Although some data processing has been used in the transit industry, historically the emphasis has been on keeping records on parts rather than on labor. In the past, the parts expense was of serious concern to the transit manager, but now the labor dollar is of such serious concern that more-quantifiable control techniques demand development. The maintenance MIS developed by the Birmingham-Jefferson County Transit Authority is directed at quantifying the labor activities in the maintenance department. The main objectives of the system are to control overall maintenance costs, to develop specific maintenance costs per vehicle, and to provide documentation for the development of maintenance payrolls.

SYSTEM OVERVIEW

In greater detail, the Birmingham-Jefferson County Transit Authority maintenance MIS is designed to accomplish the following specific functions:

1. Determine the amount of time required to perform all tasks in the maintenance department;
2. Compute nonproductive time for each employee on each working day (nonproductive time is defined as the difference between time that has been accounted for and the standard 8-h workday);
3. Compute and store the average time required to perform each function in the maintenance department;
4. Measure the current elapsed time for each maintenance task and the average time that has been previously stored and require an explanation if the current performance exceeds stored average by a stipulated margin;
5. Account for all activities such as sick leave, vacation, holiday, personal time off, and jury duty;
6. Compute, by using the pay rate assigned per employee, the cost associated with each task and associate the cost with the job code, vehicle number, and the fare-account classification system;
7. Compute gross pay per employee in a form compatible with the payroll system;
8. Provide a job-code report that compares the performance of all employees on each activity and associates the activity with the vehicle, date, employee, elapsed time, average time, and explanation for excess time;
9. Provide the gross-pay report that computes gross pay for the entire period per employee in terms of straight time, overtime, and miscellaneous paid time;
10. Recap the gross-pay total into the fare-account classification system; and
11. Provide individual vehicle-maintenance reports that show all of the activities performed, date of such performance, employee performing such activity, amount of time expended and cost for each activity, and total cost per vehicle.

All of these activities were merely a means of providing better records about the activities of the maintenance department. The data-processing capabilities necessary to provide this information were readily available from software suppliers. The major problem encountered in implementing the MIS program involved the instruction of the individual mechanics and supervisors in the use of the data-processing system.

ELEMENTS IN THE MAINTENANCE MIS

The Birmingham-Jefferson County Transit Authority maintenance MIS program requires active personnel to be familiar with the three key elements of the system discussed below.

Activity Code

Of utmost importance is the proper codification of all maintenance department activities. It proved to be particularly difficult to define activities so that everyone who used the program (including the director of maintenance, shop foremen, mechanics, bus hostlers, and janitors) has a mutual understanding of what each job code entails in terms of performance. It is extremely important to define the jobs in such a manner as to provide comparability. For example, "relining brakes" is not an appropriate job code; there are distinct differences in the time and effort required to reline front brakes rather than rear brakes or to reline brakes on different models of buses. Therefore, it proved necessary to define specific job codes for each type of brake assignment that could be encountered in the maintenance shop.

Considerable effort must go into developing the activity code or else no maintenance-labor performance standards can be developed. In Birmingham, the process began with the maintenance director and key maintenance personnel, who examined all sections of vehicle-repair manuals. Through this process, individual tasks were described and defined. These tasks were then reviewed extensively with operating foremen and mechanics to determine precision of definition. At the outset, the jobs described were, at best, somewhat tentative. After time and experience had been accumulated, additional modifications to the definitions were implemented. Allowance was made in the computer program for a high degree of flexibility in the job-code-definition process. This permitted a considerable degree of freedom in adding, deleting, and modifying job codes that experience had proved to be an important feature of the computer program. When job codes are developed and become operational, the codes are permanently stored in the data base of the computer program and are called forth simply by job-code number.

Time Cards

The time card is intended to capture all of the relevant information needed to run the system and to provide such tests of the information as are necessary to provide adequate verification with data stored in the computer. Certain information, such as employee name and job-code description, is stored in the master files of the computer. When the employee number is entered, the computer will respond with the employee name, which is compared by the operator with the name that appears on the time card. Similarly, when the job code is entered, the computer responds with the job description, which is compared with that written on the card. Vehicle number and fare-account code are similarly controlled. Date and base rate will apply to all future activities on the time card unless modified by the program operator.

The computer must have information regarding the completeness of the job in order to properly process the activity. Many times a job will be started in the morning, dropped, and picked up later in the workshift. The program is designed to accommodate these circumstances and has been modified recently to deduct 30 min of lunchtime from any activity on demand. This iteration in the program was included to avoid the necessity to punch in and out of a job-code activity simply because of breaks. Other features of the program permit a redefinition of pay rate whenever a mechanic performs an activity outside of his or her normal work classification. Furthermore, overtime work can be readily added to the system.

After all of the workday activities have been entered, the MIS program will automatically generate a nonproductive entry that charges the nonproductive job code the difference between the time the employee actually accounted for and the normal 8-h workday. This report provides documentation for review of employee performance by foremen and other supervisory personnel. The total posting time for the 52 time cards of Birmingham-Jefferson County Transit Authority's maintenance department requires approximately 2.5 h/day.

The Computer System

The program is written in BASIC, which is a readily transferable language. The program is processed by an HP3000 computer that has a cathode-ray tube (CRT) unit located on the premises and that is connected with a high-volume modem that is linked by telephone to the computer service bureau. The program can be operated by clerical personnel with minimal training. This limited training is in part the result of internal controls and the question-and-answer style of the conversational BASIC program. Specific features of the overall program are as follows:

1. The time-card loading program (a) provides date-validation, employee-verification, job-code-validation, and vehicle-number checks and balance with the fare-account coding system; (b) permits computation of total elapsed time for work performance and storage of jobs in progress; (c) automatically calculates work time for jobs delayed; (d) reports specific jobs that exceed average work time; (e) handles special calculations such as work time, including overtime, lunch break, and allotments; and (f) permits time-card corrections to be readily made.
2. The excess-time program requires an explanation to be entered on all activities for which excess time has occurred and automatically calls up work tasks that require such explanations.
3. The employee master program provides for the addition, deletion, and modification of employee names and numbers; requires the confidential code for access; and provides the capability to change rates for employee.
4. The fare-account master program provides for the addition, deletion, or modification of fare-account codes and descriptions.
5. The job-code master program provides for the addition, deletion, or modification of job codes and specific descriptions.

All of these key program elements are explained to every employee in the maintenance department. Once the program procedures are understood, operating employees need only complete daily time sheets to provide the necessary record-keeping capabilities. In this manner, the maintenance MIS program has had little or no influence on daily maintenance-work activities.

ACHIEVEMENTS OF THE MAINTENANCE MIS

The Birmingham-Jefferson County Transit Authority has been using this maintenance MIS for approximately a year. During that year, it has become apparent that data-processing efforts can be readily implemented at transit operating properties. The maintenance personnel in Birmingham have become quite familiar with the reporting requirements, and these requirements have had little adverse impact on daily work activities. In addition, the data-processing system has provided the type of information necessary for supervisory and management control of maintenance activities. Specific records on individual work performance, as well as detailed maintenance records for each bus, are available for analysis. Specifically, it would appear that labor productivity in the maintenance department has increased significantly as a result of these data-processing efforts. During a recent nine-month period, overtime has been reduced to one-third that of the similar period of the prior year. This productivity has improved not only because the employee is aware of the monitoring capability but also because of the additional training that has been focused on many employees. Evidence of results can be seen in the FY 1980 budget; maintenance costs were reduced to little more than 96 percent of the prior year's cost over a similar nine-month period, whereas other operating functions continued to experience double-digit inflationary increases.

Maintenance is a significant area of cost incurrence in the public transit industry. As transit operations continue to expand, further management attention must be directed to maintenance problems. In Birmingham, experience with data processing and analysis of maintenance labor requirements has yielded some tangible benefits. It is hoped that, by means of further analysis and review, additional cost savings can be identified and implemented.

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Work Sampling as a Performance Measure for Maintenance Functions

MATTHEW K. du PLESSIS

The way in which two work-sampling studies were used as tools for objectively measuring activity levels in transit-vehicle maintenance shops is discussed. Positions ranging from utility worker to foreworker were sampled in four shops to determine how time was utilized, i.e., productively or nonproductively. The results of the studies are summarized and their implications examined. Improvements were found as a consequence of recommendations implemented after the first study; however, foreworker control over the work force was found to be insufficient in both studies. Increases in essentially nonproductive activities were attributed to decreased work load, and the issue of sufficient work load raised the possibility of adjustment of staffing levels. The data compiled from the work-sampling study were used to estimate the potential for reducing staff through attrition and transfer.

Managers in transit agencies today are vitally concerned with the effective use of their employees. Underutilized employees mean lower operating efficiency and, therefore, higher costs. Although they are not usually involved in direct labor supervision, managers are responsible for providing the necessary control to ensure that workers are fully productive and that costs are kept down. However, determination of the amount and type of control to apply requires that managers get accurate information on the work being done and on the effort being applied. Often the issue is how to evaluate fairly the feedback given by different supervisors and foreworkers on the performance levels of their employees. The question for managers, then, is how to objectively determine the amount of productive time that exists for various position classifications, shifts, and shops.

One prevalent method of objectively measuring productive time is a work-sampling study. The advantages of using work sampling for measuring people's activities are that

1. It is a widely accepted, low-cost, work-study technique;
2. Many positions or machines can be analyzed at the same time by one analyst;
3. People who have little technical background are able to do the actual sampling; and
4. Observations can be made over a long period of time so as to compensate for variations in the work performed.

One of the objectives of this paper is to familiarize the reader with the procedure of performing a work-sampling study. The other is to present an example of how work sampling can be used as a performance measure in maintenance shops.

STUDY OBJECTIVES, DESIGN, AND IMPLEMENTATION

As in any study, there are some basic steps a person must follow to successfully complete the analysis. The following description of the studies conducted at San Francisco's Bay Area Rapid Transit (BART) will outline the seven steps that constitute a work-sampling study.

Discover the Need for a Study

In 1976, BART was experiencing a car-availability problem. Shop management felt that the low number of cars released to revenue service was caused by low productive time in the shops. Since BART was planning to expand service, it was imperative that the car count be increased. Therefore, shop management decided that an objective work study should be conducted by the industrial engineering group that had just been formed within BART.

Define the Objectives

The purpose of performing the work sampling studies was twofold: (a) to analyze the production time of the work force and to quantify it by activities (subsequent studies would reveal the changes that had occurred) and (b) to identify and recommend solutions to problems that affect productivity. Naturally, additional research would be required to achieve the latter objective.

Decide on the Accuracy Desired

Work sampling was a new concept to the maintenance personnel at BART. Therefore, BART management decided that an accuracy of ±3 percent was necessary. This accuracy requirement would necessitate a large number of observations but, at the same time, would assure the employees that the results were reliable.

To determine the number of observations necessary to achieve the ±3 percent accuracy, an estimate had to be made of the amount of nonproductive time in the shops. Rather than make a short preliminary study to derive an estimate, an approximation based on past experience was used in the calculations. The required number of observations could then be determined from the formula or nomograph found in any textbook on work sampling (1).

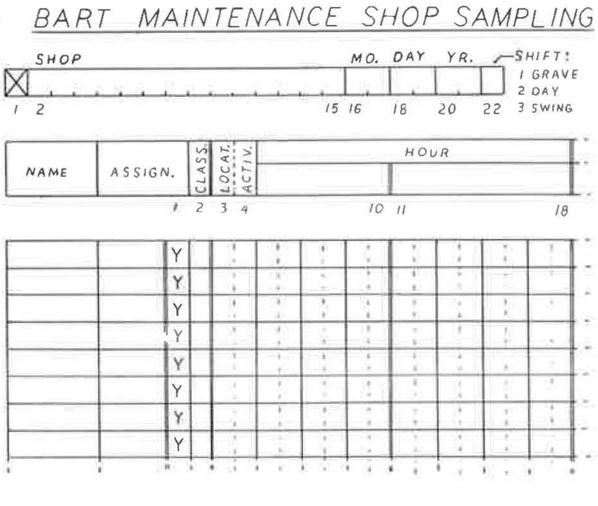
Design the Study

An informal review of the shops was first made to determine the work activities and shop locations that should be measured. An important limitation was that the smaller the percentage of occurrence, the larger the number of samples required. For this reason, various activities and locations were grouped together in one category. In the end, 20 activities and 16 locations were delineated and coded for easy notation on the sampling sheets. The list of locations, activities, and job classifications is shown below.

Location:

A-Pit
B-Floor service and inspection
C-Floor main shop at Hayward Yard (OHY)
D-Pad
E-Yard
F-Foreworker's office
G-Shop office
H-Blow pit
I-Secondary repair shops (OHY)
J-Stock room and storage room
K-Tool room
L-Electronics technicians shop
M-First floor upholstery shop (OHY)
N-Parts cleaning area
O-Contractor shops (OHY)
P-Unknown or other

Figure 1. Work-sampling form.



BART MAINTENANCE SHOP SAMPLING

SHOP ☒ MO. DAY YR. SHIFT: 1 GRAVE 2 DAY 3 SWING
1 2 15 16 18 20 22

NAME ASSIGN. CLASS LOCAT. ACTIV. HOUR
1 2 3 4 10 11 18

Y
Y
Y
Y
Y
Y
Y
Y

Activity:

1. Direct Work
A-Work on car
B-Work on components
C-Set up or tear down
D-Operate machine tools
E-Operate heavy equipment
F-Obtain parts
G-Clean up
H-Material handling

2. Direction
I-Direction and instruction
J-Talk to management
K-Talk to engineer
L-Talk to inspector

3. Clerical
M-Paper work

4. In Transit
N-Carrying something
O-Carrying nothing

5. Other
P-Personal time, idle, make-work
Q-High-railer, move crew
R-Technical manuals
S-Unknown
T-Other
U-Union business
V-Trainee school
W-Tools

Job Classification:

A-Transit-vehicle mechanic III
B-Transit-vehicle mechanic II
C-Transit-vehicle mechanic I
D-Transit-vehicle mechanic trainee
E-Electronics technician III
F-Electronics technician II
G-Electronics technician I
H-Utility
I-Foreworker II

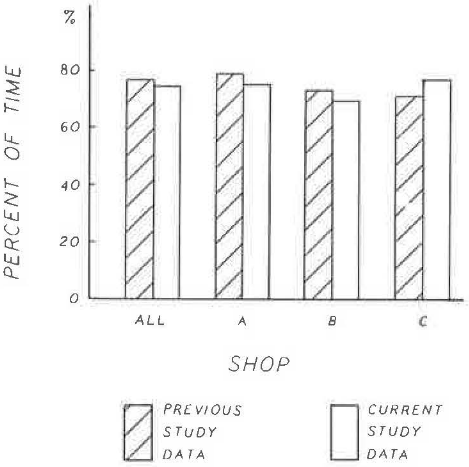
Each sample then consisted of two letters: The first letter indicated the location and the second, the activity.

The sampling sheet was designed so that (a) data could be keypunched directly from it and (b) analyses by shops, shifts, job classification, or hour of the day could easily be made. A portion of the form is shown in Figure 1. Each line of sampling is identified with the employee class entered in column 2. The columnwise location of the samples in conjunction with a certain shift implicitly identifies the samples by hour. For example, on a swing-shift sampling, samples recorded between columns 11 and 18 are identified as having been recorded between 5:00 and 6:00 p.m. The name and assignment columns on the form are provided only for the convenience of the analyst. In practice, this section was cut off the completed sampling sheets at the end of a shift and given to the shop steward. This was done to further elicit cooperative response from the workers by assuring

Table 1. Work-sampling results.

	Location				
Activity	Pit	Floor	Office	Unknown or Other	Total
Direct work (h)					
On car	250	100	0	0	350
On component	10	40	0	0	50
Other	150	105	5	0	260
Direction (h)					
Instruction	20	25	55	0	100
Clerical (h)	15	5	20	0	40
Other (h)					
Personal	60	40	25	0	125
Unknown	0	0	0	75	75
Total (h)					1000

Figure 2. Productive time for all employees.



them that they were not being personally evaluated.

Other decisions were made about the number of observers and their qualifications and about the times and places for making the observations.

Do the Sampling

The actual sampling was done over a two-month period. Four to eight observations of each shop employee's activity and location were recorded during each hour of the shift. Data were not collected during break and lunch periods. Samples were collected during the graveyard, day, and swing shifts at all four shops. More than 200 employees were sampled in the course of the study. The type of employees studied ranged from utility worker to foreworker.

Dissect and Compile the Data

One of the more laborious and time-consuming tasks in work sampling is to reduce the data to meaningful figures. To manually compile all the analyses desired in these studies would have taken a month or more. Fortunately, a computer program was developed to sort and compile the data. The program produced work profiles showing the breakdown for various categories, such as all employees, transit-vehicle mechanics, electronics technicians, foreworkers, all or individual shops, and all or individual shifts.

A simplified sample of a work profile is shown in Table 1. Columns for the percentage breakdown and the precision interval are not shown. Rows that indicate the totals, percentage breakdown, and precision intervals for the locations could also be added.

Work activities were condensed into the two categories of productive and nonproductive functions. Graphs such as the one shown in Figure 2 were then prepared to aid in comparisons of the various shops, shifts, and job classifications for both the current study and the previous study. The graphs permit the quick identification of shops or shifts that had low productive time or that had undergone large changes.

Deduce and Describe Conclusions and Recommendations

Analyses of the data and observations made by the management engineers during the sampling provided the basis for several major conclusions and recommendations. These are discussed below.

RESULTS OF THE STUDIES

First Study

The first study identified three major problems that were impairing shop productivity:

1. Lack of foreworker control over work force,
2. Inadequate production planning, and
3. Inadequate job organization.

Foreworkers were observed spending excessive amounts of time in their offices and not enough time on the shop floor and in the pits where the work force was located. Thus, they were unable to effectively manage the workers' activities. Furthermore, in planning the work for the shift, foreworkers were not using the schedule produced by the Maintenance Control Division. Assignments were being planned after the start of the shift, and little planning was being done to set up the shop with work for the start of the next shift.

The foreworkers also had difficulty in keeping the shops busy for the entire shift. Car movements were not being coordinated effectively, and changes of assignments were not anticipated. These difficulties and others resulted in large amounts of nonproductive time, which meant that overall shop productivity was low.

The following key recommendations were developed by the study team in conjunction with shop management:

1. Provide better foreworker supervision--restructure the foreworkers' day so that a majority of their time is spent at the various work locations rather than idle in their offices.
2. Institute more effective shop scheduling--have the foreworkers adhere to the Maintenance Control Division's schedule and have them arrive prior to the start of shift to prepare assignments and coordinate the setting up of work in the shop.
3. Expedite shop car movements--have the foreworkers provide tighter planning and scheduling of high-railer car movements to ensure a steady flow of work into the shop.
4. Reduce shop idle time--institute a hiring freeze to counteract the large amounts of nonproductive time recorded in the shops and provide tighter management control over contract break periods, clean-up activities, and shift start.

As a result of the study, various changes were made. Offices of the fishbowl type were constructed on the floor of shops that did not have such a setup. In the heavy-repair shop, the foreworker's desk was moved from the general office to the middle of the work bay, which enabled the foreworker to see almost all the employees in the shop from that position.

A hiring freeze was imposed on shop personnel. In addition, staff adjustments were made; electronics technicians (this position was found to have higher nonproductive time) from some of the less-productive shifts were moved to shifts that had more work. Shop management also had the meetings at the start of the shifts take place on the shop floors instead of in the lunch rooms.

The study was part of a successful effort by shop management to increase the average daily car count. The average daily car count went from fewer than 250 cars to more than 350 cars released per day. The improved car count enabled BART to expand to seven-day service.

Second Study

Observations made and data compiled during the second study showed that production planning and job organization had improved since the first study. Schedules produced by the Maintenance Control Division were being followed. Job assignments were being prepared by the foreworker prior to the start of the shift. The early arrival of the foreworkers also facilitated a smooth shift change and allowed for the prompt dispatching of work crews at the start of the shift. The amount of time on the high-railer had decreased and, generally, there was a steady flow of work through the shops.

At the same time, however, foreworkers' control over the work force was still insufficient, and the amount of nonproductive time for all employees in all shops had increased slightly. The foreworkers were again found to spend a large amount of time in their offices. One important exception was the heavy-repair shop. Having the desk out in the open on the shop floor seemed to increase the foreworkers' involvement with the employees. The nonproductive time for the heavy-repair shop employees was also found to have decreased.

Another area found to be hampering the effectiveness of the work force was the unavailability of parts. An investigation into the inventory operation revealed that parts were out of stock as a result of incorrect computer data on the number of parts available in the various storerooms. These incorrect data were caused by inaccurate or missing requisition slips, which stemmed from unattended storerooms and lack of supervision.

The following recommendations evolved from the second study.

1. Foreworkers should provide better control over the work force. Specifically, they should be more involved with the employees on the shop floors and in the pits, should give clear direction, and should improve motivation.
2. The amount of nonproductive time should be reduced to an acceptable level by pursuing one or both of two alternatives: First, employees should be enabled and encouraged to be fully productive during their shifts. This presupposes that there is sufficient work available to keep them occupied. If it is determined that there is an insufficient work load, then the second alternative, to reduce the work force through attrition and transfer, must be given serious consideration.
3. The inventory operation should be improved by establishing better control over the storerooms so as to ensure that information is completely and correctly submitted. This would require that the storeroom personnel be provided with closer supervision.

The issue of sufficient available work was raised because at several times during the study the shops ran out of work. This naturally led to an increased number of observations of workers being idle or performing nonproductive tasks. Shop personnel maintained that these were unusual situations. However, the data on improved car reliability and better maintenance procedures made it clear that the amount of work was decreasing. At the same time, other modification work was increasing. The question of appropriate staffing levels had to be addressed.

In recommending a reduction in staff, the study team used the data compiled from the work sampling to develop estimates of the potential number of employees that could be reduced. First, an achievable short-term goal for percentage of nonproductive time was established. This figure was subtracted from the actual percentage of nonproductive time found in each shop to ascertain the excess nonproductive time. This excess percentage was multiplied by the average attendance per shift during the study to determine the estimated excess staff. An example of such a staffing analysis is shown below. The analysis was done separately for transit-vehicle mechanics and for electronics technicians.

Shop	Average Number of Employees per Shop	Excess Nonproductive Time (%)	Estimated Number of Excess Staff
A	15	10	1.5
B	18	15	2.7
C	22	8	1.8
Total	55		6.0

CONCLUSIONS AND IMPLICATIONS

The work-sampling studies had provided BART managment with definitive measures of the level of activity in the vehicle-maintenance shops. At the time of the first study, BART management felt that the low car availability was a result of low production time in the shops. The work-sampling study showed clearly that the percentage of nonproductive time was high. As objective data, the results of the study were a convincing basis for the corrective actions taken--the hiring freeze and foreworker training.

The second work-sampling study demonstrated that the activity level was again down, even though the car count remained high. Management was then required to consider the reduced amount of work available in the shops as a result of improved car reliability and better maintenance procedures. The study also brought to management's attention the problems in the inventory operation.

These work-sampling studies gave management information essential to the performance of the control and planning functions. Performing the studies on a periodic basis gave the studies an audit type of character that highlighted changes in activity levels for various shifts and job classifications. As can be seen from the experience at BART, work sampling is an effective tool for objectively measuring activity levels in maintenance shops.

ACKNOWLEDGMENT

Credit must be given to the other management engineers involved in the work-sampling studies: Charles Goldenberg, Robert Hookey, and Margurite Fuller. Charles Goldenberg was primarily responsible for the design of the project and for the development of the computer program used to compile the data. I would also like to thank those who re-

viewed drafts of this report.

REFERENCE

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Priority-Setting Method for Road Maintenance

HENRY M. STEINER AND ROBERT J. LYNCH, JR.

The Bureau of Indian Affairs (BIA) is responsible for maintaining approximately 25 500 miles of low-volume rural roads on the 179 Indian reservations. The BIA provides services to the Indian tribes through an agency organization that is located either on or near the reservation. The procedures described in this paper provide the BIA agency road engineer with a method for ranking the relative economic importance of the various routes within the reservation road network. This ranking provides a quantifiably supportable starting point for the tribal leaders to introduce the noneconomic considerations (i.e., the social needs and preferences of the tribes) to develop a maintenance priority listing that includes both economic and noneconomic considerations. A benefit-cost analysis approach is used. Input data currently available at BIA were identified and adapted to be used at the agency-tribal level without computer support. The method, described in the context of the BIA situation, is equally applicable to other activities involved with decision making about maintenance of low-volume rural road systems.

The Bureau of Indian Affairs (BIA) is responsible for maintaining approximately 25 500 miles of roads that are open to the public on the 179 Indian reservations. In 1978, this included 4777 miles of paved road, 3225 miles of gravel-surfaced road, and 17 546 miles of earth road (1).

The BIA provides services to the Indian tribes through an agency organization that is located either on or near the reservation. Usually a small maintenance section within the Branch of Roads at the BIA agency level maintains the roads on the one or more reservations that the agency serves. These maintenance sections consist of 8 to 10 persons and about the same number of pieces of (in most cases) antiquated, fully depreciated equipment. (For example, one agency road-maintenance section we visited in 1978 had a nine-person payroll, six road graders, one bulldozer, one oil distributor, one low-boy trailer, and one roller to maintain 948 miles of roads on 10 reservations.) In the practical sense, the agency road-maintenance section does the best it can with available resources to maintain the several hundred miles of roads within its responsibility. It not only must provide some semblance of scheduled maintenance to keep the roads open but must also be responsive to the changing day-to-day maintenance priorities specified by the tribal leaders. An agency road engineer, who heads a Branch of Roads, functions as the technical advisor to the tribes and is responsible to the agency superintendent for reservation road-construction and road-maintenance programs.

The agency road engineer works with the tribal governing body to establish road-maintenance priorities so that the highest level of service possible within funding limitations is provided. Since there are insufficient resources to provide optimum maintenance for all reservation roads, some trade-offs must be made. This is a two-step trade-off process. During the formal band analysis (described below), the tribal governing body determines what portion of the banded funds allocated to the tribe will be devoted to road maintenance. At a later time it determines how the road-maintenance funds will be applied to the reservation network. To facilitate this two-step process, we proposed, as a part of a research project conducted by George Washington University for the BIA, a simplified priority-setting method for road maintenance that can be used at the agency level. This paper describes the general approach and illustrates the method in the BIA context.

For the past few years, the BIA has used a system known as band analysis as a tool to provide opportunity for the local tribes to affect the budgetary process. Priorities established by the tribes provide the basis for determining total funding levels and distribution of funds to the various programs at the BIA level. This system does not provide additional funds but, rather, gives tribes a chance to allocate money among programs within established funding limits. Road maintenance is a banded program. Road construction is not a banded program.

ECONOMIC BENEFITS AND COSTS OF ROAD MAINTENANCE

The principal economic benefit of road maintenance is the avoidance of increased user costs that will result if maintenance is not performed. The user costs consist of vehicle-running and travel-time costs that will increase as road condition deteriorates. Poorer road-surface condition means slower average vehicle-operating speeds that account, in large part, for the increased user costs.

If the construction of all roads were based solely on economic considerations, each road route could be required to justify its own maintenance based on economic benefits that result from the avoidance of increased vehicle-running and time costs. However, many rural roads in the United States, including BIA roads, have been constructed or surfaced based on social considerations and the stated preferences of the county or reservation population. For example, a road to a religious shrine used only once or twice a year might have been paved, even though traffic alone would not have justified such an expenditure for economic reasons. Thus there may be benefits other than reduced vehicle-running and time costs to be considered in the establishment of road-maintenance priorities. If a road that has been paved as a result of social considerations is not maintained, it could eventually deteriorate to the point that it is no longer passable.

If this occurs and if the original justification for paving the road is still valid, rehabilitation of the road will require a significant expenditure of BIA road funds. Therefore, in addition to the economic benefit of the avoidance of increased vehicle-running and time costs, an economic benefit to be considered for roads is the reduction in the level of future maintenance and reconstruction expenditures that will be required to provide the same service standards if maintenance is not done in a timely manner on such "social" roads (2). For this case, where we are assuming equivalent annual maintenance costs, if road reconstruction is expected to cost F dollars at the end of n years, it is worth A dollars per year for maintenance to avoid the future reconstruction costs. This is the economic relationship shown by the equal-payment-series sinking-fund formula, which is A = F[(A/F) i,n], where i is the discount rate and the factor for the given i and n can be read from interest tables.

Since the maintenance priority-setting method does not include consideration of social factors, the priority for roads that cannot be justified on a strictly economic basis must be integrated into the maintenance priority listing based on tribal preferences. If a given road route has been paved because of erroneously established preferences and has a very low current use, the tribal governing body might well consider acceptance of a lower service standard for that route rather than its abandonment. However, it is up to the tribe to make such noneconomic decisions on maintenance. Thus a maintenance priority listing ranked according to diminishing benefit/cost (B/C) ratios provides a quantitatively supportable initial listing to be adjusted by the tribal governing body to best meet the overall needs of the reservation within funding limitations.

The method proposed to assist the tribal governing bodies in establishing the reservation road-maintenance priority listing is based on a benefit-cost analysis approach. Benefits to the Indian people are the avoidance of increased vehicle-running and time costs that will result if a road segment is allowed to deteriorate through lack of necessary maintenance. The costs considered are those of maintaining the road in its current condition so that user costs will not increase.

INPUT DATA REQUIREMENTS

The input data required to support the road-maintenance priority-setting method are

1. Average daily traffic (ADT) and the vehicle mix,
2. Road-condition inventory,
3. Vehicle-running and time costs, and
4. Road-maintenance costs.

The basic approach was to identify and use data readily available to BIA. It was also desired to have data in a form that could be used at the operational level (agency-tribal) without the necessity for computer support. The BIA Road Inventory and Needs Study (Turquoise Books) provides data on the existing BIA road system, including ADT and road-condition information by route for each reservation (3). Figure 1 is a sample page from the Southern Pueblos Turquoise Book for a road route on the Acoma Reservation. The Turquoise Books are a useful source of information to support economically based road-maintenance and construction priority-setting methods. Each of the input data requirements is discussed below as it relates to the proposed priority-setting method for road maintenance.

