SIMULATION MODELING OF HIGHWAY MAINTENANCE OPERATIONS APPLIED TO ROADSIDE MOWING

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NOMENCLATURE

Work Sequence - A simulated work day in which the driver of a tractor-mower unit cuts grass.

Rain Sequence - A simulated day in which rain occurs. The clock is advanced 480 minutes and no grass is cut nor is a cost charged to the mowing project.

Cycle - Either a work sequence or a rain sequence.

Observation - A set of cycles which comprise the total time required to complete the mowing project.

Sample - A set of observations (mowing project completion times).

CHAPTER I

INTRODUCTION

Statement of the Problem

Highway maintenance is big business. In the United States in 1970, 4.3 billion dollars were spent for highway maintenance. Of the total expenditure, approximately 10 per cent or 430 million dollars was expended for vegetation control. Although highway maintenance is not dependent upon competition for actual survival, it can become a critical problem to the taxpayer unless better and more efficient methods are found to reduce the cost of maintenance operations. All too often, the maintenance division of state highway departments is content to follow the procedures of their predecessors.

With the interstate highway system nearing completion, the increased cost of vegetation control becomes an additional burden on the maintenance budget. The landscaping of interstate highways adds acreages of grass at the rate of 15 to 25 acres per mile of highway plus 20 to 60 acres per interchange. Considerable amounts of time and money have been expended over the past 20 years by state highway departments and the Bureau of Public Roads in an effort to reduce mowing costs for vegetation control.

Several state highway departments have made comprehensive cost studies in an effort to determine a procedure for evaluating the time and cost associated with grass cutting. The results of the studies indicated that the times and costs were highly variable. Thus, the use of average values of time and cost for budgeting and equipment assignment lead to erroneous decisions.

In Louisiana a linear programming model was developed to predict the best assignment of equipment to various grass areas in order to minimize the cost of mowing. The variations between predicted cost and actual cost of the assignments ranged from 40 to 117 per cent. The high percentages were mainly attributed to the deterministic nature of the model.

Purpose of the Study

The purpose of this dissertation is to develop a simulation model of a mowing operation.

Many questions to which quantitative comparisons can be applied for management decisions related to mowing can be answered quickly and at a relatively low cost with the simulation model developed in this dissertation. Among the questions which might be proposed are: "What would be the expected change in time and cost if a different size and/or type of mower was used to cut the grass?"; "What would be the expected savings in time and cost if all 3:1 side slope mowing were eliminated?"; "What would be the expected time and cost for cutting grass on a new section of highway?"

The simulation model consists of a core program and four data packs. The data packs, which contain information relevant to determining mowing project costs and times, are:

(1) Speed functions which relate mower production to terrain

features as described in Chapter III.

(2) Cost functions which relate to hourly equipment costs.

(3) Delay functions which are associated with nonproduction activity times.

(4) Area distribution functions which describe the subsections of the highway right-of-way and the respective percentages of each type of terrain classification.

The core program, through random number generators which select random variables from cumulative probability density functions within each of the data packs, determines mowing project times and costs.

The model considers the probability of rainfall delays, and variations in daily nonproduction times such as travel to and from the field, preventative maintenance, personal delays, and equipment breakdowns.

By changing information in the data packs, the model is capable of handling any size or type of tractor-mower unit, one at a time. Because adequate data were not available to the author, the model does not include major delays such as flat tire repairs, replacement of parts on the mower, or engine overhauls for the tractor.

The results determined by the model give the following information:

(1) Time required to complete the work including the effect of rainfall.

(2) The time required to complete the work excluding rainfall.

(3) The production time expended on the project.

(4) The total tractor-mower unit cost based upon production time.

(5) The total transportation cost going to and from the field.

(6) The total project cost which includes truck, tractor, mower, and labor costs.

(7) The amount of area cut per day.

(8) The section of highway where the grass cutting stopped each day.

Definitions

A model is a representation which abstracts reality. For this dissertation, the model will be defined as a logical system of events that adequately reflect those parts of highway grass cutting which are most relevant to the daily operation.

Simulation is a process by which logic models, which are too complex for an analytical solution, can be solved numerically. The simulation process involves the performing of controlled experiments on the model and observing the performance of the model under a given set of conditions.

General Purpose Simulation System/360

The General Purpose Simulation System/360 (GPSS/360), developed by the International Business Machine Corporation, is a fourth generation of the simulation language which is adaptable to the IBM 360 computer series. The model, when represented by the GPSS/360 simulation language, is described by a block diagram. The block diagram can have as many as forty-six different types of blocks, each of which performs a special simulation-oriented function.

The computer program creates transactions, moves them through the specified blocks, and executes the action associated with the block. The movement of the transaction is an event that is due to occur at some point in time. The computer program maintains a record of the times at which the events are due to occur, then proceeds to execute the events in their correct time sequence.

Some blocks, such as ADVANCE, represent time delay. Other blocks, such as SIEZE, represent logical operations and are executed without delay. All programming takes place within the context of the forty-six blocks.

Other GPSS/360 entities are discussed in Chapter IV.

Reports of Vegetation Control Costs

As early as 1953, before the Interstate Highway System was fully conceived, Robert O'Brien (1), Assistant Highway Landscape Supervisor for the Massachusetts Department of Public Works, stated that Massachusetts was paying an estimated $614 per mile per season to mow the vegetation within the highway rights-of-way. This cost amounted to a total budget of approximately one million dollars per year.

From a study of mowing maintenance costs, Cox and Rester (2) reported that the State of Louisiana in 1963 expended approximately 2.5 million dollars, or 8.5 per cent of the total maintenance budget, for vegetation control on 15,300 miles of State maintained highways. At that time, the State owned 466 mowers.

William Records (3), Highway Engineer, Office of Research, Bureau of Public Roads, estimated that in 1966 the total expenditure for vegetation control of the highways in the United States exceeded 200 million dollars.

David Grimm (4), Chief Maintenance Engineer for the New Jersey Turnpike Authority, in a private communication, advised that the 110 miles of the New Jersey toll road has 2,000 acres of grass in the right-of-way and median, and 300 acres of grass in the interchanges. This area is mowed by a fleet of 77 mowers at an estimated annual cost of $95,000 in 1968.

Louis O'Brien (5), Chief Maintenance Engineer for the Pennsylvania Department of Highways, reported that in 1969 Pennsylvania spent more than five million dollars to maintain 44,000 miles of State highways. Of the five million dollars, 14 per cent was expended for vegetation control. All highways in the State were mowed at least once during the year, with interstate and portions of the primary system being cut eight to 11 times during the year. It was estimated that the highway department cuts 75,000 acres of grass each season. In 1969, the Pennsylvania Department of Highways owned 340 tractor drawn mowers and rented a fleet of 475 tractor-type mowers.

At the Highway Maintenance Management Workshop held at the University of Illinois in August, 1970, Mr. Morgan Kilpatrick (6), of the Bureau of Public Roads, during his introductory remarks estimated that the total highway maintenance expenditures in the United States in 1970 would exceed four billion dollars. This is an increase in the highway maintenance index from 100 in 1958 to 165 in 1970. At the same workshop, Niles Blood (7), Maintenance Engineer, Illinois Division of Highways, reported that in 1969 the State of Illinois' maintenance budget was six million dollars of which 11 per cent was for vegetation control. Joel Katz (8), an engineer for the Minnesota Department of Highways, stated that the State of Minnesota had an annual maintenance budget of 36 million dollars in 1969 and expected the budget to triple by 1980. Of the annual budget, 10 per cent was for vegetation control.

The State of Delaware, where the major portion of the data for this dissertation was collected, reported that the 1970 maintenance budget was 4.8 million dollars. Six per cent of the budget was for vegetation control on an estimated 9,850 acres.

The above figures indicate that an effective modern management decision model is needed in order to analyze the production capacity of mowing equipment and, thus, initiate policies which can significantly reduce the cost of vegetation control.

CHAPTER II

LITERATURE SEARCH

This chapter reviews the methods, the studies, and the models which have been used in an effort to predict and reduce the costs of vegetation control on highway rights-of-way.

In 1953, the State of Massachusetts started a pilot program for contract mowing (1). Specifications were written in accordance with terrain criteria and specific areas to be mowed. The terrain was classified according to slopes which ranged from flat to 4:1 [14°] slopes. Areas were specified by median strips, interchange bowl areas, divided strips at ramps, traffic islands, traffic rotaries (or circles), and guardrail trimming. In the first year of the program, 77 miles of highway mowing, containing 14 contract projects which included all grass growth within the full width of the right-of-way along the entire length of a contract section, were offered to bidders. Thirty-two bids were received by the State. Of the 32 bidders, only five were awarded contracts. During the first year, the work was carefully inspected by State highway maintenance personnel. It was concluded from the inspections that contract mowing was an acceptable procedure to reduce the force account work of the State.

In 1956, the program was expanded to 371 miles of highway with 20 contract projects. Eighty-six bids were received even though the specifications were modified to include penalty clauses for work not performed within specified periods of time. Of the 86 bidders, only 12 were awarded contracts to do the work.

The efficiency of the contractors to perform the work within specified periods of time was developed through field experience. In order for a contractor to qualify as a bidder, he had to have a supervisor with at least two years experience in handling mowing operations. The Department's policy was to award only one project to new bidders their first year in order for the Department to evaluate the ability and interest of the contractor in the mowing operation. This policy minimized the possibility of a contractor failing.

The report on contract mowing by the Massachusetts Department of Highways was published in 1962, at which time 2,396 miles of highway vegetation control were under contract with 86 projects and 15 contractors performing the work.

The report further indicated that contract mowing was costing the State 50 per cent less per mile than if State forces had been used to do the mowing. No indication was given in the report as to the total number of miles which the State forces still maintained.

Today, contract mowing is used in almost every State but normally as a supplementary work force to the State crews.

The most important outcome of the Massachusetts study was the development of detailed specifications as to how much area was to be mowed and the terrain characteristics of the areas as related to equipment production.

The specifications developed by the State of Massachusetts were the forerunner of the AASHO "Guide for Roadside Mowing" (9) which was released for publication in 1962 by the AASHO Committee on Maintenance and Equipment.

From 1950 to 1964 the Office of Research, Bureau of Public Roads, conducted an extensive series of field studies of highway construction and maintenance methods, and performances and job costs. A part of this study included the mowing of highway vegetation. Teams of four to seven men made complete daily time studies of mowing operations. More than 150 industrial and farm type tractor-mower units were observed. The studies were conducted in the States of Colorado, Connecticut, Indiana, Iowa, Oklahoma, North Dakota, Virginia, and Washington. Each man on the team observed a particular operator for a complete day. The observers recorded all delay times and speeds of the tractor-mower unit. The speeds were recorded with respect to the following terrain features: median level, median slope, shoulders, foreslopes, ditches, back slopes, and right-of-way. The tractor-mower units which were observed included five-foot rear mounted rotary mowers, six-foot rear mounted flail mowers, five-foot side mounted sicklebar mowers, and fifteen-foot three-section trailer mounted rotary mowers.

The results of the studies were compiled into individual State reports (10) (11) (12) (13) (14) (15) (16) (17). The reports gave the average percentages of net available working time that particular types of tractor-mower units spent on various terrain classifications and the percentages of time spent in various delays. Average production rates, in acres per hour, for different tractor-mower units working on various terrain classifications were also determined.

The objective of the fifteen-year study was to show that highway maintenance operations could be classified for cost estimating purposes.

In particular, the study showed that performance time of tractor-mower units could be associated with terrain classifications.

In 1964 the Office of Research, Bureau of Public Roads, through the Louisiana Department of Highways and Louisiana State University, sponsored a research study to model a mowing operation, using linear programming. The study was conducted by Cox and Rester (2). A total of 143 acres in the Brittany Maintenance Unit, District 61, of the Louisiana Department of Highways was divided into eight sections. The eight sections were sub-divided into six classifications according to width of the area and the density of driveways and sign posts per mile.

Time studies were conducted in the field using Servis Recorders which were special time recording devices attached to the tractor wheel. The recorder contained a clock and pendulum arrangement. The clock rotated a circular chart once every 24 hours. When the mower was in operation, the vibrations of the tractor would cause the pendulum to oscillate, causing a jagged line on the chart. When the mower was not in operation, the pendulum would remain motionless and a solid line was recorded on the chart.

Examination of the chart told the time of day the mower was started, the time and duration of each rest stop, the time and duration of the lunch period, and the time the work day ended.

The tractor-mower units for which the time studies were made were as follows: a 15-foot three-section trailer type mower, an eight-foot rear mounted rotary mower, three seven and one-half foot rear mounted rotary mowers, and two five-foot side mounted sicklebar mowers. The multiple tractor-mower units were considered as single team units in the model.

Costs for the equipment were based upon rental rates established by the Louisiana State Highway Department. The cost coefficients for the objective function of the linear program were determined from the rental rates. Mowing times per acre for each terrain classification were obtained from the information provided by the Servis Recorders.

The constraint equations in the model were:

(1) All areas assigned to mower (i) must be greater than or equal to zero.

(2) The total time for mower (i) to cut its assigned areas plus its idle time was equal to the total available time assigned to mower (i) to perform its mowing operation.

(3) The area of class (j) type mowing cut by all the assigned mowers to that class plus any uncut area of class (j) was equal to the total area of class (j) in the given section of highway.

The model considered only productive working times of the tractor-mower units in the system. No consideration was given to the time consumed by nonproduction activities, such as travel time to and from the field, travel between plots, down time for repairs, personal delays, and lunch hour extensions.

Cox and Rester (2) extended their model to show that linear programming could be used to determine an optimal combination for a given set of mower units. With 10,000 hours of available machine time given to each type of mower, a linear programming solution was obtained. The solution showed that fractional numbers of each type of mower were to be selected. The fractions were arbitrarily rounded or truncated to form integered sets of the given types of mowers. A selected number of feasible integered sets were re-entered into the linear programming algorithm and an optimal cost for each integered set was obtained. Cox and Rester stated that, by comparing the optimal cost of each integered set, an optimal combination of mower units could be obtained by choosing the integered set with the minimum optimal cost.

The Office of Research, Bureau of Public Roads, sponsored a follow-up program with the Louisiana State Department of Highways to evaluate the linear programming model which was developed by Cox and Rester (18). Special weekly gang report forms were used to record the daily acreage mowed, machine breakdown times, travel times, and weather. The study was conducted from April to September 1965. The actual costs of production were compared with those predicted by linear programming. The error between the actual costs and the predicted costs ranged from 40 to 117 per cent. The results indicate that linear programming is not an acceptable technique for estimating mowing production costs.

During the period from 1963 to 1965, the State of Indiana made a comprehensive study of mowing costs (19). The objective of the study was to determine a distribution of average costs per acre for mowing in order to better prepare a mowing maintenance budget.

Indiana was divided into four sub-districts: Frankford, LaPorte, Seymour, and Terre Haute. Data were obtained for hours and wage rates which were applicable to each right-of-way section within the sub-division. The results of the survey showed that 83 per cent of the road sections investigated had mowing costs per acre of less than $14.00, while the costs of 11 per cent of the sections exceeded $20.00 per acre with a maximum value of $106.00 per acre. The higher costs were obtained in the LaPorte and Terre Haute sub-districts where the physical nature of the terrain was not conducive to uniform mowing procedures. The study showed the probabilistic nature of mowing costs for highway vegetation control systems.

In a 1969 report, Adrian Clary, Maintenance Engineer for the Highway Research Board (20) indicated that mowing costs were still a critical item in highway maintenance budgets. He stated that to reduce mowing costs, the trend was toward contour mowing, eliminating the practice of mowing from right-of-way fence to right-of-way fence. Clary also suggested the use of the AASHO "Guide for Roadside Mowing", the elimination of mowing slopes steeper than 3:1 [18°] and the use of mowing units such as tractors with 15-foot gang mowers on types of terrain where their inherently high capacity can be utilized.

From the studies performed over the past 20 years, it is evident that a need still exists for a comprehensive time and cost model which will give the highway maintenance engineer a tool by which he can make decisions as to equipment to purchase and areas to cut without spending exorbitant amounts of time and money to achieve an answer. The simulation model developed in this dissertation gives the engineer just such a tool.

CHAPTER III

EXPERIMENTAL PROCEDURE

Scope of Study

In this research study, the speeds of tractor-mower units cutting grass on interstate highways were measured during a six-week period. Included in the study were nine tractors each with six-foot rear mounted flail type mowers. In addition to the speed measurements, full-day time studies of activities relevant to a daily highway grass cutting operation were observed during a two-week period.

The observations were conducted in the eastern part of the United States. The speed measurements were made on Interstate Highway I-95 and on the Pennsylvania Turnpike. The section of Interstate Highway I-95 was in the New Castle Maintenance Division in the State of Delaware. The section extended from the Pennsylvania state line to the intersection of Interstate Highways I-95 and I-295, a distance of 10.6 miles containing 169 acres of mowed grass. On the Pennsylvania Turnpike, the study sites were located at the Willow Grove Interchange and the Valley Forge Interchange.

The full-day time studies were conducted on Interstate Highway I-95 in the New Castle Maintenance Division. These studies involved only the State of Delaware mowing crew which was working between the Pennsylvania state line and the intersections of I-95 and I-295. The activities which were relevant to a daily mowing operation are described in Chapter IV.

Classification of the Mowed Area

The terrain features associated with the mowed area were classified according to six conditions. These six conditions were:

(1) 0° to 8° [less than 5:1] side slope or Class A

(2) 9° to 12° [5:1] side slope or Class B

(3) 13° to 16° [4:1] side slope or Class C

(4) 17° to 22° [3:1] side slope or Class D

(5) Obstacle areas or Class E

(6) Roading or Class F.

Obstacle mowing included traffic islands, cutting along lines of delineation markers and lamp post standards, and cutting adjacent to guardrails and fences.

Roading was travel between grass plots where the areas become asphalt or concrete.

Layout of the Mowed Areas

Architectural landscape drawings for the section of Interstate Highway I-95 between the Pennsylvania state line and the intersection of Interstate Highways I-95 and I-295 were obtained from the Delaware State Highway Department.

All mowed areas were detailed on the landscape drawings. The detailing included the field checking of degrees of side slope, and the location of guardrails, trees, lamp posts, delineation markers, and other mowing obstructions. A typical, detailed section is shown in Figure 1.

The simulation model developed in this dissertation required that the section of highway be divided into subsections with each subsection being divided into a set of terrain classifications. The section of Interstate Highway I-95 in Delaware, used in this study, was divided into seven subsections with a set of six terrain classifications per subsection (see Appendix A).

The areas of grass associated with classes A, B, C, and D were obtained by scaling the widths and lengths or by a planimeter. The areas in classes E and F, which were related to single cutting passes such as along lines of delineation markers, lines of lamp post standards, guardrails, fences, and travel between grass plots, were determined by multiplying the length of the pass in feet by the effective width of the mower. An effective width of five and one-half feet, for the six-foot rear mounted flail type mower observed in the study, was used.

Plans of the areas of cut grass on the Pennsylvania Turnpike were not made available to this author but side slopes were measured for each plot of grass cut during the study.

Time Study of Tractor-Mower Units

Delaware

On Interstate Highway I-95, time studies were conducted on six drivers and three types of tractor-mower units. The tractor-mower units were:

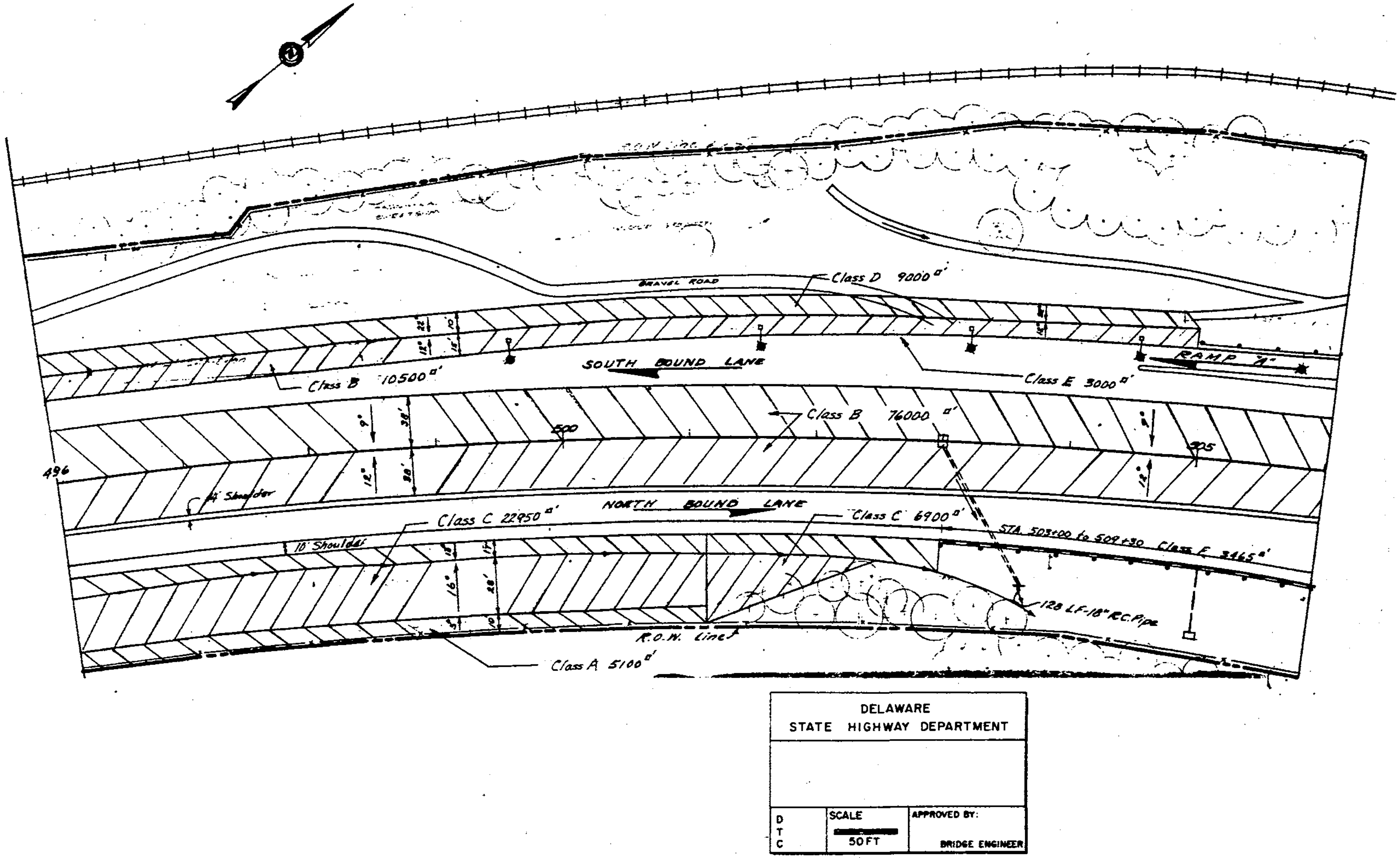

Figure 1. Typical Layout of Mowing Areas by Terrain Classifications

(1) Three International Harvester 340 tractors each with a six foot rear mounted flail mower and a five foot side mounted sicklebar mower.

(2) An International Harvester 2424 "Low Boy" tractor with a five foot side mounted sicklebar mower.

(3) Two Ford 600 tractors each with a six foot rear mounted flail mower.

The state mowers and hired mowers each worked as teams, but independently of each other. As teams, the mowers worked in the same general vicinity of each other, but independently.

Times were measured for each of the tractor-mower units to determine their speeds when cutting on side slopes; classified as 0° to 8° (Class A), 9° to 12° (Class B), 13° to 16° (Class C), 17° to 22° (Class D). A state safety regulation prohibited the cutting of side slopes which were steeper than 22°.

The distances over which time intervals were measured varied according to the distances between natural or man-made obstructions which required the driver to turn the mower around. The distances ranged from 250 feet to 1000 feet with the most frequent distances occurring between 450 and 550 feet with time intervals ranging from one and one-half minutes to two and one-half minutes.

Distances were measured most often by pacing. If the distance could be referenced to landmarks which appeared on the plans, the distance was scaled from the plans. Other measuring techniques were to use the spacing of guardrail fence posts and chain link fence posts.

Pennsylvania Turnpike

A three-day study of mower operations on the Pennsylvania Turnpike was conducted in order to supplement the field data obtained from the Delaware study. Three drivers and two types of tractor-mower units were observed. The tractor-mower units were:

(1) Two Ford 2110 tractors, each with a six-foot rear mounted flail mower and a five-foot side mounted sicklebar mower.

(2) A Ford 2000 tractor with a six-foot rear mounted flail mower.

At the Willow Grove interchange, there was only one mower while at the Valley Forge interchange there were two mowers. A one-day study was conducted at the Willow Grove interchange and a two-day study at the Valley Forge interchange.

Additional time study data were obtained from the Office of Research, Bureau of Public Roads. This author was permitted to extract, from the files of the Bureau of Public Roads, field data which had been obtained by Office of Research teams. Terrain speeds, travel speeds between plots, and turn times for three six-foot rear mounted flail mowers were acquired from the field data file of the Indiana study (12), and incorporated in this dissertation.

The rates of speed for all drivers in each of the terrain classifications, as obtained in this research study, are shown in Appendix B. All speeds were for a grass height interval of 6 to 20 inches. A typical histogram of the distribution of mower speeds is shown in Figure 2.

The complete set of histograms for the distribution of speeds for each of the six terrain classifications is shown in Appendix C. The histograms for the distribution of nonproduction activity times for each

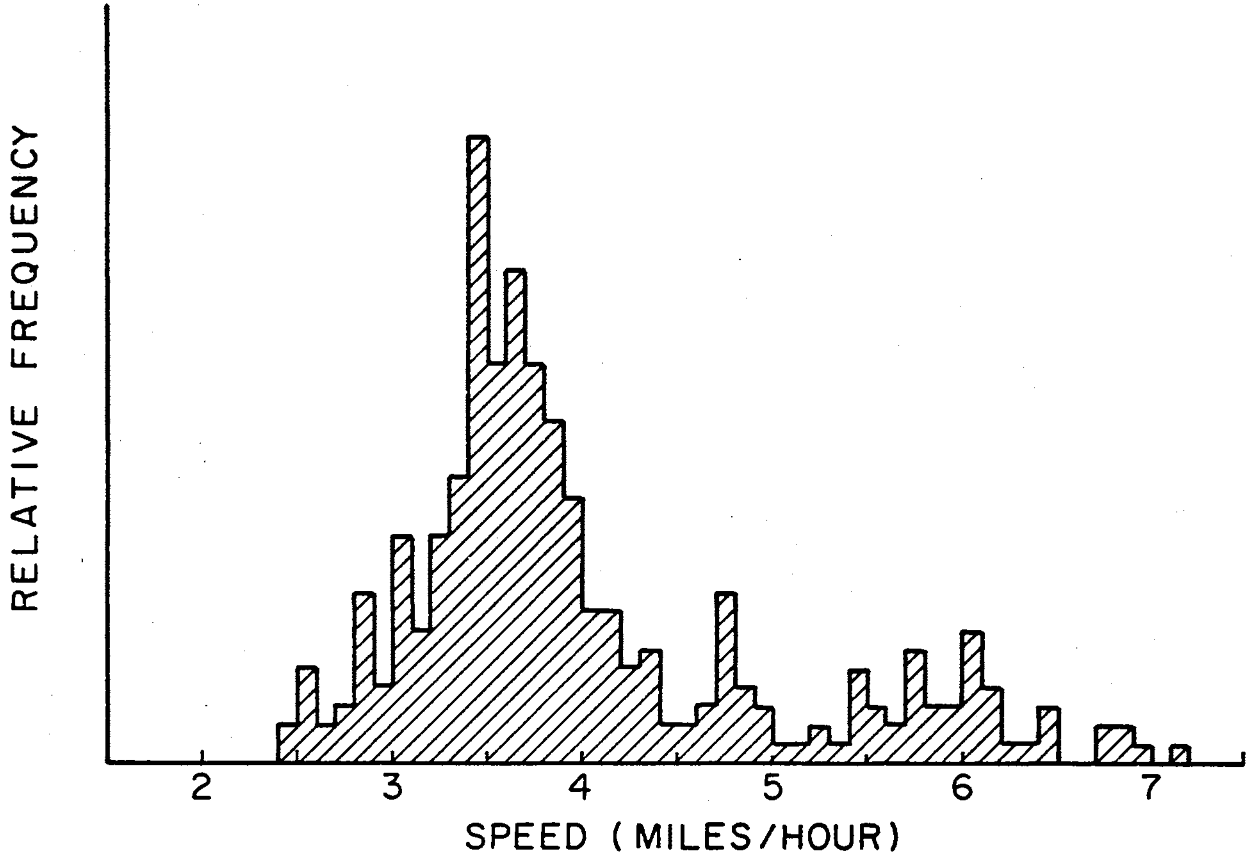

Figure 2. Histogram of Mowing Speeds

of the activities in a daily mowing operation, which were recorded from the field observations of this research study, are shown in Appendix D.