ADT and Vehicle Mix

The Turquoise Book shows an estimated ADT figure for each arterial and collector road route. During field trips it was reported to us that the figures recorded as existing in 1974 were, in many cases, still high compared with the actual 1978 ADT. It was not possible, however, to obtain data about the vehicle mix on the Indian reservations or any evidence that such information might be available. Since Indian-owned vehicles operating only on the reservation need not have a state license plate, it

Figure 1. Sample route sheet and benefit-cost calculation.

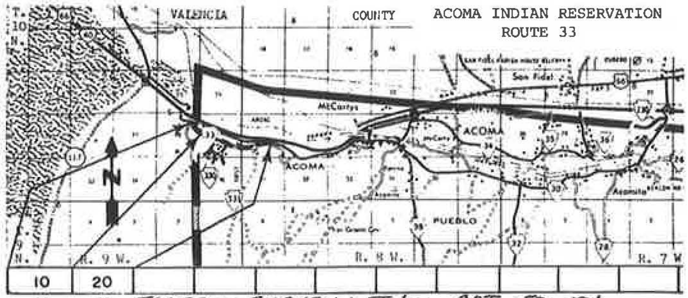
```
AREA          M   ALBUQUERQUE
           (CODE)            (NAME)
AGENCY      20  SOUTHERN PUEBLOS
           (CODE)            (NAME)
RESERVATION    703 ACOMA PUEBLO
                 (CODE)      (NAME)
ROUTE 0033          2          2.4
          (NO.)   (CLASS)  (LENGTH MI.)

ESTIMATED COSTS FOR IMPROVEMENT
   RIGHT OF WAY                    M-$
   INCIDENTAL CONSTRUCTION             24.0
   GRADE & DRAIN                      216.0
   BASE AND/OR SURFACING              192.0
   BRIDGES

              TOTAL                M-$ 432.0

DATE OF THIS REPORT      05/02/77

SECTION NUMBER                                10      20
COUNTY                                        61      61
CONGRESSIONAL DISTRICT                         2       2
STATE                                         NM      NM
LENGTH                              (MILES)   .2     2.2
BRIDGE NUMBER                         (NO.)
       LENGTH                        (L.F.)
SURFACE WIDTH                         (FT.)   24      24
        TYPE                                ERTH    HBIT
SHOULDER WIDTH                        (FT.)    0       2
         TYPE                                       ERTH
ROADWAY WIDTH                         (FT.)   24      28
RIGHT OF WAY WIDTH                    (FT.)   67      67
ADT (EXISTING)                        (YR.) 1974    1974
    (EXISTING)                     (V.P.D.)   50      50
    (ESTIMATED FOR YEAR 1990)(V.P.D.)         75      75
ADEQUACY DESIGN STANDARD NO.          (NO.)    8       8
FUTURE SURFACE TYPE                         HBIT    HBIT
RATING                                        49      72
   SURFACE WIDTH & TYPE                (25)   12      25
   SHOULDER WIDTH & TYPE                (6)    0       0
   STOPPING SIGHT DISTANCE              (8)    8       0
   NON-PASSING SIGHT DISTANCE           (6)    0       0
   HORIZONTAL ALIGNMENT                 (8)    8       8
   GRADIENT                             (6)    6       6
   SAFETY                               (6)    0       0
   FOUNDATION CONDITION                (15)   12      15
   WEARING SURFACE CONDITION           (10)    0       8
   DRAINAGE CONDITION                   (5)    3       5
   SHOULDER CONDITION                   (5)    0       5
```



TRAFFIC SURVEY: Total ADT <u>50</u> vpd
Cars <u>20</u>, Buses <u>5</u>, Pickups <u>20</u>, Trucks <u>5</u>

SECTION 10 EARTH FAIR*

$B = [20(.09^{*}) + 5(1.201^{*}) + 20(.088^{*}) + 5(.501^{*})]\ 365\ \frac{\text{days}}{\text{yr.}}$

$= \$4{,}406/\text{mi/yr.}$ (Users' VOC savings)

C (Road maint. Cost) = \$721/mi/yr (From Table 2)

SECTION 10 $B/C = \frac{4{,}406}{721} = \boxed{6.11}$

SECTION 20 HBIT FAIR*

$B = [20(.021^{*}) + 5(.255^{*}) + 20(.018^{*}) + 5(.095^{*})]\ 365$

$= \$923/\text{mi/yr}$

C = \$1,560/mi/yr (From Table 2)

SECTION 20 $B/C = \frac{923}{1{,}560} = \boxed{0.59}$

* From Table 1.

Table 1. Wearing-surface condition ratings.

Computer Code	Turquoise Book Rating	Priority-Setting Method Classification
0 No surfacing	0	–
1 Generally good (adequate)	10	Good
2 Serious to moderate deficiences (extensive repair, replacement, and/or rehabilitation required)	8	Fair
3 Condition critical for users (needs reconstruction of either the paved or gravel surface)	4	Bad
4 Condition critical (needs reconstruction of both the base course and paved surface)	2	Bad

Table 2. Total vehicle-running and travel-time costs.

Road Type	Road Condition	Average Speed (mph)	Cost ($/vehicle mile)			
			Passenger Car	Bus	Pickup	Truck
Paved	Good	45	0.128	0.727	0.142	0.415
	Fair	35	0.136	0.855	0.149	0.455
	Bad	25	0.157	1.110	0.167	0.550
Gravel	Good	35	0.166	0.919	0.183	0.519
	Fair	25	0.180	1.155	0.192	0.595
	Bad	15	0.225	1.777	0.236	0.844
Earth	Good	30	0.199	1.064	0.214	0.597
	Fair	20	0.214	1.419	0.227	0.719
	Bad	10	0.304	2.620	0.315	1.220

Note: Uniform speed on level tangents as of December 1977.

is not possible to examine state motor-vehicle-department statistics to determine the reservation's vehicle population and mix.

A determination of current ADT and vehicle-mix information on the various routes is required to support economically based methods for road-construction and road-maintenance priority setting.

Road Condition Inventory

The Turquoise Books provide condition ratings for foundation, surface, drainage, and shoulders for each route section, whereas the method proposed in this paper classifies road types and conditions as follows:

Surface Type	Surface Condition
Paved	Good, fair, or bad
Gravel	Good, fair, or bad
Earth	Fair

A match had to be made between the two systems. The method proposed herein uses wearing-surface condition rating to classify paved and gravel roads in accordance with the categories given above and the Turquoise Book descriptions and ratings (see Table 1).

The condition of earth roads, which are not considered all-weather roads, may fluctuate from good to fair to bad and back to good several times in a given year. For this reason, the method considers earth roads to be in fair condition (average) throughout the year but to deteriorate to a bad condition if required motor-grader bladings are not made.

The agency road engineer makes periodic inspections of the reservation road routes. These can provide more up-to-date road condition information than that contained in the Turquoise Book. There appears to be no difficulty in using existing road-inventory condition information to support the proposed method, particularly if Turquoise Book revision procedures can be adapted to provide for more-frequent updates of those data subject to periodic change.

Vehicle-Running Costs

Vehicle-running cost data are provided in the 1977 American Association of State Highway and Transportation Officials (AASHTO) Manual (4). Appendix B to that manual provides vehicle-running cost factors as functions of speed, highway gradient, and horizontal curvature for three types of vehicles. The components of running costs included in the tables of that appendix are fuel (excluding taxes), engine oil, tires, maintenance, and the portion of depreciation that varies with mileage driven.

The vehicle classes considered in the proposed road-maintenance priority-setting method are (a) 4-kip passenger cars, (b) buses (using 12-kip single-unit truck-running costs), (c) 5-kip pickup trucks, and (d) 12-kip single-unit trucks.

January 1975 vehicle-running costs are provided in the AASHTO Manual for the passenger car and the 12-kip truck. The manual indicates that the 12-kip truck class includes buses. Vehicle-running costs for these three classes of vehicles were obtained directly from appendix B of the AASHTO Manual and updated to December 1977 by individually updating each of the cost factors through use of the consumer price index (CPI) and producer price index (PPI), as specified in the manual. The manual treats pickups and commercial delivery trucks as passenger cars "because their costs do not vary significantly enough, considering their usual proportion in the total vehicle stream, to warrant a separate category." Because of indications that a large proportion of the vehicles on Indian reservations are pickup trucks, the research team included pickups as a separate vehicle class.

The method uses running costs at uniform speed on level tangents. The application of highway gradient and horizontal curvature and other considerations would overly complicate the procedure and provide a higher degree of apparent precision than is warranted by the data or needed for the method.

The AASHTO Manual provides running costs on high-design pavement only. The multiplicative factors to convert running cost on paved roads to cost on gravel and stone or earth roadway surfaces are provided in graphic form (4, p. 62). The curves were plotted from data extracted from Winfrey (5). Running costs on gravel and earth roads were calculated by using these conversion factors. The manual states that the effect of gravel and earth roads on highway speeds will vary with condition but, in general, the design speeds of high-design loose-surfaced roads are probably 20 percent, or about 10 mph, below those for surfaced roads and about 15 mph lower for unsurfaced sections. These assumptions were used as a basis for the average operating speeds shown in Table 2.

Travel-Time Costs

The value of travel-time savings is an important component of user benefits associated with road construction or maintenance. The unit value of time is usually the most significant decision variable in an economy study, and its magnitude should, first of all, be acceptable to the decision maker. Although considerable research has been conducted in an attempt to assign a dollar value to travel time, the choice of time value is an empirical judgment about the value of time and a social judgment of the weight to be given to these valuations. For purposes of demonstrating the method, the research team used the following vehicle loading and time values:

1. Passenger car: 1.8 passengers (including driver) per vehicle x $1.00/h per passenger = $1.80/h travel-time cost.
2. Bus: 32 passengers/bus x $0.50/h per passenger = $16.00/h per bus + driver wages at $8.00/h = $24.00/h per bus total travel-time cost.
3. Pickup truck: same as passenger car = $1.80/h per vehicle travel-time cost.
4. Single-unit truck: 1.25 occupants/truck (driver 100 percent of the time plus helper 25 percent of the time) x $8.00/h per occupant = $10.00/h per vehicle total travel-time cost.

Tables 2 and 3 present a summary of the total vehicle-running and travel-time costs and the savings per vehicle mile by road type and condition and vehicle type. The tables use data and updating procedures set forth in appendix B to the AASHTO Manual and the travel-time cost assumptions given above.

Road-Maintenance Costs

A survey of literature on road maintenance was made in an attempt to locate costing data for support of the proposed road-maintenance priority-setting method (6-9). Most of the literature examined presents information not readily adaptable to BIA use.

BIA currently uses a computerized road-maintenance model to support its road-maintenance costing estimates. The outputs from that model, contained in the BIA Summary Report of Road Maintenance Data, provide estimates of total road-maintenance funding needs for optimum maintenance of all BIA reservation roads. The program uses the basic data contained in the BIA Road Inventory and Needs Study computerized files. General maintenance costs for each route are calculated as a function of road type, ADT, roadway width, and wearing-surface condition. Snow and ice removal, which is not a part of the general maintenance, is shown as a separate cost on the summary report. Snow and ice removal is not included in the proposed method, which considers general maintenance priorities only.

The BIA computer road-maintenance costing program sums the maintenance input factors for ADT, roadway width, and wearing-surface conditions for the particular type of road surface. The sum of the individual input factors multiplied by the current average cost per mile per year for optimum maintenance for the particular surface type and by the length of the road segment gives an estimated total general maintenance cost for the road segment.

The research team considered the BIA road-maintenance model to be an available source of road-maintenance costing information suitable for the maintenance priority-setting method. To permit use at the agency-tribal level without the need for a computer, the general maintenance factor was calculated for each combination of road type, ADT, roadway width, and surface condition. Factors for ADTs up to 100 are shown in Table 4. Each factor multiplied by the appropriate current estimated optimum maintenance cost gives tabled costs of maintenance that can be easily used at the agency-tribal level. As average optimum maintenance costs change, new general maintenance cost-per-mile figures can be quickly calculated, since the general maintenance input factor remains unchanged.

The use of this average annual maintenance cost per mile implies that maintenance operations and costs will be constant for each year. This presupposes that a mile of road will receive the same amount of annual attention each year. Obviously

Table 3. Savings per vehicle mile.

	Savings ($/vehicle mile)			
Road-Type Comparison	Passenger Car	Bus	Pickup	Truck
Good paved versus fair paved	0.008	0.128	0.007	0.040
Fair paved versus bad paved	0.021	0.255	0.018	0.095
Bad paved versus bad gravel	0.068	0.667	0.069	0.294
Good gravel versus fair gravel	0.014	0.236	0.009	0.076
Fair gravel versus bad gravel	0.045	0.622	0.044	0.249
Bad gravel versus bad earth	0.079	0.843	0.079	0.376
Good earth versus fair earth	0.015	0.355	0.013	0.122
Fair earth versus bad earth	0.090	1.201	0.088	0.501

Table 4. Calculation of annual road-maintenance cost.

				Roadway Width							
				8-20 ft		21-22 ft		23-24 ft		25 ft and Over	
Road Type	Average Cost of Optimum Maintenance[a] ($/mile)	ADT	Road Condition	Factor	Cost ($/mile)	Factor	Cost ($/mile)	Factor	Cost ($/mile)	Factor	Cost ($/mile)
Earth	869	0-50	Fair	0.75	652	0.78	678	0.83	721	0.89	773
		51-100	Fair	1.00	869	1.03	895	1.08	939	1.14	990
Gravel	1281	0-50	Good	0.93	1191	0.98	1255	1.00	1281	1.02	1307
			Fair	1.03	1319	1.08	1383	1.10	1409	1.12	1435
			Bad	1.21	1550	1.26	1614	1.28	1640	1.30	1665
		51-100	Good	1.08	1383	1.13	1448	1.15	1473	1.17	1499
			Fair	1.18	1512	1.23	1576	1.25	1601	1.27	1627
			Bad	1.36	1742	1.41	1806	1.43	1832	1.45	1857
Paved[b]	1950	0-50	Good	0.65	1268	0.67	1306	0.68	1326	0.70	1365
			Fair	0.75	1462	0.77	1502	0.78	1521	0.80	1560
			Bad	0.93	1814	0.95	1852	0.96	1872	0.98	1911
		51-100	Good	0.75	1462	0.77	1502	0.78	1521	0.80	1560
			Fair	0.85	1658	0.87	1696	0.88	1716	0.90	1755
			Bad	1.03	2008	1.05	2048	1.06	2067	1.08	2106

[a] Costs in use by BIA in December 1977.
[b] High-design bituminous mat > 2 in.

this is not the case, for all of the paved road segments will not require extensive maintenance each year. Greater expenditures on one segment will be balanced by lesser outlays on another. Maintenance-cost figures are assumed to represent the long-run equivalent annual costs of maintaining a mile of road.

PRIORITY-SETTING METHOD

The objective of the method is to provide the agency road engineer with a quantitative procedure for ranking the relative economic importance of the various routes within the reservation road network. This is a supportable starting point for the tribal governing body to rearrange the listing to meet the overall needs and political and social preferences of the tribe.

It is postulated that

1. Traffic on reservation roads is primarily Indian related, and vehicle-running and travel-time cost savings will accrue as benefits to Indians;
2. Failure to accomplish required maintenance during a given year will allow the road route segment to deteriorate to the next lower condition and create increased vehicle-running and travel-time costs; and
3. Many BIA roads may have been constructed or surfaced as a result of social considerations and tribal preferences (such roads may have a maintenance B/C ratio < 1.0 if only economic factors are considered.

Calculation of B/C Ratio

The output from the method provides a road-maintenance priority listing for performing maintenance ordered by decreasing values of the B/C ratio calculated for each reservation road route. Benefits of performing maintenance are the savings in vehicle-running and travel-time costs that accrue to the Indians by maintaining the road and by not allowing it to deteriorate to the next lower condition, at which vehicle-running and travel-time costs are higher. Tables 2 and 3 reflect the road deterioration pattern employed in the method, the total vehicle-running and time costs at the average speeds estimated for each road type and condition, and the savings between road-condition levels. Annual vehicle-running and travel-time cost savings (benefits) for a road in a given condition are calculated by

$$B = \sum_{i=1}^{4} \Delta C_i (ADT_i)(365) \tag{1}$$

where

B = benefits ($/mile per year);
i = vehicle type;
ΔC = difference in vehicle-running and travel-time costs by vehicle type between present road condition and the next lower condition category, as shown in Table 3 ($/vehicle mile); and
365 = number of days in a year.

For example, what are the annual benefits per mile of maintaining a 24-ft gravel road in fair condition if the ADT is composed of 20 passenger cars, 5 buses, 20 pickups, and 5 single-unit trucks? Use of Table 2 and the above formula yields

$$B = [(20)(0.045) + (5)(0.622) + (20)(0.044) + (5)(0.249)]\ 365 = \$2239/\text{mile per year}.$$

Costs are the annual maintenance costs for the particular road type, ADT, surface width, and surface condition, as shown in Table 4. That table indicates that the cost for maintaining in fair condition a gravel road that has a 24-ft-wide roadway and an ADT of 50 is $1409/mile per year.

The B/C ratio for this road route would then be

$$B/C = (\$2239/\text{mile per year})/(\$1409/\text{mile per year}) = 1.59.$$

Maintenance of this road route is justified based on economic considerations.

The B/C ratio is calculated for each reservation road route in this manner.

Preparing the Reservation Road-Maintenance Priority Listing

The research team found that the BIA Road Inventory and Needs Study (Turquoise Book) description for each road route provided a useful work sheet for applying the method. Copies of the route-report pages can be reproduced and used by the agency road engineer as work sheets to record results of traffic surveys as well as any changes to road-surface condition that might affect the calculation of the maintenance B/C ratio for that route.

The updated BIA road-route pages, the vehicle-running and time-cost data shown in Table 2, and the road-maintenance costs shown in Table 4 provide the necessary data to apply the method. The B/C ratio is calculated on the road-route page as illustrated in Figure 1, the Turquoise Book page for Acoma Route 33. Assumed updated traffic data on which the B/C computation is based are also shown. This example is more cluttered than a typical work sheet would be because of the parenthetical explanatory material included that would normally not appear.

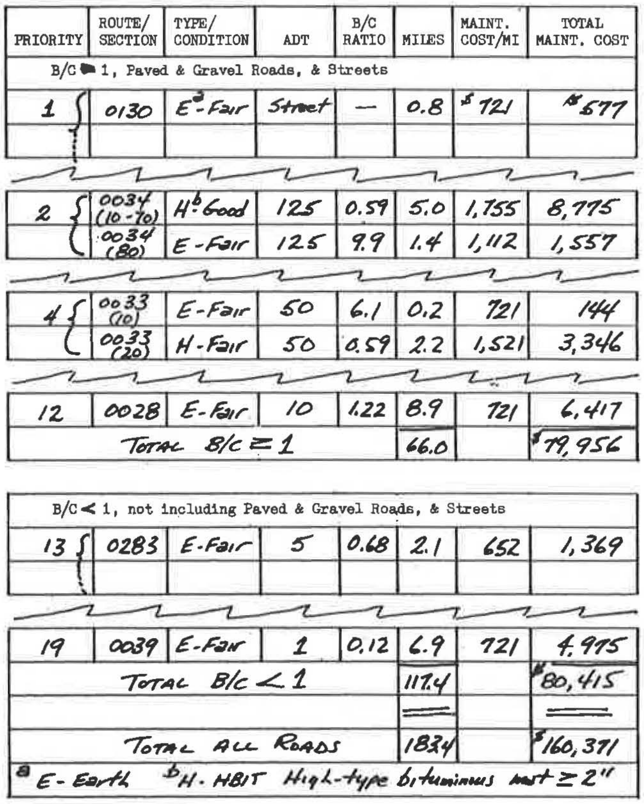
Such a calculation is made for each reservation route. The B/C ratio is recorded in the upper-right-hand corner of the sheet to facilitate later sequential arrangement of the route pages in order of decreasing B/C ratio.

After maintenance B/C ratios for all routes within the reservation have been calculated and road-route pages arranged in order of decreasing B/C ratio, the agency road engineer may draw up the reservation road-maintenance priority listing by using a locally prepared work sheet. Figure 2 gives examples of entries on such a priority listing for the Acoma Reservation, which is one of the 10 reservations supported by the Southern Pueblos Agency. Figure 2 assumes that the tribal governing body had specified to the agency road engineer that all existing paved and gravel roads and streets would be maintained even though the B/C ratio for such maintenance might turn out to be < 1.0. Therefore, all paved and gravel route segments and streets are listed with the earth roads as having a B/C ratio > 1.0.

Road Maintenance Map

To show the roads on which the maintenance effort should be concentrated, the paved and gravel roads and streets and those earth roads that have a maintenance B/C ratio > 1.0 are plotted on the highway system map for the particular reservation. The other roads for which the B/C ratios are < 1 are indicated in a contrasting manner. Such a plot is shown for part of the Acoma Reservation in Figure 3. The plot and the priority listing provide a useful starting point for the tribal governing body to look closely at the roads--earth, gravel, and paved--that have a maintenance B/C ratio < 1.

Figure 2. Example of priority-list entries for the Acoma Reservation.



PRIORITY	ROUTE/ SECTION	TYPE/ CONDITION	ADT	B/C RATIO	MILES	MAINT. COST/MI	TOTAL MAINT. COST
B/C ≥ 1, Paved & Gravel Roads, & Streets							
1	0130	E[a]-Fair	Street	—	0.8	$721	$577
2	0034 (10-70)	H[b]-Good	125	0.59	5.0	1,755	8,775
	0034 (80)	E-Fair	125	9.9	1.4	1,112	1,557
4	0033 (10)	E-Fair	50	6.1	0.2	721	144
	0033 (20)	H-Fair	50	0.59	2.2	1,521	3,346
12	0028	E-Fair	10	1.22	8.9	721	6,417
Total B/C ≥ 1					66.0		$79,956
B/C < 1, not including Paved & Gravel Roads, & Streets							
13	0283	E-Fair	5	0.68	2.1	652	1,369
19	0039	E-Fair	1	0.12	6.9	721	4,975
Total B/C < 1					117.4		$80,415
Total All Roads					183.4		$160,371

[a] E-Earth [b] H-HBIT High-type bituminous mat ≥ 2"

Questions that might be asked are, Is there some reason why the road must be kept open even though the maintenance B/C, based on economics considered in this method, is < 1? If it is to be kept open, what trade-offs do we make on road maintenance or on other banded reservation programs to allow for its maintenance? Would it be possible to abandon certain of the roads that have a maintenance B/C < 1?

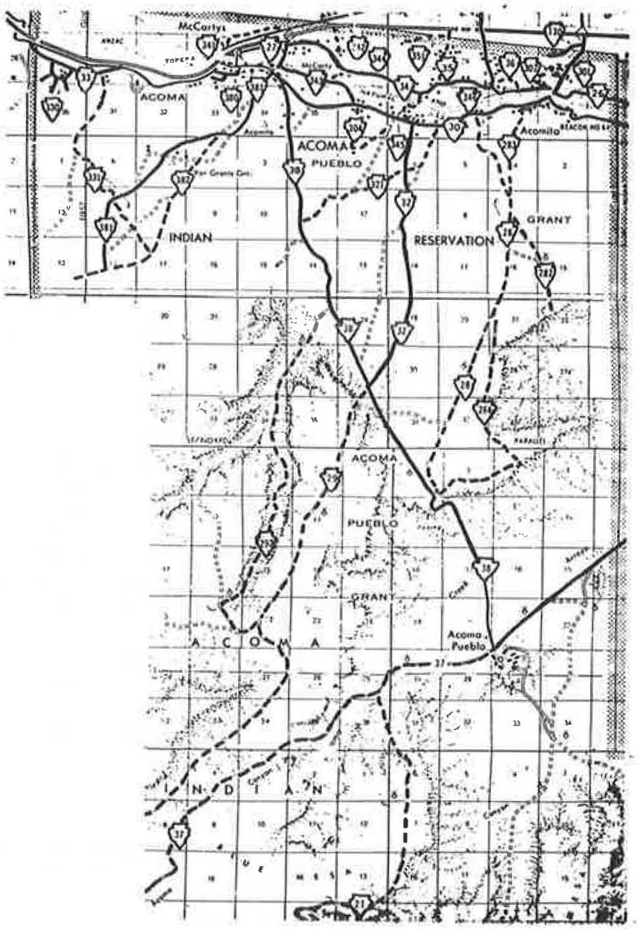
CONCLUSION

This road-maintenance priority-setting method can be applied readily at the operating level, in this case the agency-tribal level. The output provides understandable information that can cause the on-scene decision makers to examine their low-volume road network in the light of economic realities. A road-maintenance priority listing based solely on economic factors provides a supportable starting point for the application of noneconomic criteria in order to rearrange the listing in accordance with overall road needs and the political and social preferences of the users.

ACKNOWLEDGMENT

The research on which this paper is based was sponsored by the Division of Transportation of the Bureau of Indian Affairs under a U.S. Department of Interior contract. We are (as of summer 1980) applying this method to develop road route maintenance-priority listings for the 10 Southern Pueblos Agency reservations in the Albuquerque, New Mexico, area. This work is being accomplished under another U.S. Department of Interior contract.

Figure 3. Road-maintenance plot.



——— Roads with Maintenance B/C ≥ 1, Streets, Paved & Gravel Roads

- - - - Roads with Maintenance B/C < 1, not including Paved & Gravel Roads

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Highway-Maintenance Simulation Model

JAMES M. PRUETT AND RODOLFO G. PERDOMO

The functions related to highway maintenance are often conceptually simple (repair the highway) and administratively complex (alternatives related to priorities, approaches, resources, and many others). Highway maintenance administrators are often faced with questions for which little or no definitive information exists and are asked to make the proper decisions. The highway-maintenance simulation model described in this paper is intended to help alleviate this problem by providing a flexible highway-maintenance decision laboratory in which alternative courses of action may be tested. An earlier version of the model included several simplifying assumptions that made actual considerations regarding highway maintenance operations unrealistic (e.g., one manpower type, one equipment type). The model development is now complete, however, so that typical highway maintenance dilemmas may be considered by using the simulation program. This paper includes an example that depicts model input, output, and interpretation of the results for one particular situation. Also included is a description of how the model works to simulate a highway maintenance operation.

Highway maintenance is an important function that is administratively complex. Virtually everything related to highways requires maintenance, and there are many types of maintenance activities. There are many types of highway surfaces; numerous types of defects, which often have varying approaches available for repair; a spectrum of weather conditions; an infinite number of terrain variations; a divided land-work area that may have overlapping assignments of responsibility; an ever-present element of danger; a variety of equipment types, quantities, and breakdown rates; and various numbers, levels, and types of personnel and abilities. This sampling of variations does not even mention the human considerations of personalities, interests, absentee levels, and interpersonal relationships. Also omitted from this discussion have been the unique and demanding tasks of planning, priority assignment, scheduling, monitoring, and controlling the maintenance activities. In addition, it should be mentioned that these tasks are all performed in a political arena, supported by the taxpayers' money. There is little question, after even cursory assessment, that administration of highway maintenance activities is a difficult and challenging task.

This paper describes an analytical tool capable of lending order, to some degree, to a number of the dilemmas that are frequently faced by highway maintenance administrators. A highway-maintenance simulation model is described that considers many of the interrelated factors already mentioned and provides quantitative output that allows orderly analysis of the situation.

PREVIOUS WORK

A thorough review of earlier work related to this area of study has been previously presented (1). The only directly related work described was the study Application of Systems Analysis to Highway Maintenance (completed in 1968) that was sponsored by the Office of Research and Development of the Bureau of Public Roads and conducted by the National Bureau of Standards (NBS) in two phases. Phase 1 was a broad examination of highway maintenance operations and the identification of problem areas in which systems analysis techniques appeared to offer some promise. At the conclusion of the phase 1 effort, it was decided that the remaining time and resources should be directed toward the application of some systems technique to a particular problem identified in the first phase. The development of a highway-maintenance simulation model was selected.

The phase 2 effort (2) was not sufficient, however, to develop a working simulation model to its full potential. The program had extensive detail in some areas and showed excellent potential in many ways, but it had one significant shortcoming: The simulation model would not run, at least not to the extent intended. The major error seems to have been in including too much detail too soon, in addition to the project's time restriction.

The NBS work did, however, indicate the promise and potential for simulation analysis of a highway maintenance system. Ten years later, sponsored jointly by the Louisiana Department of Transportation and Development (LDOTD) and the Federal Highway Administration, researchers in the Department of Industrial Engineering at Louisiana State University (LSU) began a new look at the same problem--the development of a highway-maintenance simulation model.

The LSU group had several advantages. First, they started with the NBS study; second, computer capabilities and simulation languages had been developing rapidly during the previous 10 years; third, highway maintenance engineers within LDOTD were eager to help develop such an analytical tool. This paper describes the model developed by the combined efforts of LSU researchers and LDOTD highway maintenance engineers.

MODEL OBJECTIVES AND MODEL USE

The purpose of the simulation model is to aid users in better understanding the response and behavior of the highway maintenance system under different conditions, that is, to provide highway maintenance engineers with a computer-aided simulation laboratory in which to test and evaluate various alternative courses of action.

For example, suppose a particular highway maintenance district requests two 5-ton dump trucks. How might such a request be evaluated? How much would these two trucks really help? Would they cause additional staff shortages? Would they sit idle too much of the time--and how much is too much? The

Table 1. Comparison of level of detail in early model and in current model.

Item	Early Model	Current Model
Number of possible work activities	Five	Unlimited number
Weather	Good, bad	Graded weather types and severity, some weather-dependent activities, seasonality
Seasons	One	Any number (typically, four)
Resources (personnel, equipment, and material)	One type each	Many types of each resource; detailed differentiation in terms of capabilities, costs, and availabilities for each resource
Resource locations	One location for all resources	Many locations possible for each; may be considered individually
Time	One year only, standard five-day week	Many years, workweek of one to seven days

example presented later in this paper deals with this problem in some detail, but a brief analysis is warranted here.

The district in question would be evaluated thoroughly enough to define the input values required for the model. (Input is presented in more detail when the example problem is considered later in the paper.) Such items as the quantity of each equipment type and personnel type available, the absenteeism and equipment breakdown rates, evaluation of work activities (frequency, severity, and location of problems), and travel distances throughout the district are obviously needed if any reasonable analysis is to be made. After these values are entered into the model, the current situation can be simulated (i.e., run). Model output should be reasonably close to actual records for some test period (e.g., the last fiscal year) if the model input provided is fairly good and if the district's productivity is close to the work standards used for prediction.

Next, the input may be changed to reflect two additional dump trucks, and the model is rerun. Again, a close look at output values may reveal any number of ideas. For instance, it is possible that the dump trucks were vastly underutilized. Perhaps insufficient material was available, or the wrong types of equipment operators were available, or the particular work activities that were generated did not require use of the trucks, or extremely bad weather happened to occur. Each of these possible reasons could be found through evaluation of the output provided. Subsequently, other related situations could be simulated, further enhancing user understanding of the situation.

For example, suppose the previous run of the model indicated that a shortage of equipment operators of type 1 negated much of the productivity possible by the inclusion of the two additional dump trucks. A third run of the model could be quickly executed that included some reasonable increase in the number of type 1 operators available (e.g., maybe three more). Similar evaluation of performance reports for the district might indicate that the increase in operators (along with the addition of the dump trucks) was precisely the action needed. At this point, administrators charged with evaluating requests from maintenance districts would have a realistic (though certainly not exact) view of the probable results of the possible actions they might take about the district's request for equipment.

It is important to understand that the simulation model is not expected to find the optimum solution for any particular problem. Rather, it is intended to provide sufficient statistical results to adequately describe the state of the system over a period of time during which a particular course of action was followed.

MODEL OVERVIEW

Model Structure: A Brief Discussion

The highway-maintenance simulation model has evolved to its current state. Part of its evolution was planned, and part of it has been developed to meet needs that were not recognized initially. Earlier versions of the simulation model included a number of simplifying assumptions that have since been modified to make the model more realistic. For example, at one time the model considered only one type of personnel, one type of equipment, and one type of material, whereas the current model includes consideration of many types of each. Nevertheless, the basic modeling approach has remained constant throughout the duration of the project. A comparison of several simplifying assumptions from the early stages of the model's development are presented in Table 1 along with the current model status. The comparison is intended to illustrate the evolutionary process the model has undergone and to provide a glimpse into the level of detail included.

The simulation model was developed by using the FORTRAN-based simulation language known as General Activity Simulation Program IV (GASP IV). This language was chosen because of its flexibility and because it was known from the project's outset that the model would probably be modified on numerous occasions.

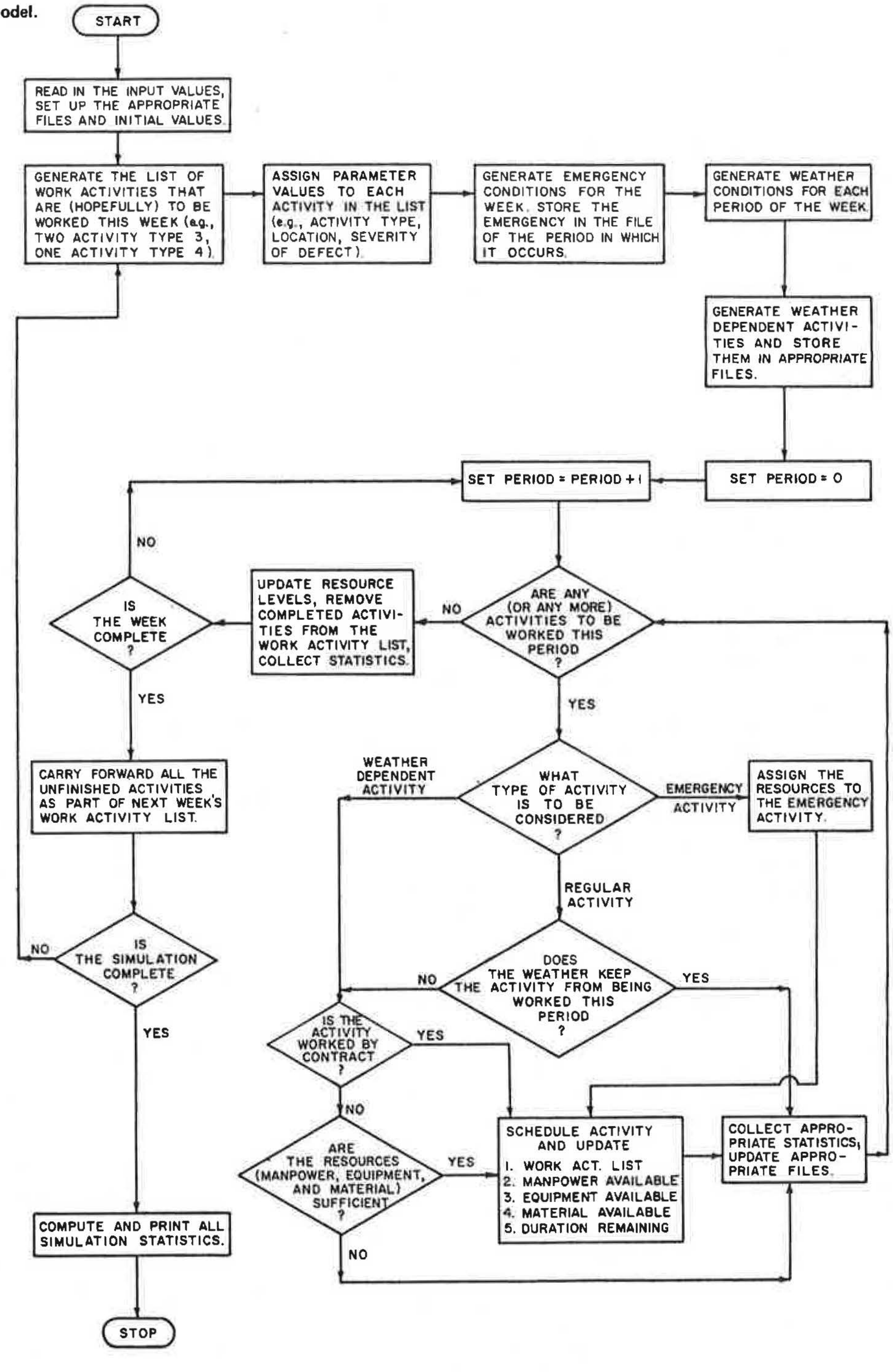
The key to understanding the model lies in gaining a basic understanding of the files that are used. The list below indicates the files employed.

File	Contents
1	Event file (specified by GASP IV)
2	Work-activity list for period 1
.	.
.	.
.	.
15	Work-activity list for period 14
16	List of work activities that have been generated but that have not yet been scheduled and are interruptible

File 1 contains events that are to be processed by the model. GASP IV dictates that file 1 be used in this manner. Files 2 through 15 are the work-period files. [A work period represents a half day (4 h) in the model.] File 16 contains interruptible activities that have not yet been scheduled. (Interruptible activities are simply activities that may be preempted at any subsequent scheduling period by an activity of higher priority, even though the interruptible activity has not been worked to completion.) Activities in file 16 are moved to the next period's file and are considered after the activities already in that file have been examined for possible scheduling.

In general, the simulation model accesses the files as follows: (a) a list of the activities that are to be worked is created and stored in file 2, the first period's work file; (b) these activities are removed from file 2 one at a time and are considered for scheduling. A decision is then made regarding the activity--either it can be scheduled for work or it cannot. If it can be scheduled, that fact is noted and (c) it is placed in file 3 for work continuation in the next period or, if the work activity is complete after the current period, it is removed from the model. If it cannot be scheduled,

Figure 1. Flowchart for simulation model.



(d) the activity is placed in the next period's file and is considered again next period. This process of file manipulation is performed on each activity during each work period until the simulation is complete.

Model Logic

The model's logic (which follows the macro flowchart logic of Figure 1) is described next in an attempt to provide insight into the modeling approach and into the inner workings of the model itself. The simulation is begun by entering the necessary input values. This part of the model is extremely important since it provides the user with an opportunity to specify the particular conditions that are to be examined, as well as the values that establish the boundaries of the simulation. An example of the first type of input is the specifying of the number of dump trucks to be used in the simulation; an example of the second type of input is the value indicating the number of work periods that are to be simulated. An abbreviated list of the model's input is given below:

1. Single-value constants that provide limiting values for the simulation (e.g., number of work-activity types, number of years to be simulated);
2. Descriptions of activity types, equipment types, staff types, and range of weather conditions;

3. Distribution parameters for absenteeism and breakdowns of equipment;
4. Staff, equipment, and material costs;
5. Resource availability files (staff, equipment, and material);
6. Equipment characteristics file;
7. Point-to-point travel times;
8. Work-activity characteristics file (specification by activity type for each crew option, equipment, and staff needs; material needed; performance rate; indicators of effect of various weather types on work activity; etc.);
9. Probabilistic description of weather by season;
10. Information regarding preferences of base locations for personnel, equipment, and material ordered by location within the district (or parish);
11. Work-activity parameter sets for use in work-activity occurrence distributions;
12. Parameter sets for weather-dependent activities;
13. Parameter set for emergency-activity duration and time between occurrence specification; and
14. Simulation specifications (length of simulation, number of files, etc.).

Once these values are established, the actual simulation process may begin.

Based on the work-activity probability distributions entered as input to the model, a list of work activities that are to be accomplished is generated. Next, probability distributions read into the model at the outset (for items such as location and severity of the activity to be performed) are called, and a number of identifying parameters are specified for each work activity in the list. These activities are then stored in file 2 to be called on when actual scheduling begins.

Emergency activities, if any happens to occur, are generated next. These are not part of the normal sequence of work activities since emergencies occur at unexpected points in time. Therefore, an emergency activity is considered for scheduling during that period before any regular activities are considered.

Weather conditions for the week are generated next. Since the increment of time chosen for use in the model is a half day, 10 different weather conditions (1 for each period of the five-day week) are generated. These are stored in an array and referred to later.

A special set of weather-dependent activities is generated next. On reflection, the reason for such an activity type is apparent, i.e., some activities are worked only in specific weather conditions. For example, snow removal is necessary only when it snows. This type of activity is similar to an emergency activity in that its occurrence cannot be anticipated. It is different from an emergency activity, however, in that it is dependent directly on the weather. Once generated, these activities are placed in the file for the period in which they are to occur with top priority.

At this point, the simulation's clock is changed from zero to one. This means that period 1 is now to be considered for scheduling work activities. The file containing work activities for period 1 is checked. If any work activities are in the file, the activity that has the highest priority is removed first for possible scheduling. This activity may be an emergency activity, a weather-dependent activity, or some type of regular activity. Regardless of the activity type, a search of the resource files is made to see whether the activity can be worked with the resources available. This is quite an involved procedure because of the large number of possible resource combinations capable of satisfying the work-activity (i.e., job) requirements. Several factors must be considered. For example, it may be that the work activity can be accomplished through the efforts of more than one crew arrangement (and the most preferred one that is available should be chosen) and that more than one resource base location may be required to provide the necessary resources. Also, since the resources for an entire work activity must be accounted for, each type of personnel, equipment, and material need must be considered individually against the corresponding resource availabilities; the existing possibility of resource substitution should be included in the consideration. If consideration of the work activity is successful and acceptable resources are available to perform the task, the activity is scheduled, and each of the resource-availability files is updated.

Statistics are collected for the activity, and control of the simulation process returns to the question, Are any more activities to be worked this period? This question emphasizes the fact that the modeling process discussed so far has dealt with only one activity. Each activity in the work-activity file must go through the same process for each period during the course of the simulation.

Eventually, after all the possible work activities have been considered, the work period ends. At this point, some of the activities may have been completed, whereas others are still in progress. The completed activities are removed from the possible work-activity list, some statistics are collected, and consideration is given to the question, Is the week complete?

If the week is not complete, the period number is increased by one and the activities currently on the work-activity list (first, activities in the next work period's file and then activities in file 16) are again considered one at a time. If the week is complete, it is necessary to carry forward all the unfinished activities as part of next week's work-activity list. The activities already begun have a higher priority than those that have not yet been started.

Since the week has been completed, the simulation model next asks whether the entire simulation process is complete. If it is (and eventually, of course, it will be), all the final simulation statistics are computed and printed. If the simulation process is not complete, this means that another workweek is to begin and the processes of activity generation, emergency generation, weather generation, and so forth are performed again.

The simulation model was designed and developed to be able to address a wide variety of frequently occurring highway maintenance dilemmas. Therefore, a large number of statistics are collected during the model's execution and are printed at the conclusion of each simulation run.

None of the statistics actually claim to be "the" answer. The simulation results must be taken as a whole and examined in light of the particular situation being considered. Statistics provided by the model are

1. Input listing--a complete listing of all model input;
2. Quarterly performance report--report by activity type, which includes planned and actual quantities for material and labor hours used, total cost, cost per unit, and hours per unit, as well as labor cost, material cost, overtime labor cost, travel cost, fringe benefits, and operational service (contract) costs;
3. Activity frequency table--the number of occurrences of each type of work activity in each

section of the district (or parish);

4. Manpower characteristics table--a summary for each resource base location that lists by staff type the number of periods worked, the number of absentee hours, the number of overtime hours worked, the average number of staff units not assigned each period, the absenteeism cost, and the standby cost;
5. Equipment characteristics table--a summary for each resource base location that lists by equipment type the number of periods the equipment was in use, the number of hours the equipment spent in transit, the capacity of the equipment, the number of times breakdowns of the equipment occurred, and the average number of each equipment unit not assigned (leftover) to an activity each period;
6. Material characteristics table--a summary for each material base location that lists by material type the average number of each material type remaining in inventory, the number of times each material was required, the average demand for each material type per period, the number of times an activity could not be worked because of lack of material, and total material demand per year;
7. Time-loss table--a summary by activity number of the frequency and percentage of the reasons (such as insufficient staff, unavailable equipment, insufficient material, and bad weather) for time loss;
8. Time-loss breakdown by resource type--a more detailed version of the time-loss table that summarizes, for each activity, the number of times that each equipment and staff type caused a delay;
9. Personnel substitutions--a summary of the personnel substitutions performed during the period simulated, e.g., the number of times (work periods) that equipment operators of type i were used when less-qualified operators (type j) would have been adequate; and
10. Overall work-activity statistics--summary statistical values for each activity regarding its overall time in the system, including the number of occurrences, the average length of occurrence, longest and shortest activity time span, and others.

The example presented in the next section provides a more detailed look at the output.

As should be apparent at this point, the simulation modeling approach is very direct. Like most simulation models, the highway-maintenance simulation model is complex primarily because of the interrelationships that exist in the physical situation, i.e., in the actual highway-maintenance program itself.

EXAMPLE

Situation

The situation selected for this example is a fairly typical highway maintenance district. It consists of 30 men and 28 pieces of equipment. The district is currently recognized as producing at less than an acceptable level. There are many reasons for the poor productivity; some of the reasons are external (exceptionally large work load, poor weather conditions), and some are internal (insufficient resources). Highway maintenance engineers are asked to assess the district's activities and current status and to make recommendations to rectify the situation.

Input

The first step is to determine the district's present condition and to collect the necessary input values to allow the simulation model to be run. This step is of extreme importance, since it is on the foundation created by the input values that all future decisions are based.

Some of the input required is readily available and factual (e.g., the number of equipment operators of type 1); some of it requires research (e.g., weather parameters for each season of the year); and much of it requires good judgment (e.g., the effect that a particular poor weather condition has on an activity). Lists of work-activity types, staff types, equipment types, and material types are entered early in the input process, just after the entry of a series of single-valued variables. These single-valued variables include such things as the number of work-activity types, the number of resource base locations within the district, the number of material base locations, the number of weeks that the simulation is to be run, and several others.

Later, a series of input arrays are required that describe a multitude of circumstances, including absenteeism; breakdown rates; personnel costs; material costs per unit; initial availability levels for staff, equipment, and material; equipment characteristics; point-to-point travel distances; and variables that describe which operator types are required to work which equipment units. Also included among the arrays entered is the activity characteristics file. This array includes (for each activity type) the specifications of equipment, staff, and material required to do a particular task, as well as a performance rate (and a performance-rate variation factor), weather parameters (to describe the effect of various weather types on the activity), the overtime hours allowed per day, and a constant that tells whether the activity is interruptible.

After the activity characteristics file is entered, parameter sets (by season) for activity generation are entered. Also entered are a series of arrays that contain probabilities and related quantities dealing with the occurrence of emergencies, the resources required for these emergencies, the location of work activities, and the severity of the problem. It should be apparent that the amount of detail required in the form of input is significant. In fact, the GASP IV program requires one more set of values that defines its parameters before the input section may be called complete. At this point, after the input quantities are entered and the program is run, a close look at the output is warranted.

Output: Initial Run

The initial run is meant primarily to reflect current conditions. In this case, the output was sufficiently close to that expected to be used as the basis for change. Of course, it might be that further fine tuning of input values is necessary before the user can feel comfortable with the values generated.

The output provided a number of clues concerning the reasons for low productivity. Some of these are listed below.

1. Unused staff: The personnel units initially available of the five personnel types specified (foremen, equipment operator type 1, equipment operator type 2, equipment operator type 3, and labor utility) were 3, 9, 4, 1, and 13, respectively. Significant percentages of each manpower type were not used for productive tasks each period.
2. Unused equipment: Results similar to those for staff were found for equipment as well.

3. Stockouts: A number of inventory shortages were noted.

4. Time-loss reasons: Twenty-five activities were defined, and some of each were generated. It is expected that not all jobs could be worked, but it is hoped that the higher-priority jobs are worked consistently and that only lower-priority tasks are held up.

The initial run showed that, of the six top-priority jobs, staff was never a problem but that the main causes for the job not being worked were lack of equipment, inclement weather, and insufficient material, in that order. The problem of insufficient equipment may be further investigated by determining (at least among the highest-priority activities) which equipment units are being required. A brief look at the six top-priority jobs from the activity characteristics file shows the following needs (only the first-crew option is shown):

	Equipment Type									
Job	1	2	3	4	5	6	7	8	9	10
1	0	3	1	1	1	0	0	0	0	0
2	0	1	0	1	0	0	0	0	0	0
3	1	2	0	1	0	0	1	0	0	0
4	0	3	1	1	1	0	0	1	0	0
5	0	4	0	1	1	1	0	0	0	0
6	0	3	1	1	1	1	0	0	0	0

Each job (work activity) requires at least one equipment unit of type 2 and exactly one equipment unit of type 4. No other equipment type has as much demand. The difference between equipment types 2 and 4 lies in their availabilities. There are eight type 2 units available, but only one type 4 unit. This means that only one of the six top-priority jobs can be worked at any one time. An obvious alternative (although certainly not necessarily the best) is to obtain at least one more type 4 unit. Since the tool of simulation is being used, that equipment type may be added immediately and the situation revisited.

Output: Run 2

The results of the second run of the model were also quite revealing. Slightly more money was spent on maintenance activities (as expected with one additional piece of equipment); productive personnel use was up; productive use of equipment was increased (in fact, the addition of one type 4 unit increased the utilization for all the other equipment units as well); material use was increased; and successful scheduling of the higher-priority jobs increased significantly. So, as a first step, the addition of a single unit of equipment type 4 to the resources of the district appears to be a step in the right direction.

There are still deficiencies, however. There is still much more demand for work (i.e., planned work activities) than there are resources to accomplish it. Unavailable equipment is still the primary reason for work stoppage. Personnel and material shortages still exist at a relatively high level.

Subsequent Steps

Before considering other possible resource alternatives, a more thorough analysis of the initial situation is probably warranted. Two alternatives might be mentioned. First, it has been noted that weather conditions have contributed heavily to problems of scheduling work activities. A run in which weather parameters are slackened (i.e., statistically improved weather) might be performed to see what effect better weather might have on the situation. Or next, since all activity generation, defect severity, weather, and many other factors depend on random-number generation for their existence, another run with new random-number seeds (entered via GASP IV input) might be enlightening.

Assuming that the above alternatives do not change the basic problems encountered, the next logical step is to return to those factors that highway maintenance engineers can influence--primarily, those factors associated with scheduling policies and resource levels. An example of affecting scheduling policies may be described by considering a typical work activity's characteristics. Suppose that the work standard for the task of patching the road base specifies that a foreman, two equipment operators of type 1, one equipment operator of type 2, one equipment operator of type 3, and one laborer are required. If, however, it is common practice for operators to work out of class (e.g., a type 2 operator might perform the work of a type 1 operator), it would not be unreasonable for highway maintenance engineers to group resources (i.e., combine operator types), which might improve scheduling success.

Another similar alternative also deserves mention. Experience has shown that, even though the standard work crew may not be available, work may still be successfully accomplished at a rate approximating the standard rate. Such alternative work-crew arrangements could be entered as second and third crew options.

The most obvious actions that might be tried by highway maintenance engineers are, of course, those related to varying of resource levels. The next step for this particular example would probably deal with an increase in staff availability, but more detailed analysis might lead the analyst to try any of a number of alternatives.

Simulation performed in this manner does not yield instantaneous results. It is apparent that the analyst is still very much responsible for the alternatives tried and the decisions made. In fact, the process is much like that of actually making the changes in reality, but the time, cost, and hassle factors are reduced to a minimum.

SUMMARY

The highway-maintenance simulation model is an attempt to provide highway maintenance management personnel with a laboratory in which various decisions may be tested. As in all laboratory experiments, the results are not replicas of real-world activity. However, it is apparent that the model is of sufficient detail to provide output values that are reasonable approximations to reality and valuable aids to decision making.

The simulation model is currently operative on the LDOTD computer facility. As such, it has already been successfully applied. The work currently being done regarding the model may be classified as fine tuning. This includes such work as improvement in the form of output presentation, improvement in the input procedure, and complete documentation of the model.

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The simulation model is the result of a two-year project sponsored by LDOTD and the Federal Highway Administration. During this time span, a number of people have contributed to the research effort. The most significant contributions have come from LDOTD highway maintenance engineers Gerald Ray, John Melancon, and Robert Blouin, as well as research engineer S.C. Shah. To them and many others, our

sincere appreciation is given.

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Abridgment

Systematic Procedure for the Development of Maintenance Levels of Service

RAM B. KULKARNI, KAMAL GOLABI, FRED N. FINN, AND RUBIN JOHNSON

One of the basic requirements for the proper management of highway maintenance activities is the establishment of maintenance levels of service. A systematic methodology was developed for determining the maintenance levels of service that would maximize the user benefits subject to the constraints on available resources. A demonstration of this methodology for two maintenance problems is described. The necessary inputs for the methodology were obtained from the data base of information currently available to the Louisiana Department of Transportation and Development. The data base included information available in the literature, studies conducted within the department, information available from maintenance management systems, and experience and judgment of knowledgeable individuals within the department. Results of the analysis produced levels of service that were intuitively satisfactory. Sensitivity analyses were conducted to determine the impact of conditions such as budget cuts and changes in the relative weights of different considerations on the determination of optimum levels of service.

Maintenance levels of service are defined as threshold conditions at which maintenance is considered to be needed. At the present time, there is no systematic, structured procedure for establishing maintenance levels of service or for adjusting such levels when resources are constrained or increased. Woodward-Clyde Consultants has completed a study for the National Cooperative Highway Research Program (NCHRP) to develop a methodology for establishing levels of service based on well-documented principles of decision analysis.

The purpose of this report is to describe the methodology by means of a demonstration of the procedures for two maintenance problems in the state of Louisiana.

APPROACH

The methodology to select maintenance levels of service involves the following steps:

1. Structuring the problem,
2. Estimation of the effects of alternative maintenance levels of service on various considerations,
3. Evaluation of the effects of alternative maintenance levels of service,
4. Determination of the optimum combination of maintenance levels of service,
5. Making a sensitivity analysis, and
6. Formulation of recommendations.

Structuring the Problem

The following tasks are involved in structuring the problem:

1. Select maintenance elements (e.g., shoulders, pavement),
2. Select maintenance conditions (e.g., edge of traveled-way drop-off) for each maintenance element (e.g., shoulders),
3. Specify alternative levels of service for each maintenance condition,
4. Select considerations (e.g., safety) for each maintenance element (e.g., shoulders),
5. Select attributes (e.g., percentage of drivers who cannot recover control) for various considerations (e.g., safety), and
6. Identify the maintenance conditions (e.g., edge of traveled-way drop-off) that affect each attribute (e.g., percentage of drivers who cannot recover control).

For the demonstration example in Louisiana, two maintenance elements--shoulders and roadside vegetation--were analyzed. Edge of traveled-way drop-off and undesirable vegetation growth on the roadside were selected as the maintenance conditions of concern. Alternative levels of service that included the current level of service, as well as those better and worse than the current level of service, were included. The attributes considered for the example were percentage of drivers who cannot recover control of car after driving over the edge of the traveled way, percentage of change in pavement rehabilitation cost because of edge of traveled-way drop-off, index of pleasing appearance of roadside vegetation, and index of environmental pollution caused by herbicide spraying used in controlling growth of vegetation.

Estimation of Effects of Alternatives

The effect of alternative maintenance levels of service on a given consideration (e.g., safety) is estimated in terms of the attribute of the consideration (e.g., percentage of drivers who cannot recover control of the car). The effects were estimated in Louisiana by interviewing the department specialists for given attributes. To assist the specialists in the estimation, pertinent information and data available in the literature were reviewed with the specialists.

Because of limitations of applicability associated with information in the literature, it was concluded that this source could not be used directly to establish the effects or impact of levels of service on pertinent considerations.

Therefore, the specialists were asked to extrapolate the available information to the real-world situation, based on their experience and judgment.

Evaluation of the Effects of Alternatives

The objective of this step is to establish a preference (value) structure for evaluating the effects of alternative levels of service on various considerations, such as safety and aesthetics. The effects on the considerations are measured in terms of the selected attributes. For example, in considering an edge of traveled-way drop-off, the effect of level of service on safety is measured in terms of the percentage of drivers who cannot recover control of the car. The assessment of preferences involves two steps:

1. Assessing individual value functions of different attributes: The objective of this step is to determine how much better (or worse) one level of an attribute (e.g., percentage of drivers who cannot recover control of the car) is relative to another (e.g., level 5 versus level 10). This assessment is best done by those individuals in a state agency who are most knowledgeable about a given attribute.
2. Assessing value trade-offs between different attributes: If a decision problem involves multiple attributes and limited resources, it may not be possible to achieve the best levels of all the attributes. The decision maker, therefore, is required to think about how much he or she may be willing to sacrifice on one attribute (e.g., aesthetics) in order to improve another (e.g., change in rehabilitation cost). These value trade-offs determine the relative weights of the attributes. The assessment of value trade-offs should involve individuals who are responsible for setting and implementing maintenance levels of service.

The first step was completed in Louisiana during meetings with department specialists about edge of traveled-way drop-off and roadside vegetation control. The second step was completed during a group session that involved maintenance engineers both from headquarters and from the district offices. A Delphi procedure was used to obtain group consensus regarding value trade-offs between different attributes.

Determination of the Optimum Combination

The objective of this step is to determine the optimum combination of maintenance levels of service for all of the maintenance conditions included in the system. The criterion used for optimization is to maximize the overall value of highway-user benefits subject to the constraints of available resources (dollars, person days, etc.). The user benefits are specified in terms of the effects of levels of service on various considerations, such as safety, aesthetics, and protection of investment. The effects on these considerations are measured by the appropriate attributes, such as percentage of drivers who cannot recover car control, index of pleasing appearance, and percentage of change in pavement rehabilitation cost.

The resources required to maintain the current levels of service for edge of traveled-way drop-off and roadside vegetation growth were assumed for the base-case analysis. The optimum levels of service are

1. For the edge of the traveled-way drop-off, to repair when the drop-off is 1 in and
2. For vegetation growth, to mow 300 000 acres and spray 120 000 acres; this vegetation-control program would allow mowing grass full width before it reaches 8 in in urban areas and mowing grass 30 ft from the edge of the traveled surface after it exceeds 12 in in rural areas.

The costs of the selected policy are as follows:

Item	Available	Used
Material ($ 000s)	5130	5130
Labor (h 000s)	644	644
Equipment ($ 000s)	3380	3377

The attributes are evaluated as follows:

Attribute	Individual Value	Weighted Value
Safety (percentage of drivers who cannot recover car control)	1.000	0.438
Percentage of change in rehabilitation costs	1.000	0.321
Pleasing appearance	0.962	0.173
Environmental pollution	0.500	0.031

The value of this policy is 0.96.

The optimum levels of service provide the highest user benefits possible for the two maintenance conditions. No improvement in these levels of service would be possible even if higher amounts of resources were available. An examination of the contributions of the four attributes to the overall value reveals that the two attributes related to edge of traveled-way drop-off (percentage of drivers who cannot recover car control and percentage of change in rehabilitation cost) contribute 76 percent of the total value, and the roadside-vegetation attributes contribute the remaining 24 percent of the total.

Sensitivity Analysis

The objective of this step is to assess the influence of changes in some of the major inputs and assumptions on the selection of the optimum combination of levels of service. The output of this analysis would identify the parameters to which the selection of optimum levels of service is very sensitive. The assessment of such parameters would obviously warrant more careful consideration.