Cost Data

The hourly costs for operating tractors, mowers, and trucks were obtained from monthly cost records. The hourly rates were for the months of May through September in the years 1968 and 1969. The data were obtained from the Oklahoma State Highway Department, the Delaware State Highway Department, and the Pennsylvania Turnpike Commission. The data contained the rates for 24 service trucks of the Perry Maintenance Division of the Oklahoma State Highway Department, 11 tractors of the New Castle Maintenance Division of the Delaware State Highway Department, 36 tractors of the Perry Maintenance Division of the Oklahoma State Highway Department, 6 flail mowers of the Plymouth Meeting Maintenance Division of the Pennsylvania Turnpike Commission, and 12 flail mowers from the New Castle Maintenance Division of the Delaware State Highway Department.

Histograms of the distribution of hourly cost rates for operating service trucks, tractors, and flail mowers are shown in Appendix E.

Rainfall Data

The effect of rainfall as a factor in extending the completion time of a mowing project was incorporated as a part of the simulation model developed in this dissertation.

The rainfall data were obtained from the weather station at the Philadelphia International Airport, which is located 18 miles from the study area on Interstate Highway I-95 in Delaware. Twenty years of rainfall data, dating from 1951 to 1970 inclusive, were used in the forecast analysis. The data were further reduced to five-day work week conditions. The relative frequency of the number of rainy days during a five-day work week are shown in Figure 3.

From the analysis of the data, the following probabilities were obtained:

$$P(B_1) = 0.73$$

where

$P(B_1)$ is the probability a clear day will occur between May 1 and November 1.

$$P(B_2) = 0.27$$

where

$P(B_2)$ is the probability a rainy day will occur between May 1 and November 1.

$$P(X_1/B_1) = 0.78$$

where

$P(X_1/B_1)$ is the conditional probability that if today is clear tomorrow will be clear.

$$P(X_2/B_1) = 1 - P(X_1/B_1) = .22$$

where

$P(X_2/B_1)$ is the conditional probability that if today is clear tomorrow will be rain.

$$P(X_1/B_2) = 0.60$$

where

$P(X_1/B_2)$ is the conditional probability that if today is

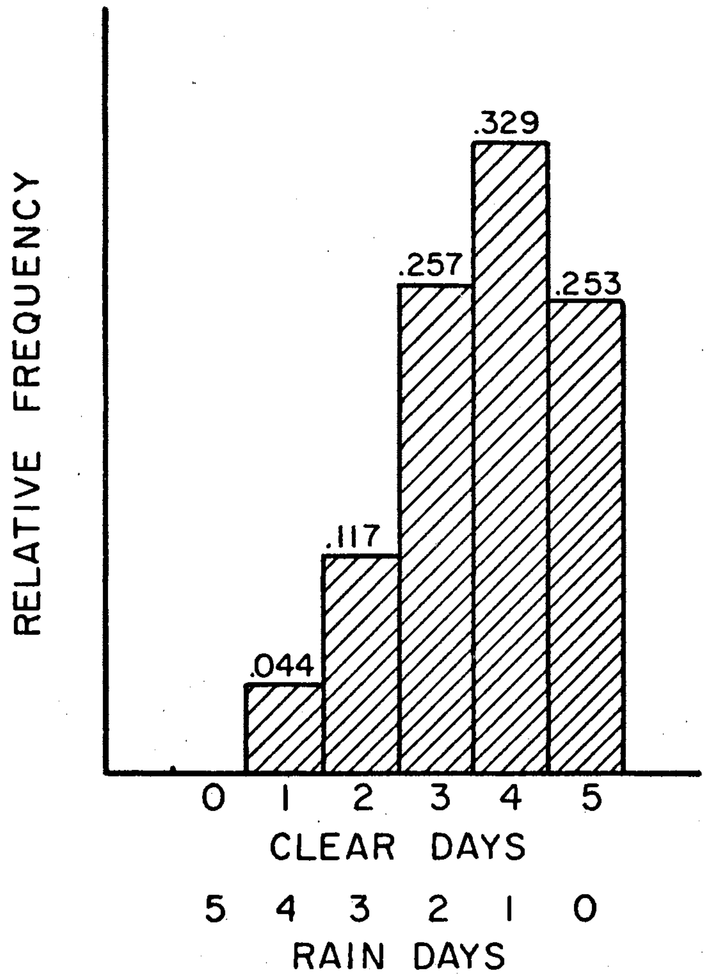

Figure 3. Frequency Distribution of a Twenty-Year History of Rainfall for Five-Day Work Weeks on a 10.6 Mile Section of Interstate Highway I-95 in Delaware Beginning at the Pennsylvania State Line

rainy tomorrow will be clear.

$$P(X_2/B_2) = 1 - P(X_1/B_2) = 0.40$$

where

$P(X_2/B_2)$ is the conditional probability that if today is rainy tomorrow will be rainy.

The probabilities $P(B_1)$, $P(B_2)$, $P(X_1/B_1)$ and $P(X_1/B_2)$ are prior probabilities which when used in Bayes' theorem emerge with the posterior probability of forecasting clear or rainy weather.

Bayes' theorem for forecasting clear weather given that a clear condition exists is given by the formula:

$$P(B_1/X_1) = \frac{P(B_1)P(X_1/B_1)}{P(B_1)P(X_1/B_1) + P(B_2)P(X_1/B_2)}$$

where

$P(B_1/X_1)$ is the posterior probability of clear weather.

$P(B_1)$, $P(X_1/B_1)$, $P(B_2)$, and $P(X_1/B_2)$ are the prior probabilities which were previously defined.

Therefore,

$$P(B_1/X_1) = \frac{(.73)(.78)}{(.73)(.78) + (.27)(.60)} = \frac{.5694}{.7314} = .779 .$$

Bayes' theorem for forecasting clear weather given that a rainy condition exists is given by the formula:

$$P(B_1/X_2) = \frac{P(B_1)P(X_2/B_1)}{P(B_1)P(X_2/B_1) + P(B_2)P(X_2/B_2)}$$

where

$P(B_1/X_2)$ is the posterior probability of clear weather.

$P(B_1)$, $P(X_2/B_1)$, $P(B_2)$, and $P(X_2/B_2)$ are prior probabilities which were previously defined.

Therefore,

$$P(B_1/X_2) = \frac{(.73)(.22)}{(.73)(.22) + (.27)(.40)} = \frac{.1606}{.2686} = .598 .$$

Time Preparation of Data for the Model

A question asked by several maintenance engineers was "How much time is required to prepare data for the model?" To answer this question, the author recorded the time spent in preparing data for the model. The area of grass cut was 169 acres along 10.6 miles of interstate highway. The layout of the area and field checking the accuracy of the plans required 45 man-hours. The quantity take-off of the area required 56 man-hours.

CHAPTER IV

SIMULATION MODEL OF A MOWING OPERATION

The simulation model for grass cutting on an interstate highway was formulated from the observations of a series of daily time consuming activities during a field study of a mowing operation. The time and frequency with which each activity occurred were measured and recorded.

General Purpose Simulation System (GPSS) Language

For one to comprehend the simulation model presented in this chapter, a basic understanding of the formal concept of the General Purpose Simulation System (GPSS/360) language is needed.

The GPSS/360 model is considered as a block diagram of a set of interrelated logical and mathematical symbols which depict the modeled system. Each model consists of various elemental abstractions, called entities, by which the system is represented. Each of these entities has associated with it a set of properties or attributes that describes its status at any given time. These attributes have either numbered or logical values and describe the system being modeled. The entities referred to in this chapter are FUNCTION, VARIABLE, and SAVEVALUE.

FUNCTION is a computational entity. Each FUNCTION relates the values of the FUNCTION argument, which is some independent variable in the simulation model, to dependent variable values of the FUNCTION. In the mowing model, the FUNCTION argument is a uniformly distributed random number, while the dependent FUNCTION values are random variable elements in the simulation model, i.e., speeds, hourly operating costs, travel times, and delay times.

VARIABLE is a computational entity which is a FORTRAN-like arithmetic combination of values. FVARIABLE indicates floating-point arithmetic variables. With floating-point arithmetic, the elements of the equation are not truncated before arithmetic operations are performed. Truncation occurs only when the final result has been determined.

SAVEVALUE is an entity which serves to retain the values of other attributes for future reference. Field B argument of the SAVEVALUE specifies the attribute to be retained and field A argument designates the SAVEVALUE location.

Operation of the Model

The model contains six speed functions relating to the production capacity of the mower, three cost functions which reflect equipment cost, sixteen functions of nonproduction time activities occurring during a normal work day, and seven functions which relate to the proportional amounts of area to be mowed under each of six speed distributions.

The section of Interstate Highway I-95 in the State of Delaware was divided into seven subsections with six terrain classifications associated with each subsection. The subsections were identified as SAVEVALUES and the terrain classifications by sets of SAVEVALUES.

Random variables were selected from the FUNCTIONS listed in the program by means of eight pseudo-random number generators. The generators were assigned sequentially to the FUNCTIONS as they were listed at the beginning of the program in order to make the entire model random.

Simulation began by setting the simulated clock time within the program to zero. The simulated time unit in the model was equivalent to one minute of actual time.

As a transaction, which represented the driver of a tractor, proceeded from one component to another in the system, the clock time was updated by variable time increments which were added to the clock time. A transaction was generated every 500 clock units of simulated time so that each transaction would terminate from the system before another transaction entered the system.

The simulation model accrued time on a day-to-day basis until all grass areas within the section of highway were mowed. This approach required that a sufficient number of daily work sequences be run to assure that all the grass areas were cut. From previous studies of mower production and several trial runs with the computer program, it was established that twelve cycles of daily work sequences per observation of project completion time was adequate.

At the end of every twelve cycles, the clock time was reset to zero. Also, all SAVEVALUES were reset to zero, except for those SAVEVALUES that designated the areas of the subsections and terrain classifications. The seeds of the eight random number generators were not reset. Thus, each twelve cycle run was an independent observation of the project completion time.

Three time interruptions within a daily work sequence were instituted from field studies. The first was the time to stop cutting in the morning and go to lunch. The second was the time to leave the field and return to the maintenance division headquarters. The third was the time for the transaction to leave the system. The times specified for the three interruptions were 11:40 A.M., 3:05 P.M., and 4:00 P.M., respectively.

As shown in Figure 4, the first consideration in the model was to ascertain if rain had occurred. Rain determined whether the driver was sent to the field or assigned to another task. On the first of each twelve cycles, the probability was 0.73 that a clear day would randomly occur during the mowing season from May 1 to November 1 at the study area on I-95 in Delaware. A random variable was selected by means of a random number generator and compared with the probability of 0.73. If the variate was less than or equal to 0.73, the driver was assigned to the field. If the variate was greater than 0.73, the driver was assigned another task and the simulated clock time was advanced 480 minutes without a cost being charged to mowing.

After the first day the probability of forecasting a clear day fluctuated from 0.78, which was the Bayesian posterior probability that if today was clear tomorrow would be clear, to 0.60, which was the Bayesian posterior probability that if today was rainy tomorrow would be clear.

If the work sequence was entered the first day, the probability of 0.78 was stored in SAVEVALUE 10 when the transaction terminated the work sequence. If rain occurred the first day, the probability of 0.60 was stored in SAVEVALUE 10 when the transaction terminated the rain sequence. From the second cycle and henceforth to the end of the twelve cycles a random variable was generated and compared with SAVEVALUE 10 at

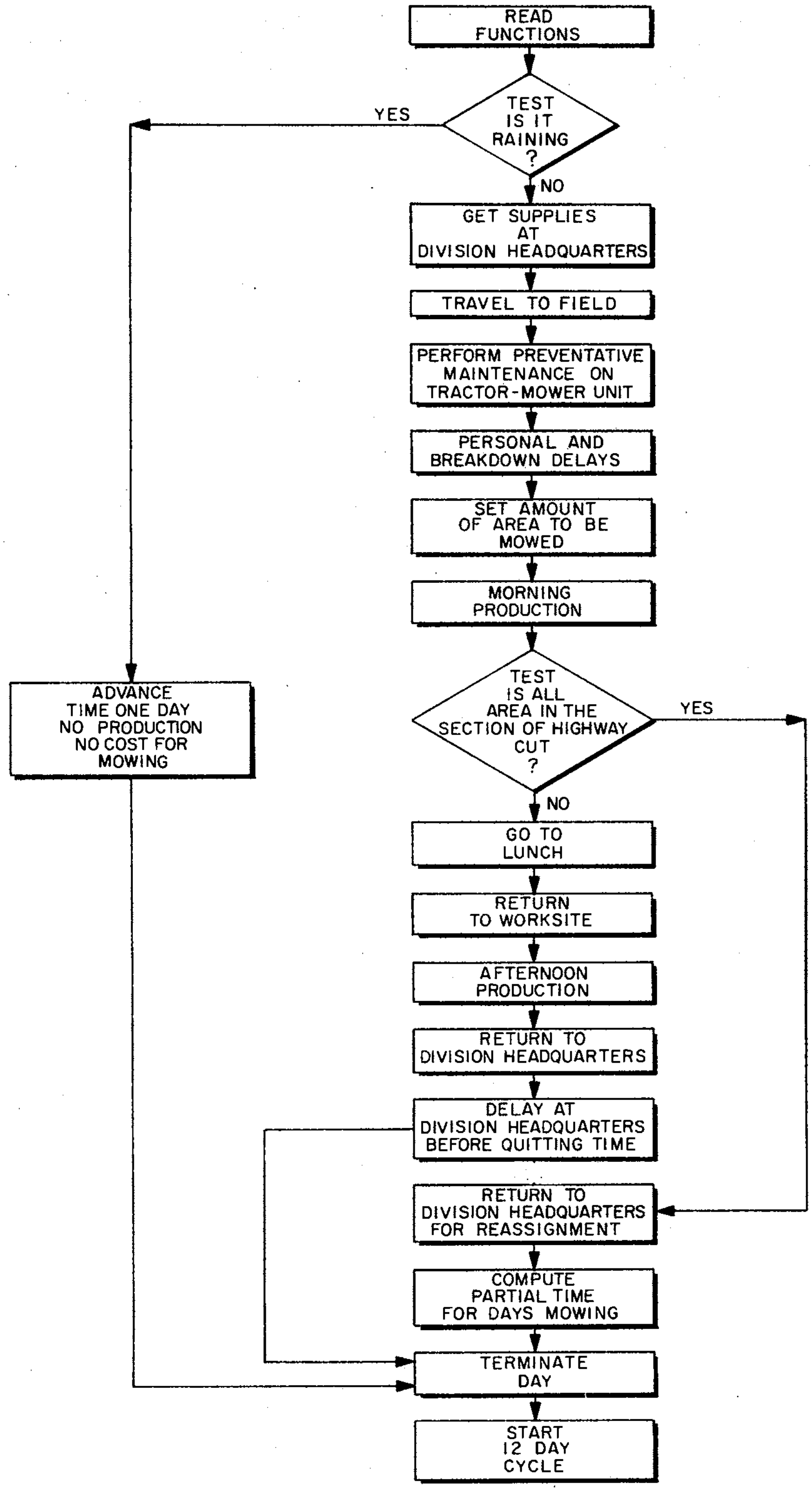

Figure 4. Flow Diagram of Mowing Simulation Model

the beginning of each cycle. If the variate was less than or equal to the number in SAVEVALUE 10, the driver was assigned to the work sequence of the model and a probability of 0.78 was stored in SAVEVALUE 10 when the driver terminated the work sequence. If the random variable was greater than the number in SAVEVALUE 10, the driver was assigned to another task and the simulated clock was advanced 480 minutes. No cost was charged to mowing for the rainy day and a probability of 0.60 was stored in SAVEVALUE 10 when the transaction terminated the rain sequence in the model.

The work sequence was divided into two sessions, morning and afternoon. In the morning, six variates associated with each of six nonproduction activities were generated and added to the clock time in proper sequential order, as follows:

(1) The delay time at the maintenance division headquarters to secure supplies, such as water, gas, and repair parts.

(2) The travel time from the division headquarters to the work site.

(3) Preventive maintenance and minor repairs prior to beginning work.

(4) Travel time from the truck to the mowing area.

(5) Personal delay times, such as getting a drink of water, picking up trash, personal relief, etc.

(6) Mower breakdown delay times for removing objects which had become lodged in the mower, adjusting cutting height of the blades, etc.

The morning production period began after the simulated clock was advanced for the six nonproduction time variates, some of which might have been zero. The production period was subdivided into 10-minute work intervals. It was the opinion of this author that, from his field observations, the fluctuations in speed over a 10-minute interval were not significantly large. Thus, it was assumed that the speed variate was constant over the 10 minute interval.

The subsections of the highway were called sequentially while the speed classifications within each subsection were called randomly. A discrete random variable was generated in order to select the terrain classification within a subsection. The terrain classification was designated by a two digit number. The units digit related to the speed FUNCTION associated with the classification. By means of modulo division by 10, the units digit was isolated and stored in a PARAMETER. For example, in subsection 30, if the discrete random variable 12 was selected by the random number generator then the 9°-12° side slope terrain classification had been designated. Modulo division by 10 gave a remainder of 2 which was stored in PARAMETER 7. FN*7 generated a speed variate from the FUNCTION whose number was stored in PARAMETER 7. Thus, a speed variate was selected from FUNCTION 2.

The amount of area mowed in a 10-minute interval was given by:

1 FVARIABLE = FN*7(5280/60)*(55/10)*10

where

FN*7 is a speed variate expressed in miles per hour.

5280/60 is a constant which changes miles per hour to feet per minute.

55/10 is the effective width of cut which was assumed as 5.5 feet for a 6 foot rear mounted flail mower.

10 is the interval of time over which the speed was assumed constant.

1 FVARIABLE is the total number of square feet of grass, which was cut in 10 minutes, in the terrain classification specified by PARAMETER 7.

The model checks the square footage which was mowed, in the terrain classification specified by PARAMETER 7, against the amount of area remaining to be mowed in that terrain classification. If the square footage mowed was greater than that which was to be mowed, the 10-minute interval was reduced linearly by the ratio of the area remaining to the total area cut in 10 minutes. The simulated clock was advanced the proportionate amount of time and the terrain classification area was set to zero. If the square footage mowed in 10 minutes was less than the area remaining to be mowed, the simulated clock was advanced 10 minutes. The areas of both the subsection and the terrain classification were reduced by the number of square feet mowed.

In addition to the 10 minutes, the simulated clock was also advanced for turn-times. It was assumed that on the average there were three turns per 10 minutes. A turn-time variate was generated from FUNCTION 27 and multiplied by three. The product, which was truncated, advanced the simulated clock. In most instances the clock showed no advance because of the fractional nature of the turn-time variates, which when truncated became zero.

After each 10-minute work interval, a series of checks were performed. First, the simulated clock was checked against the time to stop work for lunch. If the clock time was greater than 11:40 A.M., the morning work period ended and the driver went to lunch. If the clock time was less than 11:40 A.M., the model checked to see if all the area of the subsection had been cut. If more than 100 square feet of area remained, the driver returned to work for another 10-minute work interval. If 100 square feet or less of area remained in the subsection, the area was set to zero and a check was made to determine if the subsection was the last subsection on the highway. If all sections had been cut, the driver returned to the truck and then to the division headquarters for another assignment.

During a normal day the driver went to lunch and areas of uncut grass remained for the afternoon work session. When the driver went to lunch the simulated clock was advanced five variate time intervals, each associated with a nonproduction activity. The five nonproduction activities were:

(1) Travel time from the work area to the truck.

(2) Lunch time.

(3) Travel time from the truck to the work site after eating.

(4) Personal delay times.

(5) Equipment breakdown delays.

The afternoon production period began after the simulated clock was advanced for the five nonproduction time variates, some of which might have been zero. The work cycle in the afternoon session was the same as that described for the morning session.

After each 10-minute work interval in the afternoon, the model performed a series of checks. First, the simulated clock was checked against the time to stop work and return to the truck for transportation to the division headquarters. If the clock time was greater than 3:05 P.M., the driver returned to the division headquarters. The simulated clock was advanced two time-variate intervals, each associated with nonproduction activities. The two intervals were:

(1) Travel time from the work area to the truck.

(2) Travel time from the job site to the division headquarters.

The last nonproduction time variate, which was the delay time at the division headquarters before going home, was developed by the model. The clock time at which the truck arrived at division headquarters was called in the program and subtracted from 4:00 P.M. to obtain the variate delay time.

If the clock time was less than 3:05 P.M., the model performed the same set of area completion checks that it did during the morning session. If all the area was cut before 3:05 P.M., the driver returned to the division headquarters and a partial day's work was indicated in the program printout.

Cost Information

Costs were accumulated at various stages in the program. The costs were printed out at the end of each cycle as SAVEVALUES. The following list of costs was determined in the model and their corresponding SAVEVALUES:

SAVEVALUE 1 - Cumulative transportation cost for going to the field in the morning.

SAVEVALUE 3 - Cost of transportation for returning to division headquarters at the end of a partial work day.

SAVEVALUE 4 - Cumulative transportation cost for returning to division headquarters at the end of a regular work day.

SAVEVALUE 5 - Total transportation cost for the mowing project.

SAVEVALUE 6 - Total truck depreciation charge for the mowing project.

SAVEVALUE 79 - Cumulative production cost of a tractor-mower unit doing fractional parts of 10-minute work intervals during the morning.

SAVEVALUE 87 - Cumulative production cost of a tractor-mower unit doing 10-minute work intervals during the morning.

SAVEVALUE 89 - Cumulative production cost of a tractor-mower unit doing fractional parts of 10-minute work intervals during the afternoon.

SAVEVALUE 97 - Cumulative production cost of a tractor-mower unit doing 10-minute work intervals during the afternoon.

SAVEVALUE 137 - Cumulative cost of truck depreciation for regular scheduled work days.

SAVEVALUE 138 - Cumulative cost of a tractor-mower unit for regular scheduled work days.

SAVEVALUE 140 - Cost of truck depreciation for a partial work day.

SAVEVALUE 147 - Cost of a tractor-mower unit for a partial work day.

SAVEVALUE 148 - Total cost of tractor-mower unit for the mowing project.

SAVEVALUE 149 - Total cost of the mowing project including equipment and labor.

Time Information

The printout of the computer program for GPSS/360 designated each cycle or day of the mowing project as SNAP X of 12 where X ranged from 1 to 12. Within each SNAP X information was presented which specified the number of times a transaction passed through a particular block in the block diagram and the values of all SAVEVALUES which were greater than zero. To determine the N^{th} cycle in which all the areas were mowed, a search was made of each SNAP X of 12 until SAVEVALUE 128 of the model appeared. SAVEVALUE 128 was specified in the model as the number of minutes which were utilized on the last work day to complete the mowing.

The number of days of rain N_R, which occurred during the project were determined by counting the number of times SAVEVALUE 10 in the printout retained the value 60 between cycle 1 and cycle N.

Thus:

Total Project Time (including rain) =

$$[480 \times (N-1) + \text{SAVEVALUE } 128] \text{ minutes}$$

Total Project Time (excluding rain) =

$$[480 \times (N-1-N_R) + \text{SAVEVALUE } 128] \text{ minutes}$$

Total Production Time = (SAVEVALUE 110 at SNAP(N-1) of 12)
+ (SAVEVALUE 80 at SNAP(N) of 12
- SAVEVALUE 80 at SNAP(N-1) of 12)
+ (SAVEVALUE 90 at SNAP(N) of 12
- SAVEVALUE 90 at SNAP(N-1) of 12)

+ 10 X (Current block count of ADVANCE block 66 at SNAP(N) of 12 - Current block count of ADVANCE BLOCK 66 at SNAP (N-1) of 12)

+ 10 X (Current block count of ADVANCE block 124 at SNAP(N) of 12 - Current block count of ADVANCE block 123 at SNAP (N-1) of 12)

CHAPTER V

APPLICATIONS OF THE MOWING SIMULATION MODEL

Computer simulation together with its inherent capabilities of random number generation can be used in two ways. First, by generating a "sufficient" number of simulated random samples of random variates, whose distributions have been defined, one can "test" the model against known standard distributions. Secondly, comparisons may be made between two alternatives on a relative basis for which the simulation model is much more efficient than it is in "testing" the model against standard distributions.

To compare the mowing simulation model with a norm, which in this model was a twenty-year history of rainfall data, a sample size and a method for generating independent simulated random samples was needed. As no fixed procedure is known for determining sample size prior to the actual running of the simulation, the sample size and number of samples were established by considering the model as if it were an "insitu" field sampling situation. It was proposed by this author that 10.6 miles of the southbound lane from edge of roadway to right-of-way fence on Interstate Highway I-95 in Delaware be mowed with a single 6-foot flail type mower. The time was estimated from a field observation to be approximately one work week. Based upon this knowledge, a simulated sample size of 20 observations was selected. This size sample was analogous to making field measurements of the project times for a full mowing season which extended from May 1 to November 1. It was further proposed that the model represent the recording of these measurements for five mowing seasons. Thus, the mowing model comprised five samples of 20 observations in each sample. There were no additional simulated observations required to bring the model to a state of equilibrium because after each 12 cycles of available simulated work time in each observation, all the area to be mowed in the section was restored to the model.

All eight random number generators of the GPSS/360 computer simulation language were assigned sequentially to the FUNCTIONS in order to develop complete randomization within the model. The five independent simulated samples, representing the five years of field measurements, were developed by rotating the random numbers sequentially among the FUNCTIONS so that each FUNCTION had a different random number assigned to it during each run. The sequence of random numbers which was assigned to FUNCTION 25 in each observation of the five sample runs is shown in Appendix F. The project times, project costs, and rainfall information for each sample are shown in Appendix G. Figure 5 shows the variations in project completion times with the effect of rainfall. Figure 6 shows the variations in project times without the effect of rainfall (normally referred to as scheduled completion times). Figure 7 shows the variations in the rainfall factor which is the ratio of the project completion time, with the effect of rainfall, to the scheduled completion time.

The effect of rainfall caused large differences in the total project completion times and the rainfall factors while the scheduled completion times were stable with small degrees of variation. The frequency of rainfall for five-day periods in each of the samples is

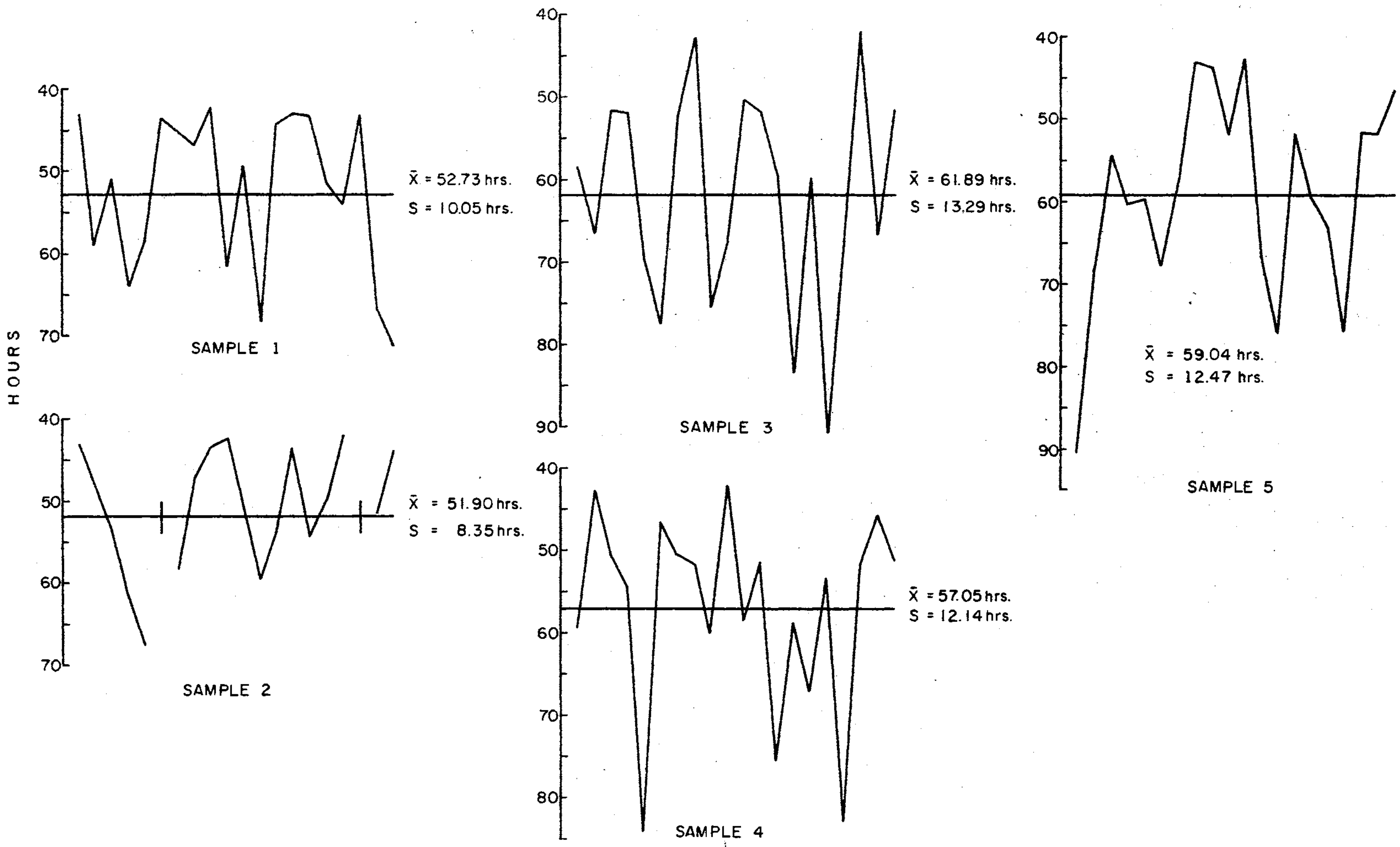

Figure 5. Variations in the Project Completion Times With the Effect of Rainfall for Twenty Observations in Each of the Five Simulated Samples of the Present Grass Cutting Assignment for the Southbound Lane

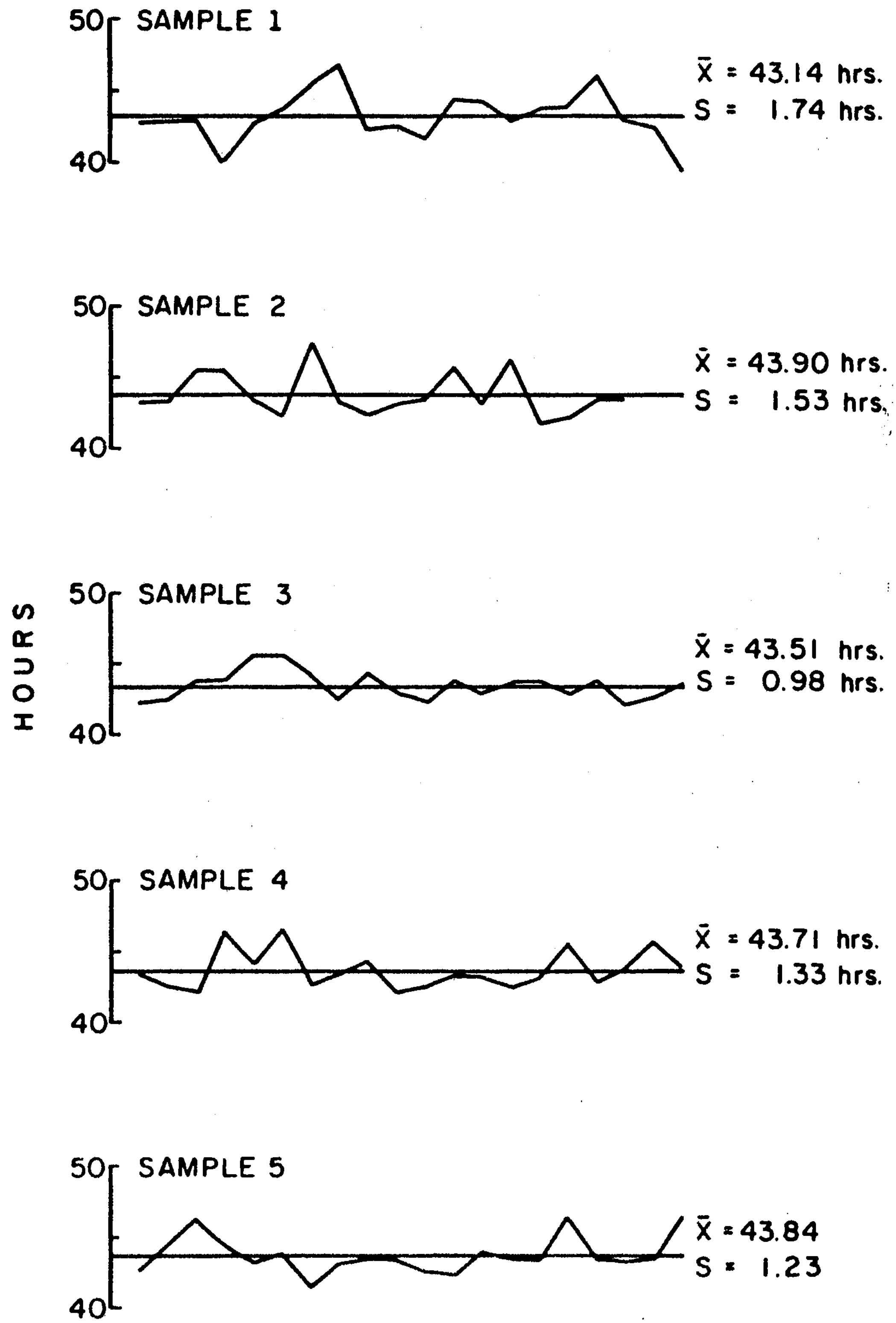

Figure 6. Variations in the Project Completion Times Without the Effect of Rainfall for Twenty Observations in Each of the Five Simulated Samples of the Present Grass Cutting Assignment for the Southbound Lane

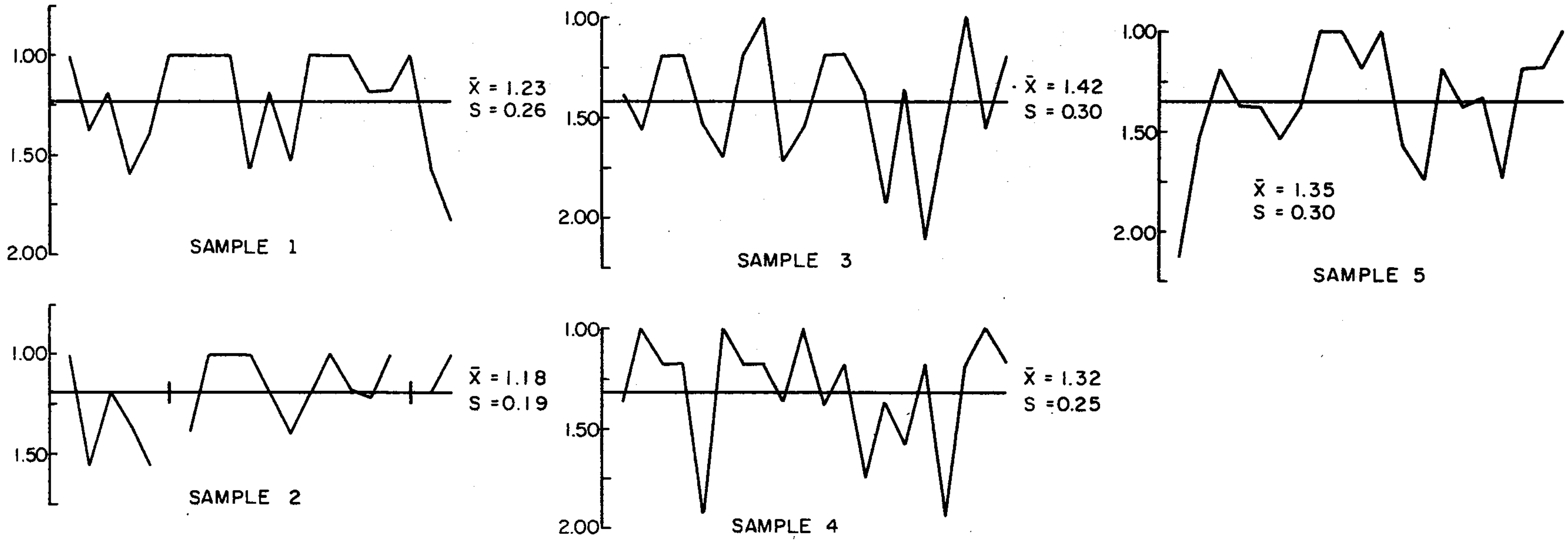

Figure 7. Variations in the Rainfall Factors for Twenty Observations in Each of the Five Simulated Samples of the Present Grass Cutting Assignment for the Southbound Lane

shown in Figure 8. The frequency distributions indicate that more simulated observations per sample are needed in order to develop the norm of the 20-year rainfall history which is shown in Figure 3 (page 24).

Because simulation requires prodigious sample sizes to adequately test simulation models against known distributions, the investigation was not pursued any further in this dissertation.

Replication of Samples

The second use of simulation modeling was to compare alternatives. In the mowing model, it was proposed by this author that the time to complete the mowing operation on the northbound lane, using a 6-foot flail type mower, be compared with the time to complete the mowing of the southbound lane, using the same size and type of mower. Further, it was proposed that this comparison be replicated.

Since a sequence of random numbers can be identically reproduced in simulation, it was possible to compare the two alternatives under conditions that were precisely the same. This unique feature of simulation is analogous to block design of statistical experiments.

The replication of the comparison was accomplished by taking another sequence of random numbers and testing the two alternatives using the new sequence of random numbers. Because the sample size was not large enough to stabilize the effect of rainfall on the project completion time, the statistical comparison of means was considered only for the scheduled completion times of the alternatives.

The first comparison of the project completion times for the northbound and southbound lanes was made using a random number sequence in

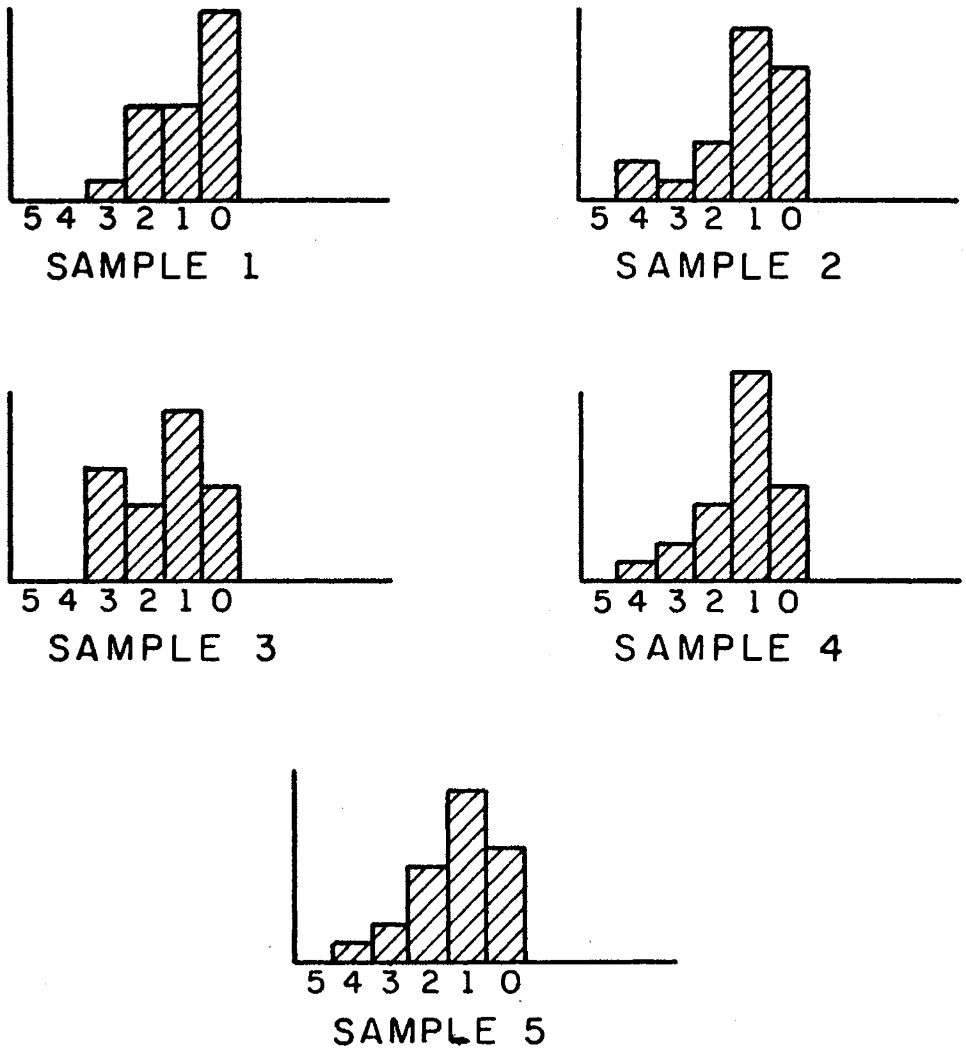

Figure 8. Histograms of Rainfall Frequencies for Five-Day Periods As Obtained From Simulation Model

which FUNCTION 1 was assigned RN 1. The other FUNCTIONS were assigned random numbers up to RN 8 sequentially with the assignment being repeated as RN 1 through RN 8 until all FUNCTIONS had random number designations. The results of the 20 observations in each sample of the alternatives, which were calculated on an IBM 360/75 computer, are shown in Appendix H. Figure 9 shows, for each alternative, the fluctuations in the project completion times with the effect of rainfall, while Figure 10 shows the fluctuations of the rainfall factors. Figure 11 shows the variations in the scheduled completion times for each alternative. The results indicate that there is no significant difference between the means of the scheduled completion times at the 95% confidence level.

The replication of the comparison between the project times for the northbound and southbound lanes was examined by using a different sequence of random numbers in which FUNCTION 1 was assigned RN 5. FUNCTION 2 through FUNCTION 4 were assigned RN 6 through RN 8 sequentially and all other FUNCTIONS were assigned RN 1 through RN 8 sequentially until all FUNCTIONS had random number designations. The tables of Appendix I show the 20 observations in each sample of the alternatives which were calculated on an IBM 360/65 computer. Figure 9 shows, for each alternative, the vacillations in the project completion times with the effect of rainfall, while Figure 10 shows the vacillations of the rainfall factors. Figure 11 shows the variations in the scheduled completion times for each alternative. The results of the replication indicate that there is no significant difference between the means of the scheduled completion times at the 95% confidence interval. Thus, it was concluded that there is a strong likelihood that the scheduled

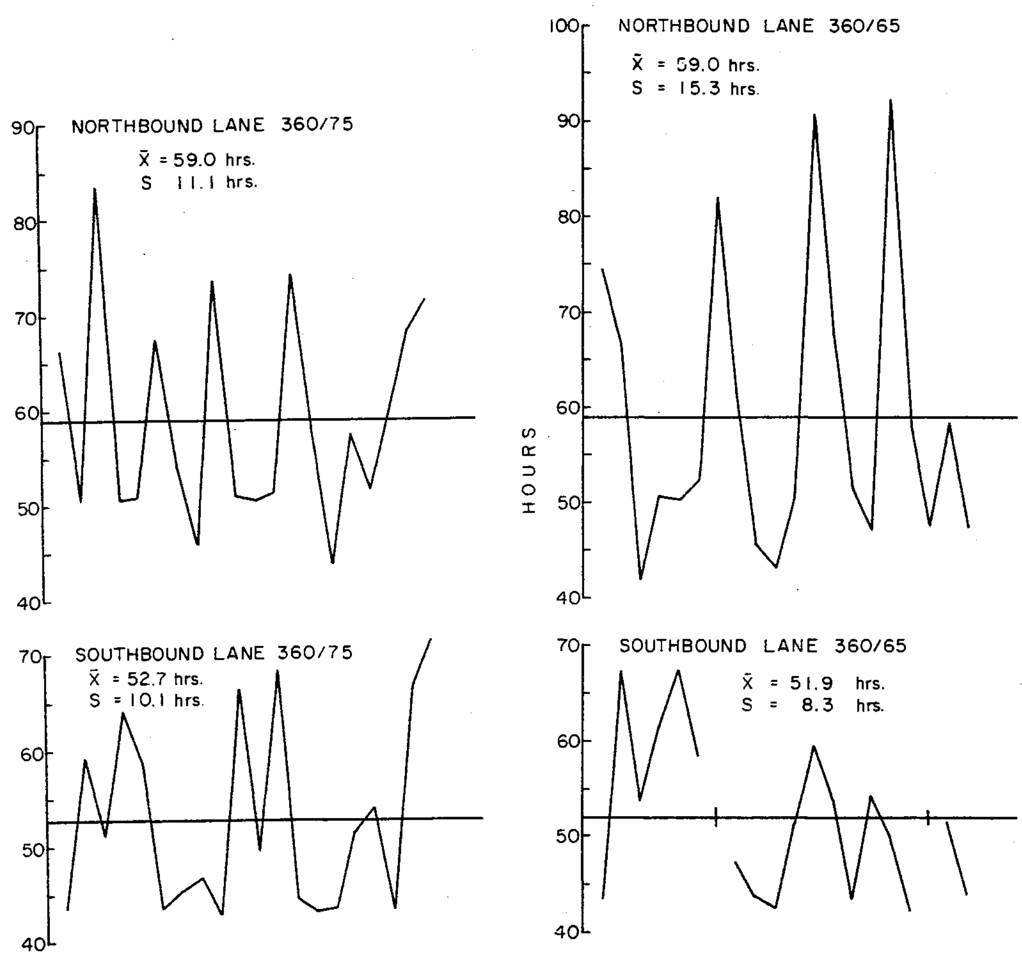

Figure 9. Variations in Project Completion Times With the Effect of Rainfall for Twenty Observations in Each Simulated Sample for the Replication of the Comparison Between the Present Cutting Assignments for the Northbound Lane and Southbound Lane

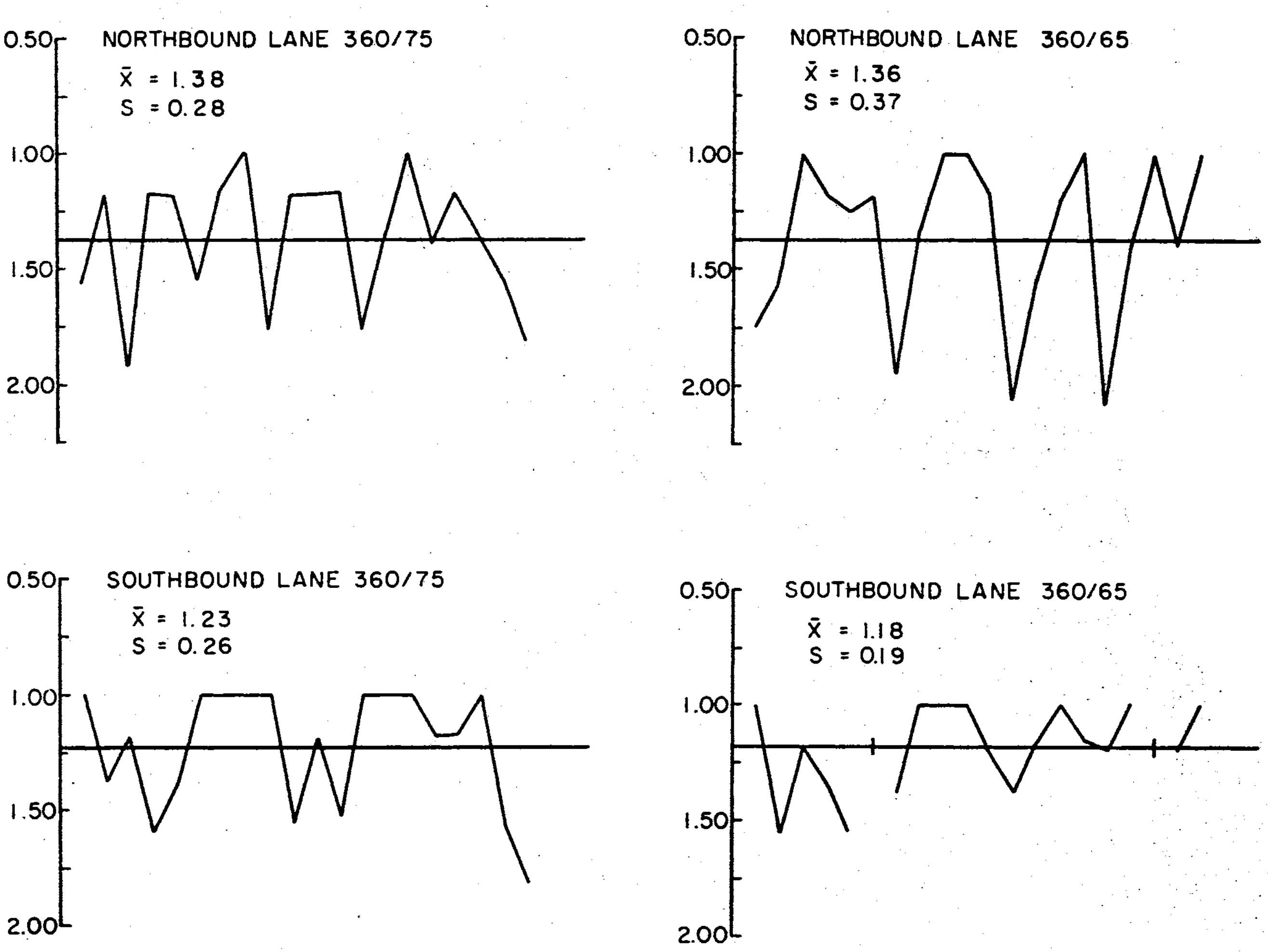

Figure 10. Variations in the Rainfall Factors for Twenty Observations in Each Simulated Sample for the Replication of the Comparison Between the Present Cutting Assignments for the Northbound Lane and Southbound Lane

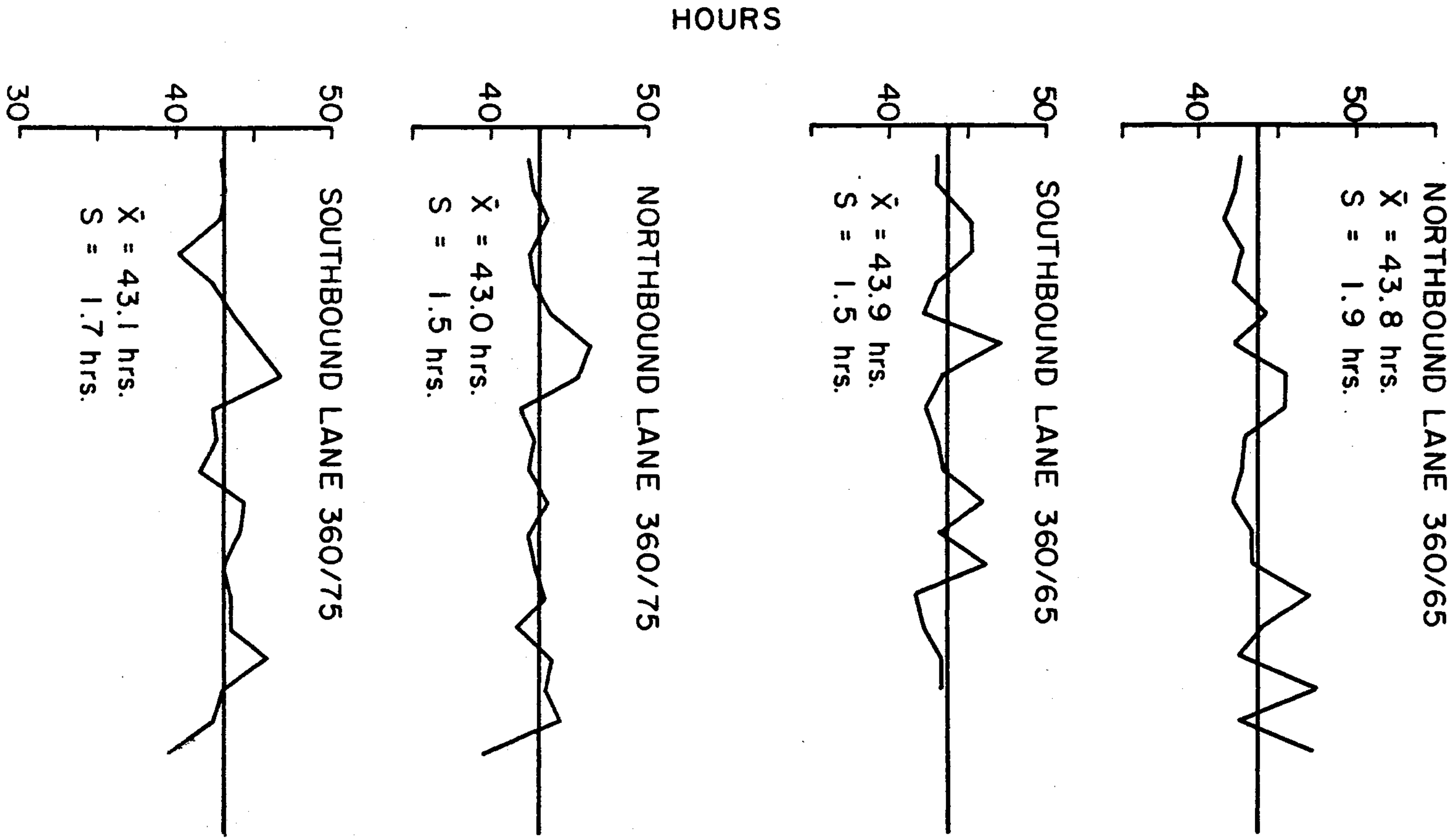

Figure 11. Variations in Project Completion Times Without the Effect of Rainfall for Twenty Observations in Each Simulated Sample for the Replication of the Comparison Between the Present Cutting Assignments for the Northbound Lane and Southbound Lane

completion times for the northbound and southbound lanes could have the same population means.

Other Comparisons

A comparison between the total project times to mow the median and the southbound lane with a 6-foot flail type mower was investigated. The sequence of random numbers used in this comparison was the same as that used in the first comparison of the replication study in which FUNCTION 1 was assigned RN 1. Appendix J shows the 20 observations in the sample of the project completion times for cutting grass in the median. Figure 12 shows for the median the vacillations in the project completion times with the effect of rainfall, while Figure 13 shows the vacillations in the rainfall factors. Figure 14 shows the fluctuations in the scheduled completion times for the median. The results indicate that on the average the median would require 9.5% more scheduled mowing time than that needed to cut the southbound lane.