Formulation of Recommendations

Recommendations are formulated after an evaluation of the results of the base case and the sensitivity analyses. The recommendations should include (a) the optimum level of service for each maintenance condition in the system, (b) resources that would be used in implementing the optimum levels of service, and (c) situations (e.g., budget cuts) that would require significant changes in the optimum levels of service.

CONCLUSIONS

The effort in Louisiana shows that it is feasible to use the methodology developed in this project to select levels of service for highway maintenance that would maximize user benefits subject to the constraints of available resources. The types of inputs required for the analysis can be obtained from the data base of information currently available to a state transportation department. The data base includes information available in the literature, studies conducted within the department, information available from maintenance management systems, and experience and judgment of knowledgeable individuals within the department.

The methodology requires the assessment of value judgments regarding trade-offs between such considerations as safety, protection of investment, aesthetics, and environmental pollution. A Delphi procedure was used in Louisiana to obtain group consensus regarding trade-offs from a number of individuals who are responsible for selecting levels of service both in the field and at headquarters. Certain improvements in the implementation of the Delphi procedure would seem desirable based on the experience in Louisiana. However, the types of assessment questions that need to be asked in the Delphi procedure are certainly practical and relevant to individuals involved in highway maintenance.

It would be desirable to provide certain types of objective data to the participants in the Delphi exercise in order to obtain more consistent and reliable value judgments. Examples of such data include statistics on accidents resulting from driving over the edge of the traveled way at various depths of drop-off and surveys of user opinions regarding aesthetics of roadside vegetation under varying levels of service. These kinds of data are currently not available. The initial implementation of the methodology will identify the critical parameters on which objective data would be most useful. Limited studies to collect these data can be undertaken. The reliability of the results of the methodology would be expected to increase with the availability of additional data.

The computer program prepared for the use of the methodology facilitates the analysis significantly. The program is designed so that the assessed data can be directly input, and all parameters (such as value coefficients, relative weights, and regression coefficients) are computed internally in the program. This relieves the user of the burden of making external calculations, which would require some theoretical background in decision analysis techniques.

The demonstration example in Louisiana involved only 2 maintenance conditions--edge of traveled-way drop-off and roadside vegetation growth. However, a complete system of highway maintenance could involve 20 to 25 maintenance conditions of practical significance.

ACKNOWLEDGMENT

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Abridgment

Location of District Maintenance Centers by Least Transport Cost

Z. ANDREW FARKAS

The largest and most difficult cost to determine in the economic life of a U.S. Forest Service ranger district maintenance center is usually the transportation cost of personnel to the work sites. Decreasing this cost through optimum location of centers presents one of the best opportunities for energy conservation and increased efficiency. The method described here permits the determination of the total transport cost to each work site so that costs can then be contoured; the least-cost contour delimits an area that may be analyzed for site location. Location analyses of five districts estimated savings from relocation in three districts that ranged from $12 700 to $32 000 over the life of the facility.

Government regulations have mandated that investments in government facilities must be cost effective and must conserve energy. The Energy Policy and Conservation Act of 1975 requires a 20 percent reduction in all federal agencies' energy consumption by 1985, during a time of increasing demands on public resources. The U.S. Department of Agriculture Forest Service, the agency primarily responsible for managing federal timber lands, consumes a great deal of its energy allotment in the construction, operation, and maintenance of support facilities for land management.

The smallest administrative unit in national forests, the ranger district, is responsible for maintenance of roads on the forest road system and of recreation areas, trails, timber stands, and fire-prevention facilities. Ranger district maintenance operates out of a work center that may or may not be in close proximity to the ranger's office. Location of the ranger's office must take account of administrative and public access considerations, but the location of the maintenance center must be influenced by the spatial distribution of the work sites. In most cases the largest and most difficult cost to determine in the economic life of a ranger district maintenance center is the transport cost of personnel to the work sites. Decreasing this cost through optimally locating maintenance centers presents one of the best opportunities for energy conservation and increased efficiency.

Studies of the location of industries and public service facilities abound in the literature, and the concepts involved may be applied to the location of maintenance centers (1,2). If there were only one work site in a ranger district, location of the maintenance center to minimize transport cost would be simple: The maintenance center would be located at the site and the transport cost would be zero. However, when several sites "pull" at this maintenance center location, some analysis must be made to determine the location that will minimize transport costs to all sites. Each site exerts a pull that is a function of trip cost and the number of trips to the site. By hypothetically locating a maintenance center on each work site and by calculating the transport costs to every other work site, one can determine the total transport cost at each location. Contours of total cost (isocost lines) may then be derived. These total-cost contours would actually be the interpolated result of combining all the transport isocost lines emanating from each location. Once total-cost contours are formed from these several locations, the least-cost contour delimits an area that may then be analyzed for site location.

Contours of transport cost connect points of equal value. The least-cost contour serves as a boundary of an area in which, theoretically, transport costs are at a minimum. It should be noted that the only relevant portions of contours are at intersection points with the transportation network. Obviously, where no roads exist, transport costs would be much higher.

The first case study of this method occurred on the James River Ranger District of the George Washington National Forest in the mountains of western Virginia. The district is approximately 64 km (40 miles) long and 32 km (20 miles) wide. The objectives of the study were to test a method of analyzing the transport costs of work trips and to delimit an area of least transport cost for further site analysis of maintenance center location.

CASE-STUDY ANALYSIS

The location analysis of the maintenance center is based on the following formula:

$$C_i = \sum_{j=1}^{n} (D_{ij} \times V_c + W_a \times S_{ij})\, 2T_{ij} \quad (i = 1, \ldots, n) \tag{1}$$

where

C_i = total costs of transportation from a maintenance center location i to every other work site j,
V_c = vehicle operating cost per unit of distance,
W_a = average wage rate per hour for average number of crew members,
S_{ij} = travel time between i and j,
D_{ij} = distance from i to j, and
T_{ij} = total number of trips from i to j.

Thus, the formula takes into account total vehicle operating cost and labor cost of work trips. The first major step to derive values for the formula is to code the transportation network of the ranger district into links and nodes. The second step is to determine the lengths and travel times of the links. The nodes correspond to road intersections, changes in road standards, and work sites. In the third step, average wage rates, average number of work crew members, vehicle operating costs, and number of trips per unit of time to each work site must be determined. This information was estimated from district records and measured by field personnel.

The following assumptions were made for the James River study:

1. Each work trip is a single-destination trip to a work site.
2. The ranger's office, which is located for public access as well as for administrative needs, is a fixed location and is treated as a work site that attracts administrative trips.
3. Vehicle operating costs are assumed to be the same in both directions of travel.
4. Vehicle operating costs do not include the monthly fixed ownership rate, only the equipment-use rate, since the former does not vary by usage. Also, vehicle operating costs in this analysis do not vary by speed.
5. Several nearby work sites may be represented by one node, and trips are not differentiated by resource or activity purpose.
6. The number of trips to a work site is not affected by distance to the site.

The link values of length and travel time and the corresponding nodes were put into a matrix, and link speeds in kilometers per hour were calculated. By using the average number of persons in work crews multiplied by the average wage rate per hour and added to the vehicle operating cost per kilometer, a simple FORTRAN program calculated the cost per kilometer for link speeds from 8 to 89 km/h (5 to 55 mph). Following are the link speeds and transport costs for the James River Ranger District (1 km = 0.6 mile).

Link Speed (km/h)	Van Rate ($/km)	Pickup Rate ($/km)
8	3.19	1.52
16	1.69	0.85
24	1.19	0.62
32	0.94	0.51
40	0.79	0.44
48	0.69	0.40
56	0.61	0.36
64	0.56	0.34
72	0.52	0.32
81	0.49	0.31
89	0.46	0.29

The van rate represents the vehicle-use cost of $0.185/km ($0.296/mile) plus the crew cost for an average of four crew members at $6.00/h each divided by the average link speed. The pickup rate represents the vehicle-use cost of $0.170/km ($0.272/mile) plus the crew cost for an average of two crew members at $5.40/h each divided by the average link speed.

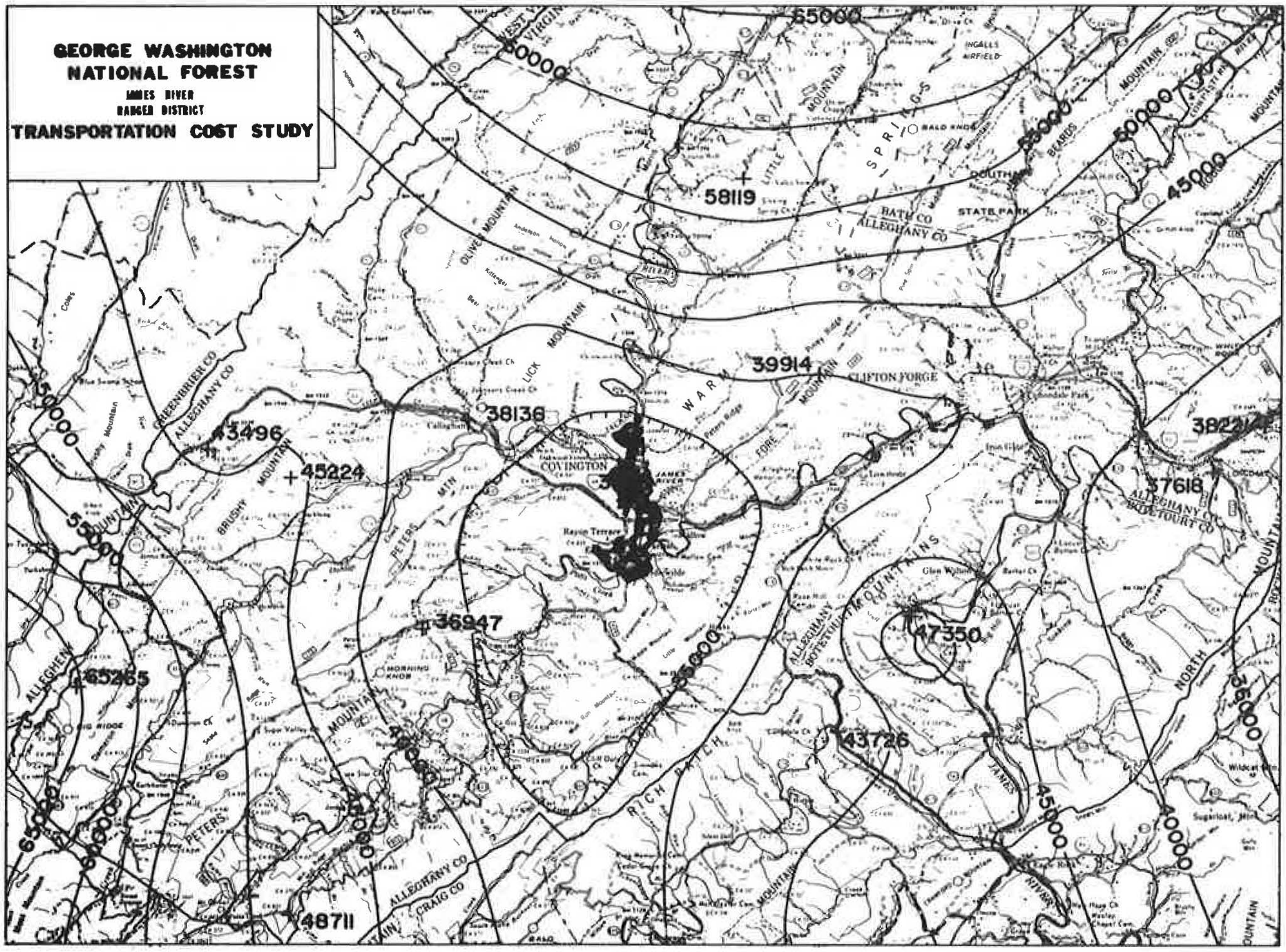
A linear programming transportation analysis determined the minimum-distance links from each work site to every other work site (3). The model multiplied link distances by each link's cost per kilometer and by number of trips to and from each work site. These calculations produced a location's total transport cost for work trips to every other site.

The transport cost calculations were made for two types of vehicles (pickup trucks and vans) and two average numbers of crew members. Costs were calculated from the maintenance center's record of the past five years of operation and converted to a yearly average. Thirteen nodes were selected as points for mapping contours on the basis of number of trips attracted and spatial distribution. The mapping of the contours was performed by the Topographical Analysis System (TOPAS), an in-house computer mapping program.

LOCATION STUDY FINDINGS

In the James River district analysis, the plot of the isocost lines indicates that the least-cost contour is centered on the town of Covington,

Figure 1. Total transport cost contours for James River Ranger District.



Virginia, where the ranger's office is located (Figure 1). The present maintenance center is located on the southeastern side of Covington and is within the least-cost contour. One may conclude at this point that this exercise only quantified what was intuitively obvious to some past decision maker. The advantage to the procedure in this case is that we now know that other locations should minimize the cost of transportation. Also, if the ranger's office were not fixed, then several alternative locations of the office could shift the most efficient location of the maintenance center significantly, and these locations may not be so obvious.

The area within the least-cost contour is, in reality, not equally accessible. Although the contour shifts south of Covington, the transportation network in the south is minimal. The contours spread outward along the east-west Interstate highway through Covington. Therefore, the best locations would probably be in the southern half of the city and along the Interstate highway. Site-specific costs, property ownership, construction, and site preparation would be some of the relevant factors to consider in final site selection. If alternative locations that lie outside the least-cost contour must be considered, then the closest contour value to the alternative sites may be used in a present-worth-of-costs analysis.

Location analyses of four other ranger districts in the George Washington National Forest in Virginia yielded varying results. In one district, the present maintenance center is within the area of least transport cost. In three districts, the annual transport cost savings of moving the maintenance centers to the least-cost area range from $1500/year to $4000/year. Although the present worths of these amounts at 10 percent for 20 years range from $12 700 to $32 000, moving these centers would probably be worthwhile only if the physical lives of the existing centers were expended. In one of these districts, moving the maintenance center would result in an additional 32-km (20-mile) commute one way for the present maintenance employees. The benefit from moving the center must be weighed against the additional employee transport cost or the cost of an agency commuting program.

CONCLUSIONS

The location study resulted in an analysis technique that used available computer programs and readily determined data. The technique visually displays in terms of transport costs an area of optimal maintenance center location that can be further analyzed in detail for site selection. At the very least the technique has helped justify location decisions that were made with little knowledge of the costs of location. In several cases the technique has quantified substantial monetary savings and, concomitantly, savings in energy use that could be gained from future relocation of maintenance centers.

The economic analysis of transport costs of maintenance operations addresses an important consideration of maintenance center location. As is true of any economic analysis, it is merely a tool to provide the decision maker with the information to make effective decisions, not to provide the decision itself. Many other considerations must enter into the location decision: ease of center administration, the pattern of private and federal land ownership, distance to employee's existing residential locations, other facility location costs, and location of personal and agency services to employees.

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Highway Maintenance Game: A Manual Simulation Model for Training Maintenance Crews

G. L. RAY AND JOHN M. MELANCON

A manual simulation procedure was developed to supplement highway maintenance training in Louisiana. The game was designed with emphasis on the planning and scheduling of activities in order to train first-line administrators by simulating the performance of one week's work. This method appears to be effective on the basis of administration of the training package in four districts. Plans are being made to refine and automate this concept to better train maintenance supervisors.

Since the implementation of Louisiana's maintenance management system in 1969, field studies have revealed several scheduling problems that have limited the effectiveness of maintenance crews. Typical scheduling problems were related to lack of adequate forethought in order to achieve the most efficient use of available resources. For example, an extensive leveling job was scheduled without consideration of equipment availability. After five truckloads of hot mix had been delivered, the foreman realized that the roller was inoperative and that the hot mix could not be effectively applied. In numerous cases, additional people were assigned to activities simply because it was convenient, even though additional labor was not required.

Maintenance specialists who were charged with assisting parish superintendents to plan and schedule maintenance operations were surveyed. The survey led to the realization that only 50 percent of the superintendents were scheduling at all. Discussion with maintenance superintendents produced such comments as "maintenance cannot be scheduled", "scheduling time is wasted when things go wrong", and "scheduling takes too long".

Work was then begun to respond to these concerns through the development of a training course that included simulation of maintenance activities as a means to change the superintendents' attitudes and to improve planning skills. The training course was developed for presentation to first-level administrators--parish maintenance superintendents, foremen, and clerks. The course was designed to teach techniques that should help reduce the time required for scheduling maintenance. The roles of superintendent, foreman, and clerk were presented to show how each individual was expected to assist in the scheduling process. Realization that the superintendent is not expected to schedule all operations without assistance from his principal aides was expected to further speed the scheduling process. Finally, a manual simulation procedure was developed to accomplish five basic objectives:

1. Exercise techniques learned in the training course,
2. Examine the benefits of proper roles and interactions among key members of the parish organization,
3. Reduce the time required to perform scheduling tasks,
4. Demonstrate the feasibility and effectiveness of work-order scheduling techniques, and
5. Measure the level of potential effectiveness of the training process.

The manual simulation forced interaction among the three team members in a real-time enactment of the scheduling function; accomplishment of the work was handled in a quick-time fashion. A measurement procedure was also included in the simulation to determine how well the student had applied the techniques learned or acquired prior to the training.

MECHANICS OF THE GAME

A major effort was made to reinforce the idea that coordination and interaction among the three key people in the parish organization is necessary. Role-playing techniques were used during simulation of maintenance work to physically illustrate how each individual was expected to assist the others to accomplish the scheduling function. The district was asked to provide the three key individuals in the parish organization so that a parish superintendent, a foreman, and a clerk constituted one training team. Where this was not possible, individual roles were assigned. Normally, it was expected that roles would be assigned within the individual's career path.

In order to place each team on an equal basis, a hypothetical parish, Pelican Parish, was developed, complete with maps, personnel, equipment, and the same set of initial conditions. Differences in outcome were directly attributable to the decisions made by the team. Pelican Parish maintains a road network of 449 miles, about average for Louisiana parishes; 29 miles of this system are Interstate highway. All facilities contained in Pelican Parish represented the average inventory of facilities found in Louisiana parish maintenance organizations. Resources used to maintain these facilities were also representative of average numbers. In conformance with the department's maintenance management system, 36 persons and 42 numbered equipment units were assigned to Pelican Parish. Each team was provided a copy of the superintendent's record of prescheduling inspections that listed all of the work found during the latest inspection of Pelican Parish. A list of carryover work from the preceding week and a list of expected operating conditions for the next week was also included at the outset.

The simulated day began at Friday noon. The team was required to schedule the work for the coming week. They were to consider any emergencies that they were aware of at the time, any work left over from the current week, and conditions found during the prescheduling inspection. Other considerations should have included alternative plans in the event of bad weather, material shortage, or similar problems. Each team was instructed to use work-order methods of scheduling in order to assign maintenance crews. These work orders were required to be prepared in advance by using all available data, including estimates of work quantity, materials, and productivity. At this time the foreman and clerk were instructed to assist the superintendent in scheduling work for the coming week. After next week's schedule had been completed, the clerk was instructed to begin preparing daily work orders for the primary and alternate plan. The clerk used standard daily work report forms for this purpose.

At this point the team was given some latitude. Since work orders may be prepared at any time prior to execution of the work, the team had the option of preparing work orders either a day or a week in advance. Regardless of the method used, the total effort is the same. When work orders were prepared in advance, they could be used on any day that the crew, equipment, and material could be scheduled as intended. If plans did not materialize, the schedule was abandoned, and a daily work report was prepared by the foreman to report what had been accomplished.

A parish work-control board was also provided to each team. The board showed the planned accomplishment for each function and the actual work accomplished for that function up to the biweekly period being simulated. This made the team aware of the annual plan and allowed them to consider the plan while decisions were formulated for the week being scheduled. Other special forms were provided to the team so that accomplishment could be tracked during the simulation.

Once scheduling was completed, the real-time part of the game was terminated, and a time-step method was used to simulate work performance. The clock was advanced to Monday morning and work performance began. Each day was simulated in three parts, morning, noon, and afternoon. Problems cropped up as the game proceeded. For example, on Monday morning four employees called in sick. Then at Monday noon, the state police called to report an accident at a bridge approach and to request that the surface be sanded to increase skid resistance. Monday afternoon was relatively quiet, and the plan proceeded on schedule.

At the completion of each simulated day, daily work reports were given to the maintenance specialist controlling the simulation. Each day was scored by assigning work accomplishment based on the decisions made and simulated conditions. If assigned crew and equipment were less than ideal for the condition and activity, an accomplishment penalty was administered. If additional people were assigned, no increase in productivity resulted unless these additional people were required for the specific condition. If an excessive haul distance was encountered, the team had to adjust the normal crew to add crew members and equipment for hauling in order to maintain expected productivity.

After the week had been simulated, the total accomplishment for each activity was multiplied by a weighting factor and summed for all activities in order to come up with a single score for each team. The weighting factor was calculated to penalize teams that had selected low-priority items ahead of higher-priority work. An ideal score was computed to allow the team to compare their performance against "perfect" decision making (20/20 hindsight). This method allowed results to be controlled by the priority and crew-assignment decisions of the team. In order to force the team to assess priorities, more work was assigned than could be accomplished within the one week provided.

SIMULATION PAPERWORK

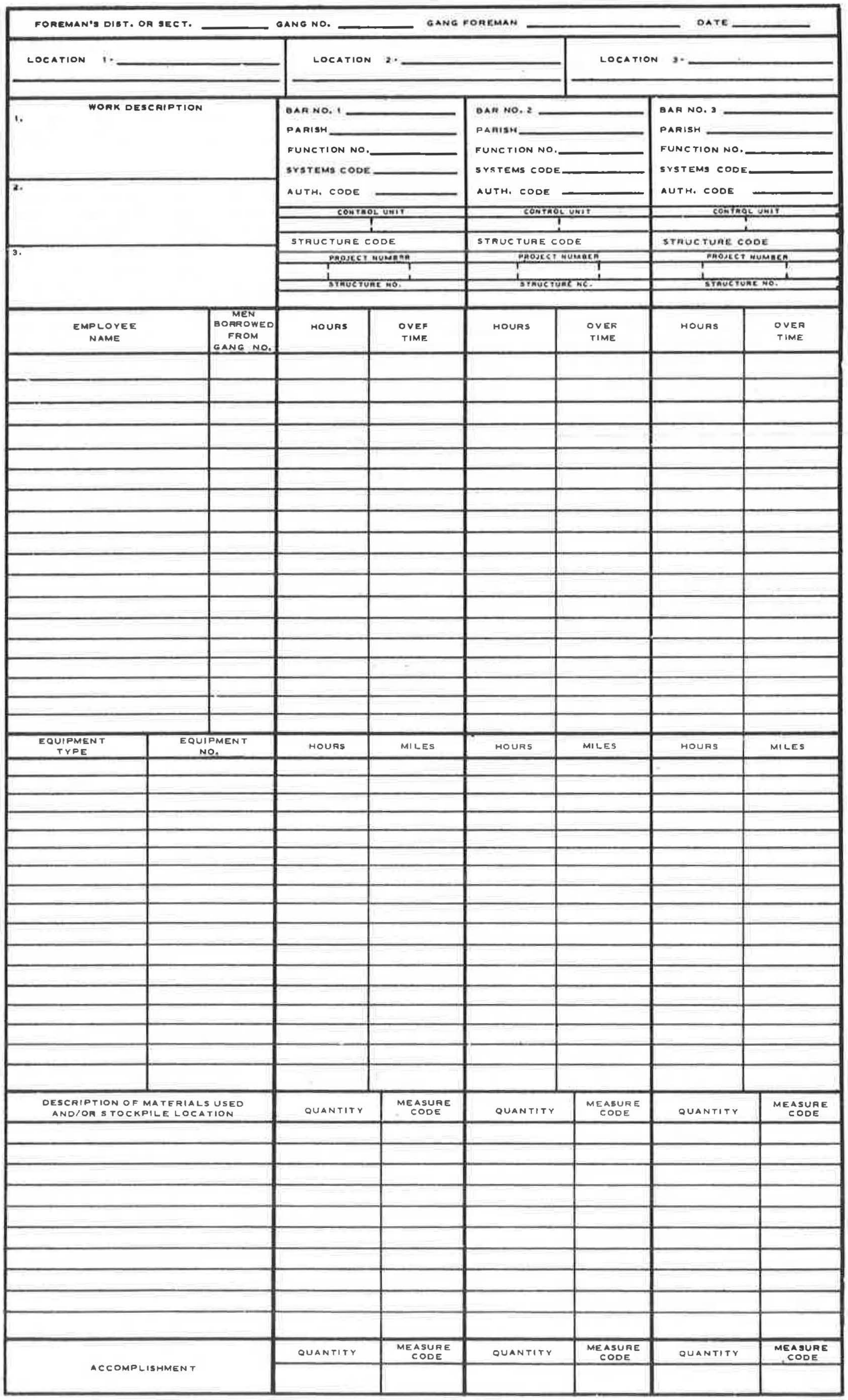
A copy of Louisiana's standard daily work report is shown in Figure 1. This report can be used as a work order or as a work report. Its use was physically demonstrated during the simulation. An example of the superintendent's record of prescheduling inspections that supplies the work load the team must consider is shown in Figure 2. The list was supplied to each team at the beginning of the simulation. In addition, a detailed map of Pelican Parish was given to each team in order that travel distances could be estimated.

A list of Pelican Parish personnel was supplied; employees are listed in categories by job title and, for each employee, room is provided to indicate the work function planned for each day of the week. A similar list of equipment was supplied. A work-control board showing the status of planned and actual work through the current biweekly period is shown in Figure 3. The master work-schedule form used by the team to assign maintenance crews is shown in Figure 4. The master work schedule was prepared from the estimates contained in the superintendent's record of inspections and the maintenance management systems standards. A uniform list of function codes for district maintenance-work reporting was used by each team to schedule and report their work.

The game was controlled by the maintenance-training specialist through the use of a time-step narrative. An example follows for Tuesday morning:

1. Conditions: Rain started during the night and is continuing. Forecast is for clearing by mid-morning. Only the three employees on scheduled leave are absent. A check of the equipment shows that roller 250-001 is not operational. The local

Figure 1. Maintenance daily work report format.



FOREMAN'S DIST. OR SECT. ______ GANG NO. ______ GANG FOREMAN ______ DATE ______

LOCATION 1 - ______ LOCATION 2 - ______ LOCATION 3 - ______

WORK DESCRIPTION			
1.	BAR NO. 1 ____ PARISH ____ FUNCTION NO. ____ SYSTEMS CODE ____ AUTH. CODE ____	BAR NO. 2 ____ PARISH ____ FUNCTION NO. ____ SYSTEMS CODE ____ AUTH. CODE ____	BAR NO. 3 ____ PARISH ____ FUNCTION NO. ____ SYSTEMS CODE ____ AUTH. CODE ____
2.	CONTROL UNIT	CONTROL UNIT	CONTROL UNIT
	STRUCTURE CODE	STRUCTURE CODE	STRUCTURE CODE
3.	PROJECT NUMBER STRUCTURE NO.	PROJECT NUMBER STRUCTURE NC.	PROJECT NUMBER STRUCTURE NO.

EMPLOYEE NAME	MEN BORROWED FROM GANG NO.	HOURS	OVEF TIME	HOURS	OVER TIME	HOURS	OVER TIME

EQUIPMENT TYPE	EQUIPMENT NO.	HOURS	MILES	HOURS	MILES	HOURS	MILES

DESCRIPTION OF MATERIALS USED AND/OR STOCKPILE LOCATION	QUANTITY	MEASURE CODE	QUANTITY	MEASURE CODE	QUANTITY	MEASURE CODE

ACCOMPLISHMENT	QUANTITY	MEASURE CODE	QUANTITY	MEASURE CODE	QUANTITY	MEASURE CODE

hot-mix plant expects to operate if the rain stops. District calls and needs two crew members to flag all day with a districtwide crew working in the parish.

2. Superintendent: Assign crew and equipment for wet-weather plan. Adjust plan as necessary because of the loaned crew members. Start the gang working on the wet-weather functions.

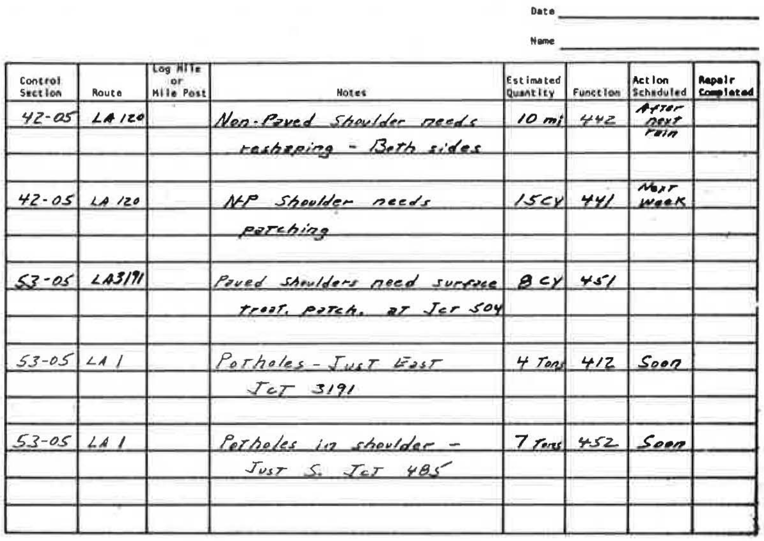
3. Clerk: Assist superintendent in making assignments; list assigned crew and equipment on work orders. List on the accomplishment sheet the accomplishments for each function worked on Monday. This will be continued all week so that weekly totals can be obtained easily for each function. It is important to fill in the "repair completed" column of the prescheduling inspection form daily when jobs are completed. For this simulation, the scorer will determine when jobs have been completed.

4. Foreman: Help the clerk with the tabulation of accomplishments. Complete any daily work reports from Monday, if necessary.

The following list illustrates a sample of the scoring instructions provided to each maintenance training specialist in order to assess the outcome of the simulation.