A final comparison of alternatives was made in which all Class D or 3:1 side slope mowing was eliminated from the cutting assignments for the northbound and southbound lanes. The alternatives were to compare for each lane the time and cost of the present cutting assignment with the times and costs associated with the reduced cutting assignments. Figure 15 shows the fluctuations in project completion times with the effect of rainfall, scheduled completion times, and rainfall factors for 20 observations in each of the samples of the present cutting assignments for both the northbound and southbound lanes. Figure 16 shows the variations in project completion times with the effect of rainfall, scheduled completion times, and rainfall factors for 20 observations in

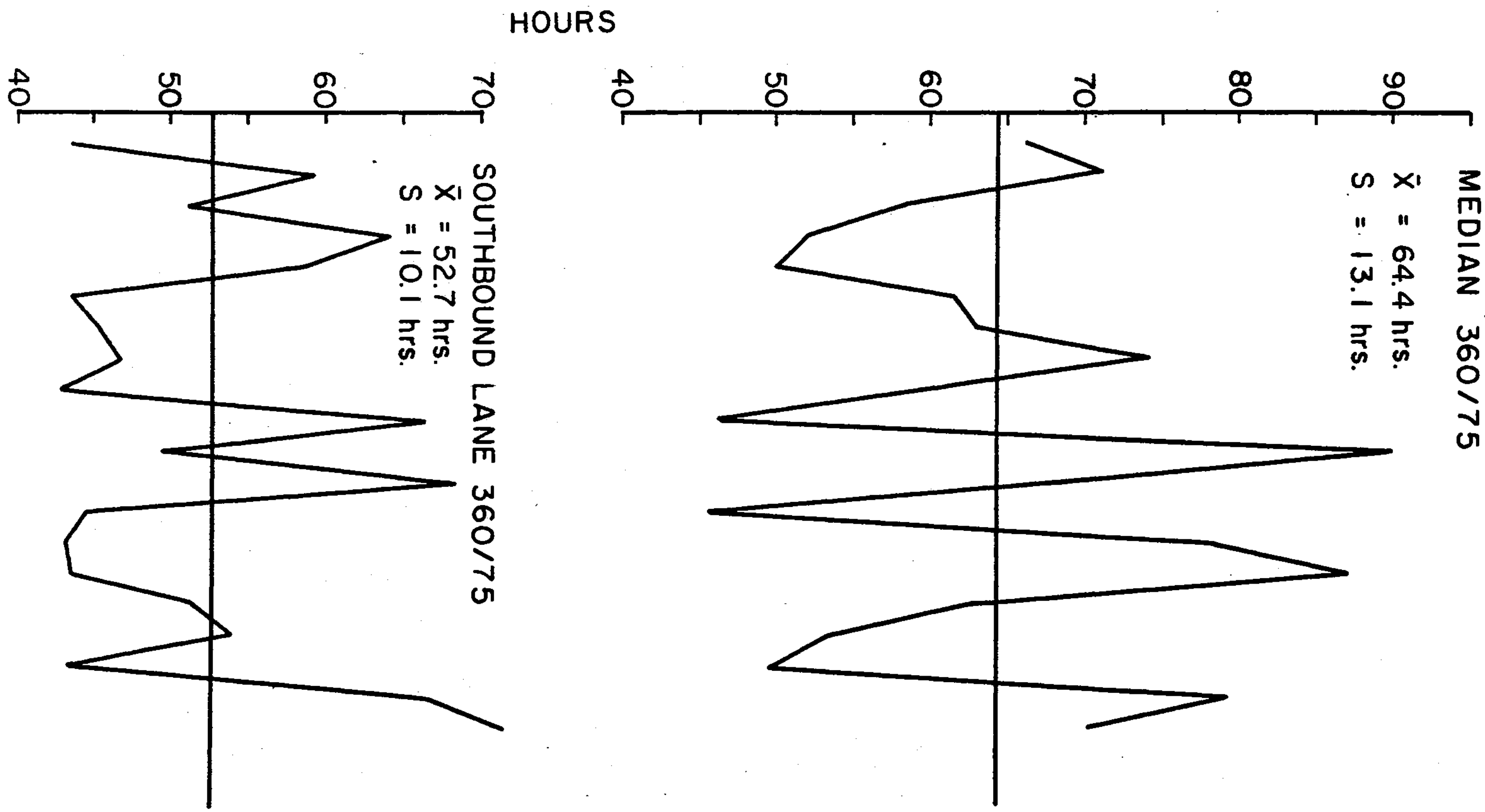

Figure 12. Variations in Project Completion Times With the Effect of Rainfall for Twenty Observations in Each Simulated Sample for the Comparison Between the Present Cutting Assignments for the Median and Southbound Lane

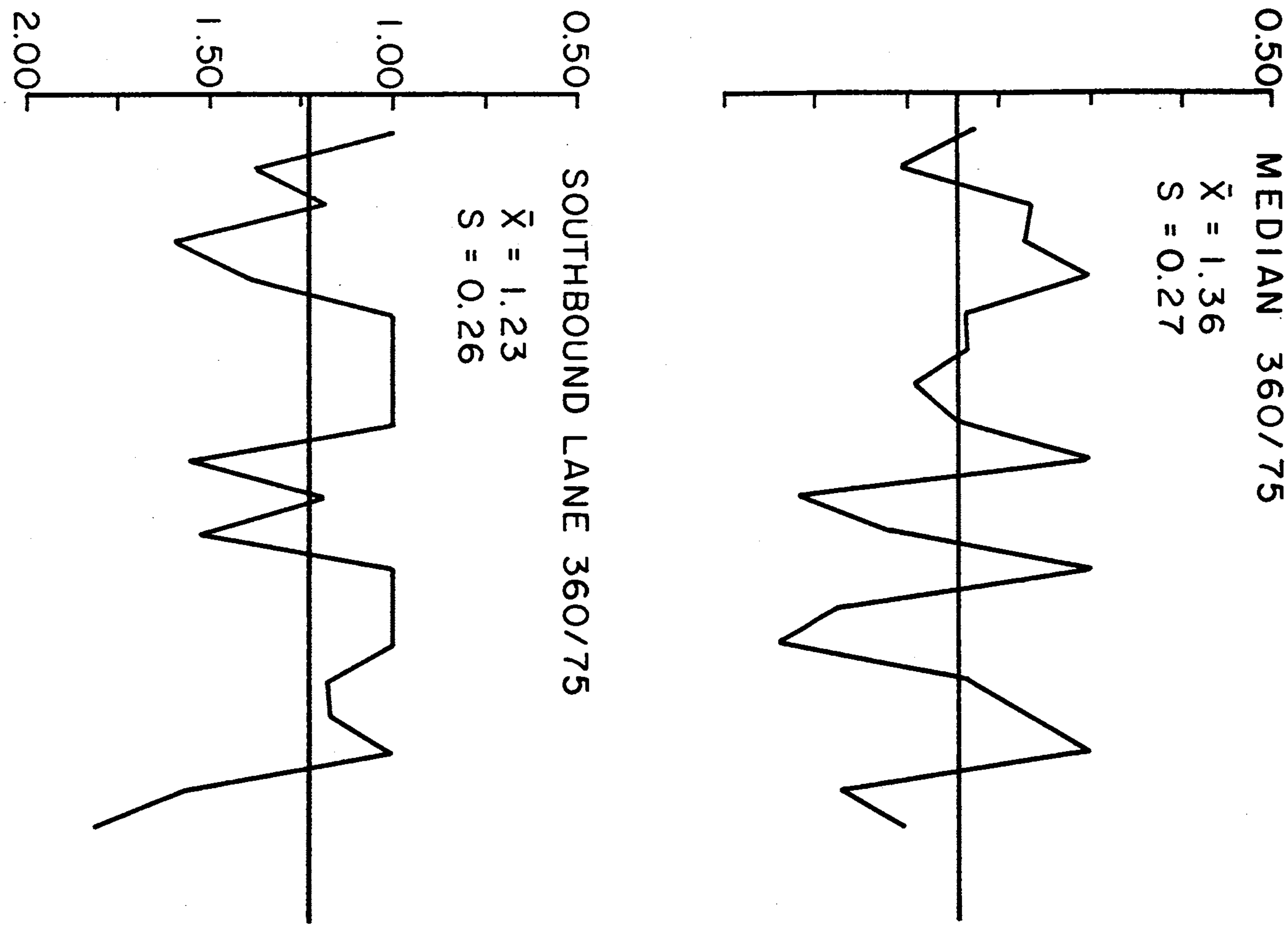

Figure 13. Variations in the Rainfall Factors of Twenty Observations in Each Simulated Sample for the Comparison Between the Present Cutting Assignments for the Median and Southbound Lane

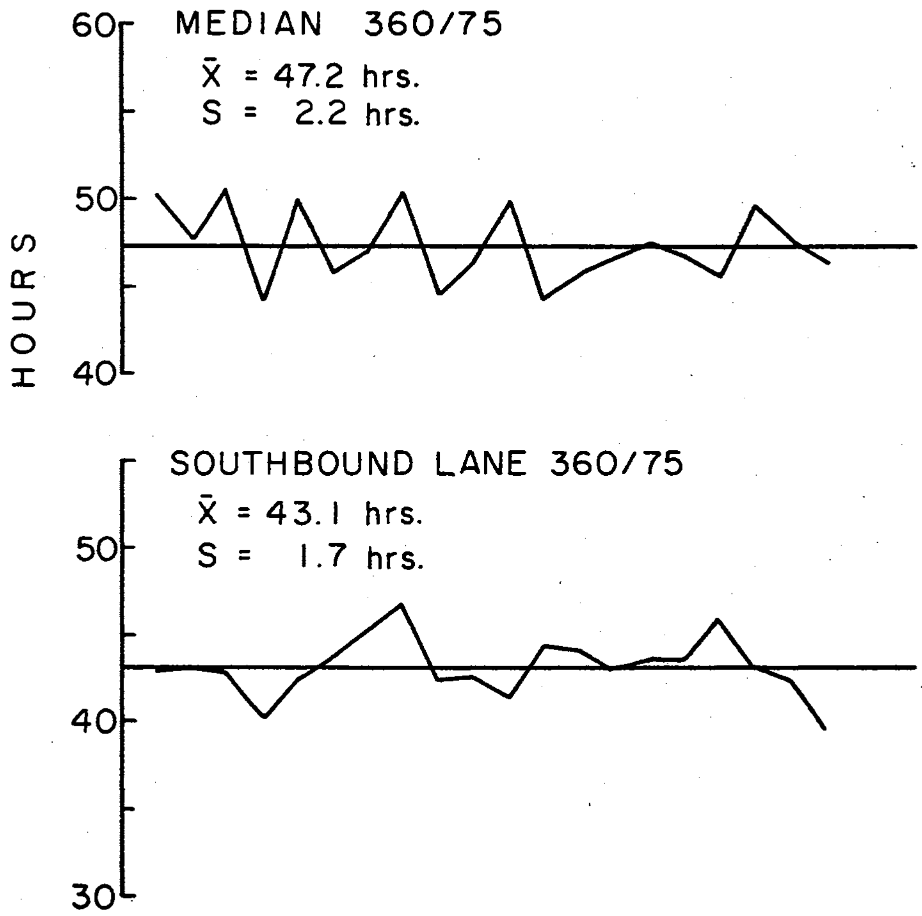

Figure 14. Variations in Project Completion Times Without the Effect of Rainfall for Twenty Observations in Each Simulated Sample for the Comparison Between the Present Cutting Assignments for the Median and Southbound Lane

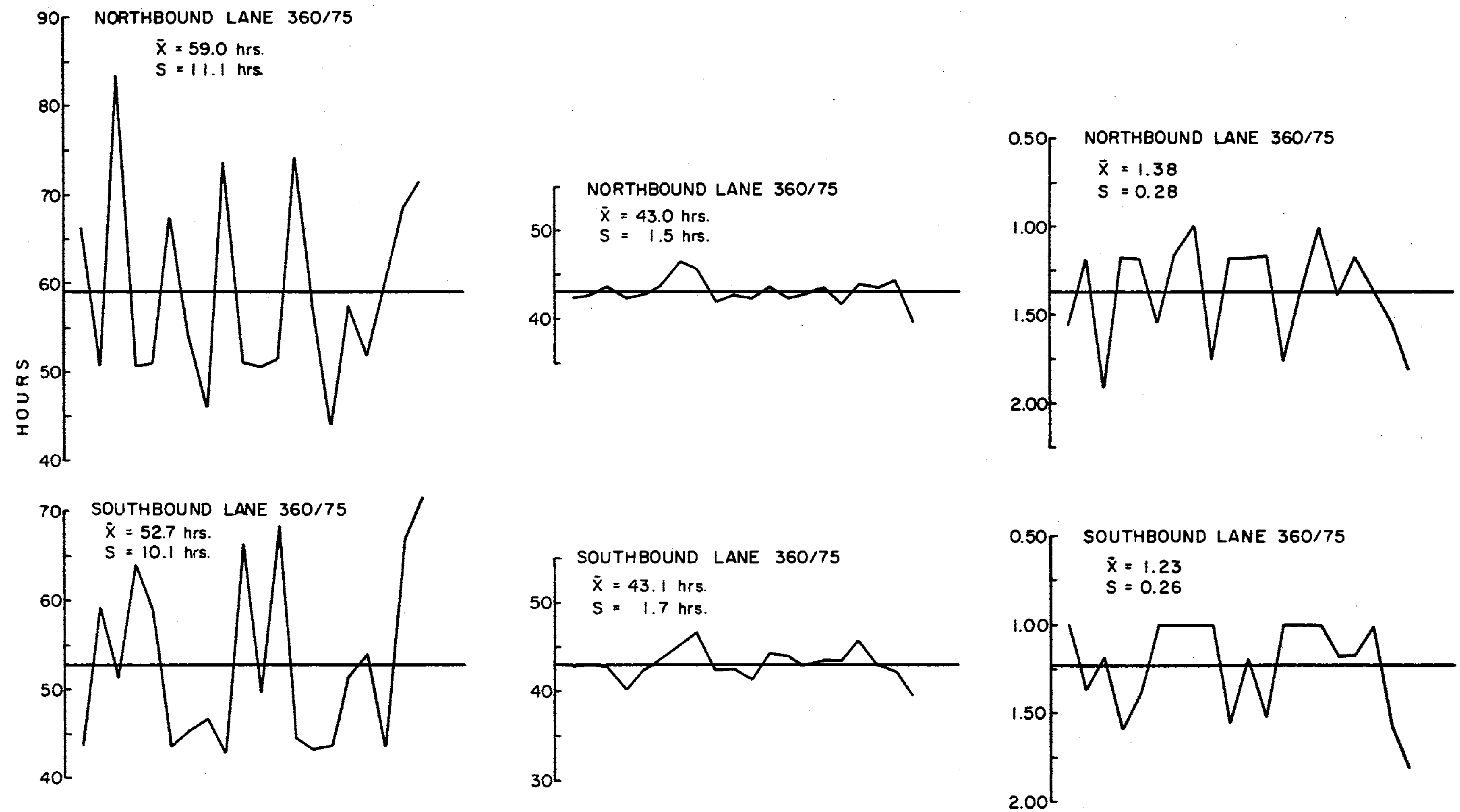

Figure 15. Variations in the Project Completion Times With the Effect of Rainfall, Without the Effect of Rainfall, and the Variations in the Rainfall Factors for Twenty Observations in Each Sample of the Present Cutting Assignments for the Northbound Lane and Southbound Lane

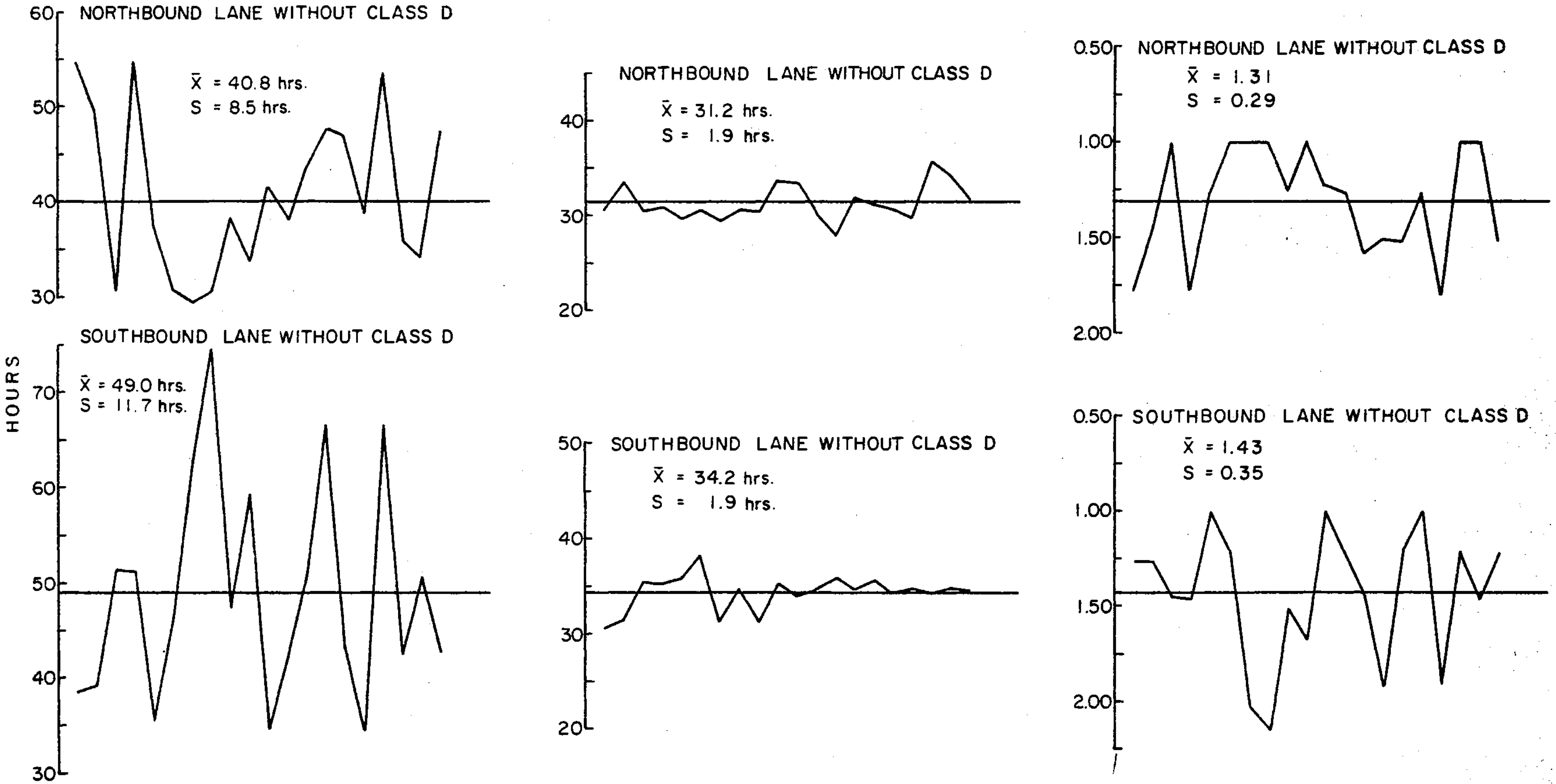

Figure 16. Variations in the Project Completion Times, With the Effect of Rainfall, Without the Effect of Rainfall, and the Variations in the Rainfall Factors for Twenty Observations in Each Sample of the Cutting Assignments Without Class D for the Northbound Lane and Southbound Lane

each of the samples of the reduced cutting assignments for both the northbound and southbound lanes. The results indicate that on the average the scheduled completion time and cost per mowing of the northbound lane were reduced 13.7% and 12.8%, respectively, while for the southbound lane the reductions were 12.5% for the scheduled completion time and 12.1% for the cost per mowing.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The mowing simulation model developed in this dissertation was a block diagram which represented the logical flow of the activities which an operator of a tractor-mower unit performed in a daily mowing operation. The simulated operator had associated with him, attributes in the form of frequency distributions obtained from field measurements, which, through random number generators, described the probabilistic status of the operator at any point in time during the working day. The production portion of the work day was divided into ten-minute intervals. The simulated speed of the mower was controlled by random sampling the speed distributions which were associated with various terrain features of the highway right-of-way. Included in the model were travel times, delay times, equipment operating costs, and speeds which related to the production capacity of the mower.

The computer programming language used for the model was the General Purpose Simulation System language which was applicable to the International Business Machine 360 series computers. The output of the computer program provided the following information about a mowing operation:

1. The total completion time of the project including the effect of rainfall.

2. The total time to complete the project excluding the effect of rainfall or sometimes called the scheduled completion time of the project.

3. The morning and afternoon production times for each day.

4. The total production time in the project.

5. The total project cost including equipment, transportation, and labor.

6. The total cost in the project for the tractor-mower unit.

7. The total cost in the project for transportation to and from the field.

8. The total production cost associated with the time the mower was cutting grass.

9. The subsection of the highway where the tractor-mower unit stopped cutting each day.

Comparisons between mowing alternatives were investigated for a 10.6 mile section of Interstate Highway I-95 in Delaware. The first comparison was between the expected completion times for cutting the grass area between the edge of roadway and the right-of-way fence on the southbound lane, for cutting the grass area of the median, and for cutting the grass area between the edge of roadway and the right-of-way fence on the northbound lane. A second comparison was made between the project times and costs if all 3:1 side slope mowing were eliminated from the cutting assignments of the northbound and southbound lanes.

The rainfall effect on project completion time was checked against the 20-year rainfall history for the study area in Delaware. As with most random number simulations, the sample size was inadequate to "test" against a norm. Because simulation requires prodigious sample sizes to adequately test simulation models against known distributions, the investigation was not pursued further.

This author investigated the linear programming model developed at Louisiana State University for optimizing the assignment of mowing equipment for a least cost. The time considered in the model was limited only to production time. No consideration was given to other time elements associated with the daily mowing operation. From the investigation, this author concluded that the linear programming model could not be extended to handle additional time elements of the daily mowing operation.

Conclusions

The mowing simulation model gives the highway maintenance engineer an effective tool by which he can make quantitative decisions about mowing programs for various sections of the highway system. The model is easily modified to handle any mowing situation which involves the production of a tractor-mower unit.

Although the data used to illustrate the capabilities of the model were for a specified section of Interstate Highway I-95 in Delaware, this does not in any way restrict the model from being used by any highway department or road commission to analyze the mowing operation on their respective highway system.

If the highway maintenance engineer is of the opinion that his work force performs more efficiently than the one represented in the model, he can remove the delay data pack from the program and replace it with a set of data that is applicable to his work force.

To apply the model to another section of highway, one needs to remove from the present program the subsection and terrain classification data pack and the initialization of the subsections and terrain classification areas. These data are replaced with data that describes the new section of highway according to its subsections and terrain classifications. If the number of subsections is other than seven, the program must be further modified to accommodate the change (see statements 78 and 136 in the program). The model is capable of handling 34 subsections with 9 terrain classifications in each subsection when used on an IBM 360 series computer with a 65k to 128k capacity.

The model can be modified to handle any size or type of mower. This modification requires that the speed data pack presently in the program be replaced with speed data which are applicable to the performance of the new mower on the terrain classifications. If the effective width of the new mower is other than five and one-half feet, the production capacity of the new mower must be modified in the program (see FVARIABLE 1 and 7 in the program).

With the development of this mowing simulation model, the highway maintenance engineer now has reason to perform time studies on mowing equipment and classify the terrain according to mower performance capabilities.

The model can be used effectively to:

1. Determine the expected cost for mowing the grass cover on new sections of highway.
2. Analyze highway beautification programs in which only certain portions of the grass cover are to be cut.

3. Compare the differences in expected times and costs related to various cutting assignments using different sizes and/or types of tractor-mower units.
4. Analyze the effects on production time if more management control of the field operation is provided.
5. Aid in the establishment of mowing standards for sections of highway.

Recommendations for Future Research

Future study is needed to verify the model with field operating conditions. Most important is the verification of project completion times with respect to different combinations of subsections and terrain classifications.

Research in the area of extending the simulation model to include two or more mowers working in groups but independently of each other is needed. This model will require that the speed distribution functions be independently sampled by each of the simulated mower units. Particular attention in the design of the model should be given to the computer output so that each mower can be identified with its production capacity and location in the mowing sequence of the subsection areas at the end of each work day.

A study is needed to determine feasible combinations of mowing equipment and to establish maximum numbers of types and sizes of mowers that are practical in field operations.

Dynamic programming for optimizing the assignment of mowers within a given section of highway should be fully developed. This author has started research on the problem but has found that practical limitations of the combinations of mower units is needed in order to make the model realistic and workable.

The GPSS program developed for the model is a utility program which can be extended to other highway maintenance operations such as road patching in which the variance in the number of square feet of patching layed per day by a paver can be estimated; or a snow plowing where the number of square feet per hour of cleared roaded surface can be estimated for different size plows and depth of snow; or a ditching where the cubic yards of excavated material per day can be estimated as a function of the density of the material.

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APPENDIX A

AREAS OF SUBSECTIONS AND TERRAIN CLASSIFICATIONS FOR THE NORTHBOUND LANE, MEDIAN, AND SOUTHBOUND LANE

TABLE I

NORTHBOUND LANE AREA DISTRIBUTION PRESENT CUTTING
(Square Feet)

Section	Class A	Class B	Class C	Class D	Class E	Class F	Total Area	SAVE-VALUE
Naamans Interchange	105,240	93,100	49,170	112,030	59,070	9,075	427,685	X30
	.25	.22	.11	.26	.14	.02		
Naamans to Harvey	39,270	0	44,730	132,410	8,450	31,625	256,485	X31
	.15	0	.17	.52	.04	.12		
Harvey Interchange	18,300	0	0	0	15,780	10,340	44,420	X32
	.41	0	0	0	.36	.23		
Harvey to Marsh	265,590	0	127,730	30,020	0	60,475	483,815	X33
	.55	0	.26	.07	0	.12		
Marsh Interchange	34,800	0	34,860	4,200	37,890	3,795	115,545	X34
	.30	0	.30	.04	.33	.03		
Marsh to Rte. 202	109,010	0	53,800	0	0	49,500	212,310	X35
	.52	0	.25	0	0	.23		
Rte. 202 Interchange	369,010	40,030	106,830	246,560	0	0	762,430	X36
	.48	.06	.14	.32	0	0		
Total Area	941,220	133,130	417,120	525,220	121,190	164,810	2,302,690	
Decimal Fraction	.41	.06	.18	.23	.05	.07	1.00	
							52.9 Acres	

TABLE II

SOUTHBOUND LANE AREA DISTRIBUTION PRESENT CUTTING
(Square Feet)

Section	Class A	Class B	Class C	Class D	Class E	Class F	Total Area	SAVE-VALUE
Naamans Interchange	141,285	36,360	40,460	48,650	36,850	3,880	307,485	X30
	.45	.11	.14	.16	.12	.02		
Naamans to Harvey	139,875	102,180	116,300	104,000	0	27,610	489,965	X31
	.28	.21	.24	.21	0	.06		
Harvey Interchange	28,150	10,065	8,200	15,980	11,620	12,595	86,610	X32
	.33	.12	.09	.18	.13	.15		
Harvey to Marsh	56,185	76,130	127,800	122,745	0	16,225	399,085	X33
	.14	.19	.32	.31	0	.04		
Marsh Interchange	0	0	0	0	10,980	2,530	13,510	X34
	0	0	0	0	.81	.19		
Marsh to Rte. 202	229,355	46,380	112,150	76,770	0	32,560	497,215	X35
	.46	.09	.23	.15	0	.07		
Rte. 202 Interchange	243,810	140,130	103,955	78,830	25,335	4,620	596,680	X36
	.41	.24	.17	.12	.04	.02		
Total Area	838,660	411,245	508,865	446,975	84,785	100,020	2,390,500	
Decimal Fraction	.35	.17	.21	.19	.04	.04	1.00	
							54.9 Acres	

TABLE III

MEDIAN AREA DISTRIBUTION PRESENT CUTTING
(Square Feet)

Section	Class A	Class B	Class C	Class D	Class E	Class F	Total Area	SAVE-VALUE
Naamans to Harvey	0	361,930	174,500	0	0	3,740	540,170	X30
	0	.67	.32	0	0	.01		
Harvey to Marsh	64,975	639,655	82,400	25,920	0	6,160	819,110	X31
	.08	.78	.10	.03	0	.01		
Marsh to Rte. 202	132,640	368,130	87,400	218,825	0	9,185	816,180	X32
	.16	.45	.11	.27	0	.01		
Rte. 202 to Viaduct	0	0	0	0	0	32,285	32,285	X33
	0	0	0	0	0	1.00		
Plots Below Viaduct	105,750	0	39,850	11,960	100,050	5,885	263,495	X34
	.40	0	.15	.05	.38	.02		
Plots to Viaduct S.	0	0	0	0	0	19,250	19,250	X35
	0	0	0	0	0	1.00		
Viaduct S. to I 95-295	0	166,800	39,400	0	0	9.845	216,045	X36
	0	.77	.18	0	0	.05		
Total Area	303,365	1,536,515	423,550	256,705	100,050	86,350	2,706,535	
Decimal Fraction	.112	.568	.156	.095	.037	.032	1.00	
							62.1 Acres	

TABLE IV

NORTHBOUND LANE WITHOUT CLASS D
(Square Feet)

Section	Class A	Class B	Class C	Class D	Class E	Class F	Total Area	SAVE-VALUE
Naamans Interchange	105,240 .33	93,100 .29	49,170 .16	-	59,070 .19	9,075 .03	315,655	X30
Naamans to Harvey	39,270 .32	0 0	44,730 .36	-	8,450 .07	31,625 .25	124,075	X31
Harvey Interchange	18,300 .41	0 0	0 0	-	15,780 .36	10,340 .23	44,420	X32
Harvey to Marsh	265,590 .58	0 0	127,730 .28	-	0 0	60,475 .14	453,795	X33
Marsh Interchange	34,800 .31	0 0	34,860 .31	-	37,890 .34	3,795 .04	111,345	X34
Marsh to Rte. 202	109.010 .52	0 0	53,800 .25	-	0 0	49,500 .23	212,310	X35
Rte. 202 Interchange	369,010 .71	40,030 .08	106,830 .21	-	0 0	0 0	515,870	X36
Total Area	941,220	133,130	417,120		121,190	164,810	1,777,470	
Decimal Fraction	.53	.08	.23		.07	.09	1.00	
							40.8 Acres	

TABLE V

SOUTHBOUND LANE WITHOUT CLASS D
(Square Feet)

Section	Class A	Class B	Class C	Class D	Class E	Class F	Total Area	SAVE-VALUE
Naamans Interchange	141,285	36,360	40,460	-	36,850	3,880	258,835	X30
	.55	.14	.16		.14	.01		
Naamans to Harvey	139,875	102,180	116,300	-	0	27,610	385,965	X31
	.36	.26	.30		0	.08		
Harvey Interchange	28,150	10,065	8,300	-	1,620	12,595	70,630	X32
	.40	.14	.12		.16	.18		
Harvey to Marsh	56,185	76,130	127,800	-	0	16,2251	276,340	X33
	.20	.28	.46		0	.06		
Marsh Interchange	0	0	0	-	10,980	2,530	13,510	X34
	0	0	0		.81	.19		
Marsh to Rte. 202	229,355	46,380	112,150	-	0	32,560	420,445	X35
	.54	.11	.27		0	.08		
Rte. 202 Interchange	243,810	140,130	103,955	-	25,335	4,620	517,850	X36
	.47	.27	.20		.05	.01		
Total Area	838,660	411,245	508,865		84,785	100,020	1,943,575	
Decimal Fraction	.43	.22	.26		.04	.05	1.00	
							44.6 Acres	

APPENDIX B

DRIVER OPERATING SPEEDS ON SIX TERRAIN CLASSIFICATIONS

TABLE VI

FLAIL MOWER SPEEDS 0°-8° SIDE SLOPE

Miles Per hour.																		
Delaware Drivers									Pennsylvania T.P. Drivers						Indiana Drivers			
1		2			3	4	5		1	2			3		1		2	3
2.8	3.4	3.2	3.1	4.2	4.3	2.9	3.5	3.4	3.8	3.8	3.8	3.6	2.8	3.3	5.8	5.9	5.7	4.6
3.3	3.2	4.2	3.2		4.2	2.8	3.5	3.5	4.1	3.9	3.7	3.7	2.4	3.5	6.8	6.1	4.7	4.3
2.8	3.4	3.7	3.3		6.0	2.9	3.3	3.5	3.6	3.6	3.8	3.8	2.4	3.3	6.0	5.7	4.7	5.0
2.8	3.3	3.4	3.5		4.1	3.0	3.3	3.4	3.6	3.8	3.7	3.7	3.3	3.2	5.6	6.3	4.5	4.4
3.0	2.8	4.1	3.5		3.6	2.9	3.5	3.3	3.5	3.0	3.8	3.3	3.0	3.5	6.9	6.7	4.4	6.0
3.6	2.5	3.4	4.7		3.4	2.6	2.9	3.4	3.5	2.6	3.7	3.6	3.4	3.4	6.4	6.1	4.7	6.0
3.7	3.0	3.8	5.4		3.6	3.0	3.4	3.3	3.4	3.4	3.9	3.8	3.1		6.4	6.1	4.9	5.7
3.8	3.4	3.9	5.4		2.8	2.5	3.5	3.4	3.6	3.7	3.4		3.2		6.0	5.9	4.7	5.3
3.8	3.4	3.4	5.7		2.8	2.5	4.1	3.3	3.9	3.7	3.7		3.4		6.8		4.6	4.3
3.7	4.0	3.6	4.3		3.0	2.5	3.2	3.3	3.6	3.8	3.6		3.5		6.4		4.1	4.7
3.7	3.9	3.3	4.9		3.1	2.5	3.1	3.4		3.9	3.8		3.9		6.0			5.7
4.2	3.9	3.8	4.1		2.7	2.7	3.0	3.2		3.9	3.8		3.7		5.4			5.2
4.2		3.6	4.2		4.0	2.7	3.0	3.2		4.0	3.6		3.5		5.5			4.8
3.7		3.4	5.5		3.8	2.8	3.0	3.3		3.9	3.7		4.0		6.7			4.3
3.8		3.4	5.7		3.4		3.0	3.3		3.9	3.6		3.7		6.1			5.2
4.7		4.7	4.8		3.4		3.0	3.4		3.9	3.7		3.7		5.9			4.7
3.1		4.9	3.4		3.4		3.4			3.8	3.6		3.4		5.7			5.5
3.3		4.5	3.5		3.5		3.1			4.0	3.6		3.4		5.8			5.4
3.4		4.8	3.7		3.5		3.2			4.0	3.5		3.2		7.1			4.8
3.6		4.7	3.2		3.6		3.6			3.9	3.6		4.3		5.8			4.1
3.7		5.4	3.5		3.6		3.6			4.0	3.4		4.0		6.0			
3.4		5.1	3.6		3.6		3.6			3.7	3.5		3.6		6.2			

TABLE VII

FLAIL MOWER SPEEDS 9°-12° SIDE SLOPE

Miles Per Hour														
Delaware Drivers							Pennsylvania T.P. Drivers			Indiana Drivers				
1	2		3	4	5		1	2	3	1		2	3	
2.6	3.6	4.5	3.8	2.3	3.1	3.8	2.9	3.7	3.5	4.5	4.6	3.7	4.1	4.1
3.0	3.4	5.3	3.8	2.8	3.5	3.6	3.5	3.1	3.4	4.4	5.1	4.7	4.0	4.1
3.2	4.8	4.6	4.1	2.7	2.7	3.8	2.7	3.5	3.4	4.4	5.3	3.6	4.1	4.1
3.1	4.5	5.2	3.9	3.0	2.8	3.7	3.5	3.2	3.3	4.4	5.6	3.8	4.5	4.3
3.2	4.2	4.8	4.0	2.8	3.1	3.4	3.2	3.5	3.5	4.0	5.1	3.4	4.3	
3.4	4.6	4.2	3.9	2.7	3.5	3.3	3.0	3.8	3.5	4.9		3.3	4.5	
3.0	4.9	4.4	4.0	2.8	3.4	3.4	3.3	3.5	4.0	5.3		3.7	4.3	
3.2	5.1	4.4	3.7	2.6	3.9	4.1	3.4	3.9	3.6	4.6		3.4	3.7	
2.8	4.3	4.1	4.0	3.6	3.6	3.8		3.7	3.3	4.4		3.8	3.5	
3.8	4.2	4.3	4.6	3.4	3.4	4.1			3.6	4.0		4.0	4.2	
	3.9	3.9	4.3	3.8	3.3	3.5			3.8	5.3		3.6	4.1	
	3.5	4.0	4.4	3.7	3.4	3.8			3.4	4.7		3.3	3.9	
	3.9	3.9	4.2	3.3	4.0	4.1				4.6		3.4	3.5	
	4.9		5.1	3.3	4.0	4.0				4.9		3.3	3.8	
	5.4		4.0	2.3	4.5	3.5				4.8		3.3	3.9	
	4.7			2.8	3.4					4.7		3.4	4.0	
	5.3			3.4	3.1					5.4		3.5	3.7	
	4.5			3.5	3.1					5.0		3.3	4.0	
	5.0			3.7	3.4					5.1		3.1	3.9	
	4.9			3.6	3.6					4.6		3.5	4.0	
	5.8				3.9					5.2		3.1	4.3	
	5.7				3.9					4.9			4.0	

TABLE VIII

FLAIL MOWER SPEEDS 13°-16° SIDE SLOPE

Miles Per Hour													
Delaware Drivers								Pennsylvania T.P. Drivers			Indiana Drivers		
1		2	3	4		5		1	2	3	1	2	3
3.5	2.3	3.0	4.0	3.1	2.5	3.3	3.3	2.4	3.8	3.6	3.7	3.1	3.0
3.8	2.6	4.0	3.9	3.0	2.9	3.1	3.4	2.9	3.3	3.3	3.8	2.9	3.1
3.5	2.6	4.2	3.3	2.9	1.9	3.1	2.8	3.0	3.0	3.3	3.9	2.8	3.1
3.6		4.0	3.1	3.0	2.4	3.3	2.8	2.4	3.2	3.5	4.0	2.7	2.7
3.2		3.7	3.9	2.8	2.3	3.1	2.8	2.3	3.8	3.3	3.8	2.7	2.7
3.3		3.3	3.9	2.0	2.6	3.0	3.6	2.3	3.7		3.8	2.4	2.7
2.9		3.8	3.8	2.5	2.8	2.9	3.2	2.5	3.5		3.6	3.1	2.9
3.6		3.9	4.0	2.3	2.9	3.0	3.4	2.8	3.3		3.5	3.0	3.0
3.6		3.9	3.8	2.7		2.8	3.8	2.9	4.0		3.7	2.8	2.5
3.1		3.6	3.6	2.5		3.2	3.4	2.8	3.4		3.8	2.5	2.3
2.2		3.2	3.5	2.6		2.8	3.5	3.0	3.8		4.1	2.9	2.8
2.1		2.1	3.5	2.8		2.9	3.0		3.9		4.2	2.4	2.8
2.0		2.3	3.5	2.7		3.2					4.0		2.5
2.1		3.5	3.5	2.5		3.7					4.1		2.8
2.2		3.5	4.2	2.2		3.6					3.9		2.8
2.0		3.5		2.7		3.5							2.6
2.0		3.9		2.7		3.3							2.3
2.9		4.0		3.0		3.4							2.8
2.0		3.9		2.2		3.2							
2.3				2.1		2.8							
2.4				2.9		2.9							
2.3				2.6		3.2							

TABLE IX

FLAIL MOWER SPEEDS 17°-22° SIDE SLOPE

Miles Per Hour										
Delaware Drivers					Pennsylvania T.P. Drivers			Indiana Drivers		
1	2	3	4	5	1	2	3	1	2	3
2.5	2.5	2.9	1.6	2.9	1.7	2.9	2.7	2.9	1.3	1.9
2.3	3.6	2.9	1.9	2.8	3.0	2.8	2.7	2.9	1.8	1.5
1.7	3.5	3.3	3.0	3.5	1.8	2.9	2.8	3.2	2.1	1.9
2.8	3.6	3.2	2.8	3.3	1.7	2.9	3.0	3.0	2.1	2.3
2.6	3.5	3.1	3.2	3.0	2.4	3.5	3.1	3.3	2.2	2.2
2.0	3.7	3.2	2.9	1.4	2.7	3.6	2.9	3.3	2.0	
2.1	3.5	3.3	2.9	2.7	2.7	3.3	3.1	3.0	1.8	
2.3	3.9	3.4	3.3	2.7	2.5	3.3	3.1	2.7	1.7	
2.7	3.2	3.6	3.2	2.5	2.5	3.2	3.2	3.3		
1.6		3.2	2.8	3.5	2.2		3.2	3.0		
2.9		4.0	2.5	3.3	2.3		2.6	3.3		
2.9		3.6	2.4	2.8			3.1			
2.4		3.2	2.8	3.4			3.1			
2.4		3.3	2.5	3.3			3.0			
		3.2	2.8	3.5			3.2			
		3.1	2.9	3.3						
		3.3	2.7	3.3						
		3.3	2.7	3.5						
		3.5	2.5							
		3.4	2.7							
		3.4	2.5							
		2.3								

TABLE X

FLAIL MOWER SPEEDS - OBSTACLES

Miles Per Hour												
Delaware Drivers							Pennsylvania T.P. Drivers			Indiana Drivers		
1	2	3	4		5		1	2	3	1	2	3
1.7	1.6	2.2	1.5	1.2	1.9	1.3	1.6	3.1	2.3	2.1	1.1	1.4
1.6	1.4	1.8	1.9		1.3	1.5	1.7	2.1	2.1	2.1	1.3	1.2
1.3	1.5	3.8	1.2		2.7	1.9	1.5	3.3	1.6	2.0	1.7	1.3
1.5	2.2	3.4	2.0		1.6		1.4	2.3	1.9	3.4	1.1	1.5
1.1	2.0	2.6	1.3		2.1		1.1	2.2	1.6	2.6	1.4	1.8
1.9	2.0	2.8	1.4		2.1		1.2	2.5	2.5	2.7	1.2	1.5
2.3	2.4	2.5	1.1		1.7		1.0	2.1	2.2	2.2	1.7	2.1
1.7	2.3	2.8	1.8		1.7		1.0	2.3	1.8	2.1	1.7	1.7
2.0	3.0	3.8	1.1		1.1		1.3	2.1	1.6	1.7	1.5	1.0
1.9	2.2	2.6	1.3		0.5		1.6	2.1	1.0	1.6	1.4	1.1
1.8	2.3	3.0	1.9		0.7		1.8	3.3	2.9		1.6	1.2
1.2	1.8	3.2	1.3		0.7		1.6	2.2	2.3		1.5	1.4
1.9	2.1	2.5	1.5		0.7		0.9	2.6	3.2		1.3	
1.4	2.8	3.1	1.3		0.5		0.4	2.4	2.9			
1.0	2.7	3.0	2.0		0.8		0.6	2.7	3.3			
2.0	2.6	3.3	1.4		2.0		1.0		3.1			
1.4		2.5	1.2		1.5		0.9		2.4			
1.2		2.3	1.3		2.2				3.0			
1.7		3.0	1.5		2.4							
		2.1	1.8		2.4							
			1.2		2.3							
			1.1		2.2							

TABLE XI

FLAIL MOWER SPEEDS - ROADING

Miles Per Hour												
Delaware Drivers							Pennsylvania T.P. Drivers			Indiana Drivers		
1	2		3	4	5		1	2	3	1	2	3
15.0	13.6	3.7	18.8	17.7	16.9	4.5	6.3	16.0	11.8	18.8	15.0	15.1
10.8	12.6	3.2	15.1	13.6	15.1	4.3	6.2	12.4	11.5	16.1	14.6	12.5
10.3	11.9	3.1	15.0	13.2	13.6	4.3	5.5	12.2	11.2	12.1	14.2	12.2
7.2	11.8	2.8	14.2	13.2	12.2		4.4	11.3	10.0	11.4	14.0	10.9
5.1	11.4		14.0	13.1	12.2		4.1	11.0	9.7	10.9	12.6	10.2
5.1	10.0		13.5	12.1	9.9		3.8	8.2	8.8	10.0	10.8	9.9
5.0	9.9		12.6	10.3	9.8		3.5	7.8	7.7	8.9	10.3	9.7
4.2	9.7		12.1	10.2	9.7		3.4	7.5	6.7	8.0	9.8	8.9
4.0	6.7		10.9	8.6	9.5		2.9	6.2	6.5	7.2	8.2	8.6
3.8	6.7		10.0	8.6	9.4		2.8	5.6	5.6	6.7	7.2	8.2
3.4	6.5		8.8	8.5	8.9			5.5	4.8	6.5	6.0	7.6
	5.9		7.9	7.8	7.6			4.1	4.0	5.5	5.2	7.1
	5.1		7.5	7.7	7.3			3.7	3.4	5.4		5.5
	4.8		4.3	7.3	7.2			3.5	3.0	5.3		5.2
	4.8		3.7	6.8	7.1			3.1	2.8	4.8		5.1
	4.6		2.8	6.6	6.6				2.6	4.3		4.9
	4.6		2.6	6.1	6.6				2.4	4.1		4.6
	4.6		2.5	6.1	5.9				2.0	4.0		4.3
	4.1			5.5	5.9					3.8		4.0
	4.0			3.8	5.6					3.5		
	3.9			2.9	5.4							
	3.8				5.4							

APPENDIX C

HISTOGRAMS AND CUMULATIVE PROBABILITY DISTRIBUTION OF OPERATING SPEEDS FOR SIX TERRAIN CLASSIFICATIONS

TABLE XII

FUNCTIONS - MOWING SPEEDS
(Means and Standard
Deviations)

Function	Mean	Std. Dev.
1	4.0 m/hr	1.10 m/hr
2	3.9 m/hr	0.78 m/hr
3	3.1 m/hr	0.62 m/hr
4	2.8 m/hr	0.58 m/hr
5	1.9 m/hr	0.69 m/hr
6	7.1 m/hr	4.04 m/hr

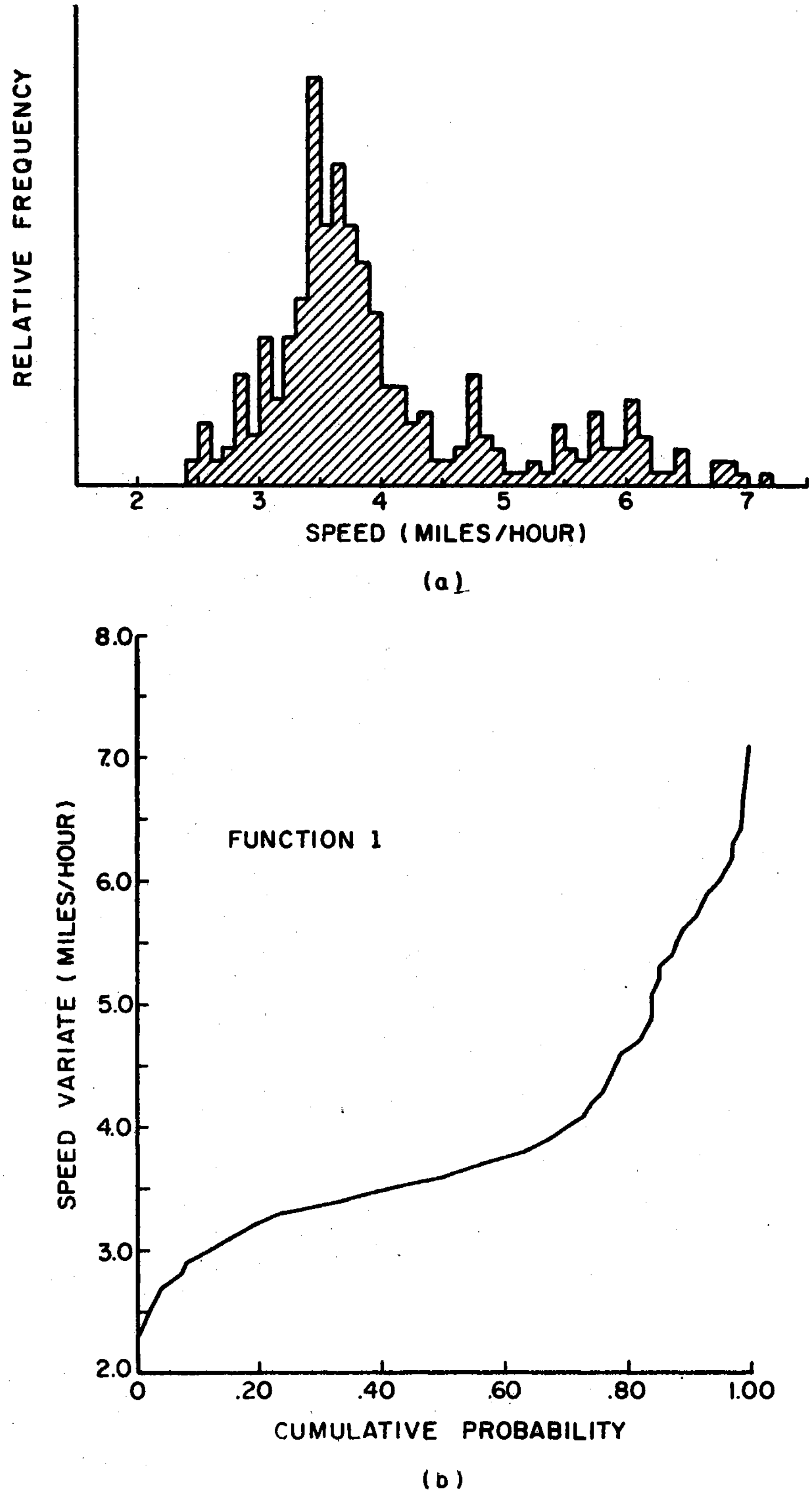


Figure 17. Speeds of Flail Mower 0^{o}-8^{o} Side Slope

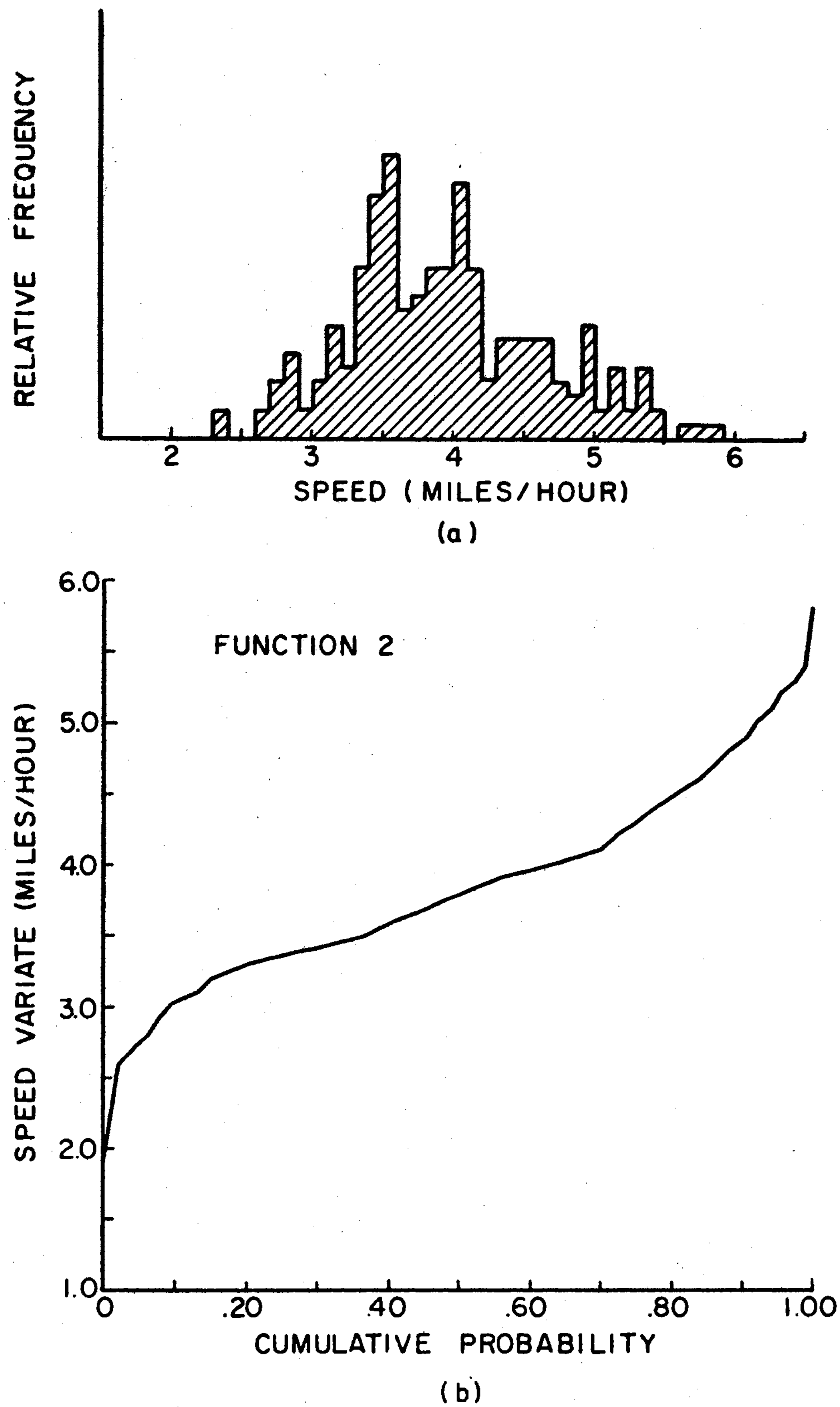


Figure 18. Speeds of Flail Mower 9°-12° Side Slope

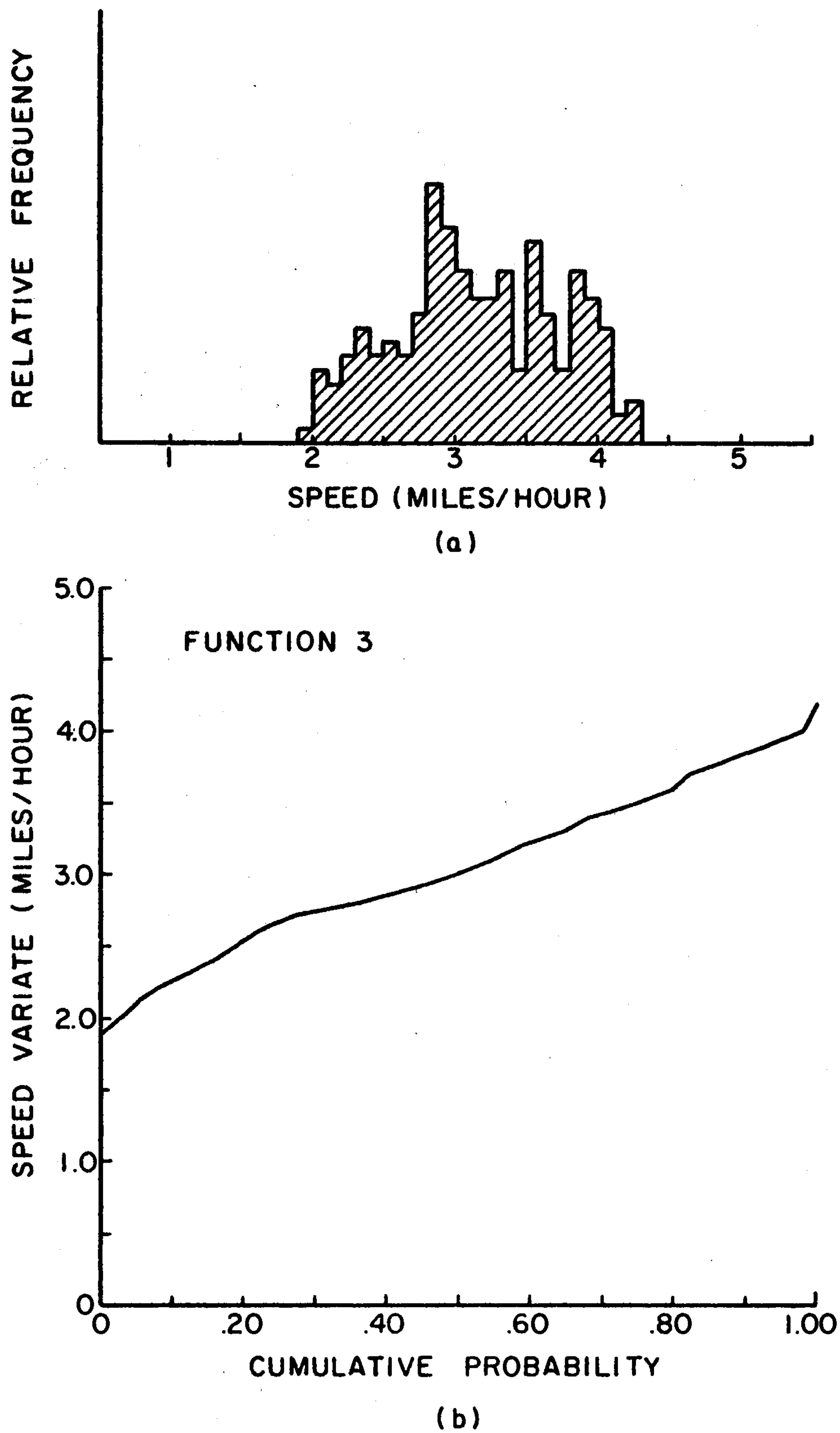
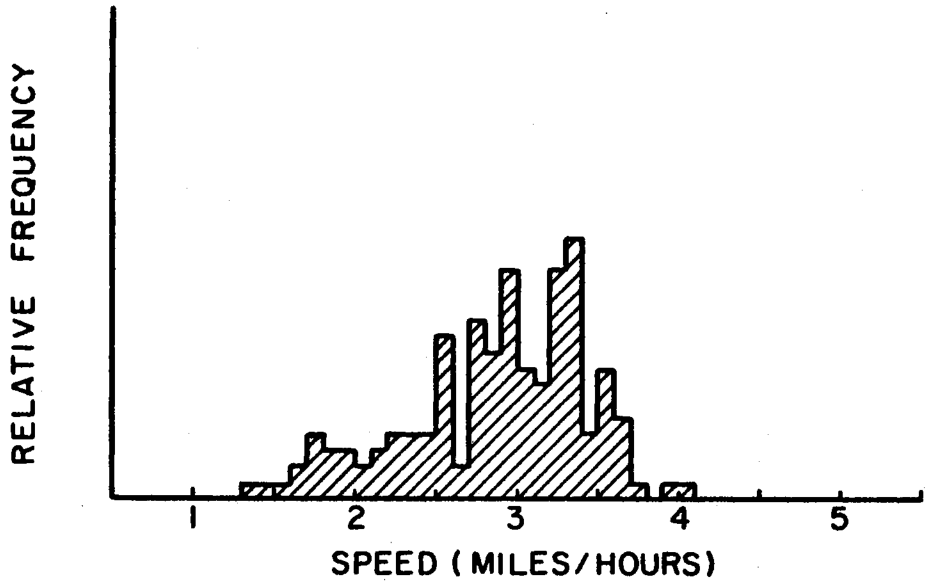
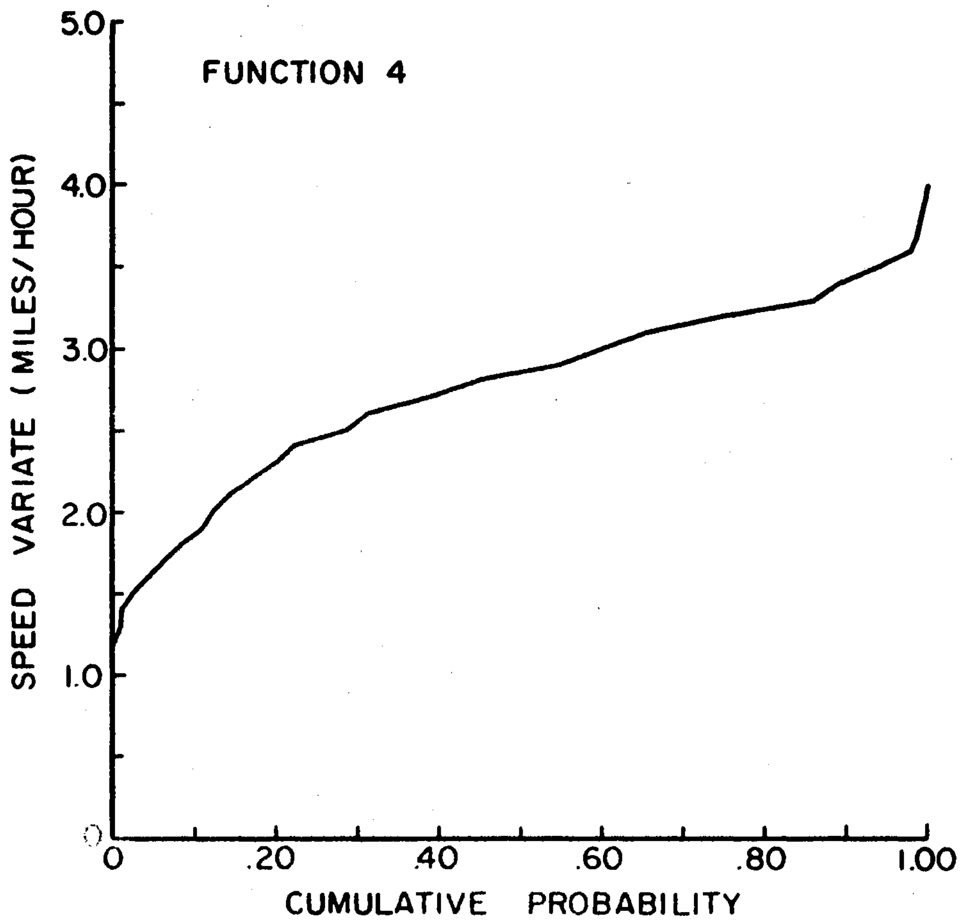