1. Compare crew and equipment on work report with normal crew on scoring charts (e.g., Table 1) and find correct line for normal, under, or over on

Figure 2. Superintendent's record of prescheduling inspections.



Date

Name

Control Section	Route	Log Mile or Mile Post	Notes	Estimated Quantity	Function	Action Scheduled	Repair Completed
42-05	LA 120		Non-Paved Shoulder needs reshaping - Both sides	10 mi	442	After next rain	
42-05	LA 120		NP Shoulder needs patching	15 CY	441	Next week	
53-05	LA3191		Paved Shoulders need surface treat. patch. at Jct 504	8 CY	451		
53-05	LA 1		Potholes - Just East Jct 3191	4 Tons	412	Soon	
53-05	LA 1		Potholes in shoulder - Just S. Jct 485	7 Tons	452	Soon	

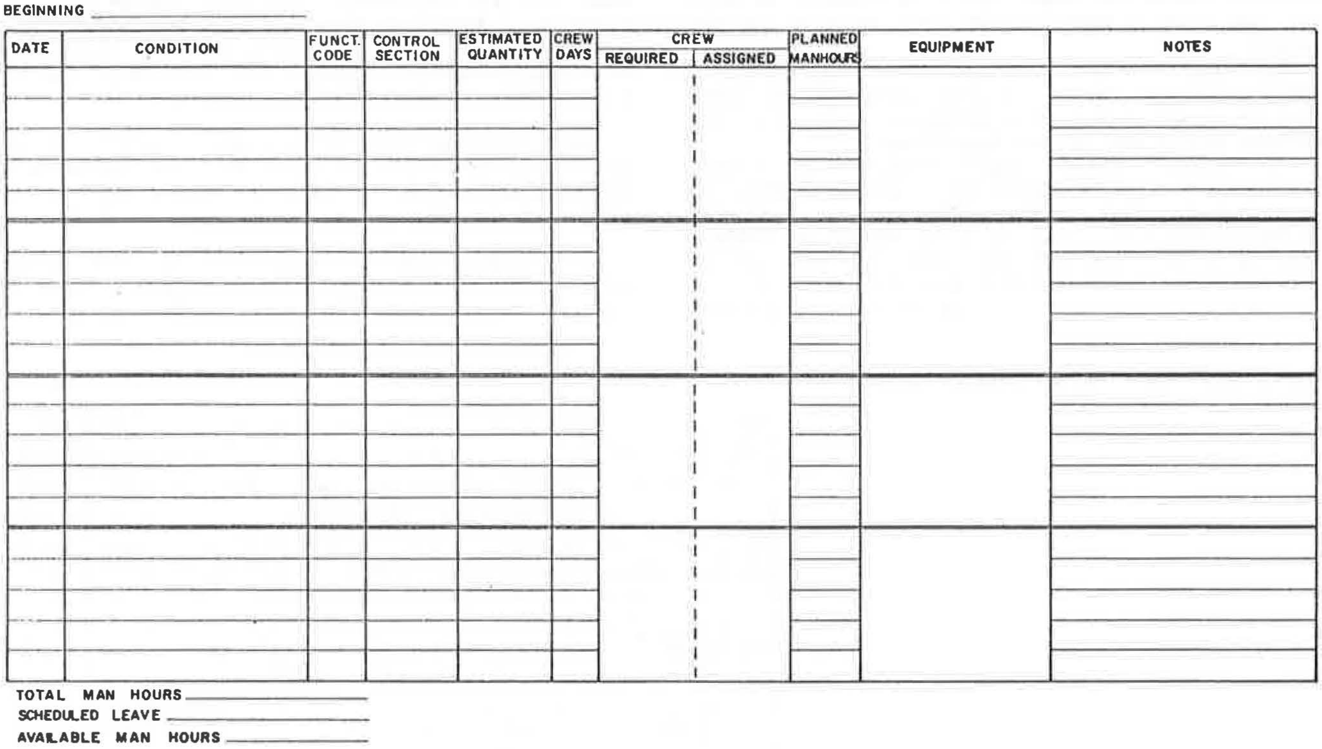
Figure 3. Work control board.

QUARTER 1 2 3 4

PERIOD ENDING September 20
Pelican PARISH

FUNCTION		PLAN QUANTITY		ACTUAL QUANTITY		MAN HOURS		RATE M-H/QUANTITY		
NAME		ANNUAL	THRU QUARTER	TOTAL TO DATE	BIWEEKLY PERIOD	BIWEEKLY PERIOD	TOTAL TO DATE	PLAN	BIWEEKLY PERIOD	AVERAGE
BITUMINOUS SURFACE										
SURF. TREAT. PATCH.	411 cy	454	227	185	104	224	481	2.0	2.2	2.6
POTHOLE PATCHING	412 tons	481	144	130	26	168	793	5.0	6.5	6.1
PATCHING BASE	413 cy	492	172	123	91	224	282	2.0	2.5	2.3
HAND LEVELING	414 tons	964	289	255	70	168	488	2.0	2.4	1.9
MACHINE LEVELING	416 tons	2830	849	518	135	192	832	1.6	1.4	1.6
SPOT SURF. REPL'MT.	417 tons	782	391	387	0	0	1208	2.8	-	3.1
OTHER BIT. SURF. MTN.	419	3832	1150	1038	119	119	1038	1.0	-	-
CONCRETE SURFACE										
PATCHING SURFACE	421 cy	10	0	3	3	35	35	9.0	11.7	11.7
PREMIX PATCHING	422 tons	13	0	0	0	0	0	3.0	-	-
JOINT REPAIR	425 100 ln.'									
OTHER CONC. SURF. MTN.	429	280	70	65	0	0	65	1.0	-	-
GRAVEL OR SHELL SURFACE MAINT.										
PATCHING SURFACE	431 cy	218	11	8	0	0	11	1.2	-	1.4
RESHAPING SURFACE	432 mi	360	54	46	0	0	86	1.6	-	1.9
RESTORING SURFACE	433 cy	450	90	84	0	0	48	.6	-	.6
OTHER GRAVEL/SHELL SURF. MTN.	439	165	8	12	0	0	12	1.0	-	-
SHOULDER MAINTENANCE										
PATCHING NON-PAVED SHOULDERS	441 cy	1544	154	137	0	0	142	1.2	-	1.0
RESHAPING NON-PAVED SHOULDERS	442 mi	892	268	235	25	40	410	1.8	1.6	1.7
RESTORING NON-PAVED SHOULDERS	443 cy	1399	140	129	0	0	104	.7	-	.8
SURFACE TREATMENT PARCHING	451 cy	70	21	26	26	112	112	3.5	4.3	4.3
PREMIX PATCHING	452 tons	26	8	5	0	0	18	3.0	-	3.6
OTHER SHOULDER MAINTENANCE	459	1644	411	465	40	40	465	1.0	-	-
ROADSIDE & DRAINAGE MAINT.										
EROSION CONTROL AND REPAIR	461	1334	334	322	0	0	322	1.0	-	-
CLEAN/REPAIR DRAINAGE STRUCT.	462	3396	475	447	0	0	447	1.0	-	-
CLEAN AND RESHAPE DITCHES	463 mi	21	3.4	3.7	0	0	659	160.0	-	178.1
MACHINING DITCHES	464 mi	7	2.1	4.2	0	0	34	8.0	-	8.1
MOWING	470 ac	6477	2591	2706	415	504	3518	1.0	1.2	1.1
CUTTING BRUSH	471	3419	342	461	112	112	461	1.0	-	-
LANDSCAPE MAINTENANCE	472	334	84	60	0	0	60	1.0	-	-
LITTER CLEANING OF ROADSIDE	473 cy	1133	113	84	0	0	286	3.0	-	3.4
SERVICING LITTER BARRELS	474 brl	416	104	120	28	24	84	.6	.9	.7
HERBICIDE APPLICATION	476 ac	2283	1142	1307	206	72	664	.4	.3	.5
OTHER RDSD. & DRAINAGE MAINT.	479	1460	365	267	0	0	267	1.0	-	-
MISCELLANEOUS ROUTINE		54295								
LEAVE				2384	614	614	2384	1.0	-	-
OVERHEAD		10489	2622	504	72	72	504	1.0	-	-
BETTERMENT										

Figure 4. Master work schedule.



BEGINNING ________________

DATE	CONDITION	FUNCT. CODE	CONTROL SECTION	ESTIMATED QUANTITY	CREW DAYS	CREW		PLANNED MANHOURS	EQUIPMENT	NOTES
						REQUIRED	ASSIGNED			

TOTAL MAN HOURS ________________

SCHEDULED LEAVE ________________

AVAILABLE MAN HOURS ________________

crew and equipment. For any function reported in person hours, the daily accomplishment is the number of person hours for the function.

2. Accomplishment is based on crew and equipment assigned and number of hours worked, except as follows:

a. Functions 412 and 452 (see Figure 5) on Wednesday: Travel time to hot-mix plant reduces work time by 2 h. Award accomplishment for 2 h less than reported. (Two crew members may work 2 h on another function on same control section).

b. Function 413 on 115-02: Requires an extra flagman for normal accomplishment. Award accomplishment for one crew member fewer than actually assigned.

c. Functions 414, 416, and 417 on Wednesday: Travel time to hot-mix plant requires use of one extra dump truck and truck driver for normal accomplishment. Award accomplishment for one crew member and one equipment unit fewer than actually assigned.

d. Function 414 and 416 on 115-01: Same as b.

e. Function 414 and 416 on 115-02: Same as b.

f. Function 417 on 835-10: Same as b.

g. Function 441 on 42-05: Function requires only type I equipment operator and dump truck for normal accomplishment if Motor Patrol is working on same section (function 442) on the same day.

Each daily work report was carefully scored in order to properly evaluate the team's decision-making ability. The scoring method outlined in Table 1 exhibits a sample accomplishment assignment table the specialist used along with the scoring instructions to evaluate each activity based on the crew assigned and the number of hours assigned. Figure 5 provides an example of the minimum requirements for completion of a job to determine whether the crew must come back to that same location a second time in order to complete the activity. As mentioned earlier, the final score consisted of a combination of accomplishment and a weighting factor based on the priority of job assignment. An example of the final scoring sheet is shown in Figure 6.

RESULTS TO DATE

The training course and the simulation were tested in one highway district. From this test, several modifications were made to the simulation in order to speed the process and correct deficiencies noted. The training package was implemented by conducting a seminar for all maintenance training specialists within the state that included completion of the simulation with training specialists playing assigned roles.

It was expected from the outset that headquarters personnel would be required to attend the first training presentation in each district in order to overcome some of the negative attitudes that were expected. To date, four districts have administered this training package. Its effectiveness appears to be directly related to the attitude and enthusiasm shown by district management. In areas where district management has received this effort with a positive attitude and a sincere desire to conduct this training, the results have been extremely good.

Currently, the average score is 70.11 (N = 28), compared with a maximum possible score of 93. Results to date are summarized in Figure 7. During the pilot study, before-and-after tests were used to validate the audiovisual training given prior to simulation. Validation test scores are contained in Table 2. An average gain rate of 57 percent compares favorably with the expected gain rate of 70 percent used to evaluate the effectiveness of training materials. No before-and-after testing was conducted during implementation; simulation was used as the sole indicator of the effectiveness of training. Another two years will be required to thoroughly analyze the results of this effort. We intend to conduct another survey of maintenance specialists to determine the amount of scheduling performed by the parish superintendents after the training has been given statewide. Judging from results achieved thus far, our expectations for the successful implementation of this process are extremely high.

FUTURE REFINEMENTS

Louisiana is currently constructing an automated maintenance simulation model in cooperation with Louisiana State University under a federally funded contract. The model is designed to electronically simulate highway maintenance operations and may be modified to play the highway maintenance game. This would allow training to be focused on the decision-making process by eliminating a great deal of manual effort now required. Completion of the automated simulation project is expected in September 1979. It will probably take another two or three years to convert the manual training simulation into an automated procedure.

Since data processing terminals are not readily available in support of the training function, this

Table 1. Accomplishment assignment table for hand leveling.

	Accomplishment (tons)							
	Hours Worked							
Condition	1	2	3	4	5	6	7	8
Short 2 CMs and 2 EUs	0	1.8	3.5	5.2	7	9.3	11.7	14
Short 2 CMs and 1 EU	0	2.1	4.2	6.4	8.5	11.3	14.2	17
Short 1 CM and 2 EUs	0	2.1	4.2	6.4	8.5	11.3	14.2	17
Short 1 CM and 1 EU	0	2.5	5	7.5	10	13.3	16.7	20
Short 2 CMs	0	2.5	5	7.5	10	13.3	16.7	20
Short 2 EUs	0	2.5	5	7.5	10	13.3	16.7	20
Short 1 CM	0	2.8	5.5	8.2	11	14.7	18.3	22
Short 1 EU	0	2.8	5.5	8.2	11	14.7	18.3	22
Normal (7 CMs, 6 EUs)	0	3.5	7	10.5	14	18.7	23.3	28
Over 1 EU	0	3.5	7	10.5	14	18.7	23.3	28
Over 1 CM	0	3.5	7	10.5	14	18.7	23.3	28
Over 2 EUs	0	3.8	7.5	11.2	15	20	25	30
Over 2 CMs	0	3.8	7.5	11.2	15	20	25	30
Over 1 CM and 1 EU	0	3.8	7.5	11.2	15	20	25	30
Over 1 CM and 2 EUs	0	4	8	12	16	21.3	26.7	32
Over 2 CMs and 1 EU	0	4	8	12	16	21.3	26.7	32
Over 2 CMs and 2 EUs	0	4.2	8.5	12.8	17	22.7	28.3	34

Note: CM = crew member; EU = equipment unit.

Figure 5. Minimum requirements for completion of maintenance tasks.

FUNCTION	CONTROL SECTION	ACCOMPLISHMENT M	T	W	T	F	ESTIMATED QUANTITY	MIN. OF COMPLETION
412	53-05						4 tons	3.5
412	305-01						2 tons	1.8
412	359-01						5 tons	4.5
412	359-02						6 tons	5.4
416	114-03						40 tons	36.0
416	115-01 (Near Jct. 6)						20 tons	18.0
416	115-01 (Middle of control)						30 tons	27.0
416	115-01 (S. of Allen)						25 tons	22.5
416	115-02						35 tons	31.5
417	835-10						100 tons	90.0
417	835-12						20 tons	18.0
432	116-03						8 mi.	7.2
432	360-04						7 mi.	6.3
441	42-05						15 cy	13.5
441	359-02						9 cy	8.1
441	360-05						25 cy	22.5
442	42-05						10 mi.	8.8
443	362-01						150 cy	135
451	53-05						8 cy	7.2
452	53-05						7 tons	6.3
463	119-01						1½ mi.	1.35 mi.
464	360-04						2 mi.	1.76
470	835-08							(1 mach., 1 day)
470	455-04	(No minimum for Function 470, C.S. 455-04)						
471	114-03						12 mh	10.0
473	455-04						24 mh	21 mh

Figure 6. Final score sheet.

(A) TOTAL ACCOMPLISHMENT	(B) SCORE FACTOR	(A X B) SCORE	"IDEAL" SCORE	FUNCTION
	.18		27	411
	.5		12	412
	.14		16.8	413
	.18		25.2	414
	.11		32.45	416
	.22		25.3	417
	.04			419
	.54		14.36	421
	.3		12	422
	.04			429
	.12		8.1	431
	.13		3.25	432
	.04		10.6	433
	.04			439
	.12		8.1	441
	.14		3.71	442
	.05		20	443
	.21		16.8	451
	.21		8.4	452
	.04			459
	.04			461
	.04			462
	11.2		16.2	463
	.4		2	464
	.09		25.2	470
	.04			471
	.04			472
	.12		4.8	473
	.05		6.75	474
	.03		9.6	476
	.04			479
	.04			499
	.01			533
	.04			559
	.1			602
	.02			655
	.04			656
	.04			660
	.06			667
	.04			699

TOTAL SCORE

Figure 7. Results of manual simulation.

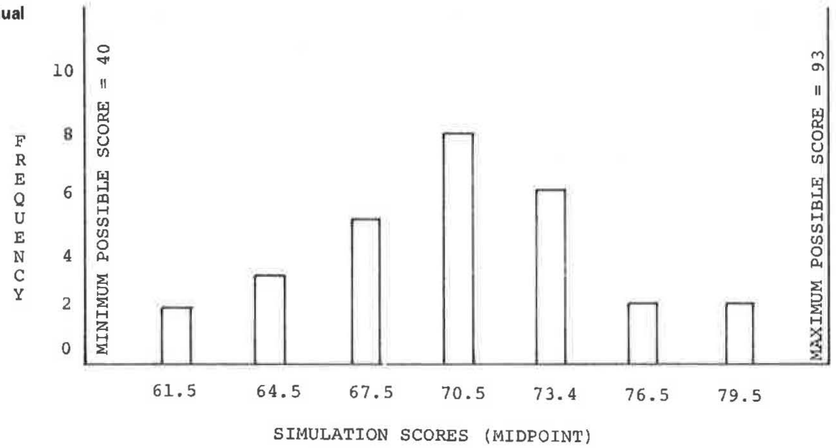


Table 2. Validation results.

Name	Before Training	After Training	Gain (%)
Guecho (ES II)	81	88	58
Phillips (superintendent)	78	90	55
Quatr. (superintendent)	80	92	60
Stein (superintendent)	77	86	39
Pascalin (foreman)	65	90	71
Babin (foreman)	75	91	64
Day (clerk)	86	98	86
Taylor (clerk)	88	93	42
Bezard (clerk)	77	86	39
Avg	78.5	90.4	57

problem will have to be resolved. Another proposal on the horizon that may lead to completely automating the scheduling process on a day-to-day basis would require terminals located in each parish office. Once this hardware is installed, the highway maintenance game can be made available to key parish personnel during slack periods to enhance scheduling proficiency. Maintenance managers hope that future technology will further reduce the cost of terminals and allow them to be used routinely for accomplishment of the training function.

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Influence of Fifth-Wheel Location on Truck Ride Quality

J. L. STEIN AND J. K. HEDRICK

A combined analytical and experimental study is described that investigates the influence of the fifth-wheel position of a tractor-semitrailer on the vertical and longitudinal cab accelerations. The analytical model used was a relatively simple six-degree-of-freedom linear frequency domain model subject to statistical road-roughness inputs. The experimental study consisted of instrumenting a cab-over-engine tractor and loaded flatbed semitrailer combination with a three-axis accelerometer package in the cab and then measuring the resulting accelerations experienced on an Interstate highway at several speeds and fifth-wheel locations. Both the analytical and experimental studies show that the ride quality deteriorates as the fifth wheel is moved forward. It is also shown that the increase in root-mean-square acceleration primarily results from the development of a resonant condition of out-of-phase tractor-semitrailer pitch in the 4-Hz region.

The levels of ride quality that exist in a tractor cab have an influence on the long-term health as well as the short-term proficiency of drivers. At sufficiently high levels of exposure to vibration over a period of hours, fatigue and decreased proficiency can result. In this paper the influence of fifth-wheel position on tractor-cab ride is determined. In particular, the ride quality achieved in a tractor is predicted analytically and measured experimentally as the fifth wheel is moved forward to allow greater load capacity within existing regulations and/or to meet tractor-semitrailer length restrictions. For specific truck configurations, the fifth-wheel location can be moved by as much as 2.5 ft to meet federal axle-load regulations. A nominal fifth-wheel location for a truck when not fully loaded is 0.5 ft in front of the rear axle.

Although a number of studies (1-7) have been concerned with truck ride quality and, specifically, with methods for improvement, very little work has been published in which the influence of fifth-wheel position on ride quality is discussed. In 1965, LeFevre (1) conducted an analytical study that showed that jerk (rate of change of acceleration with respect to time) at the driver's seat in the vertical direction increases by 550 percent as the fifth wheel is moved forward 20 in from the rear axle. The model used in this study represented the influence of the trailer on the tractor fifth wheel as a constant force and considered a single wheel excited by a sinusoidal disturbance. In a more complete 1969 study, Walther and others (2) conducted computer simulation studies with a seven-degree-of-freedom model that included heave and pitch motions of the tractor and the semitrailer plus heave motion of tractor front and rear axles and the semitrailer axle. These studies showed that the natural frequencies associated with tractor-semitrailer heave and pitch (2-4 Hz) tend to increase, as does the acceleration level associated with these modes, when the fifth wheel is moved forward.

While the literature cited provides useful background information, none determines ride quality for the case in which a tractor-semitrailer is being driven down a highway subject to typical (random) highway disturbances, and none assesses ride quality in terms of standard ride-quality measures. In the study described in this paper, ride-quality measures are defined, and both vehicle and roadway models are formulated. The model used to evaluate the influence of fifth-wheel location on ride quality is a linear model; thus, the analytical results are valid primarily with respect to the general trends predicted rather than the detailed prediction of local motions and accelerations. Such detailed prediction requires more sophisticated nonlinear models. Finally, the measurements (and their trends) obtained from a tractor-semitrailer instrumented with accelerometers are compared with the analytical predictions.

DEFINITION OF RIDE QUALITY

Ride quality, in this study, is defined by two indices: (a) total root-mean-square (rms) acceleration at the driver's seat and (b) specifications of the International Standards Organization (ISO). The criteria for International Standard 2631:1978, shown in Figure 1, define ride quality in terms of human sensitivity to accelerations as a function of frequency and amplitude. The sensitivity is expressed in terms of the length of time a person can be subjected to an acceleration of a given amplitude and frequency in a specified direction and still be comfortable. For a vehicle's ride to be compared with the specification, it is necessary to obtain the rms of the vehicle accelerations for a specific direction in third-octave frequency bands and compare it with the specification at the band's center frequency. If the rms value exceeds the criteria for any third-octave band, then the ride fails to meet the ride-comfort criterion for that exposure time. Only the magnitude of the ISO curves (and not the shape) change as the exposure time is changed. (Exposure time in this paper is used only as a convenient relative measure. There is currently a great deal of controversy over the relation between exposure time and passenger comfort.)

Although the ISO standard allows for a quantitative evaluation of ride quality, it is often useful in studying trends to use total rms accelerations. Once these trends have been established, the ISO criteria can then be used to see which specific frequencies are causing the changes to occur.

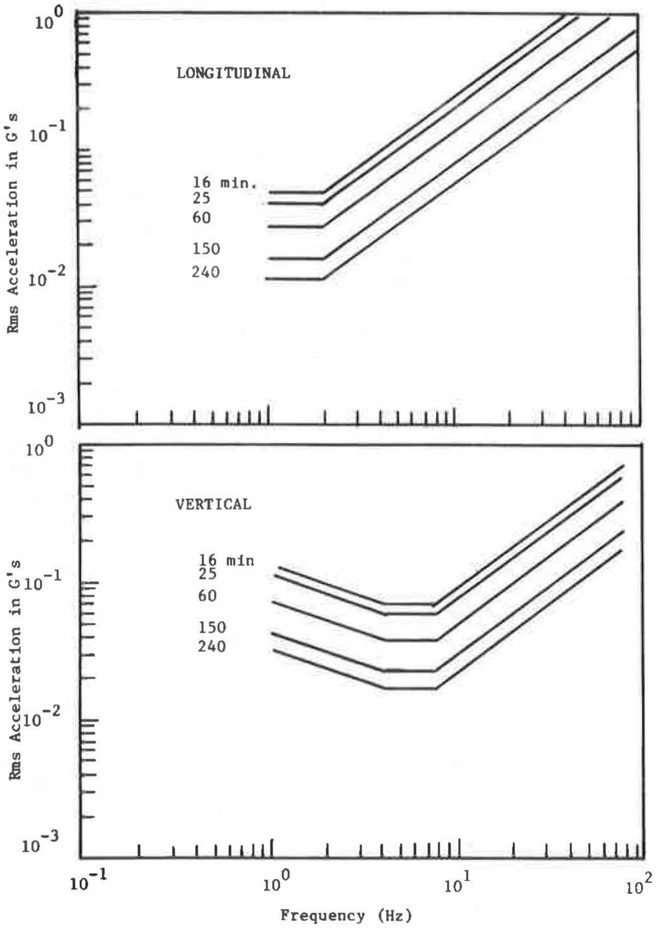
DESCRIPTION OF VEHICLE MODEL

A number of ride-quality models for tractor-semitrailers have been described in the literature. They range from a 3-degree-of-freedom model used by Ellis (3) to an 11-degree-of-freedom model including nonlinearities such as spring friction, shock-absorber characteristics, and wheel lift used by Harwood and Crosby (4). The model developed in the current study is linear; a complete description and derivation are given by Hedrick and others (8). It has been adapted from Walther's 7-degree-of-freedom model, which represents a compromise between the 3-degree-of-freedom Ellis model and the more advanced model of Harwood and Crosby.

The primary object of the vehicle model formulation has been to achieve a simple, yet sufficiently realistic, model to predict the general ride-quality trends in terms of accelerations at the driver's location as the fifth-wheel location is changed. To predict detailed vehicle motions, a model that includes the nonlinear suspension stiffness and damping effects, tractor and semitrailer frame bending, cab-mount-suspension characteristics, and the seat suspension would be required.

The model used in this study is illustrated in Figure 2. This model has six degrees of freedom: tractor heave and pitch, semitrailer heave, and the heave motion of the tractor front axle, tractor rear tandem axle, and semitrailer tandem axle. As shown in the figure, roll, lateral, and other yaw degrees of freedom are neglected, and only heave and pitch are considered. Semitrailer pitch is not a degree of freedom since, when the fifth wheel is represented as a pinned joint, semitrailer pitch motion may be represented directly in terms of tractor heave and pitch and semitrailer heave. In the model, the semitrailer and tractor bodies are assumed to be rigid (no frame bending). The axles on the truck are lumped into three equivalent axles (the front tractor axle, the rear tractor axle, and the semitrailer axle); thus, the detailed effects of tandem axles are neglected. The suspension elements between the axles and the body are represented as an equivalent linear spring and damper, and the tires on each axle are represented by a single equivalent linear spring. The disturbance inputs to the model are represented in terms of roadway displacements (U_1, U_2, and U_3, respectively), at each axle.

Figure 1. Longitudinal and vertical ISO specification for reduced comfort criteria.



A set of linear constant-coefficient differential equations can be derived directly from Figure 2 to describe the dynamic ride-quality model. These equations may be summarized in the matrix form:

$$\overline{\underline{M}}\,\ddot{\underline{y}} + \overline{\underline{D}}\,\dot{\underline{y}} + \overline{\underline{K}}\,\underline{y} = \overline{\underline{F}}\,\underline{U} \qquad (1)$$

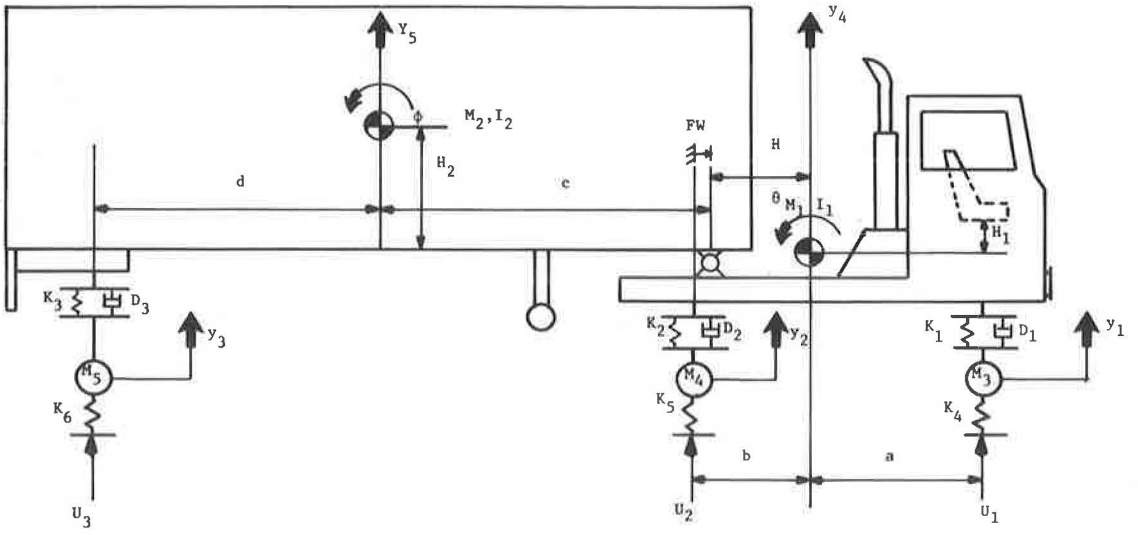
where $\overline{\underline{M}}$, $\overline{\underline{D}}$, and $\overline{\underline{K}}$ are 6x6 system mass, damping, and stiffness matrices, respectively, and $\overline{\underline{F}}$ is a 6x3 input matrix (all of which are given in the ride-quality equations of motion below). In addition, $\underline{y}$ is a 6x1 vector containing the variables associated with each independent degree of freedom where

y_1 = front axle displacement in the vertical direction (heave),
y_2 = tractor tandem displacement in the vertical direction (heave),
y_3 = semitrailer tandem displacement in the vertical direction (heave),
y_4 = tractor displacement in the vertical direction (heave),
y_5 = semitrailer displacement in the vertical direction (heave),
y_6 = tractor angular displacement (pitch, θ), and
y = dy/dt.

$\underline{U}$ is a 3x1 vector of the systems inputs where

U_1 = displacement input to the front tires,
U_2 = displacement input to the tractor tandem tires, and

Figure 2. Dynamic ride-quality model.



U_3 = displacement input to the semitrailer tandem tires.

The equations of the model are linear; however, the input vector ($\underline{U}$) contains time-delayed terms because the second input is essentially equal to the first input but delayed by a time τ_1, and the third input is equivalent to the first input delayed by a time τ_2. The delay times depend on the velocity of the truck. If the input to the front wheel is $U_1(t)$, the input to the tractor driving wheels is

$$U_2(t) = U_1(t - \tau_1) \tag{2}$$

where τ_1 = (a + b)/truck velocity and the input to the trailer wheels is

$$U_3(t) = U_1(t - \tau_2) \tag{3}$$

where τ_2 = (a + H + c + d)/truck velocity and

a = distance from the front axle to the tractor's center of gravity (c.g.),
b = distance from the tractor's c.g. to the tractor tandem's centerline,
c = distance from the semitrailer's kingpin to the semitrailer's c.g.,
d = distance from the semitrailer's c.g. to the semitrailer tandem's centerline, and
H = distance from the fifth wheel to the tractor's c.g.

By using the model equations summarized above, given a description of the roadway in terms of $U_1(t)$, the response of the tractor cab can be computed directly. A complete description of the frequency domain model and numerical methods used in this study is contained in Hedrick and others ($\underline{8}$).

Ride-Quality Equations of Motion

The linear equations of motion of the tractor-semitrailer model shown in Figure 2 were obtained by using Lagrange's equations. The result is a set of six linear constant-coefficient differential equations of the form $\underline{\bar{M}}\,\ddot{\underline{y}} + \underline{\bar{D}}\,\dot{\underline{y}} + \underline{\bar{K}}\,\underline{y} = \underline{\bar{F}}\,\underline{U}$, where $\underline{\bar{M}}$, $\underline{\bar{D}}$, and $\underline{\bar{K}}$ are matrices of the forms shown in Figures 3, 4, and 5, where

K_1 = front suspension spring stiffness constant,
K_2 = tractor tandem's suspension spring stiffness constant,
K_3 = trailer tandem's suspension spring stiffness constant,

Figure 3. $\underline{M}$ is a 6x6 system mass matrix.

$$\begin{bmatrix} M_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & M_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & M_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & M_4 + \frac{I_2}{c^2} & -\frac{I_2}{c^2} & -\frac{HI_2}{c^2} \\ 0 & 0 & 0 & -\frac{I_2}{c^2} & M_5 + \frac{I_2}{c^2} & \frac{HI_2}{c^2} \\ 0 & 0 & 0 & -\frac{I_2 H}{c^2} & \frac{I_2 H}{c^2} & I_1 + \frac{H^2}{c^2} I_2 \end{bmatrix}$$

Figure 4. $\underline{D}$ is a 6x6 system damping matrix.

$$\begin{bmatrix} D_1 & 0 & 0 & -D_1 & 0 & -aD_1 \\ 0 & D_2 & 0 & -D_2 & 0 & bD_2 \\ 0 & 0 & D_3 & \frac{d}{c} D_3 & -(1+\frac{d}{c})D_3 & -\frac{d}{c} HD_3 \\ -D_1 & -D_2 & \frac{d}{c}D_3 & D_1+D_2+(\frac{d}{c})^2 D_3 & -\frac{d}{c}(1+\frac{d}{c})D_3 & \begin{matrix} aD_1-bD_2 \\ -(\frac{d}{c})^2 HD_3 \end{matrix} \\ 0 & 0 & -(1+\frac{d}{c})D_3 & -\frac{d}{c}(1+\frac{d}{c})D_3 & (1+\frac{d}{c})^2 D_3 & H\frac{d}{c}(1+\frac{d}{c})D_3 \\ -aD_1 & bD_2 & -\frac{d}{c} HD_3 & \begin{matrix} aD_1 - bD_2 \\ -(\frac{d}{c})^2 HD_3 \end{matrix} & \frac{d}{c}(1+\frac{d}{c})HD_3 & \begin{matrix} a^2D_1 + b^2D_2 \\ + (\frac{d}{c})^2 H^2D_3 \end{matrix} \end{bmatrix}$$

Figure 5. $\underline{K}$ is a 6x6 system stiffness maxtrix.

$$\begin{bmatrix} K_1+K_4 & 0 & 0 & -K_1 & 0 & -aK_1 \\ 0 & K_2+K_5 & 0 & -K_2 & 0 & bK_2 \\ 0 & 0 & K_6+K_3 & \frac{d}{c} K_3 & -(1 + \frac{d}{c})K_3 & -\frac{d}{c} H K_3 \\ -K_1 & -K_2 & \frac{d}{c} K_3 & K_1+K_2+(\frac{d}{c})^2 K_3 & -\frac{d}{c}(1 + \frac{d}{c})K_3 & \begin{matrix} -aK_1-bK_2 \\ -(\frac{d}{c})^2 H K_3 \end{matrix} \\ 0 & 0 & -(1 + \frac{d}{c})K_3 & -\frac{d}{c}(1 + \frac{d}{c})K_3 & (1 + \frac{d}{c})^2 K_3 & H\frac{d}{c}(1 + \frac{d}{c})K_3 \\ -aK_1 & bK_2 & -\frac{d}{c} H K_3 & \begin{matrix} aK_1 - bK_2 \\ -(\frac{d}{c})^2 H K_3 \end{matrix} & \frac{d}{c}(1 + \frac{d}{c})HK_3 & \begin{matrix} a^2K_1 + b^2K_2 \\ + (\frac{d}{c})^2 H^2K_3 \end{matrix} \end{bmatrix}$$

K_4 = front tire stiffness constant,
K_5 = tractor tandem's tires stiffness constant,
K_6 = semitrailer tandem's tires stiffness constant,
D_1 = front suspension damping constant,
D_2 = tractor tandem's suspension damping constant,
D_3 = semitrailer tandem's suspension damping constant,
FW = distance fifth wheel is ahead of the tractor tandem's centerline,
H_1 = distance of the driver's seat above the tractor's c.g., and
H_2 = distance of the trailer's c.g. above the bottom of the semitrailer.

Road Input Model

The roadway has been modeled as a statistically stationary random process. Statistical roadway irregularities have traditionally been characterized in terms of mean square spectral densities. A great many road survey data have been processed for highways and runways (9) that indicate that a reasonable analytic representation is given by the spatial spectral density function

$$\phi(\Omega) = A/\Omega^2 \qquad (4)$$

where A = a statistical roughness parameter and Ω = spatial frequency (rad/ft). In this study, the value of A has been chosen as 5×10^{-6} ft, which corresponds to a very good highway. For a vehicle traveling at a constant forward speed V, the spatial density given by Equation 4 can be converted into a temporal spectral density

$$\omega = V\Omega \qquad (5)$$

$$S(\omega)d\omega = \phi(\Omega)d\Omega \qquad (6)$$

that, when applied to Equation 4, yields

$$S(\Omega) = AV/\omega^2 \qquad (7)$$

where

A = velocity of vehicle(ft/s),
ω = temporal frequency (rad/s), and
S = temporal spectral density [$(ft^2/rad)/s$].

RIDE-QUALITY PARAMETRIC ANALYSES

A series of parametric studies has been conducted by using the model described in the previous section. The influence of fifth-wheel location on the tractor-semitrailer natural frequencies and modes of vibration has been determined; vehicle acceleration levels in response to periodic and random roadway disturbances have also been determined. These parametric studies have been conducted for a tractor-semitrailer combination with the parameters summarized (10) below. These parameters represent the values corresponding to the model of Figure 6; thus, for example, the spring stiffness K_1 represents the combined stiffness of the tractor's left and right front suspension springs. Here the tractor was a 4x6 cab-over-engine White (sleeper type), and the trailer was a 40-ft Fruehauf van. D_1, D_2, and D_3 (the damping constants) were calculated by using damping ratios obtained from Walther and others (2).

Parameter	Value	Parameter	Value
a	3 ft	M_1	288 slugs
b	8.83 ft	M_2	1748.45 slugs
c	15.0 ft	M_3	40.37 slugs
d	17.58 ft	M_4	136.65 slugs
K_1	28 800 lbf/ft	M_5	93.17 slugs
K_2	249 000 lbf/ft	I_1	4447.83 $ft\cdot lbf\cdot s^2$
K_3	336 000 lbf/ft	I_2	171 250 $ft\cdot lbf\cdot s^2$
K_4	103 416 lbf/ft	H_1	1.7 ft
K_5	413 664 lbf/ft	D_1	1845 $lbf\cdot s/ft$
K_6	413 664 lbf/ft	D_2	509 $lbf\cdot s/ft$
		D_3	485 $lbf\cdot s/ft$

Natural Frequency and Mode Shapes

The natural frequencies and mode shapes of the tractor-semitrailer unit have been determined for four fifth-wheel positions. The six natural frequencies are summarized in Table 1. The lowest-mode natural frequency decreases from 1.8 to 1.6 Hz, and the mode shape changes from a dominant tractor pitch to tractor heave as the fifth-wheel position is moved forward. The second and third natural frequencies both increase as the fifth wheel is moved forward; the second-mode shape corresponds to strong tractor pitch and semitrailer heave, and the third corresponds to the tractor and semitrailer pitching out of phase. Modes 4-6 correspond to axle motions and are essentially unaffected by fifth-wheel location. In summary, the primary influence of fifth-wheel movement forward is to accentuate tractor heave of the first mode and to increase the natural frequencies of the second and third modes.

Response to a Sinusoidal Disturbance

The steady-state response of the tractor-semitrailer to a sinusoidal disturbance has been computed [$U_1(t) = U_0 \sin\omega t$ with $U_2(t) = U_1(t - \tau_1)$ and $U_3(t) = U_1(t - \tau_2)$] and displayed in Figure 6 as a function of the disturbance frequency for two fifth-wheel positions. The plots illustrate the vertical amplitudes that occur at a rigid point in the cab corresponding to the seat location. Figure 6 shows that, as the fifth wheel is moved forward, the two resonant peaks in the 2- to 4-Hz range increase in frequency and in amplitude. These peaks correspond to the second and third modes of vibration discussed above. The resonance at 12 Hz also increases in amplitude as the fifth-wheel position is moved forward. The series of successive peaks and valleys in the response above 12 Hz corresponds to the phasing of the input between the axles. In summary, as the fifth wheel is moved forward, the amplitudes of the acceleration resonant peaks in the 2- to 12-Hz range increase, yielding a less comfortable ride.

RESPONSE TO A ROADWAY IN TERMS OF RANDOM ROUGHNESS

The tractor-semitrailer response to a roadway disturbance characterized in terms of its random roughness as represented in Equation 7 has been determined for three fifth-wheel positions for a vehicle traveling at 55 mph. The vertical accelerations have been computed at a rigid point in the cab corresponding to the seat. The computed acceleration spectral densities are displayed in Figure 7. These data show that the primary contributions to acceleration occur in the 2- to

Figure 6. Cab vertical response to a sinusoidal roadway disturbance for two fifth-wheel positions at 55 mph.

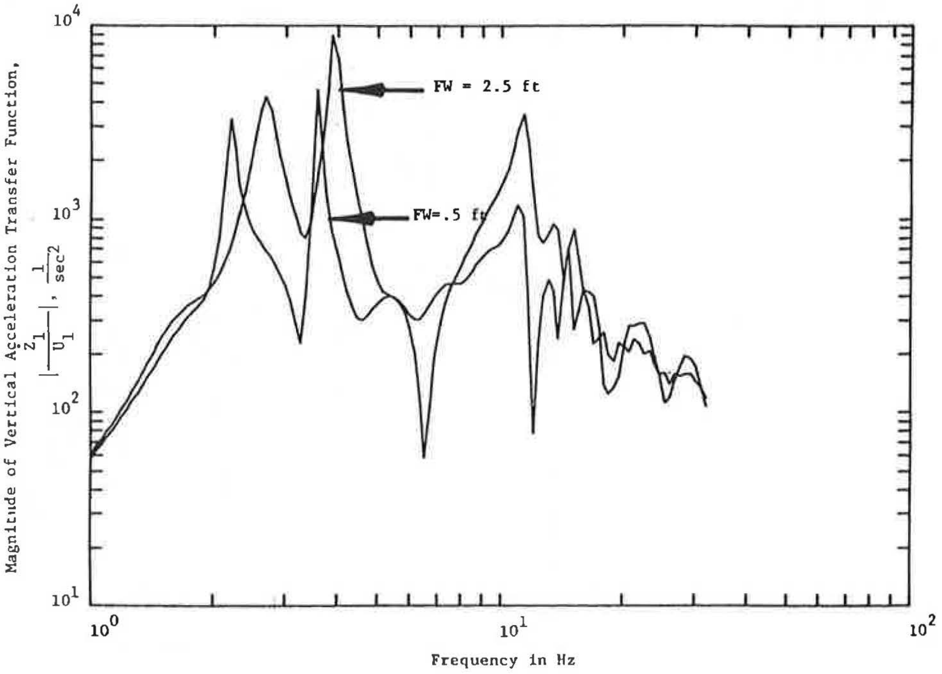


Table 1. Variations in resonant frequencies as a function of fifth-wheel position.

	Natural Frequency (Hz)			
	Fifth-Wheel Location[a]			
Mode Shape	0.5 ft Behind	0.5 ft Ahead	1.5 ft Ahead	2.5 ft Ahead
First	1.8	1.8	1.7	1.6
Second	2.0	2.2	2.4	2.7
Third	3.5	3.6	3.7	3.9
Fourth	8.7	8.7	8.7	8.7
Fifth	11.3	11.4	11.4	11.4
Sixth	14.6	14.6	14.6	14.6

[a] Location in relation to tractor tandem centerline.

12-Hz range and that, as the fifth wheel is moved forward from 0.5 to 2.5 ft, the magnitudes of the resonant peaks increase.

The total rms vertical and longitudinal accelerations at a rigid point corresponding to the driver's seat have been computed and are summarized in Figure 8. These data show that, as the fifth wheel is moved forward from 0.5 ft to 1.5 ft in front of the tractor rear axle, the rms vertical acceleration increases by a factor of 1.65 and the longitudinal acceleration by a factor of 1.5.

To provide a comparison of the ride quality predicted by the computer simulation with the standards set by ISO, the vertical seat-acceleration levels have been computed in accordance with ISO specifications. These levels and the ISO 25-min reduced comfort boundary are displayed in Figure 9. For all cases, the 25-min boundary is exceeded in the 2- to 5-Hz range because of the strong vehicle resonances in these frequency ranges. Thus, even though a relatively smooth roadway has been assumed, i.e., a roughness coefficient of $A = 5 \times 10^{-6}$ ft, the general level of ride quality predicted is relatively poor. These data also show that the vertical acceleration levels at 2-5 Hz exceed the 25-min boundary by an increasing degree as the fifth wheel is moved forward.

In summary, all the data presented have shown that vehicle acceleration in response to random road roughness increases as the fifth wheel is moved forward.

Experimental Measurement of Ride Quality

The acceleration levels in the cab of a tractor-semitrailer unit have been measured experimentally for a unit traveling on an Interstate highway. These measurements have been performed by means of an instrumentation package supplied by the Transportation Systems Center of the U.S. Department of Transportation on equipment supplied and operated by the National Highway Traffic Safety Administration Research Test Center in Maryland.

Test Equipment

For the tests, a 1975 International Harvester Transtar II with a loaded Fontaine flatbed semitrailer (19 110 lbf over the kingpin and 23 160 lbf over the rear tandem) was used (see Figure 10). [The full technical specifications for this experimental vehicle are available from the authors.]

The following instrumentation was employed. Three dc accelerometers were orthogonally oriented on a rigid aluminum housing that was securely screwed to a console located between the driver's and passenger's seats, as shown in Figure 11. (It is standard procedure not to include the seat dynamics in ride-quality measurements for convenience and because not all of the driver is isolated by the seat from the cab, e.g., hands on the steering wheel and feet on the floor.) The output sensitivity of the accelerometers was adjusted to make use of their full dynamic range and then filtered in the following manner. The longitudinal direction was low-passed filtered (Butterworth) with a break frequency of 30 Hz (the analytical models have shown no useful information above 30 Hz). The vertical direction was band-passed filtered (0.03-30 Hz) to remove the dc bias introduced by gravity. The signals were then simultaneously recorded on a seven-channel portable FM magnetic tape recorder.

Figure 7. Vertical mean square acceleration spectral density at the driver's seat for three fifth-wheel positions at 55 mph.

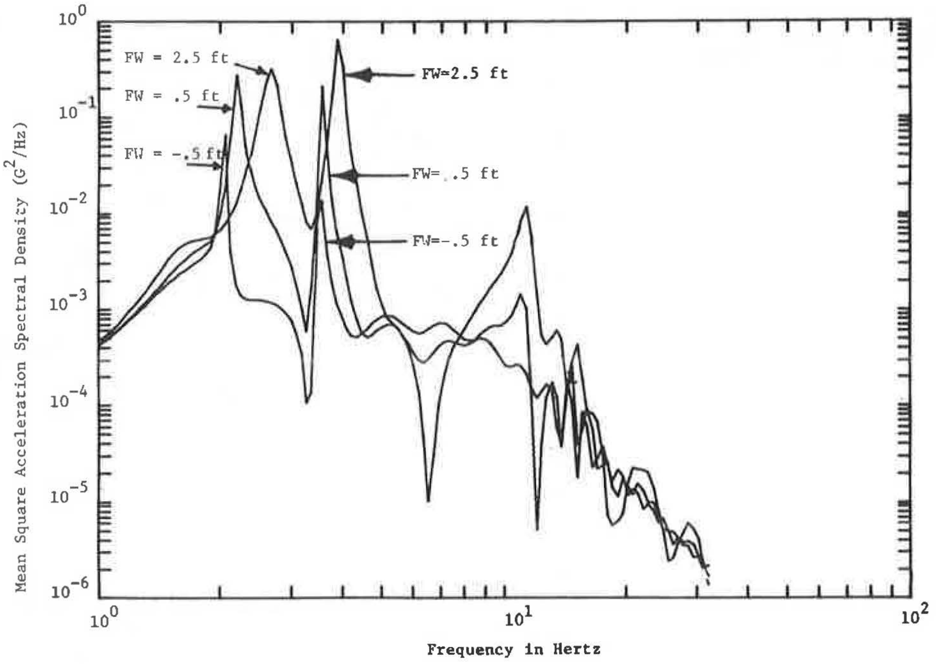
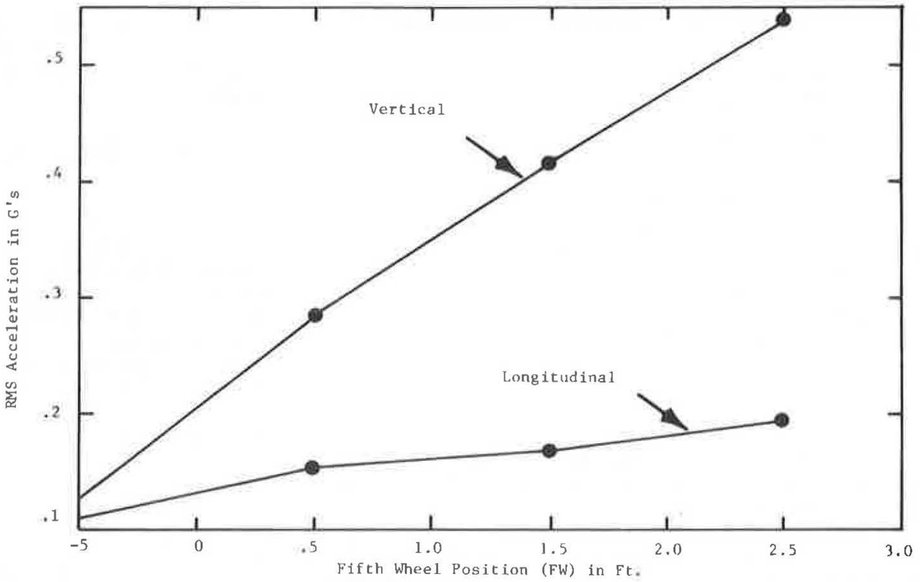


Figure 8. Fifth-wheel position versus rms acceleration at 55 mph.



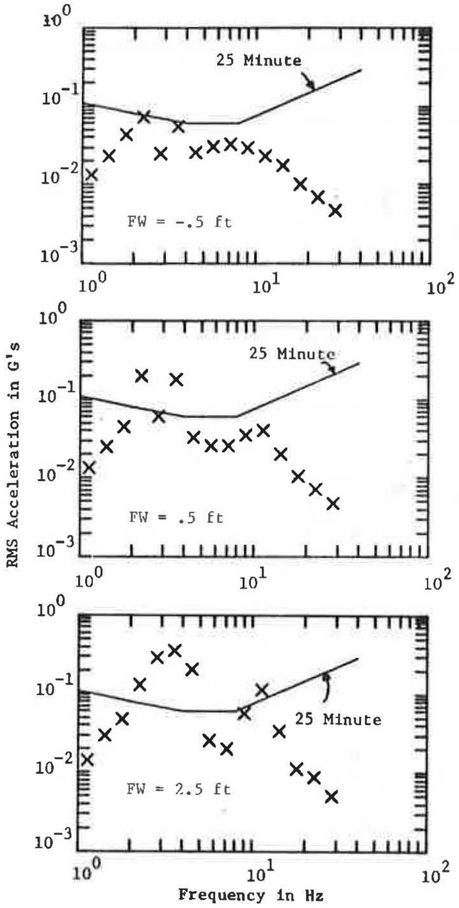
The tests were run on I-495 in Maryland between exits 28 and 37. The highway is poured concrete that has expansion joints (tar strips) every 40 ft; there are numerous overpasses. The first test made was a control test. A 5-min recording of the vehicle standing still with the engine running at a speed that corresponded to the truck traveling at 55 mph was performed to identify frequency components resulting from engine vibrations. Then six runs were made: tests at three different fifth-wheel positions (6 in behind and 3 and 15 in ahead of the tractor tandem's centerline) and at two different speeds (45 and 55 mph). All the runs at the same speed were made by traveling in the same direction while the test driver tried to maintain constant speed in the same lane. The fifth-wheel positions were changed in succession from the extreme rearward position to the extreme forward position. Approximately 20 min of data were collected on each run.

Data Analysis and Postprocessing

Each channel of data was individually processed in the following manner. The output of the tape recorder was band-passed filtered (0.06-40 Hz) to remove any dc bias and to further reduce noise that could have been introduced into the system. An analog computer was used as an amplifier to provide the signal and the proper level for the analog-digital converters. The signal was then sampled by using analog-digital converters at 102 Hz, giving 1024 points for a 10-s run. The data samples were then numerically analyzed on a digital computer by using a fast Fourier transform (FFT) Cooley-Tukey algorithm (11).

Twenty FFTs were computed from the 10-s data samples and averaged together in the frequency domain to give a consistent estimate of the mean square spectral density and to reduce the random error of this estimate to 22 percent. When 70 such 10-s samples were averaged, which reduced the random error of this estimate to 12 percent, no significant diffferences were found in the output mean square spectral density plots in comparison with the plots based on 20 sample runs. In addition, a test for stationarity was performed by comparing the mean square spectral density plots at one time in a run with those at another. No significant differences were found. The mean square spectral density plots, the total rms acceleration, and the third-octave band integration of the data were then performed on a digital computer.

Figure 9. Cab vertical ISO response at 55 mph versus 25-min reduced comfort criterion.



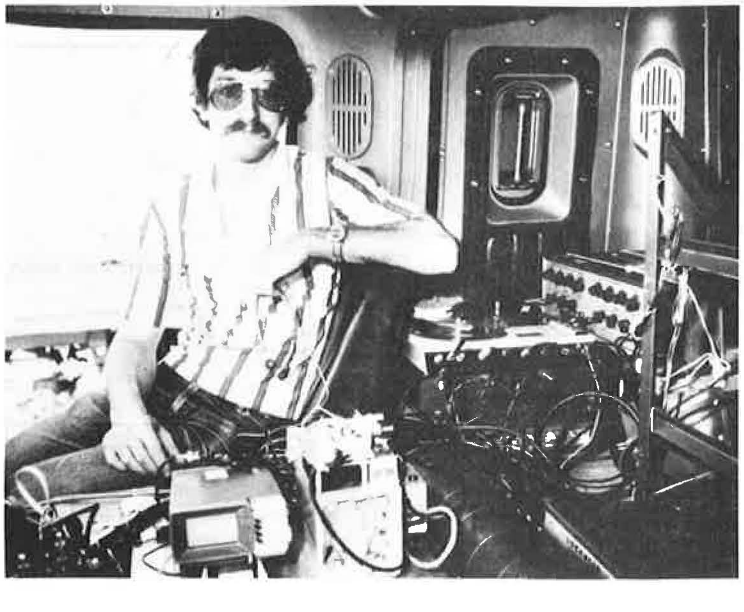
EXPERIMENTAL RESULTS

The vertical acceleration spectral densities computed from the data are shown in Figure 12 for the different fifth-wheel positions. Significant signal content in these data is associated with the 2- to 4-Hz region. As the fifth wheel is moved from 6 in behind to 15 in ahead of the tractor tandem's centerline, the dominant peak shifts upward in frequency approximately 1 Hz in the vertical direction and also increases in magnitude. The peaks at other frequencies are not strongly influenced by fifth-wheel positions. The higher-frequency peaks at approximately 15 and 30 Hz are a result of engine-induced vibrations.

The acceleration spectral density data have been processed in third-octave bands as specified by ISO and compared with the ISO 25-min reduced comfort boundary, as shown in Figure 13. In the vertical direction the criterion is violated when the fifth wheel is in the far-forward position (15 in ahead) in the 3- to 4-Hz region and is satisfied for all other fifth-wheel positions.

Figure 10. Tractor-semitrailer test vehicle.

Figure 11. Installed data acquisition and processing equipment.



The total rms accelerations in both the vertical and the longitudinal directions (at two truck speeds) are plotted against fifth-wheel position in Figure 14. In both the vertical and longitudinal directions, the worst ride is obtained with the fifth wheel in the far-forward position. In the vertical direction this increase in ride discomfort is more pronounced. The total vertical rms acceleration is higher at the lower speed because it is necessary to drive in the rough curb lane at 45 mph.

In summary, the ride quality generally degrades as the fifth wheel is moved forward. At 55 mph the total rms acceleration in the vertical direction increases by a factor of 1.5, whereas in the longitudinal direction the increase is 1.25 as the fifth wheel is moved from 0.5 ft behind to 1.25 ft forward of the axle centerline.

Figure 12. Vertical mean-square acceleration spectral densities for three fifth-wheel positions at 55 mph.

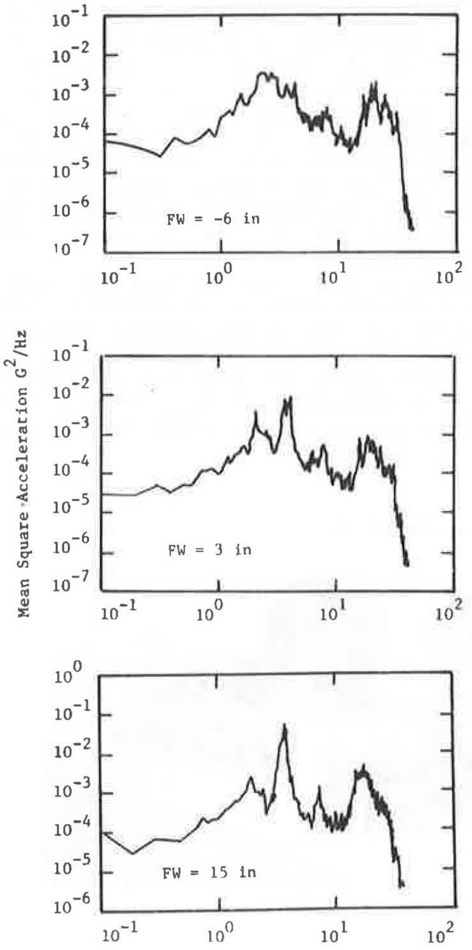


Figure 13. Vertical ISO response for three fifth-wheel positions at 55 mph versus the 25-min reduced comfort criterion.

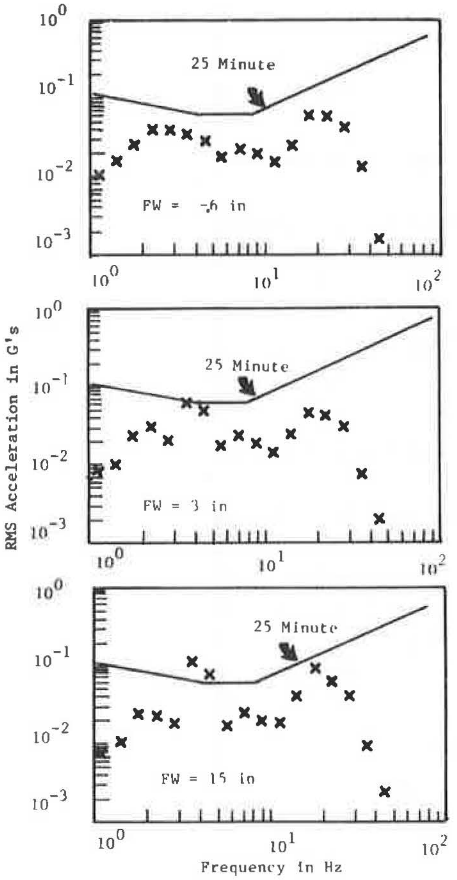
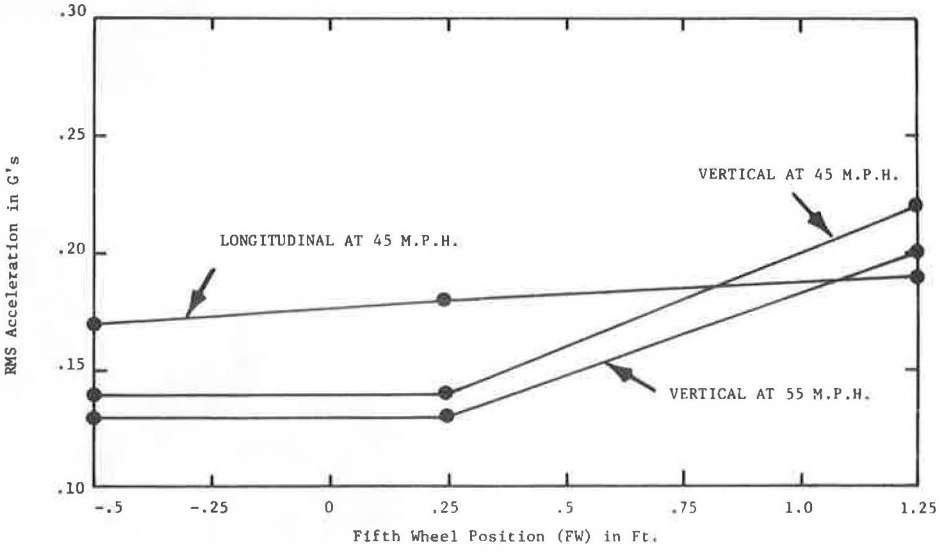


Figure 14. Fifth-wheel postion versus rms acceleration at two speeds.