Figure 19. Speeds of Flail Mower 13^{o}-16^{o} Side Slope

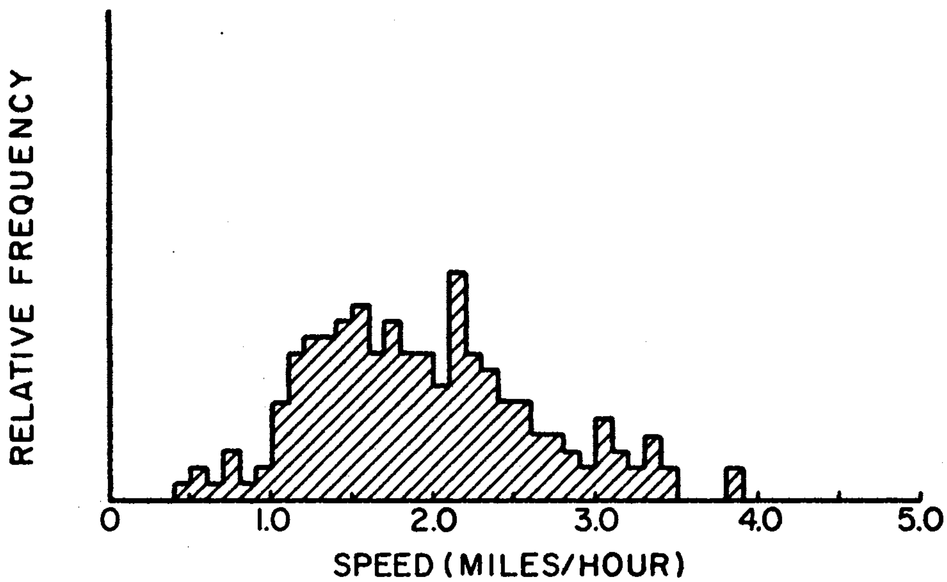


(a)

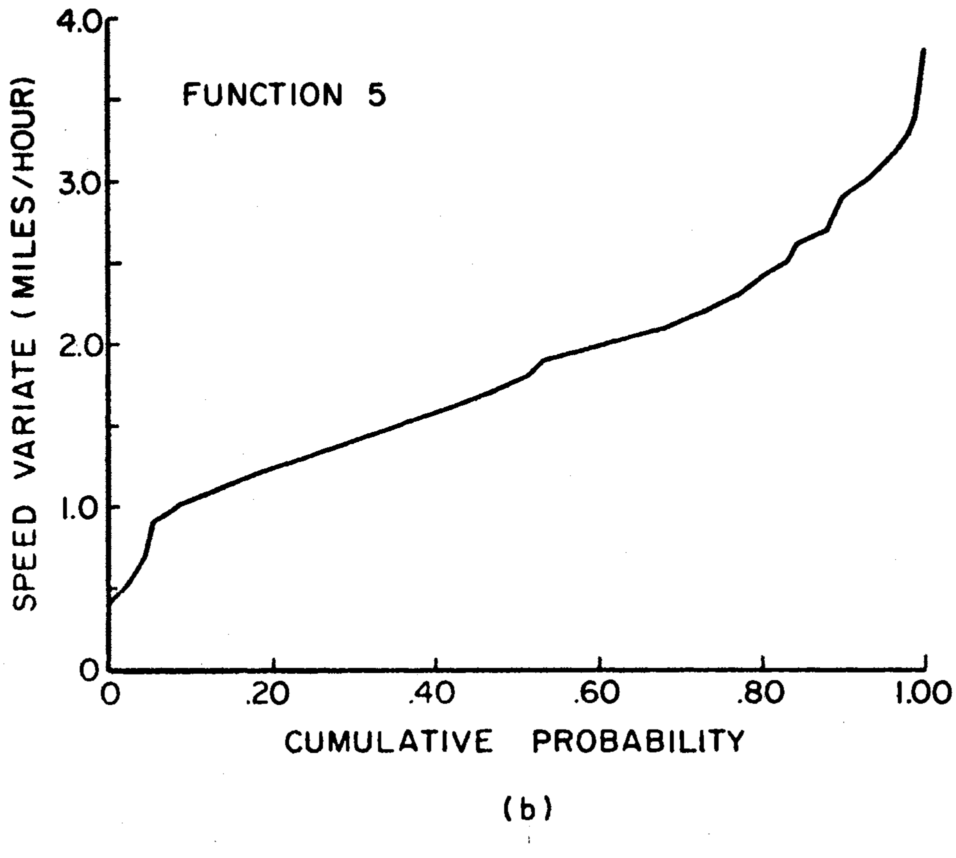


(b)

Figure 20. Speeds of Flail Mower 17°-22° Side Slope

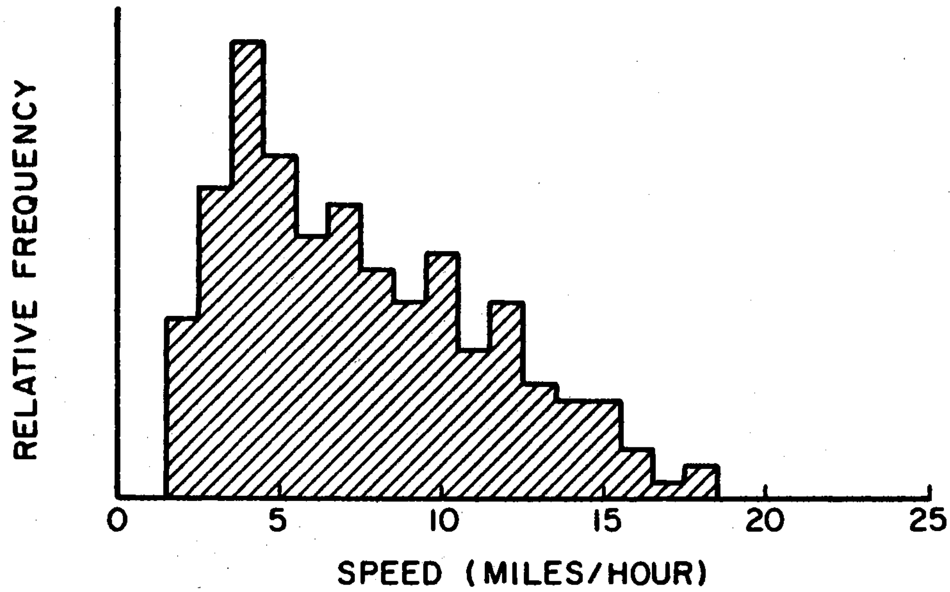


(a)

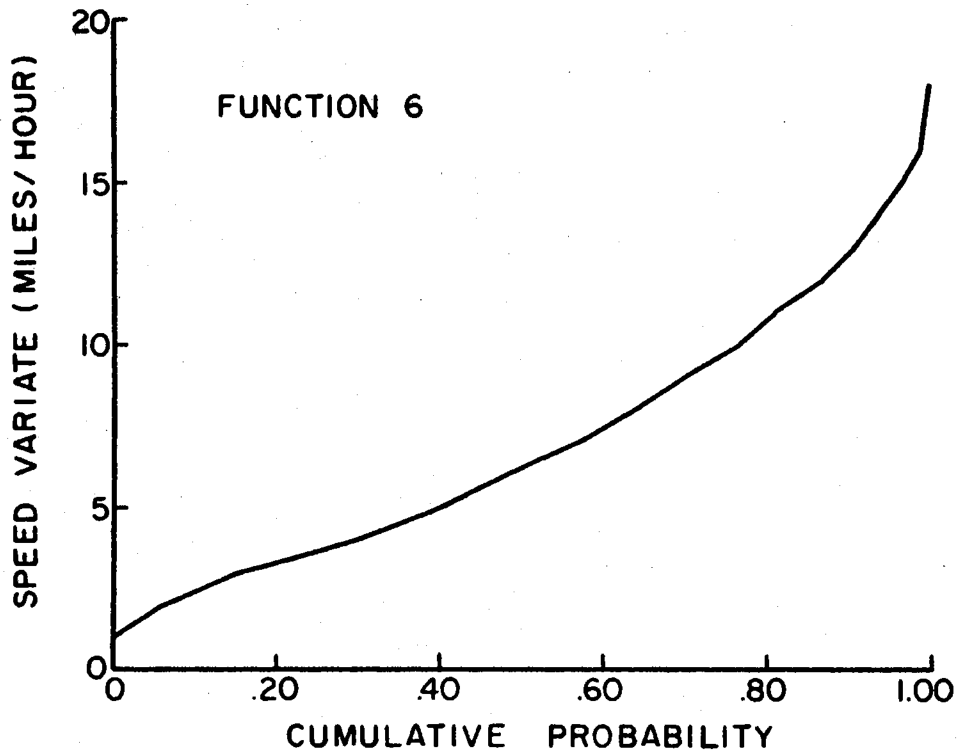


(b)

Figure 21. Speeds of Flail Mower - Obstacles



(a)



(b)

Figure 22. Speeds of Flail Mower - Roading

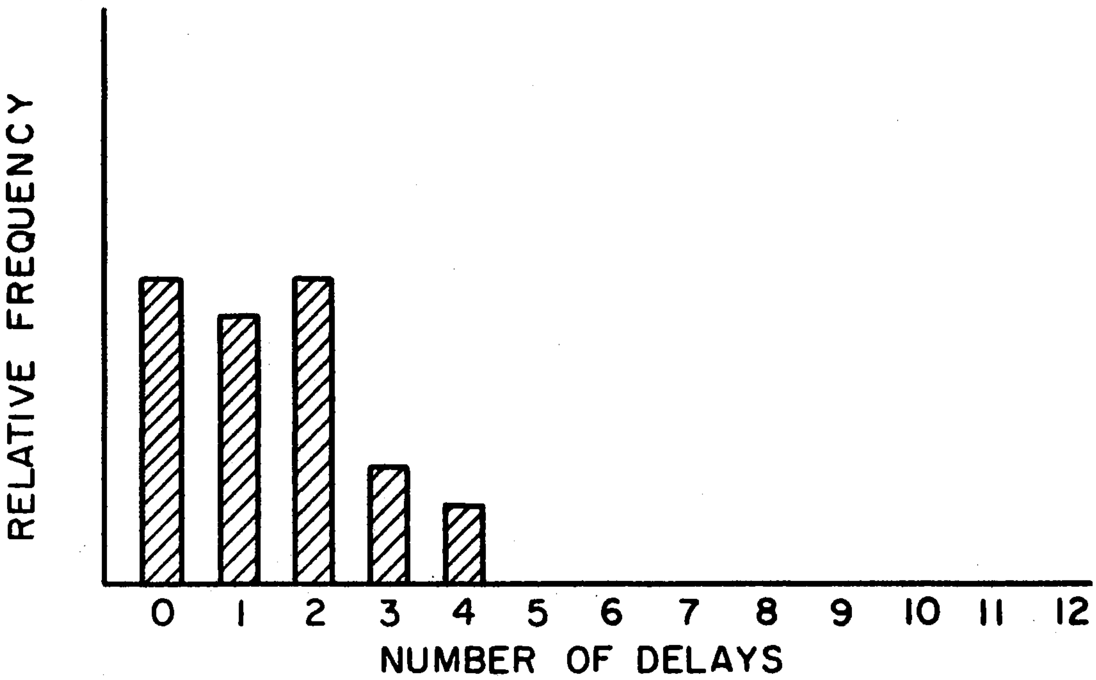
APPENDIX D

HISTOGRAMS AND CUMULATIVE PROBABILITY DISTRIBUTIONS OF NONPRODUCTION ACTIVITY TIMES

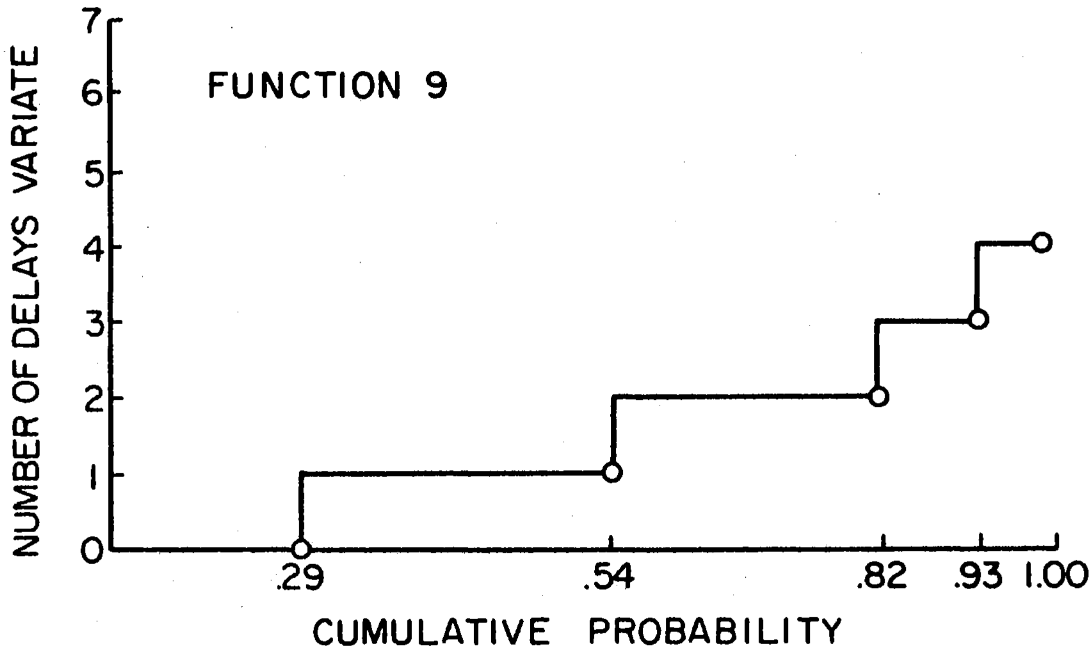
TABLE XIII

FUNCTIONS - NONPRODUCTION ACTIVITIES
(Means and Standard Deviations)

Function	Mean	Std. Dev.
9	1.4	1.23
10	6.7 min	4.01 min
11	21.8 min	6.28 min
12	20.4 min	5.64 min
13	11.5 min	3.88 min
14	4.1 min	2.44 min
15	3.8	2.11
16	4.6 min	2.29 min
17	3.9 min	2.57 min
18	54.4 min	9.49 min
19	4.2 min	2.17 min
20	4.8	1.72
21	4.0 min	2.72 min
22	4.3 min	3.00 min
23	26.7 min	7.56 min
27	0.22 min	0.14 min



(a)



(b)

Figure 23. Number of Breakdowns of the Flail Mower During the Morning or Afternoon Work Session

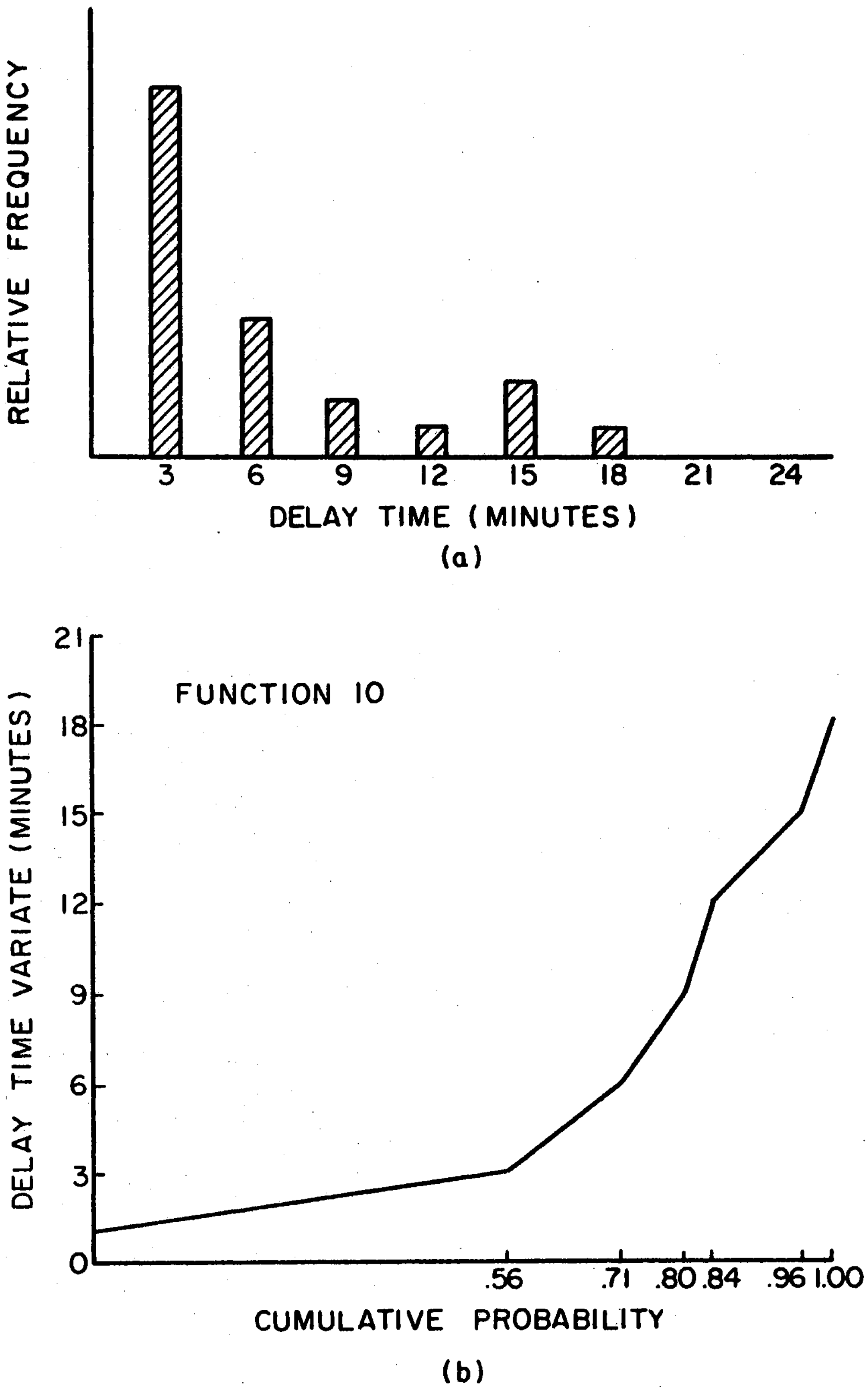


Figure 24. Times for Each Breakdown of the Flail Mower During the Morning or Afternoon Work Session

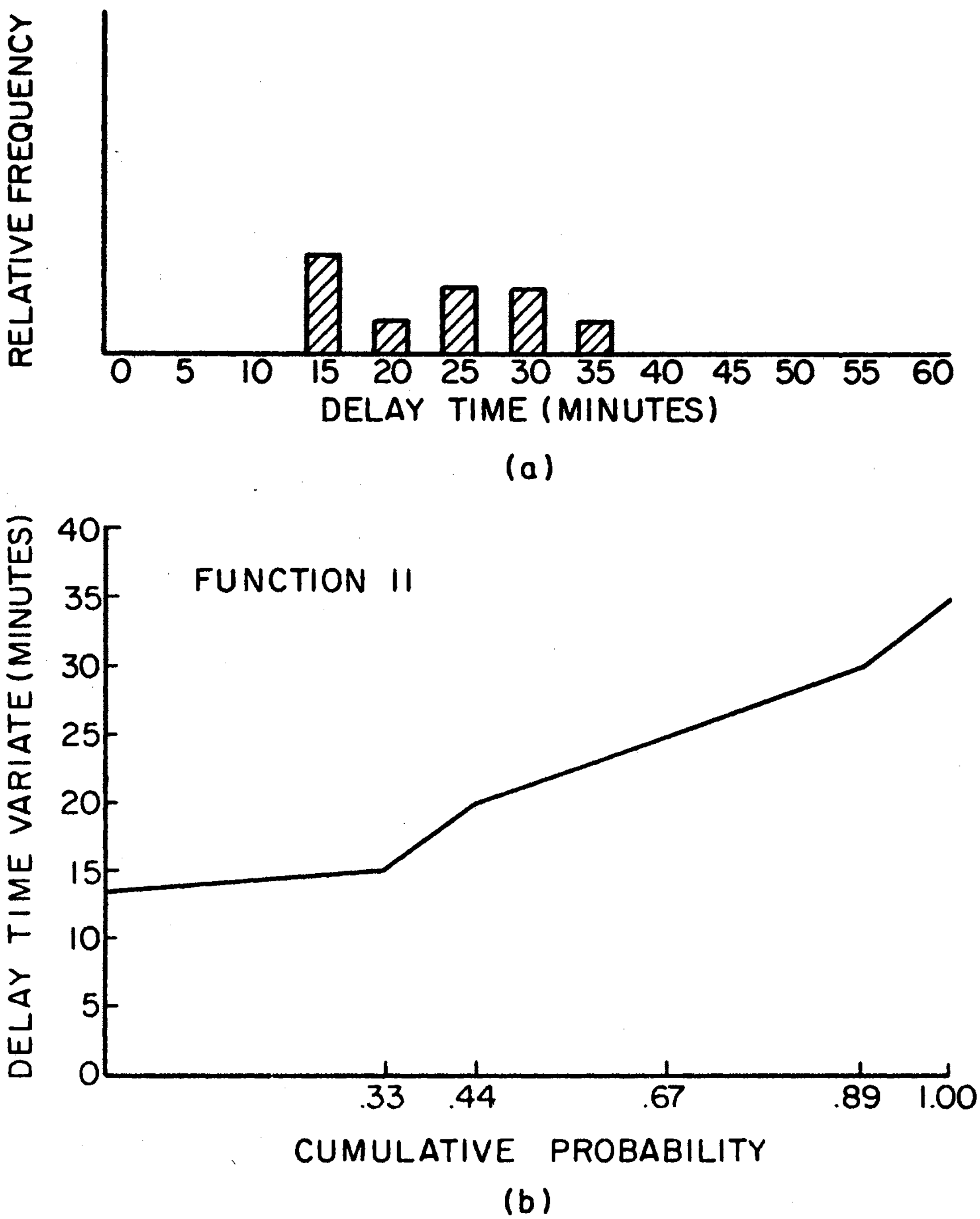


Figure 25. Morning Delay Times at Division Headquarters

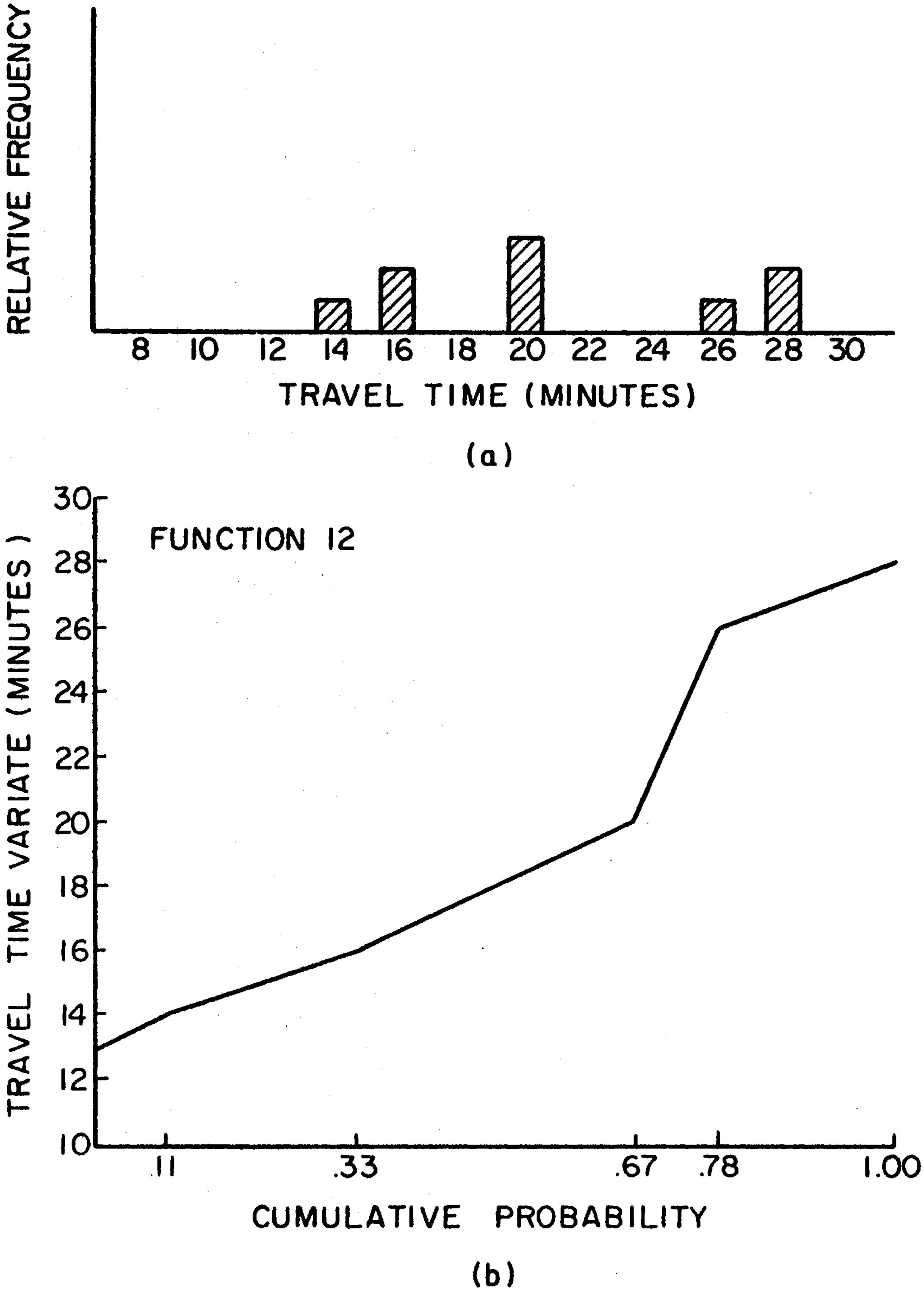


Figure 26. Travel Times From Division Headquarters to the Field

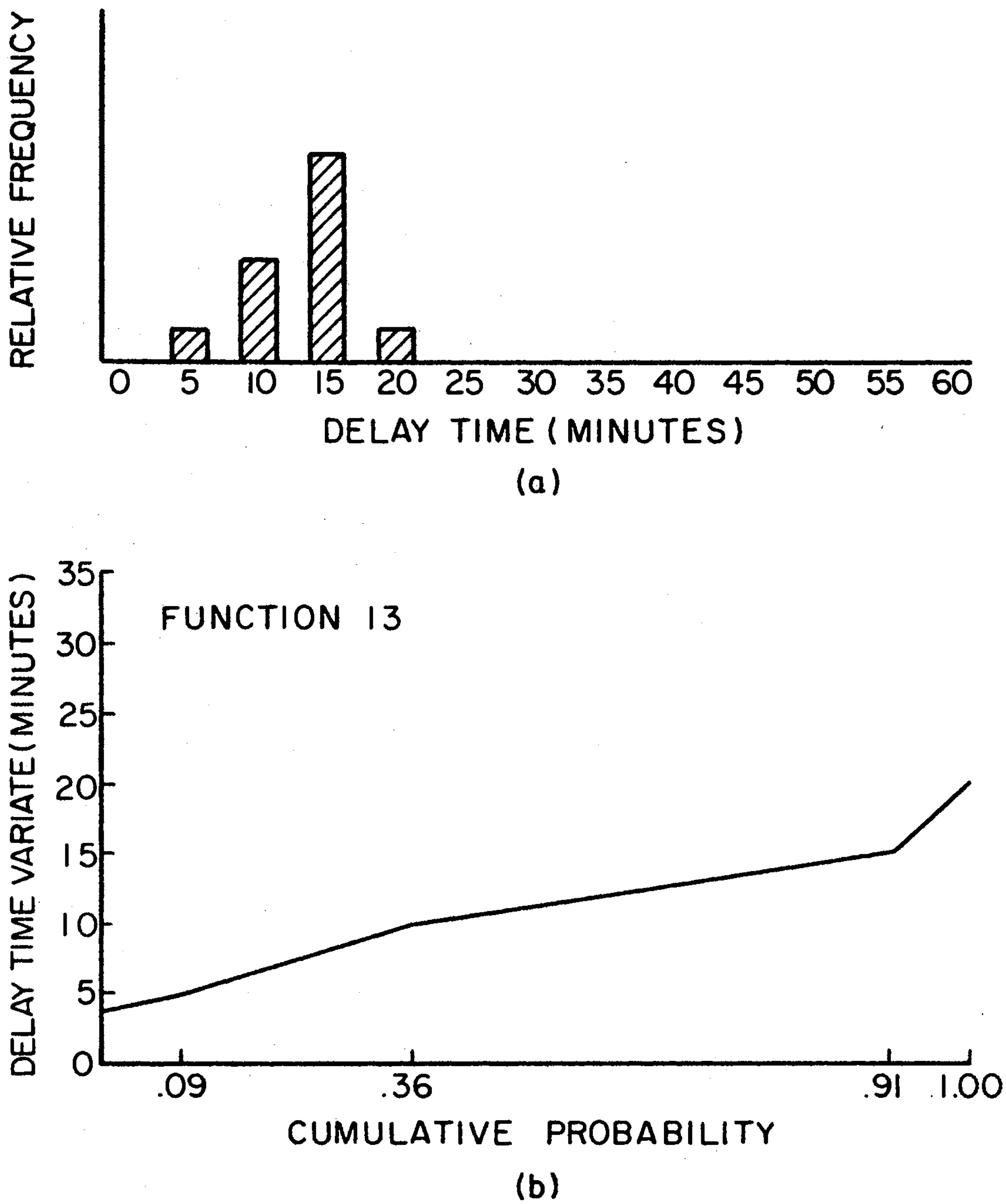


Figure 27. Times to Perform Preventative Maintenance

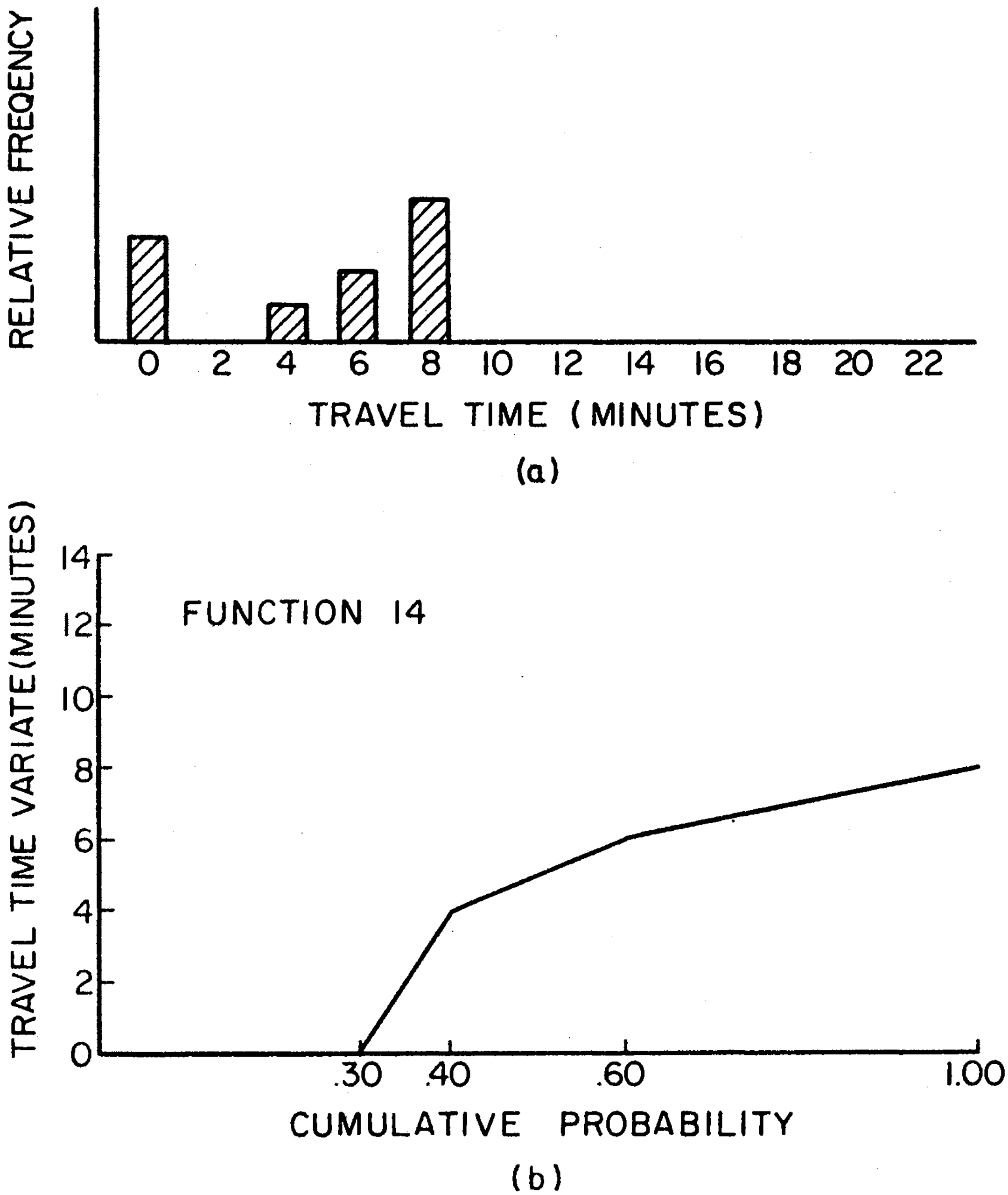


Figure 28. Travel Times From Truck to Work Area
in the Morning

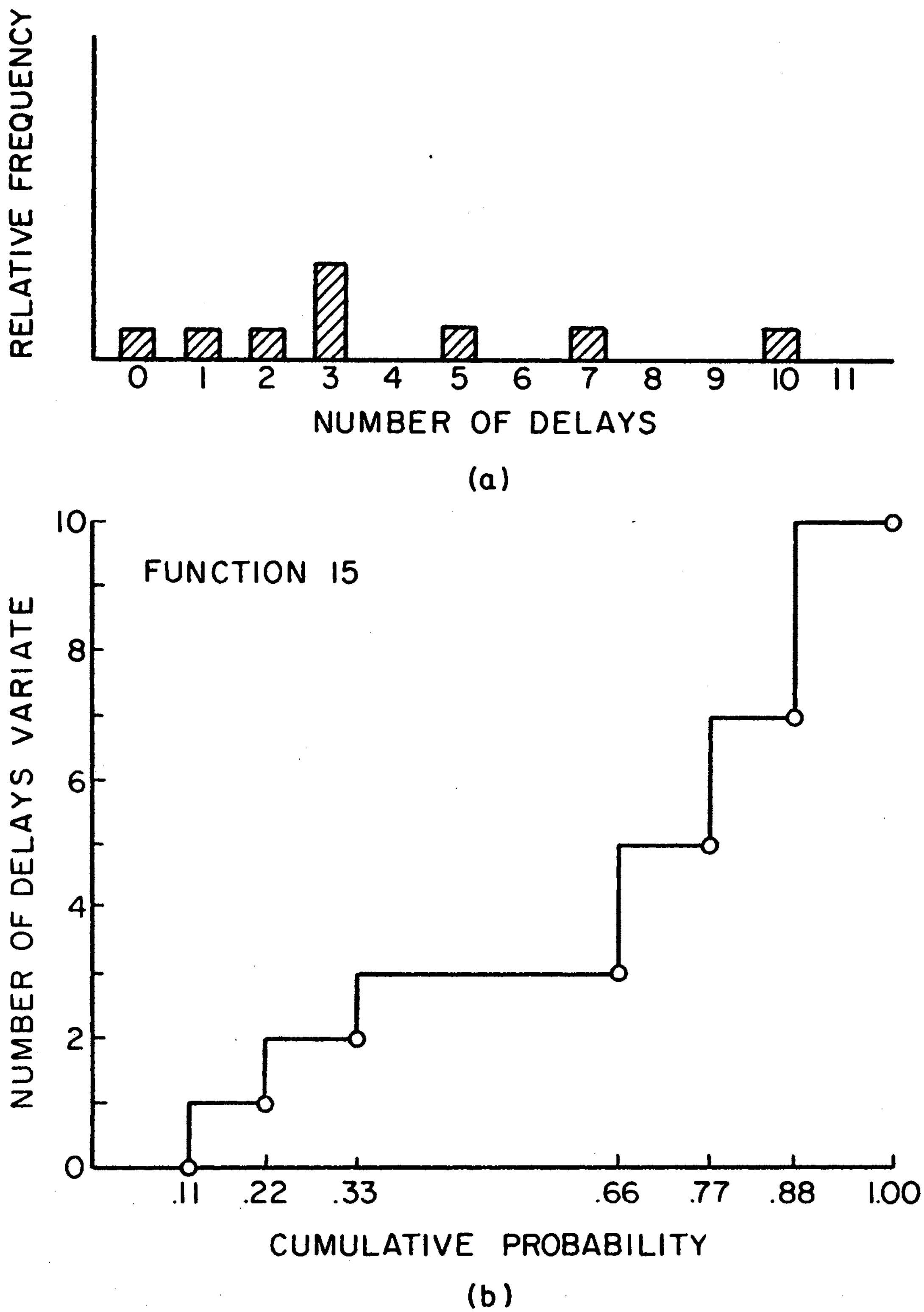


Figure 29. Number of Personal Delays in the Morning Work Session

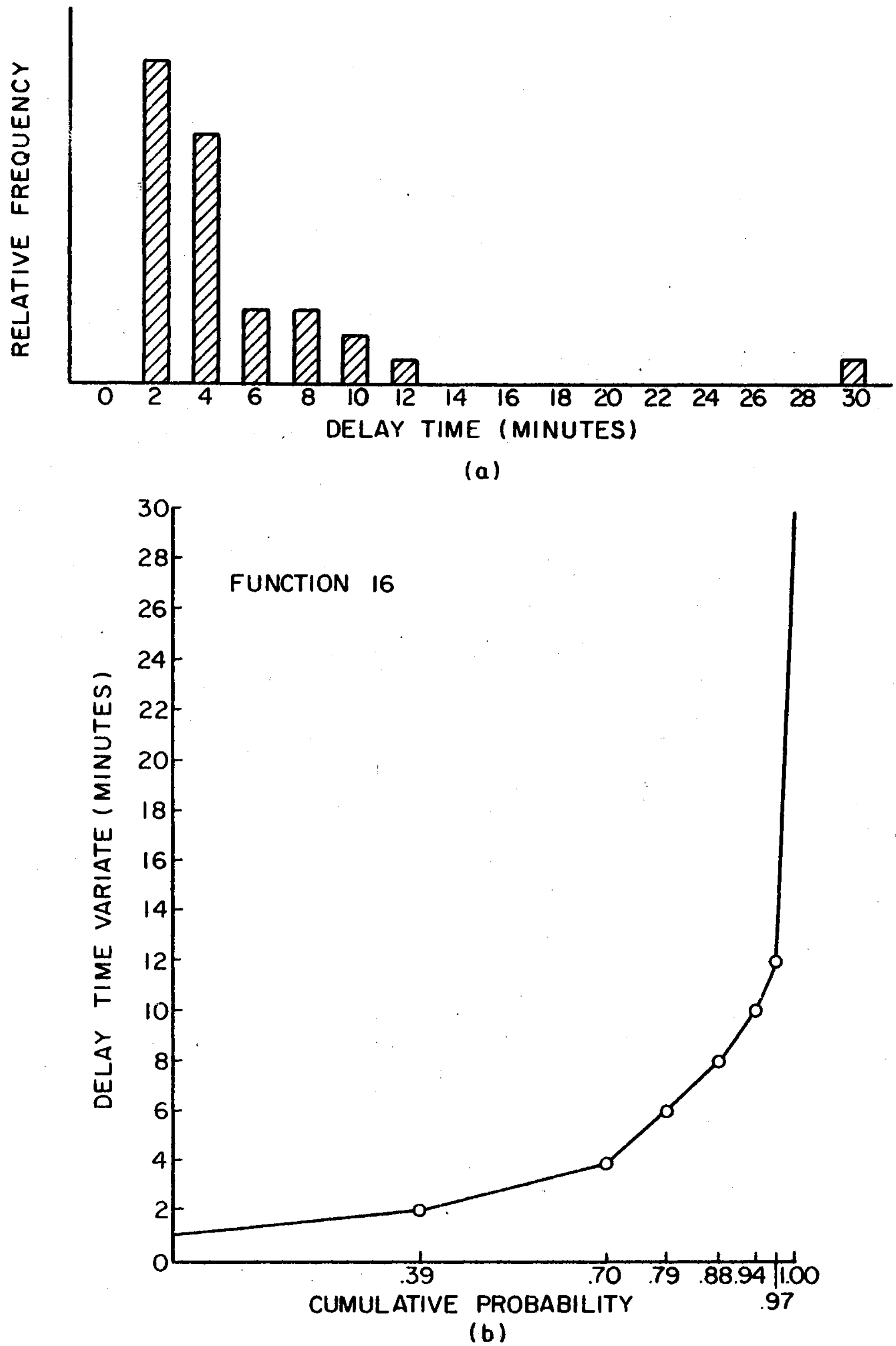


Figure 30. Times for Each Personal Delay During the Morning Work Session

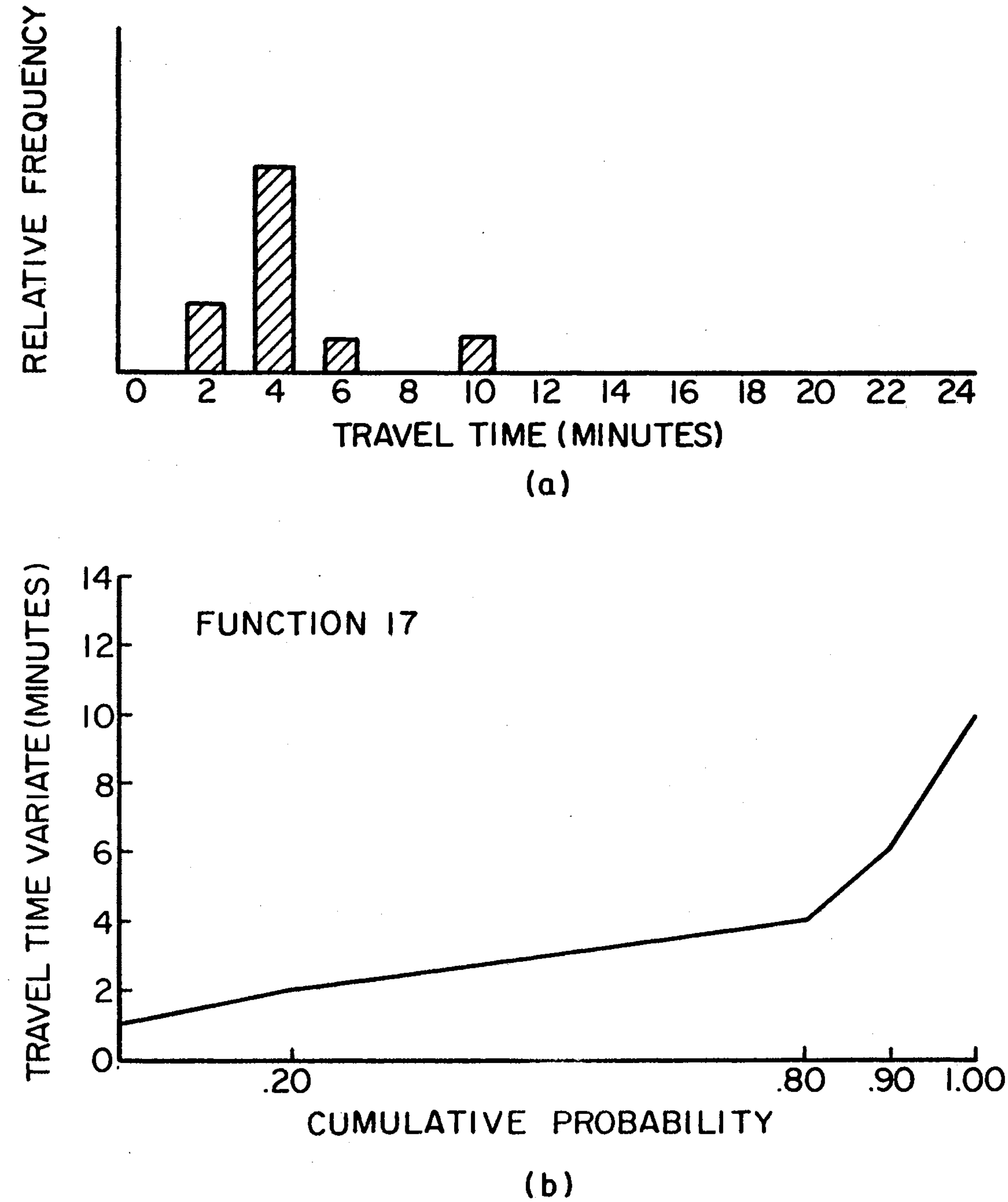
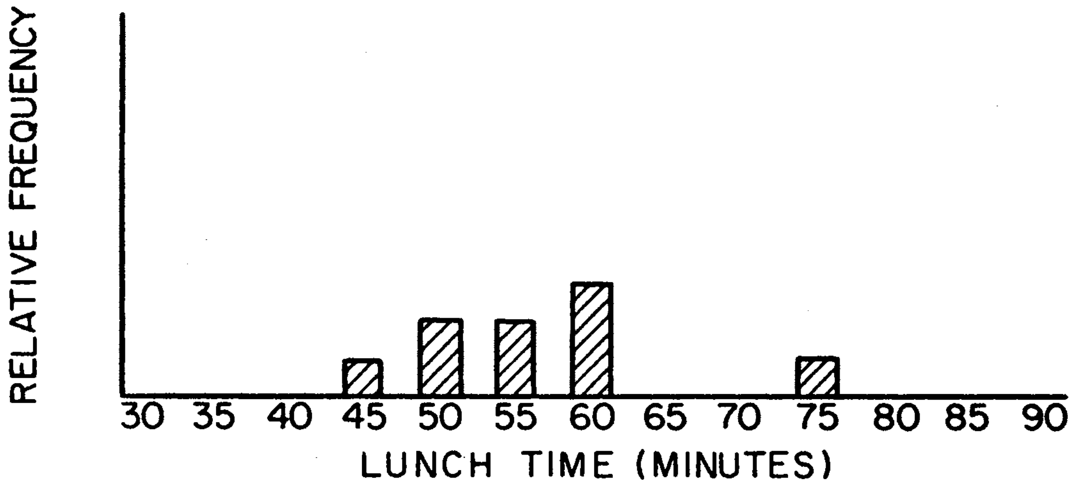
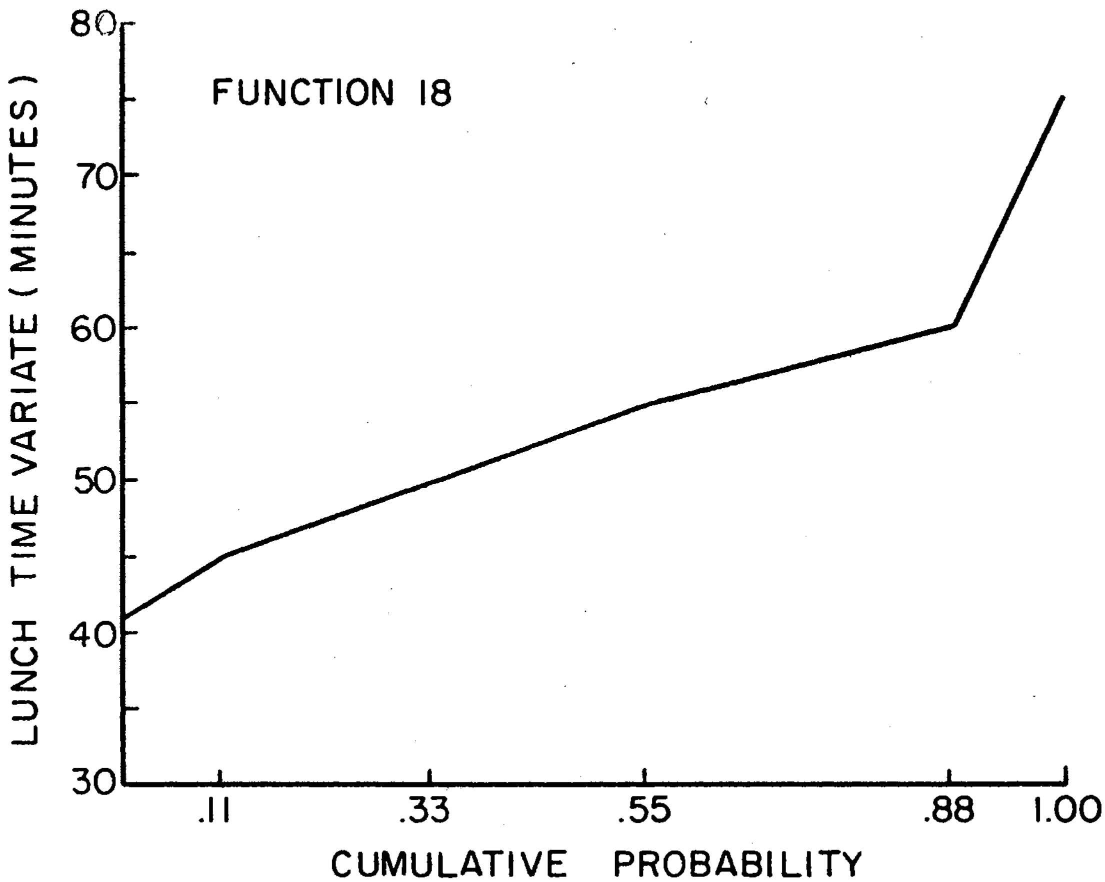


Figure 31. Travel Times From the Work Area to the Truck at Lunch Time



(a)



(b)