SUMMARY

The objective of this paper was to determine the influence of fifth-wheel placement on ride quality. A six-degree-of-freedom linear model was formulated and the following analyses were performed:

1. Natural frequencies and mode shapes--(a) Natural frequencies associated with the tractor and semitrailer modes shift up in frequency as the fifth wheel is moved forward and (b) the amplitude of tractor pitching increases as the fifth wheel is moved forward.
2. Frequency response--The large resonant peaks at 2 and 4 Hz shift up in frequency and increase in magnitude as the fifth wheel is moved forward.
3. Random road response--(a) The total rms acceleration at a rigid point in the tractor representing the driver's location in both the vertical and longitudinal directions increases as the fifth wheel is moved forward and (b) the increase in rms accelerations results from increased output at frequencies in the 2- to 4-Hz range.

In addition to the analytical studies performed, an experimental investigation yielded the following conclusions: (a) The rms accelerations at the driver's location (not including the dynamics of the seat) in both the vertical and longitudinal direction increase as the fifth wheel is moved forward and (b) the analytical and experimental rms acceleration trends as a function of fifth-wheel placement agree closely.

In summary, the analytical and experimental data show that ride quality deteriorates as the fifth wheel is moved ahead of the tractor tandem's centerline. The increase in rms acceleration primarily results from the development of a resonant condition of out-of-phase tractor-semitrailer pitch in the 4-Hz region.

The comparison between the analytical and experimental results indicates good agreement when rms values are compared; however, it should be noted that the analytical model is valid only up to approximately 7 Hz. To model accurately the higher-frequency phenomena, features such as tractor-frame bending, cab-mount suspension, and wheel out of round would need to be included.

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Ride-Quality Models for Diverse Transportation Systems

LARRY G. RICHARDS, IRA D. JACOBSON, AND RICHARD D. PEPLER

This research was undertaken to develop comfort (ride-quality) models for six specific vehicles and to refine an existing composite ride-quality model. The vehicles were an automated guideway transit vehicle, a short-haul intercity rail vehicle, an urban rapid rail vehicle, a luxury-type charter bus, a compact car, and a subcompact automobile. Experiments on most vehicles were conducted in two phases: model development and model validation. In both phases, physical variables were measured for a series of ride segments, and each segment was rated for comfort level by a group of paid subjects. The important determinants of comfort for most vehicles were roll, pitch, and vertical acceleration. These variables are highly intercorrelated; all load on the same principal component of the motion-correlation matrix. Two composite ride-quality models are presented; one has four variables (roll, pitch, and vertical and longitudinal acceleration) and one has two variables (vertical acceleration and roll). The two-variable comfort model is sufficient for most uses.

For many years, transportation specialists have recognized the need to develop a quantitative tool for 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 guidelines for human tolerance to vibration (such as International Standard 2631:1978), none of which reliably assesses nor predicts passenger comfort or the acceptability of a ride. Recent work (1,2) has provided the basis for better criteria.

Initially, the study of ride quality was undertaken as a laboratory exercise, primarily to determine the influence of vibration (almost exclusively in the vertical direction) on subjective judgments of motion and comfort. More recent laboratory work (3-5) that uses simulation facilities at the Langley Research Center seeks to determine how various components of motion and noise combine to influence subjects' judgments of comfort.

Field studies of passenger comfort have been conducted by Jacobson and Richards (6-9) and Kuhlthau and Jacobson (10). In the United Kingdom, Clarke and Oborne (11) have studied passenger reaction to public service vehicles, particularly to cross-channel Hovercraft, helicopters, and trains. Manenica and Corlett (12) assessed rider reaction to a Hovercraft and a local bus service. In Japan, panels of experts have been employed to evaluate specific industrial and agricultural vehicles (13).

Richards and Jacobson (6,8) surveyed airline passengers about their reactions to the flight environment and their perceptions of factors that influenced their level of comfort. On one questionnaire, passengers ranked various comfort-level factors; seat factors were seen to be most important, followed by noise, temperature, and motion. On a second questionnaire, passengers indicated the degree of discomfort they associated with each of a set of environmental factors. Ratings of noise, vibration, motion, and seat variables were significantly associated with passenger comfort.

Jacobson and Richards (7,9) obtained continuous recordings of the motion characteristics of aircraft while test subjects simultaneously rated their levels of comfort at intervals throughout the flights. The highest simple correlations with rated comfort resulted from root-mean-square (rms) values for vertical and transverse acceleration and roll rate. Principal-component analyses of the intercorrelation matrices for the motion variables yielded a major first component marked by transverse and vertical acceleration, roll, and pitch in all cases. This component is the physical correlate of rated comfort for the air mode.

Expanded comfort models for aircraft have taken account of the effects of noise (14) and seat factors (15), as well as temperature and pressure. A complete air model will involve all relevant environmental variables, seating and space variables, and maneuver factors. An initial formulation of such a model has been presented in two previous papers (15,16). Jacobson, Kuhlthau, and Richards (2) showed how quantitative models of this sort could be used as a tool by system designers to evaluate or predict passenger satisfaction with the ride environment of a vehicle. Their method has been proposed as a general approach to ride-quality evaluation (17).

The ride quality of ground-based vehicles has also been assessed. However, most previous studies of ground vehicles have been limited to linear accelerations. Investigators have been discouraged by the lack of correspondence between rated comfort and vertical and lateral acceleration (18), but angular rates may be important to ride quality for ground vehicles. As Higgenbotham noted at the 1977 Transportation Research Board meeting, great variations can occur among comfort ratings for three different rail cars although no differences in lateral and vertical acceleration were apparent. Comfort levels may have been determined by the angular rates, but they had not been measured.

Several field experiments were conducted to determine the effects of the environment of ground-based vehicles (city buses and intercity trains) on passenger comfort (19,20). As with the aircraft, the physical characteristics of the environment and the passengers' comfort ratings in that environment were assessed simultaneously for ride segments throughout a trip. Roll rate was strongly related to judged comfort for buses, as were noise and roll rate for trains. Richards, Jacobson, Barber, and Pepler (20) also developed a ride-quality model for buses on curved roadways that included both the mean and rms transverse acceleration. It is thus necessary to use different comfort models for different terrains and road configurations. If curves occur infrequently on a given ride, they can probably be safely ignored. However, if more than a certain percentage of the trip is on curved roads, an adjusted model would have to be used.

Passengers are clearly influenced by the dominant input on each type of vehicle. For ground-based vehicles, roll rate was generally the dominant motion, and passenger comfort judgments were strongly related to it; in the air mode, the linear accelerations, vertical and transverse, were most important. However, the correlation matrices and their principal components indicate that similarities exist in the motion characteristics of these vehicles and suggest that unified comfort models are feasible, given more extensive data (21). General models are needed to specify standards for exposure to environmental inputs and to specify criteria for the design of new vehicles or for the assessment of existing ones. Such composite models were formulated by Richards, Jacobson, Barber, and Pepler (19) for (a) ground-based vehicles and (b) vehicles having characteristics of both ground and air modes.

The major goal of the present research was to assess the ride environments of six additional vehicles. The particular vehicles have different characteristics and were selected for different reasons: Some represent state-of-the-art developments in their field; others are simply refinements of already examined vehicles; and some are new and relatively untried concepts. The second goal of this research was to examine a group of relevant contemporary vehicles to see whether they yield the kinds of results expected from the previous models. The purpose is not so much to do new modeling as to see whether these vehicles present any surprise in terms of older models. If no surprising results are found, this provides greater confidence in the previous work and its generality.

METHOD

Overview of the Research

This research program was designed to assess the ride quality of six specific vehicles, to develop comfort models for each, and to refine a composite ride-quality model in light of these data. The particular vehicles were

Table 1. Data base.

	Experimental Phase		Validation Phase	
Vehicle	Segments	Subjects	Segments	Subjects
Luxury bus			17	30
Group A	41	28		
Group B	40	33		
Compact car	16	24[a]	16	15[b]
Subcompact car	16	24[a]	16	15[b]
Metroliner rail car			17	31
Group A	11	21		
Group B	12	27		
PATCO rail vehicle			16	22
Group A	17	25		
Group B	16	30		
AGT vehicle	8	65		

Note: There was no distinction between runs for the AGT vehicle; there were 12 test runs with up to six subjects on a run.
[a] Eight groups of three each.
[b] Five groups of three each.

1. A small automated guideway transit (AGT) vehicle, operating at Morgantown, West Virginia;
2. A short-haul intercity rail vehicle, the Metroliner, operating from Washington, D.C., through New York City to Boston;
3. An urban rapid rail vehicle used by the Port Authority Transit Corporation (PATCO) system;
4. A luxury-type charter bus designed for tour use chartered from a firm near Darien, Connecticut;
5. A compact automobile, the 1978 Ford Fairmont, a four-door sedan with automatic transmission; and
6. A subcompact automobile, the 1978 Volkswagen Rabbit, a two-door model with automatic transmission.

To develop models for these vehicles, experiments on most vehicles were conducted in two phases: model development and model validation. In both phases, data were collected during actual test rides. Physical variables were measured for a series of ride segments, each of which was also rated for comfort level by a group of paid subjects. Subjects were chosen to represent different levels of age, sex, and prior experience with the transportation mode under study.

For some vehicles, 20-30 persons could ride at the same time, so that adequate sample sizes could be obtained in one or two trips. Other vehicles permitted the running of only 8 or so individuals at a time. Special test conditions prevailed for the automobile studies. Only 3 subjects could participate at one time, and 1 of these was the driver. The experimenter and equipment were also in the car during each test run. The driver rated each segment by pressing one of seven buttons on a response console to enter his or her comfort response directly onto the magnetic tape along with the motion recording for the ride segment. Table 1 summarizes the data base for this report.

Ride comfort and acceptability are significantly influenced by the external inputs to the vehicle (for example, surface conditions, track type, and vehicle speed). To ensure that the models are based on adequate samples of the vehicle's ride environment, a wide range of these variables was included in the research design. Routes were carefully selected and tested in advance of actual data collection. For some vehicles, a high degree of control over external vehicle inputs was not possible, because scheduled services over existing routes had to be used. However, trip segments were chosen to provide typical ranges of vehicle motions. Whenever possible, segments were identified by landmarks and were spatially distinct. The experimenter alerted the subjects as the vehicle approached, entered, and left the test segment. At the end of each segment, the subjects rated the comfort of the ride. The start and end of each segment were marked on the motion-recorder tape. Noise, temperature, relative humidity, and vehicle speed were measured and recorded during each segment.

Environmental Measurements

The Portable Environmental Measuring System (PEMS II), developed by the University of Virginia, was used to obtain analog recordings of motion in six degrees of freedom: accelerations along the three linear directions and angular rates about the three rotational axes. All measurements were taken on the floor of the vehicle. Various alternative representations of the data could be extracted from the analog traces, including means, rms's, power spectral densities, frequency-band content, International Standard weighted scores, etc. In past work, the rms values of the dimensions of motion were found to correlate more strongly with human reactions to the motion than did any of the alternative measures. The environmental characteristics used in this study and their units of measure are shown below.

Environmental Characteristic	Symbol	Value
Longitudinal acceleration	a_L	rms about the mean (g)
Transverse acceleration	a_T	rms about the mean (g)
Vertical acceleration	a_V	rms about the mean (g)
Roll rate	ω_R	rms about the mean (°s)
Pitch rate	ω_P	rms about the mean (°s)
Yaw rate	ω_Y	rms about the mean (°/s)
Noise	dB(A)	Single value [dB(A)]
Temperature	T	Single reading(°C)

Subjective Response Forms

Passengers' ratings of ride comfort are the primary dependent measures used for model development and validation. Comfort level for each segment of a trip was rated on a seven-point scale on which 1 = very comfortable, 4 = neutral, and 7 = very uncomfortable. Passengers were told to rate according to what they perceived as comfortable or uncomfortable.

General Modeling Logic

The basic modeling task is to relate the physical (environmental) measurements to the mean comfort levels experienced by the passengers during the segments. For each physical input, its linear regression on rated comfort is obtained. Multiple regression, both stepwise and simultaneous, is also done with the physical variables as predictors and rated comfort, or mean rated comfort, as the criterion. Principal component analyses of the intercorrelation matrices for the physical variables are used to detect multicolinearity.

RESULTS

Models for Individual Vehicles

Summary statistics for the six motion variables are presented in Tables 2 and 3. Although noise and temperature were measured, they were not included in the analyses because of lack of variability. Each table includes the bus and train data from a previous report (19), as well as the results for each vehicle in the present study. The statistics, computed on the rms values for each variable,

Table 2. Summary statistics for roll rate, pitch rate, and yaw rate for all vehicles.

	Roll Rate						Pitch Rate						Yaw Rate					
Vehicle	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range
Regular bus	2.40	0.80	0.33	1.10	4.60	3.50	2.10	0.50	0.24	1.20	3.40	2.20	2.10	0.60	0.29	1.10	3.50	2.40
Luxury bus	1.92	0.29	0.15	1.05	2.76	1.71	1.76	0.23	0.13	1.14	2.31	1.17	2.50	0.96	0.38	1.10	5.45	4.35
Group A	1.93	0.28	0.15	1.28	2.43	1.15	1.75	0.23	0.13	1.26	2.31	1.05	2.56	0.98	0.38	1.27	5.10	3.83
Group B	1.92	0.31	0.16	1.05	2.76	1.71	1.76	0.24	0.14	1.14	2.16	1.02	2.45	0.94	0.38	1.10	5.45	4.35
Validation	0.98	0.19	0.19	0.70	1.28	0.58	0.83	0.05	0.06	0.77	0.96	0.19	1.51	0.08	0.05	1.41	1.65	0.24
Compact car																		
Phase 1	2.08	0.73	0.35	1.34	3.64	2.30	2.08	0.71	0.34	1.31	3.58	2.27	2.58	1.30	0.50	1.05	5.74	4.69
Phase 2	2.13	0.77	0.36	1.15	3.80	2.65	2.10	0.72	0.34	1.08	3.70	2.62	2.56	1.25	0.49	1.04	5.58	4.54
Subcompact car																		
Phase 1	2.41	0.89	0.37	1.38	5.27	3.89	3.01	1.16	0.39	1.33	5.58	4.25	2.43	1.29	0.53	0.89	5.93	5.04
Phase 2	2.30	0.92	0.40	1.23	5.10	3.87	2.85	1.18	0.41	1.33	5.64	4.31	2.58	1.44	0.56	0.99	5.62	4.63
Train (previous)	1.40	0.30	0.21	0.90	2.60	1.70	0.95	0.10	0.11	0.76	1.10	0.34	1.30	0.30	0.23	0.80	2.70	1.90
Metroliner rail	1.72	0.45	0.26	1.37	3.19	1.82	1.62	0.76	0.47	1.22	4.58	3.33	1.68	0.34	0.20	1.31	2.58	1.27
Group A	1.56	0.15	0.10	1.37	1.81	0.44	1.37	0.09	0.07	1.22	1.51	0.29	1.59	0.24	0.15	1.31	1.92	0.61
Group B	1.87	0.58	0.31	1.38	3.19	1.81	1.85	1.01	0.55	1.32	4.58	3.26	1.76	0.40	0.23	1.33	2.58	1.25
Validation	1.28	0.21	0.16	0.77	1.63	0.86	1.01	0.16	0.16	0.66	1.31	0.65	1.13	0.29	0.26	0.77	1.80	1.03
PATCO rapid rail	1.61	0.68	0.42	0.94	3.79	2.85	1.34	0.89	0.66	0.65	4.83	4.18	1.56	0.79	0.51	0.73	3.59	2.86
AGT vehicle	1.60	0.29	0.18	0.89	2.47	1.58	1.66	0.32	0.19	1.02	2.96	1.94	3.46	1.38	0.40	1.73	5.63	3.90

Table 3. Summary statistics for longitudinal, transverse, and vertical acceleration for all vehicles.

	Longitudinal Acceleration						Transverse Acceleration						Vertical Acceleration					
Vehicle	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range	$\bar{X}$	SD	CV	MIN	MAX	Range
Regular bus	0.044	0.015	0.34	0.017	0.073	0.056	0.075	0.028	0.37	0.031	0.134	0.103	0.082	0.027	0.33	0.036	0.152	0.116
Luxury bus	0.035	0.014	0.40	0.012	0.077	0.065	0.070	0.028	0.40	0.021	0.142	0.121	0.067	0.017	0.25	0.037	0.112	0.075
Group A	0.036	0.014	0.39	0.013	0.070	0.057	0.071	0.027	0.38	0.026	0.142	0.116	0.066	0.018	0.27	0.037	0.112	0.075
Group B	0.035	0.014	0.40	0.012	0.077	0.065	0.068	0.028	0.41	0.021	0.134	0.113	0.069	0.017	0.25	0.039	0.105	0.066
Validation	0.008	0.001	0.13	0.006	0.010	0.004	0.009	0.001	0.11	0.007	0.012	0.005	0.033	0.006	0.18	0.028	0.048	0.020
Compact car																		
Phase 1	0.040	0.020	0.50	0.015	0.092	0.077	0.050	0.030	0.60	0.020	0.123	0.103	0.050	0.020	0.40	0.033	0.105	0.072
Phase 2	0.040	0.015	0.34	0.013	0.080	0.067	0.060	0.030	0.50	0.020	0.148	0.128	0.060	0.020	0.33	0.033	0.106	0.073
Subcompact car																		
Phase 1	0.040	0.020	0.50	0.014	0.090	0.076	0.050	0.030	0.60	0.021	0.134	0.113	0.070	0.020	0.29	0.036	0.112	0.076
Phase 2	0.040	0.020	0.50	0.017	0.097	0.080	0.060	0.040	0.67	0.019	0.158	0.139	0.070	0.020	0.29	0.044	0.122	0.078
Train (previous)	0.012	0.004	0.33	0.007	0.022	0.015	0.029	0.010	0.34	0.009	0.064	0.055	0.030	0.007	0.23	0.018	0.046	0.028
Metroliner rail	0.021	0.008	0.38	0.011	0.038	0.027	0.022	0.009	0.41	0.012	0.049	0.037	0.035	0.011	0.31	0.024	0.076	0.052
Group A	0.022	0.008	0.36	0.011	0.033	0.022	0.019	0.006	0.32	0.012	0.028	0.016	0.032	0.005	0.16	0.024	0.041	0.017
Group B	0.021	0.008	0.38	0.012	0.038	0.026	0.025	0.010	0.40	0.012	0.049	0.037	0.038	0.014	0.37	0.028	0.076	0.048
Validation	0.020	0.007	0.35	0.008	0.030	0.022	0.020	0.009	0.45	0.015	0.050	0.035	0.040	0.005	0.13	0.030	0.050	0.020
PATCO rapid rail	0.040	0.020	0.50	0.009	0.100	0.091	0.020	0.004	0.20	0.016	0.035	0.019	0.030	0.005	0.17	0.019	0.043	0.024
AGT vehicle	0.030	0.010	0.33	0.010	0.050	0.040	0.040	0.020	0.50	0.020	0.070	0.050	0.040	0.010	0.25	0.030	0.050	0.020

include the mean ($\bar{X}$), standard deviation (SD), coefficient of variability (CV), minimum value (MIN), maximum value (MAX), and range. Table 4 presents similar statistics for the mean comfort ratings.

The luxury bus results show substantially lower means and variability for roll and pitch rates than did the conventional bus. However, yaw had slightly higher means and standard deviations for the luxury bus. All linear accelerations were greater for the conventional bus. In particular, the luxury bus displayed less vertical acceleration. Mean comfort judgments were better for the luxury bus than for the conventional bus, except for the validation phase. The luxury bus validation study involved peculiar circumstances and severely restricted ranges for all motion variables. An unusual situation led to poor mean comfort ratings in the presence of extremely good motion characteristics.

The two automobiles showed similar patterns of results for the measured linear accelerations. Roll and pitch rates were more extreme and more variable for the subcompact than for the compact car. The phase 1 data showed that riders were more comfortable in the compact car than in the subcompact, but this difference was not apparent for the phase 2 data.

The Metroliner data from this study differed in several respects from the previous train results. The present data contain more extreme levels of roll, pitch, and longitudinal and vertical acceleration than the earlier data but less noise.

Table 4. Summary statistics for mean comfort ratings for all vehicles.

Vehicle	$\bar{X}$	SD	CV	MIN	MAX	Range
Regular bus	3.40	1.10	0.32	2.20	6.30	4.10
Luxury bus	2.56	0.55	0.21	1.48	3.85	2.37
Group A	2.57	0.47	0.18	1.78	3.46	1.68
Group B	2.54	0.63	0.25	1.48	3.85	2.37
Validation	3.48	0.72	0.21	2.47	4.87	2.40
Compact car						
Phase 1	2.99	0.98	0.33	1.33	5.67	4.34
Phase 2	3.16	1.08	0.34	1.00	5.67	4.67
Subcompact car						
Phase 1	3.27	1.08	0.33	1.33	6.33	5.00
Phase 2	3.17	1.20	0.38	1.33	6.33	5.00
Train (previous)	2.90	0.80	0.28	1.70	4.80	3.10
Metroliner rail	2.45	0.62	0.25	1.70	3.77	2.07
Group A	2.15	0.39	0.18	1.71	3.05	1.34
Group B	2.73	0.68	0.25	1.70	3.77	2.07
Validation	2.92	0.48	0.16	2.13	3.81	1.68
PATCO rapid rail	2.36	0.36	0.15	1.76	3.63	1.87
AGT vehicle	2.66	0.74	0.28	1.33	5.67	4.34

Table 5. Correlations of motion variables with comfort for all vehicles.

				Acceleration		
Vehicle	Roll	Pitch	Yaw	Longitudinal	Transverse	Vertical
Regular bus	0.76[a]	0.22	0.05	0.48	0.28	0.57[a]
Validation	0.69[a]	0.76[a]	0.31	0.11	0.53[a]	0.74[a]
Luxury bus	0.53[a]	0.63[a]	-0.02	0.04	0.03	0.70[a]
Group A	0.61[a]	0.55[a]	-0.01	0.13	-0.02	0.61[a]
Group B	0.49[a]	0.70[a]	-0.04	-0.02	0.06	0.80[a]
Validation	-0.08	0.31	-0.25	0.43	0.47	0.22
Compact car						
Phase 1	0.46[a]	0.44[a]	0.14	0.13	0.18	0.46[a]
Phase 2	0.48[a]	0.48[a]	0.22	0.12	0.27	0.57[a]
Subcompact car						
Phase 1	0.49[a]	0.51[a]	0.03	0.52[a]	0.02	0.58[a]
Phase 2	0.47[a]	0.55[a]	-0.03	0.51[a]	-0.12	0.38[a]
Train (previous)	0.44[a]	0.31	0.20	0.43[a]	0.34	0.08
Metroliner rail	0.57[a]	0.44[a]	0.42[a]	0.08	0.37	0.65[a]
Group A	0.81[b]	0.34	0.47[b]	-0.01	0.63[b]	0.20
Group B	0.46[b]	0.37	0.32	0.18	0.14	0.68[b]
Validation	0.37	0.14	0.36	0.11	0.49[a]	0.62[a]
PATCO rapid rail	-0.01	-0.03	0.09	-0.12	0.41[b]	0.06
AGT vehicle	0.22	0.26	0.35	0.50[a]	0.39	0.47[b]

[a] Significant at $\alpha \leqslant 0.001$.
[b] Significant at $\alpha \leqslant 0.05$ (small sample sizes).

Table 6. Best model of ride quality for each vehicle.

Vehicle	"Best" Model	R
Luxury bus	$C' = 0.33 + 19.33\,a_V + 0.53\omega_p$	0.76
Compact car	$C' = 1.66 + 0.36\omega_R + 10.53a_V$	0.47
Subcompact car	$C' = 0.30 + 28.98a_V + 21.96a_L$	0.66
Metroliner rail car	$C' = 1.14 + 37.33a_V$	0.65
PATCO rapid rail	–[a]	
AGT vehicle	$C' = 0.39 + 42a_V + 24a_L$	0.56

[a] There was no good model based on motion variables.

However, the two groups of experimental subjects differed in the motion characteristics of their test segments: Extreme motion values were evident only for group B. In the validation phase, the linear accelerations were comparable to the experimental data sets. However, angular rates were less for the phase 2 data than for the phase 1 data.

The range of comfort ratings for the PATCO vehicle tests was extremely limited; most passengers found their rides comfortable or very comfortable. Limited ranges of mean comfort values are also apparent for group A of the luxury bus test and for all groups in the Metroliner study.

Table 5 summarizes the correlations of all the motion variables with comfort for all the vehicles in this and the previous study. All the rows represent independent tests of ride quality models except the top rows for luxury bus and Metroliner rail, which represent combined information from two groups each and are therefore not independent of the rows for their respective groups A and B. Roll shows significant correlations with comfort in 11 of the 15 independent data sets, vertical acceleration in 12 of the 15, and pitch in 9 of 15. There were only two vehicle tests for which these variables showed no correlation with comfort, and both data sets were problematic. For the luxury bus validation data and the PATCO vehicle data, no ride-quality model worked well.

For most of the individual vehicles, the same motion variables emerged as important determinants of comfort: roll, pitch, and vertical acceleration. They are highly intercorrelated and, in principal-components analyses, all load on the same component. Thus, composite models of ride quality will reflect this component either by including one of the variables that load strongly on it or by incorporating a linear combination of all of them.

Table 6 contains the "best" multiple regression model for each of the vehicles studied. Each model is the result of both the modeling and the validation processes. The multiple correlation (R) obtained by each model is also shown. Tables 5 and 6 also reveal the selective influence of other motion parameters. Longitudinal acceleration is important in the subcompact car and for the Morgantown AGT vehicle. In the first case, longitudinal acceleration is correlated with roll, pitch, and vertical acceleration. Transverse acceleration also correlates with comfort for several vehicles. Its contribution may depend on the number of curves in the track or roadway encountered during the test run. In a previous study of ride quality for buses on a curved roadway, transverse acceleration was the only motion component in the model (20).

Composite Models

The data from the present experiment were also used to develop composite models. The data from the several vehicles were merged together into a single analysis. Since different subjects were involved in tests for the different vehicles and since the several vehicles have different frequency spectra, the equations shown here will be lower bounds on the relations that might be obtained. All six motion variables were used, but the data from PATCO and the luxury bus validation study were not included. Thus, the composite data set consisted of the luxury bus experimental data, the Morgantown AGT and Metroliner data, and all the automobile data. The phase 1 and phase 2 distinctions were ignored for this analysis. This resulted in a total of 563 usable ride segments. The regression model that best fits these data is

$$C' = 0.20\omega_r + 0.14\omega_p + 10.15a_V + 7.71a_L + 1.36 \tag{1}$$

This model has a multiple correlation of 0.54. For roll, pitch, and vertical acceleration alone, the respective correlations with comfort are 0.49, 0.50, and 0.46; models that involve either vertical acceleration and roll or vertical acceleration and pitch result in an R of 0.52. Thus the four-variable model does not improve much on a two-variable model. Furthermore, roll, pitch, and vertical acceleration all load highly on a single principal component of the motion intercorrelation matrix. However, roll and pitch are sufficiently independent of vertical acceleration to add predictability when they are included in the model.

The influence of longitudinal acceleration is a result of the automobile data. The car data represent a large part of the composite data set (350 of the 563 observations) and thus strongly influence the overall model. When the total data are partitioned into those for cars and those for other vehicles, the best equation for cars includes roll and vertical and longitudinal accelerations, whereas that for the other vehicles involves only roll and vertical acceleration. Thus, the influence of longitudinal acceleration is peculiar to a certain vehicle, just as the influences of transverse acceleration result from particular operating conditions (curved roadway). Whereas Equation 1 is statistically optimal for the composite data set, Equation 2 is more representative of ground-based vehicles in general:

$$C' = 0.41\omega_R + 11.84a_V + 1.43 \qquad (2)$$

It is recommended as a general model. The fit of Equations 1 and 2 to comfort data for each of the vehicles in this study is shown below. Clearly, the two-variable equation is adequate in most cases and preferable in some.

	Correlation	
Vehicle	Equation 1	Equation 2
Luxury bus		
Experimental	0.68	0.72
Validation	0.23	0.09
PATCO rapid rail	-0.05	0.00
AGT vehicle	0.50	0.37
Metroliner	0.33	0.43
Compact car	0.47	0.49
Subcompact car	0.59	0.54

DISCUSSION

These results reaffirm the importance of the angular rates as determinants of comfort for ground-based vehicles. Although earlier composite models appear to be generally appropriate for the data presented here, two refined composite models were presented. Except for two anomalous data sets, there were no real surprises in the new data; the right variables were important to comfort when they displayed enough variability. Models involving roll, pitch, and vertical acceleration were found in most cases. Occasionally an additional variable also proved important (longitudinal or transverse acceleration).

The previous train model had involved a noise component. However, in this study noise was not a significant determinant of comfort in the Metroliner rail-car data; it simply did not show the high mean levels and wide variability encountered in the earlier study. Both noise and temperature would be important to comfort under the right circumstances. In this study, however, both had values that fell in the comfortable range on all vehicles and showed little variation within any test run. It appears that the extreme noise variation found in the first train study is not representative of the usual environment in trains or of most other vehicles. However, it may be characteristic of certain train routes.

The two anomalous data sets (the PATCO vehicle and the luxury bus validation data) may both reflect the role of attitudes, or passenger preconditioning, on reactions to the vehicle environment. Subjects in the luxury bus replication study were extremely negative about the whole experience: It was a cold, rainy day; and the test run was delayed. For the PATCO subjects, on the other hand, everything went very smoothly and on schedule. The respondents were very favorably disposed toward PATCO in general and very cooperative with the experiment in particular. Their overall positive attitudes are reflected in their ratings of the test segments. They rated everything as comfortable.

While the six degrees of freedom of motion may be independent in theory, they are correlated in practice. For the vehicles discussed above, a high degree of multicolinearity exists among the motion inputs, particularly roll, pitch, and vertical acceleration. These vehicles have characteristic patterns of motion variation; there is a cross coupling of several degrees of freedom of motion. It is conceivable that future vehicles will have different patterns of covariation of the motion inputs. Studies are needed to explore what happens to human reactions when the existent cross correlations are broken down or altered. Such studies may be done on six-degree-of-freedom motion simulators.

Two goals of past ride-quality research have been (a) the development of a ride-quality meter and (b) the establishment of standards or criteria for human exposure to whole-body vibration. The approach described here may accomplish both of these goals. The main problem with past work on both goals has been the failure to assess vibration in all six degrees of freedom simultaneously. Traditional ride-quality meters are not good enough because they incorporate only linear accelerations. Their failures are almost certainly due to the fact that they ignore the contributions of the angular rates to ride quality. Similarly, people often report being uncomfortable in environments that existing standards (International Standard 2631:1978) deem acceptable. However, since those standards also cover only the linear accelerations, the rider's discomfort may well be due to the rotational degrees of freedom. An adequate set of standards and a successful ride-quality meter will have to incorporate equations such as those reported here.

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Maximum Deceleration and Jerk Levels That Allow Retention of Unrestrained, Seated Transit Passengers

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Three experiments performed to determine the maximum deceleration and associated rate of change of deceleration (jerk) that will allow the majority of potential users of automated guideway transportation systems to remain securely in their seats are described. In each experiment subjects representative of three anthropometric classes underwent various levels of deceleration and jerk. These experiments were performed in an instrumented vehicle controlled by an automated braking system. Seat sensors, movies, and subject ratings were employed to determine the deceleration at which subjects began to move off the seat pan. Subjects were decelerated while seated normally, sideways, and forward facing but tilted backward (facing forward with the seat pan tilted back 3, 9, or 12°). Subjects underwent jerk levels of 0.25, 0.75, and 1.25 *g*/s while seated normally only. Jerk was found not to affect maximum deceleration levels. Modifications of features common to transit seating were found to increase retention. The maximum deceleration allowing retention was determined for both forward- and side-facing seated passengers. These results are discussed and presented in tabular and graphic form.

A major design goal of transit systems, particularly of automated guideway transit (AGT) systems, is high passenger flow rate. One technique employed to accomplish this goal is to minimize the headway between vehicles moving in the same direction along the guideway. However, a sufficient stopping distance between vehicles must be maintained for the safety of the passengers. The more closely one vehicle follows another, the more quickly it must

stop in order to avoid collision. High stopping rates and decelerations, however, do increase the risk of injury to passengers who may be dislodged from their seats. Therefore, it is important to determine the maximum deceleration levels that allow retention of unrestrained, seated transit passengers.

BACKGROUND

In a previous study, Abernethy and others (1) investigated the effects of seat position, anthropometry, and jerk on passenger retention. This study used a limited number of subjects, driver-controlled deceleration, and a seat-switch technique for sensing deceleration. Each of these elements could possibly have reduced the precision of the results. In particular, it was noted that the seat-pan switches required a small but finite time to activate as a subject came off the seat pan. Therefore the deceleration readings recorded were always higher than the actual deceleration at which the subject came off the seat, and the error in deceleration readings always increased as jerk increased, i.e., readings taken at higher jerk levels indicate higher decelerations than may have actually been encountered by the subjects. In addition, the vehicle driver could not always precisely apply the brakes to achieve target deceleration levels. Finally, a limited number of subjects were available for the 1977 study, which was a particular problem in the experiment to determine the effects of jerk.

A review of the previous experimental research on emergency deceleration and jerk in public transit vehicles has been made by Jacobs (2).

The study by Abernethy and others (1) revealed that the mean maximum deceleration level at which forward-facing subjects were dislodged was 0.55 g. When the seat was tilted 5° back, the mean value increased to 0.59 g. For the retention of 84 percent (mean minus one standard deviation) of the population, the permissible emergency deceleration level was estimated to be 0.47 g for passengers tilted back 5°. For side-facing subjects, the mean deceleration was 0.49 g for retaining 50 percent of the population and 0.41 g for 84 percent of the population. Estimates of emergency braking levels in existing AGT systems are found below.

System	Deceleration Level (g)
Tampa (3)	0.11
Fairlane (4)	0.19
King's Dominion (5)	0.20
Seattle-Tacoma Airport (6)	0.13
VAL (7)	0.18-0.25
Houston Tunnel Train (8)	0.15
AIRTrans (9)	0.16-0.22
WEDway (10)	0.16
Morgantown (11)	0.31-0.37

Previous research has indicated that jerk is a factor in determining the comfort aspects of deceleration. In terms of safety, the previous research of standees had differing findings on the effects of jerk. The only study directly applicable to the seated passenger in AGT systems is that by Abernethy and others (1), which did not find jerk to be a factor in passenger retention.

APPROACH

It was decided to measure the maximum deceleration and associated jerk that will allow the majority of passengers to remain securely in their seats by a method that combines seat-switch sensors, photogrammetric data, and subject ratings. Vehicle decelerations and jerks were controlled by an automated braking system, and an increased number of subjects was used.

Twelve subjects participated in each of three experiments designed to determine the maximum deceleration level under various conditions of jerk (0.25, 0.75, and 1.25 g/s; seat orientation (forward or side facing); seat-tilt angle (0, 3, 9, and 12° backward); and passenger assists (foot and arm rests).

METHOD

Subjects

Thirty-six subjects were recruited by newspaper advertisement. Subjects were selected to ensure that the male and female participants were representative of the smallest 15 percent, the middle 15 percent, and the largest 15 percent of the general population in both height and weight, as calculated from data in Damon, Stoudt, and McFarland (12). For males, the smallest 15 percent were less than 66 in (167.6 cm) tall and weighed less than 138 lb (62.6 kg), the middle 15 percent had a mean height of 68.5 in (174.0 cm) and a mean weight of 159.2 lb (72.2 kg), and the largest 15 percent were greater than 71 in (190.3 cm) and weighed more than 187 lb (83.9 kg). For females, the smallest 15 percent were less than 61 in (154.9 cm) tall and weighed less than 109 lb (49.5 kg), the middle 15 percent were between 128 lb (58.1 kg) and 138 lb (62.6 kg), and the largest 15 percent were greater than 66 in (167.6 cm) and weighed more than 157 lb (71.3 kg). Each subject was required to pass a physician's medical examination and to sign a statement of informed consent before participating. Each subject received $25.

Apparatus

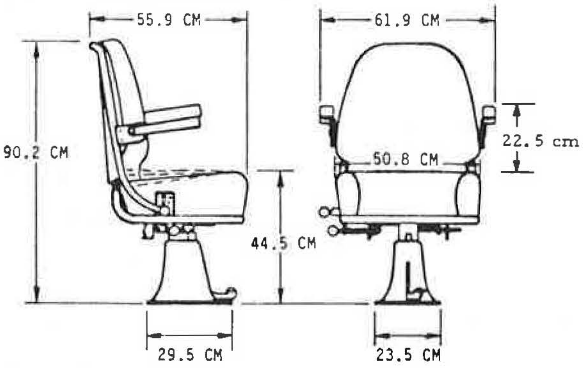
1. A commercially available seat (American Seating Company model 6318A) was selected for use in these experiments because it was both readily adjustable and representative of the type of transit seat to be used in AGT systems (Figure 1). The seat back was always positioned to maintain an approximate angle of 97° with the seat pan. The seat pan was adjustable from a 0° (flat) position to tilts of 3, 9, and 12° back. The seat cushion was contoured by using one flat 1-in (2.54-cm) layer of 70-lb (31.8-kg) compression foam with a second layer contoured along the front and sides (see Figure 2). The compression foam was such that a 70-lb weight placed on a 9-in (22.9-cm) disc depressed the foam by 25 percent. This contoured foam was covered with a nylon and wool coarse-weave fabric (Craftex K12924N). Two switches were installed in the positions indicated in Figure 2 and connected to a light that indicated their open or depressed status. This light was attached to the side of the seat. The seat was equipped with fold-down armrests, and an adjustable footrest was bolted to the floor in front of the seat.

2. Vehicle: This test seat was mounted in the rear center of a 14-ft (4.3-m) van. The van had disc brakes on the front wheels and dual wheels with drum brakes in the rear. Approximately 150 lb (62.8 kg) of ballast was added to the rear bumper to increase the braking force.

3. Braking system: The brakes were controlled by an automated braking system (Lebow Associates model 7610-112 brake test instrument). This device consisted of a hydraulic power supply that drove a brake pedal actuator that physically depressed the brake pedal on command from an electronic

programmer-controller. This electronic package was always programmed to reach the maximum deceleration attainable by the vehicle. In operation, the driver initiated a programmed deceleration by means of a remote switch. The braking system depressed the brake pedal, and the programmer-controller monitored its built-in decelerometer (attached to the van floor next to the seat) to provide a uniformly increasing deceleration (constant jerk). If required, the driver could abort the deceleration at any time by releasing the switch. The accuracy of the built-in decelerometer was calibrated against an independent force balance decelerometer (Columbia Services SA-107) and also against deceleration levels calculated from velocity measurements of a fifth wheel (Laboratory Equipment Company, truck test fifth-wheel model DD-1) mounted at the rear of the vehicle.

Figure 1. Experimental seat.



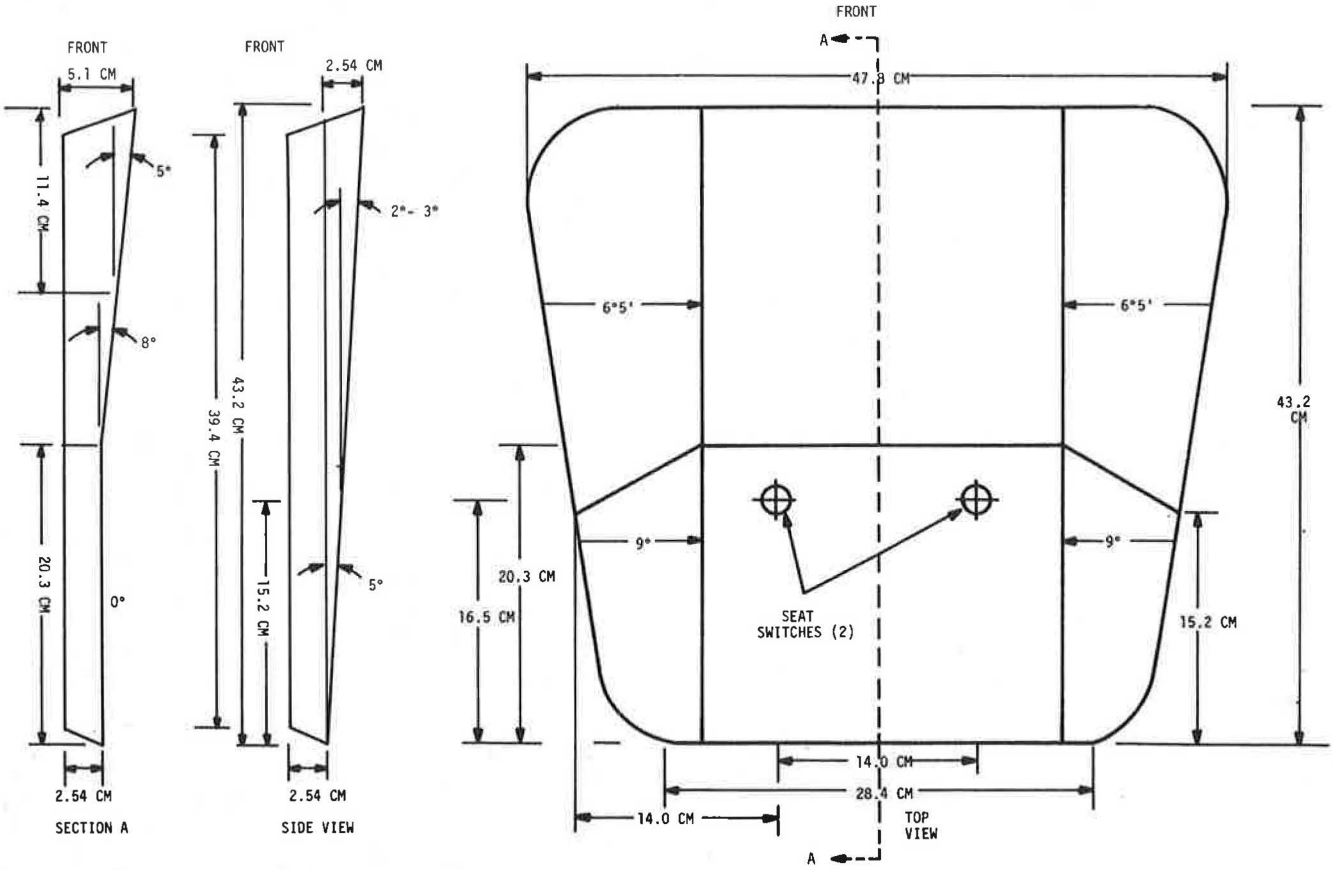
4. Recording equipment: The deceleration data taken from the braking system's built-in decelerometer and the status of the two seat-switch sensors were continuously recorded at 0.98 in/s (25 mm/s) on a two-channel strip-chart recorder (Brush model 222). A movie camera aimed at the seat side recorded not only when the subjects began to move off the seat pan but also how they moved during deceleration. This camera also filmed the light that indicated the status of the seat-pan switches. The decelerations were filmed at a speed of 64 frames/s to produce slow-motion pictures. Later, frame-by-frame analysis determined the time at which initial buttock movement off the seat pan occurred and when the seat switches responded to this movement as indicated by the light. The number of intervening frames determined the instrument lag time, if any. This lag time was subtracted from the seat-switch sensor indication time on the two-channel strip chart to calculate the actual deceleration value at the time the seat-switch sensor should have indicated it.

Procedure

General

The experiments were conducted in clear weather on an unused, straight, dry airport runway at either Hanscom Field in Bedford or Otis Air Force Base, both in Massachusetts. Each subject was briefed on the purpose of the experiment and on the entire procedure. Each was asked to sit as if in an actual

Figure 2. Fabric-covered contoured seat-pan cushion.



transit vehicle, to remain relaxed but not limp, and to not anticipate the decelerations. Each subject was fitted with a pair of denim overalls and a pair of rubber-soled shoes to eliminate the effects of frictional differences in personal clothing design or material. Each also wore a baseball catcher's chest protector and a motorcycle helmet approved for safety by the U.S. Department of Transportation. A five-point racing-type safety harness was loosely fastened about each subject and adjusted to allow the subject to slide up to the front edge of the seat but no further. The subject was cautioned not to grab the seat or seat belts during decelerations. The subject, when seated, could see through the front window of the vehicle. However, the automatic braking system could not be seen, so that the subject could not determine when the driver initiated a deceleration. The hydraulics of the automated braking system made a loud sound during warmup and activation. This sound was explained to the subject as being normal. To prevent the sound from serving as a cue to initiation of a deceleration, the braking system was kept on.

For each deceleration the driver would accelerate the vehicle to a predetermined velocity and then trigger the automated braking system with the remote switch for a preprogrammed constant deceleration until just prior to an abrupt stop. At this point the braking system was released, allowing the vehicle to coast to a stop. This procedure provided the required deceleration data at the onset of the stop; at the same time it avoided throwing the subject against the seat back as a result of the final jerk.

Specific

1. Experiment 1--effects of jerk: This study was designed to investigate the effects of level of jerk on passenger retention. Because of previous anomalous research findings, no assumptions about the effects of jerk on retention were made. Twelve subjects, two of each sex from each of the three anthropometric groups, participated. Each subject experienced three decelerations at each of three levels of jerk (0.25, 0.75, and 1.25 _g_/s. These decelerations were given in a counterbalanced order for a total of nine decelerations per subject. The subject sat in a forward-facing, untilted (0°) position on the fabric-covered contoured seat. The vehicle was decelerated from a velocity of 40 mph (64 km/h). Subject movement was filmed as described above. Each subject rated the last five decelerations on a scale from 1 to 7, where 1 = very comfortable and 7 = very uncomfortable.

2. Experiment 2--forward facing, seat tilt, and footrest: This study was designed to determine the maximum deceleration that will allow retention of passengers and to investigate the retention effects of increasing the seat-pan tilt and providing a footrest. The seat-pan tilt angles studied were 0 (flat), 3, 9, and 12°. It was assumed that passenger retention would increase with increasing seat tilt. The presence or absence of a footrest was also investigated. It was assumed that use of a footrest would enhance retention. Twelve subjects, two of each sex from each of the three anthropometric groups, participated. Each subject experienced decelerations at each tilt angle four times. Half of these 4 decelerations were with a footrest, half without, for a total of 16 decelerations per subject. The subject sat in a forward-facing position on the fabric-covered contoured seat. The footrest was adjusted so that both shoe heels rested on the floor and both shoe soles rested fully against the footrest. The vehicle was decelerated from a velocity of 30 mph (48 km/h) at a jerk of 0.5 _g_/s. Subject movement was filmed, but no ratings were taken.

3. Experiment 3--side facing, armrests: This study was designed to determine the maximum deceleration that allowed retention of side-facing passengers and to investigate the retention effects of armrests. It was assumed that armrests would enhance retention. Twelve subjects, two of each sex from each of the three anthropometric groups, participated. Each subject experienced three decelerations with armrests and three without for a total of six decelerations per subject. The subject sat in a side-facing, 3° seat-pan tilt position on the fabric-covered contoured seat. The armrest was fixed at 13.5 in (34.3 cm) above the seat pan. The vehicle was decelerated from a velocity of 30 mph at a jerk of 0.5 _g_/s. Subject movement was filmed, but no ratings were taken.

RESULTS

Experiment 1--Effects of Jerk

This experiment was conducted to determine the magnitude of any instrumentation lag and to establish the effects of levels of jerk. Several measures of subject responses to three levels of jerk (0.25, 0.75, and 1.25 _g_/s) were recorded: (a) the deceleration at which the seat-pan switch opened, which indicated initial buttock movement off the seat pan; (b) movies of actual subject movement; and (c) subject ratings of comfort level on a seven-point scale.

The first measure was the same as that employed by Abernethy and others (1). The results of this measure are reported below as the mean uncorrected deceleration as a function of level of jerk. The deceleration readings taken at the time of the seat-switch opening increase as a function of increasing jerk levels. However, film analysis did, in fact, reveal that the seat sensor lagged behind actual subject buttock movement from the seat pan. Correction of each deceleration reading removed the experimental error introduced by this instrumentation lag. The mean of these corrected decelerations is also reported as a function of jerk level, and these mean corrected decelerations do not increase with increasing levels of jerk.

Jerk Level (_g_/s)	Mean Deceleration Level (_g_)	
	Uncorrected	Corrected
Low (0.25)	0.383	0.29
Medium (0.75)	0.429	0.29
High (1.25)	0.491	0.30

An analysis of variance (Table 1) indicated that there were no significant differences in mean corrected decelerations among the three jerk levels, i.e., there was a high probability (0.73) that the measured differences were due to random variations in the data. Further, there was no significant interaction of jerk level with subject size.

The maximum deceleration for retention of 84 percent of the potential passengers is 0.30 _g_, regardless of level of jerk within the extended range employed. Thus, lower jerk levels do not contribute to increased retention.

Although they were physically unaffected by jerk level, subjects did report significant differences in terms of comfort level. Mean subjective comfort ratings were 3.5 or "somewhat comfortable" for the low jerk condition, 4.6 or "somewhat uncomfortable" for the medium, and 5.2 or "very uncomfortable" for the high jerk level. Film analysis to determine how

Table 1. Analysis of variance of forward-facing corrected decelerations as a function of levels of jerk and subject size.

Source of Variance	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Jerk (J)	2	0.0032	0.0016	0.31	0.73
Subject size (S)	5	0.0678	0.0136	2.65	0.03
J x S	10	0.0898	0.0090	1.75	0.08
Error	90	0.4608	0.0051		

Table 2. Analysis of variance of forward-facing corrected decelerations as a function of levels of seat-pan tilt, footrest, and subject size.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Between					
Subject size (S)	5	0.4715	0.0943	4.97	0.005
Error (S x R)	18	0.3417	0.0190		
Within					
Seat tilt (T)	3	0.1252	0.0417	5.94	0.001
T x S	15	0.0648	0.0043	0.62	0.846
Error (T x S x R)	54	0.3793	0.0070		
Footrest (F)	1	0.2022	0.2022	11.24	0.004
F x S	5	0.1599	0.0320	1.78	0.168
Error (F x S x R)	18	0.3237	0.0180		
F x T	3	0.0164	0.0055	1.10	0.357
F x T x S	15	0.0658	0.0044	0.88	0.589
Error	54	0.2687	0.0050		

subjects came off the seat indicated that, in most cases, the subject's shoulders moved forward, followed by a forward sliding of the buttocks.

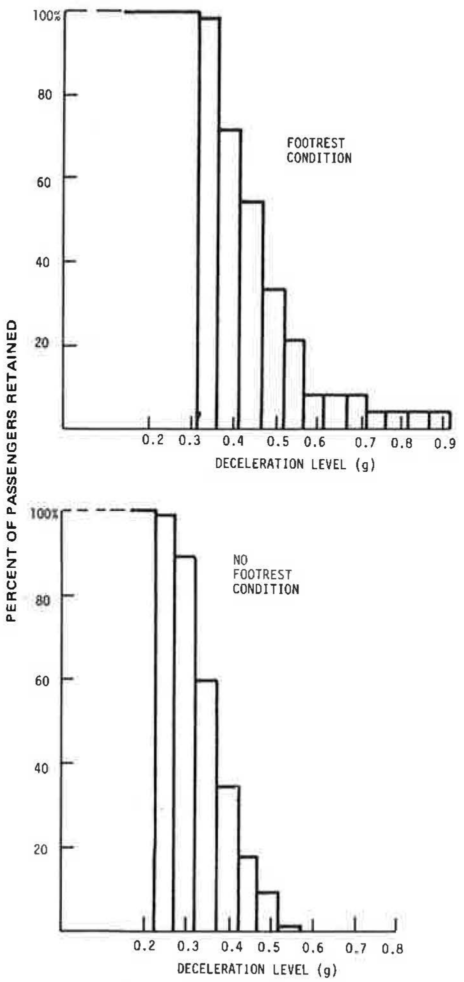
Experiment 2--Forward Facing, Seat Tilt, and Footrest

The corrected deceleration level obtained for retention of 50 percent and 84 percent of potential passengers facing forward is presented in the text table below for each seat-pan tilt (0, 3, 9, and 12° back) with and without a footrest. Both increased seat-pan tilt and use of a footrest increased passenger retention.

	Corrected Deceleration Level (g)			
	Without Footrest		With Footrest	
Seat-Pan Tilt (°)	50% Retention	84% Retention	50% Retention	84% Retention
0	0.35	0.30	0.38	0.33
3	0.34	0.28	0.41	0.31
9	0.38	0.31	0.41	0.36
12	0.43	0.33	0.46	0.36

An analysis of variance (Table 2) of the corrected decelerations indicated that there were significant differences among the four seat-pan tilts, i.e., there was a probability of less than 0.001 that their differences were due to random variation. Tukey's honestly significant difference (HSD) test [cited by Kirk (13)] of these differences among seat tilts indicated that there were only random differences among the data taken at 0, 3, and 9° tilts but that the differences between the data at 12° and those at the other tilt angles were significant, i.e., there was less than a 0.05 chance that these differences were due to random variation. The analysis of variance also indicated that there was a significant difference between data taken in the footrest and no-footrest conditions, i.e., there was a probability of less than 0.004 that these differences were due to random chance. There were no significant interactions.

Figure 3. Percentage of passengers retained in a typical transit-seat configuration compared with a seat configuration for increased retention.



The increased retention attained by simply tilting a typical transit seat pan back 12° and adding a footrest (provided it is used) is illustrated in Figure 3. The distribution of corrected decelerations for the typical transit installation (forward facing; combined 0, 3, and 9°; without footrests) is presented in the top graph, and the distribution for an increased-retention configuration (forward facing, tilted 12°, with footrests) is presented in the bottom graph. The maximum deceleration for retention of 84 percent of the potential passengers is 0.30 g for the typical transit installation, compared with 0.36 g for the increased-retention configuration.

Experiment 3--Side Facing, Armrests

The uncorrected deceleration levels for retention of 50 percent and 84 percent of potential passengers facing sideways (turned 90° counterclockwise from the direction of travel) with and without armrests is shown below.

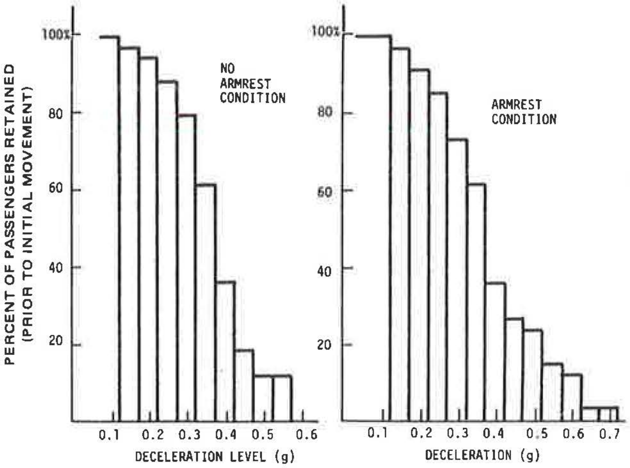
	Deceleration Level (g)	
Condition	50% Retention	84% Retention
Without armrests	0.367	0.261
With armrests	0.367	0.244

The presence of armrests does not increase retention as measured by initial body movement, although the movies showed that the armrests did act as a

Table 3. Analysis of variance of side-facing uncorrected decelerations as a function of armrests and subject size.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	p
Between					
Subject size (S)	5	0.2650	0.0530	2.31	0.072
Error (S x R)	27	0.6207	0.0230		
Within					
Armrests (A)	1	0.0050	0.0050	1.32	0.261
A x S	5	0.0130	0.0026	0.68	0.642
Error (A x S x R)	27	0.1030	0.0038		

Figure 4. Percentage of passengers showing no significant body movement on side-facing seats, with and without armrests.



physical barrier to prevent actual dislodgement. Film analysis of this experiment showed that the seat-switch opening occurred at the same time as significant body movements; therefore, there was no instrumentation error and no correction for instrumentation lag required.

An analysis of variance (Table 3) of the uncorrected decelerations indicated that the difference between having and not having armrests had a high probability (0.261) of being due to random variations.

The distribution of uncorrected decelerations for a side-facing seat without armrests is presented in the left graph of Figure 4 and for a side-facing seat with armrests in the right graph. The maximum deceleration for retention of 84 percent of the potential passengers is 0.261 g for the side-facing seat without armrests and 0.244 g with armrests. Both of these deceleration values are considerably less than those for the forward-facing configuration.

Film analysis to determine when subjects came off the side-facing seat indicated that, in most cases, the subject's upper torso moved until it was physically stopped by the leading armrest. Although actual dislodgement was prevented by this armrest, the subject's buttocks did lift off the trailing seat sensor.

DISCUSSION

This study was designed to establish, measure, and correct for the measurement errors presumed to have biased the results of previous deceleration studies, particularly those reported by Abernethy and others (1). The method employed not only seat-switch sensors but also movies and subject ratings, vehicle decelerations and jerk levels controlled by a automated braking system, and an increased number of subjects. The results of this investigation indicated that instrumentation problems had biased the data toward higher deceleration levels in previous studies. Correction of this bias resulted in the resolution of the previous anomalous results about the effects of jerk on passenger retention.

The maximum deceleration that allows retention of 84 percent of the potential passengers is 0.30 g for a typical transit seat installation (forward facing; tilted at 0, 3, or 9°; fabric-covered contoured seat pan) and 0.36 g for an increased retention configuration (forward facing, tilted back 12°, fabric-covered contoured seat pan, with footrest). These results are considerably lower than those obtained by Abernethy and others in 1977: 0.47 g for a forward-facing, untilted transit seat and 0.52 g for a forward-facing seat tilted back 5° (1).

The maximum deceleration that allows retention of 84 percent of the occupants of a side-facing transit seat is 0.25 g with or without armrests. Again, these results are considerably lower than the 0.41 g obtained by Abernethy and others (1) for a side-facing seat without armrests.

Jerk level was not found to be a factor in passenger retention, only in passenger perception of comfort. It was found that the effects of instrumentation lag increased with increasing levels of jerk.

The results of this investigation indicate that increased retention levels are obtainable through changes in seat installation (tilting back) and the presence of passenger assists (footrests). Further increases may be obtainable by providing warnings prior to deceleration.

Two cautions must be raised concerning the results of this study.

1. All subjects expected to be decelerated. Some degree of preparedness should be assumed. This preparedness implies even lower actual deceleration levels for unprepared passengers.
2. Only seated, able-bodied passengers participated in this study. These results, therefore, may not be applicable to children, the elderly, or the handicapped. Accommodation of these potential passengers again may imply that lower actual deceleration levels must be incorporated into AGT transit design.

A more comprehensive discussion of the work presented in this paper has been made by Jacobs (2).

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