Figure 32. Times for Lunch Period

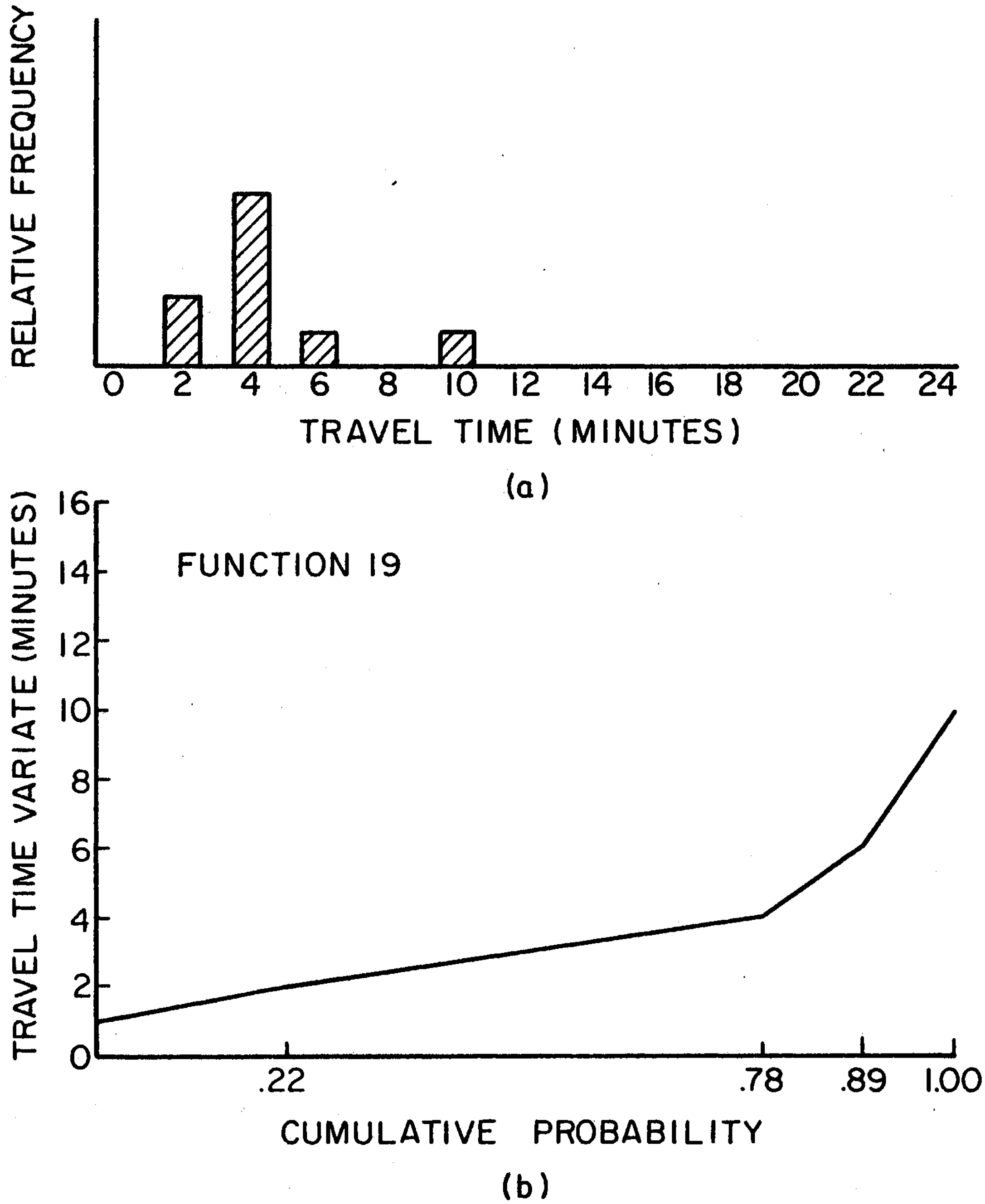


Figure 33. Travel Times From Truck to Work Area at the End of the Lunch Period

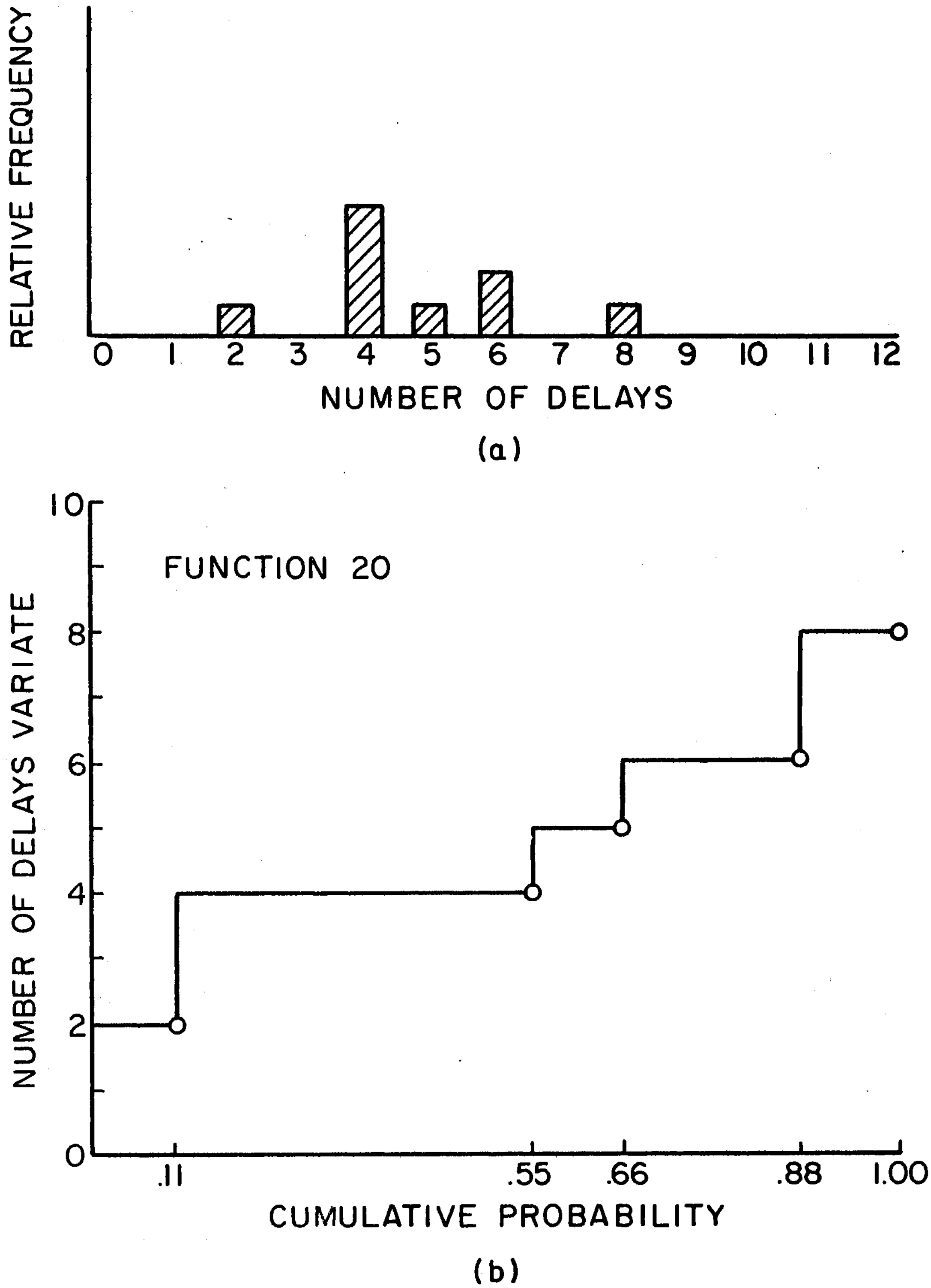


Figure 34. Number of Personal Delays in Afternoon Work Session

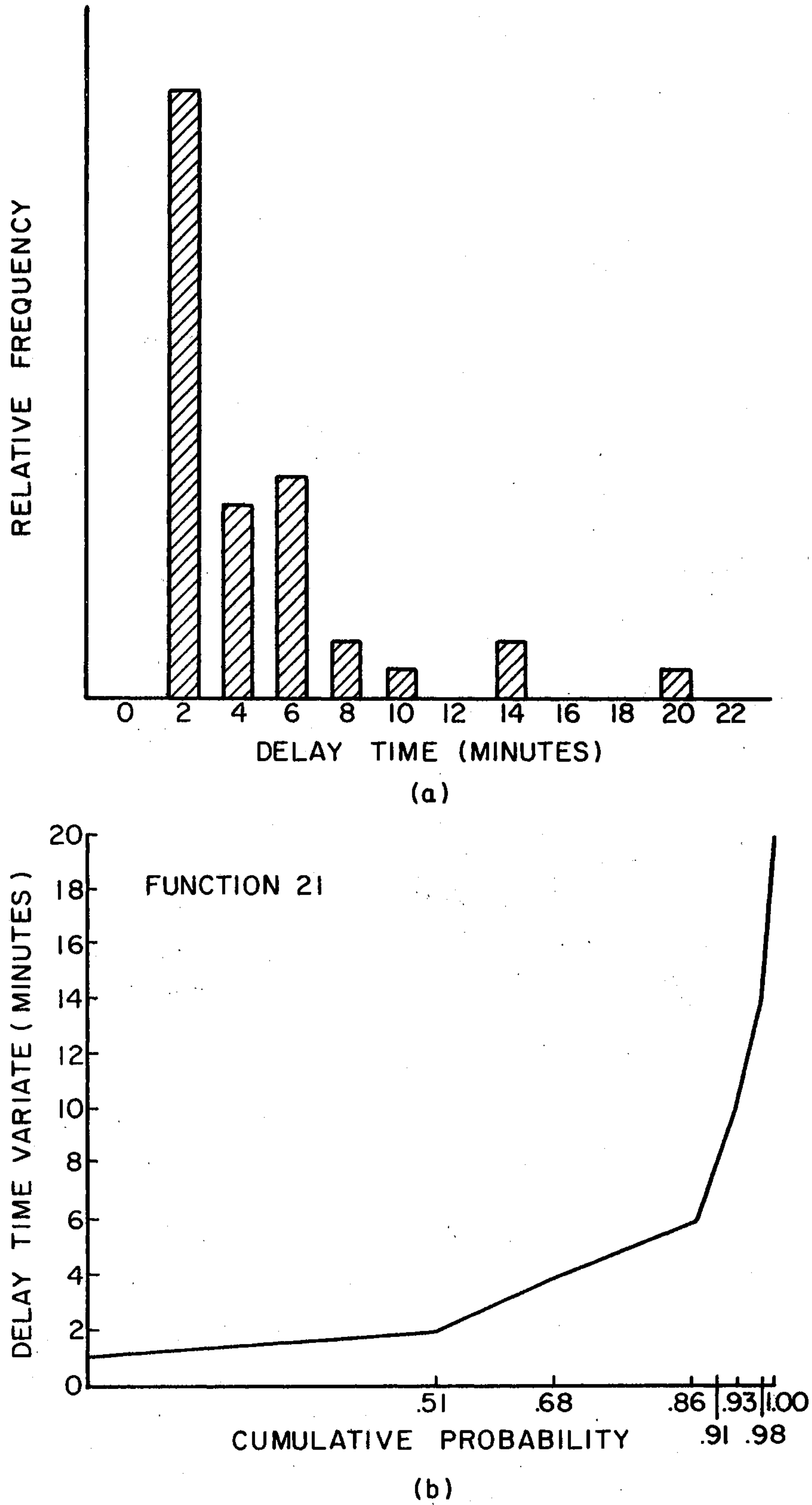
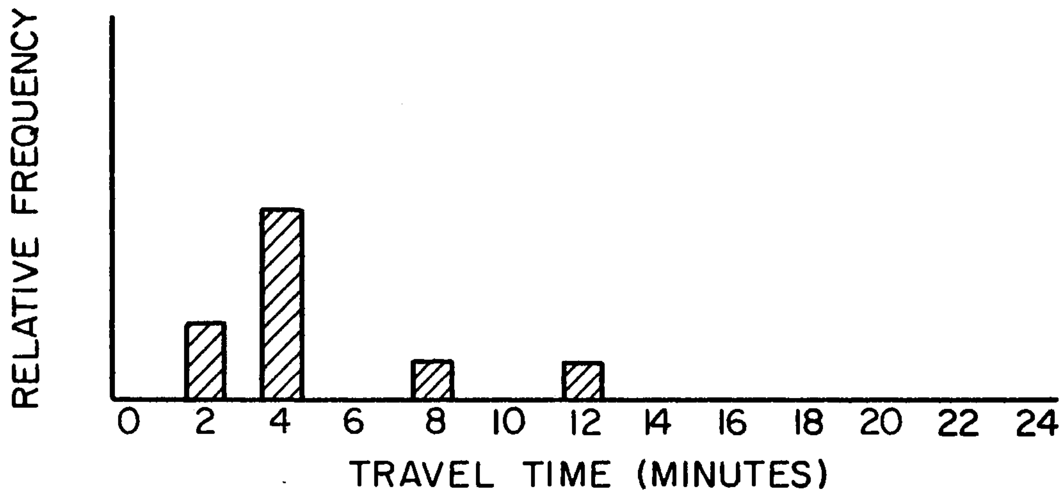
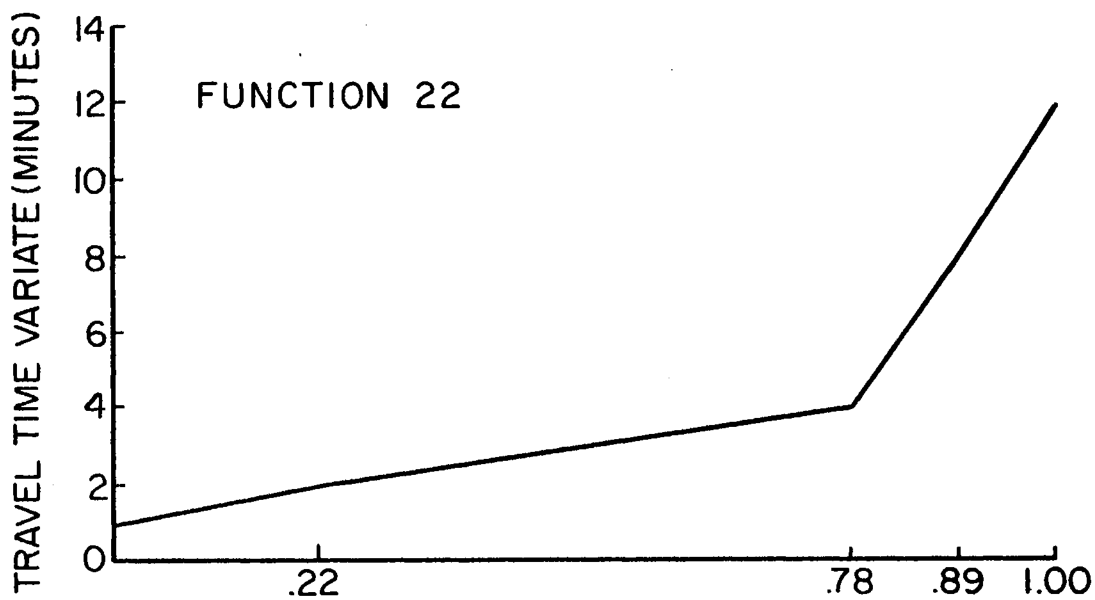


Figure 35. Times for Each Personal Delay During the Afternoon Work Session

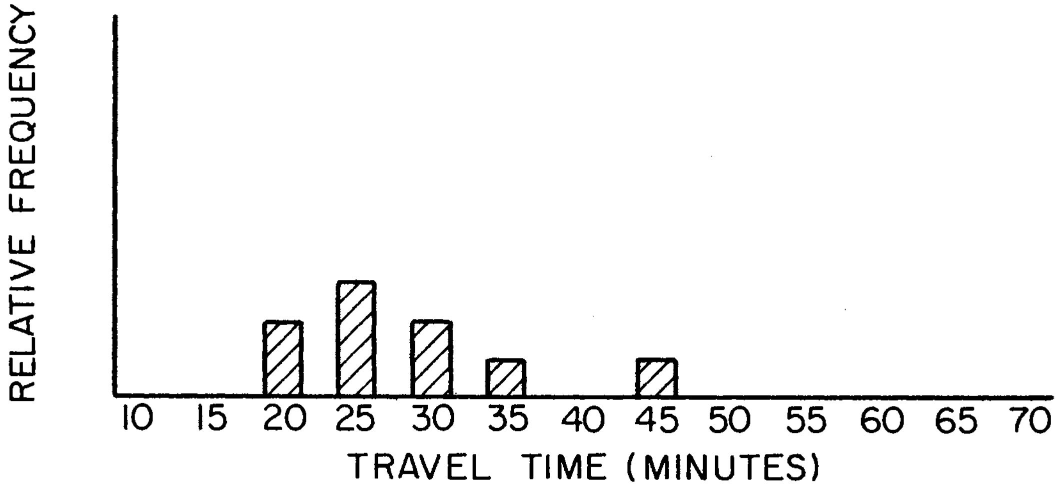


(a)

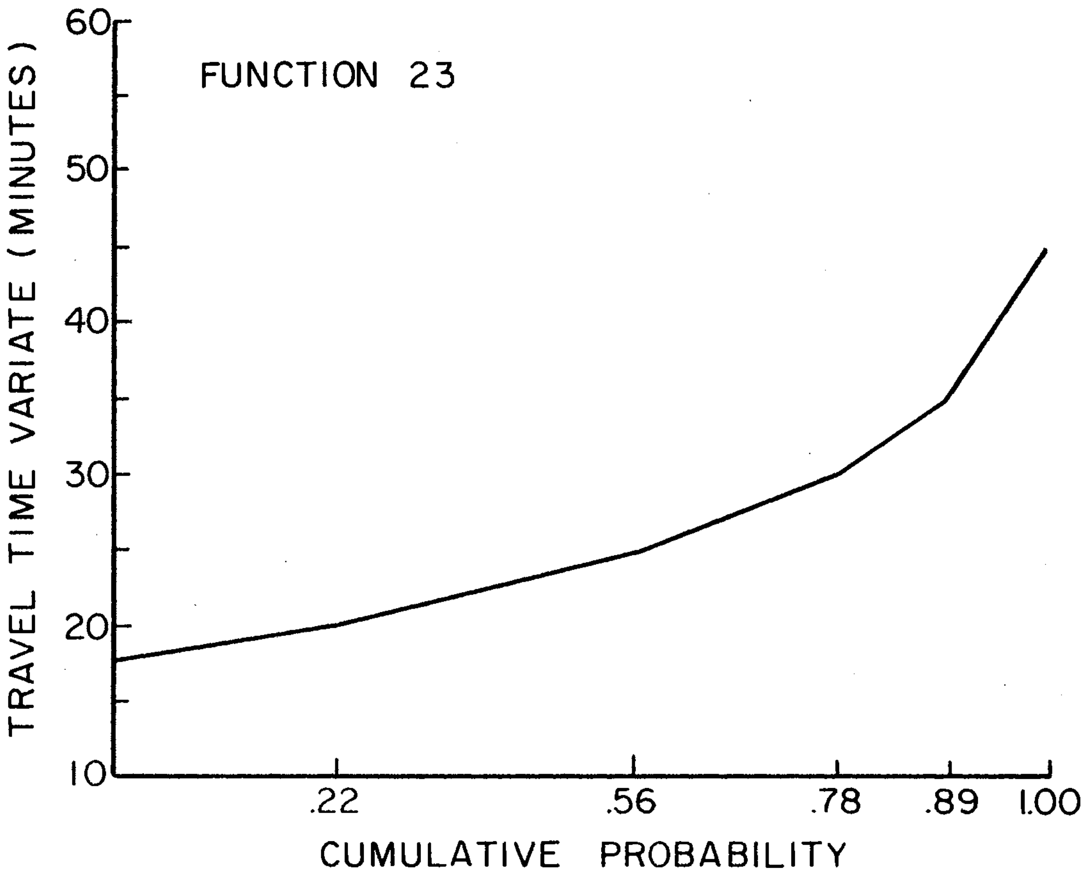


(b)

Figure 36. Travel Times From the Work Area to the Truck at the End of the Afternoon Work Session



(a)



(b)

Figure 37. Travel Times From the Field to Division Headquarters at the End of the Work Day

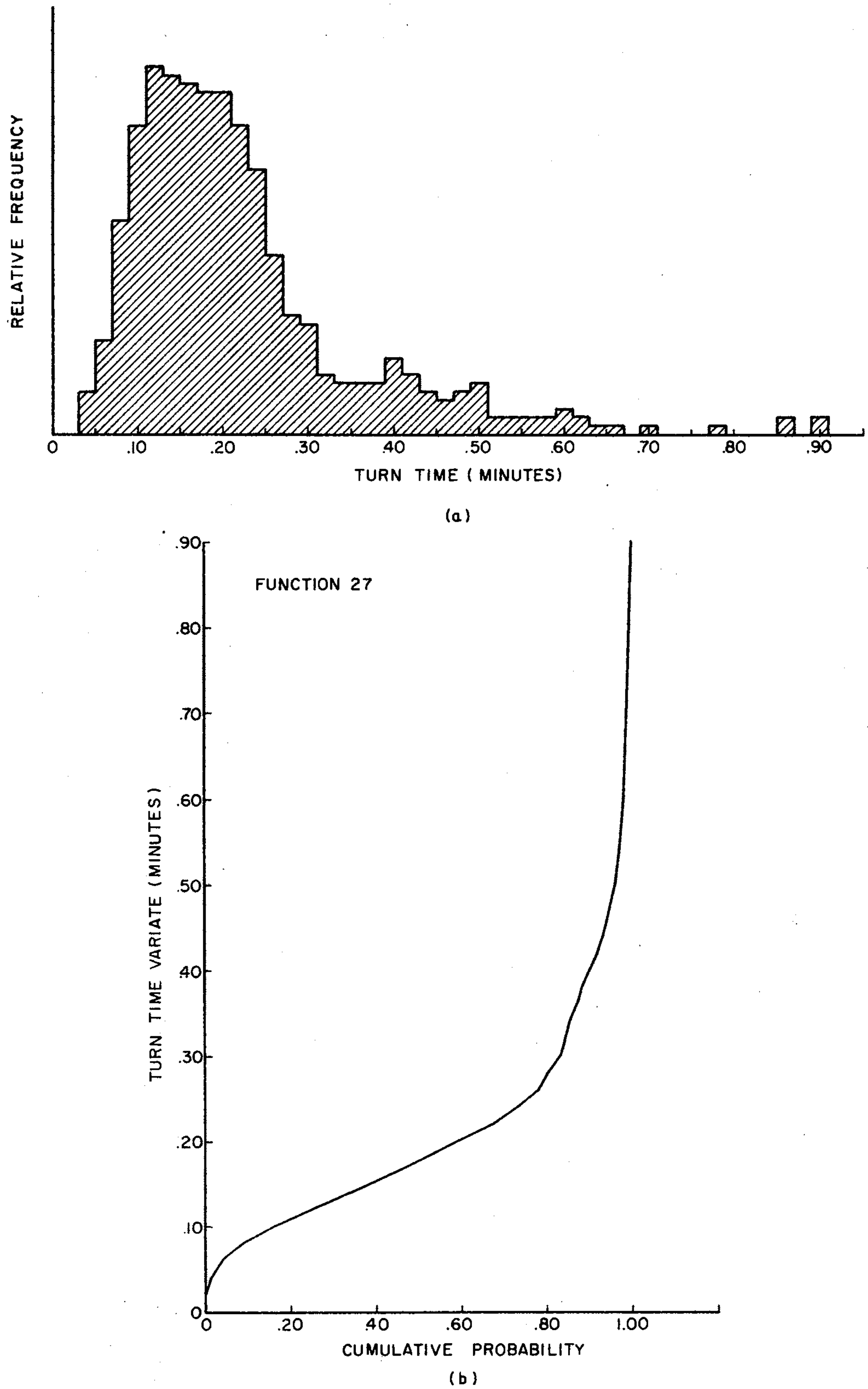


Figure 38. Turn Times for the Flail Type Mower

APPENDIX E

HISTOGRAMS AND CUMULATIVE PROBABILITY DISTRIBUTIONS OF HOURLY OPERATING COSTS OF FLAIL MOWERS, TRACTORS, AND TRUCKS

TABLE XIV

FUNCTIONS - HOURLY COSTS OF EQUIPMENT
(Means and Standard Deviations)

Function	Mean	Std. Dev.
7	1.08 $/hr	0.80 $/hr
8	0.80 $/hr	0.69 $/hr
26	1.46 $/hr	0.95 $/hr

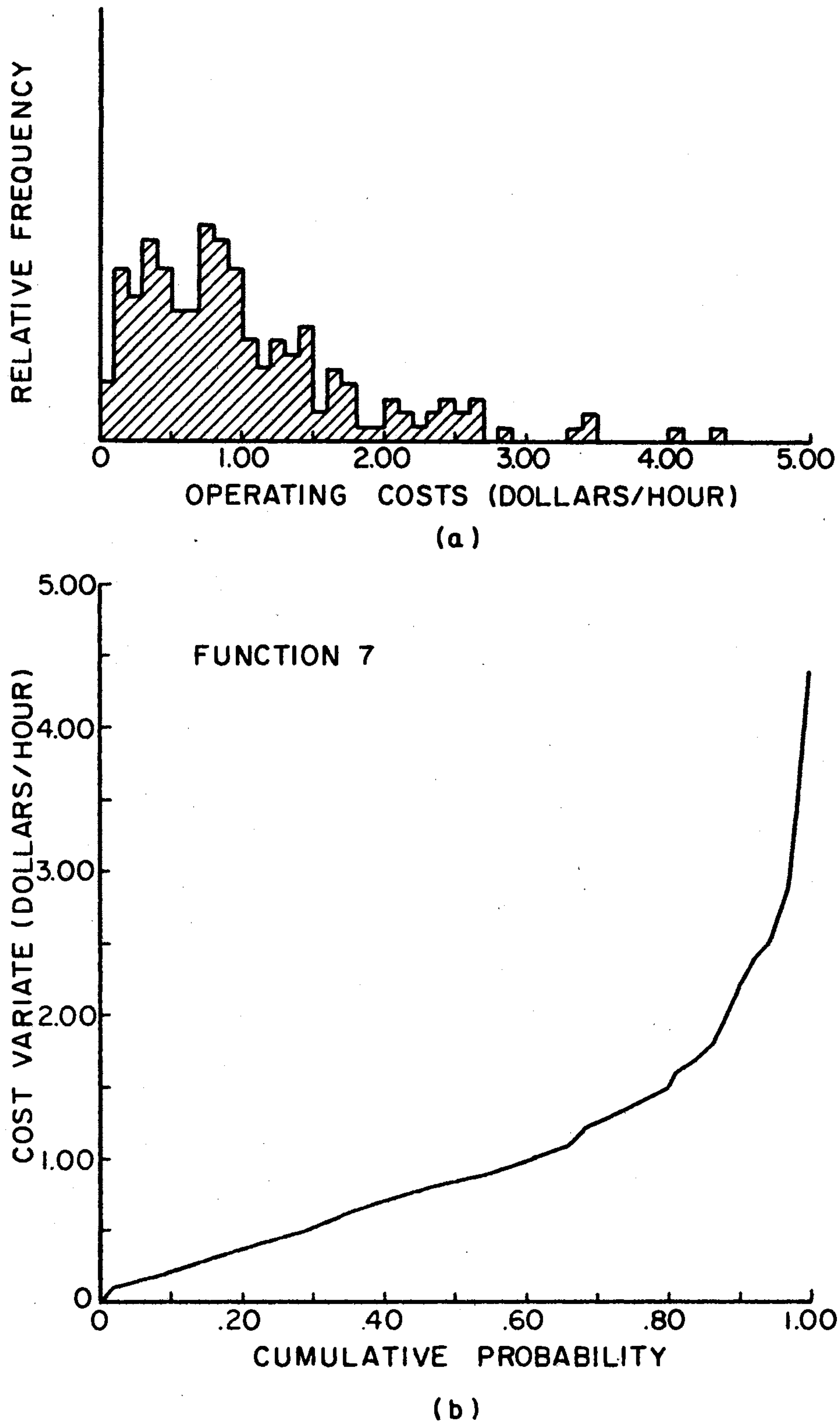


Figure 39. Hourly Operating Costs for a Flail Type Mower

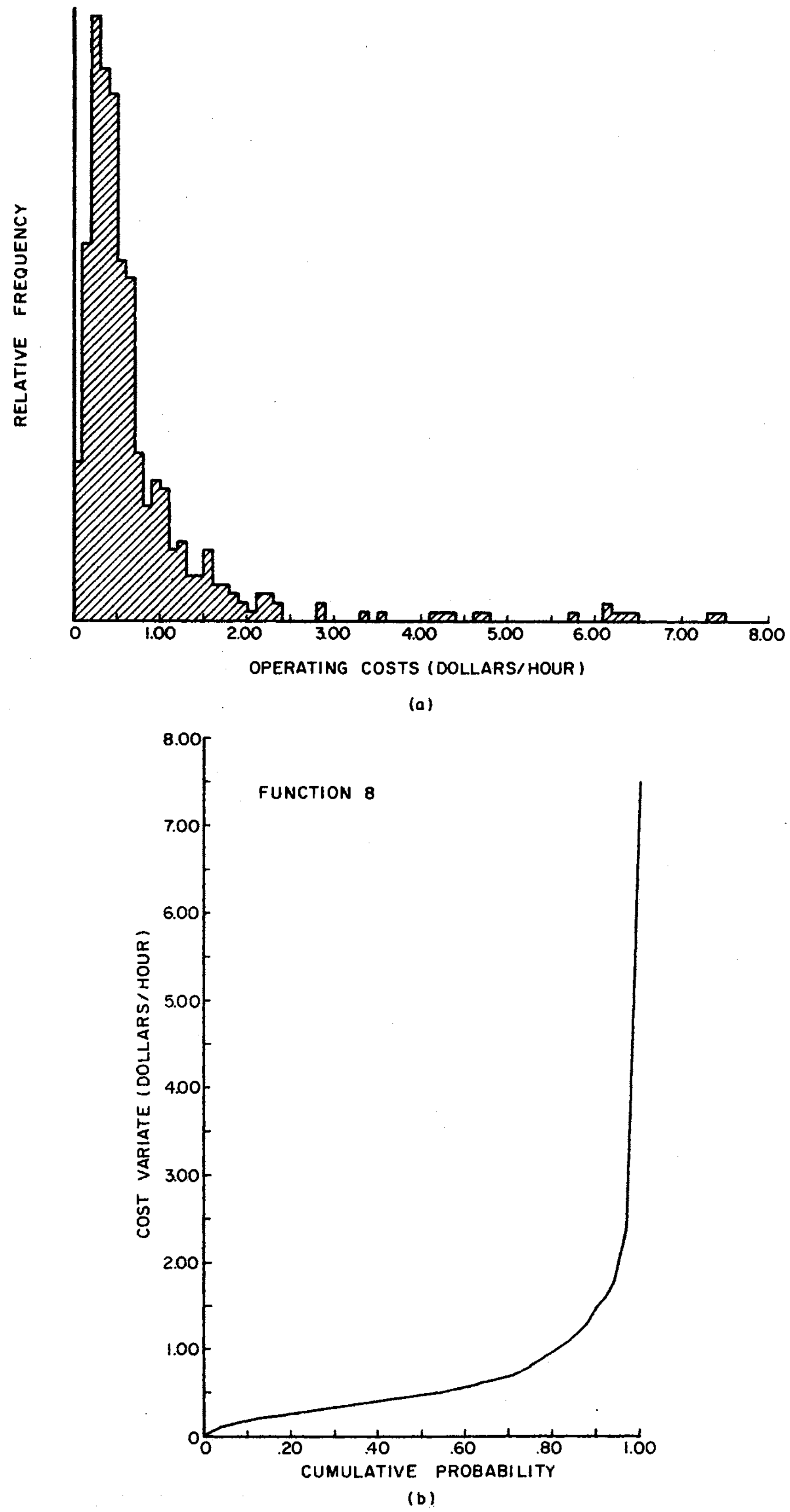


Figure 40. Hourly Operating Costs for Tractors

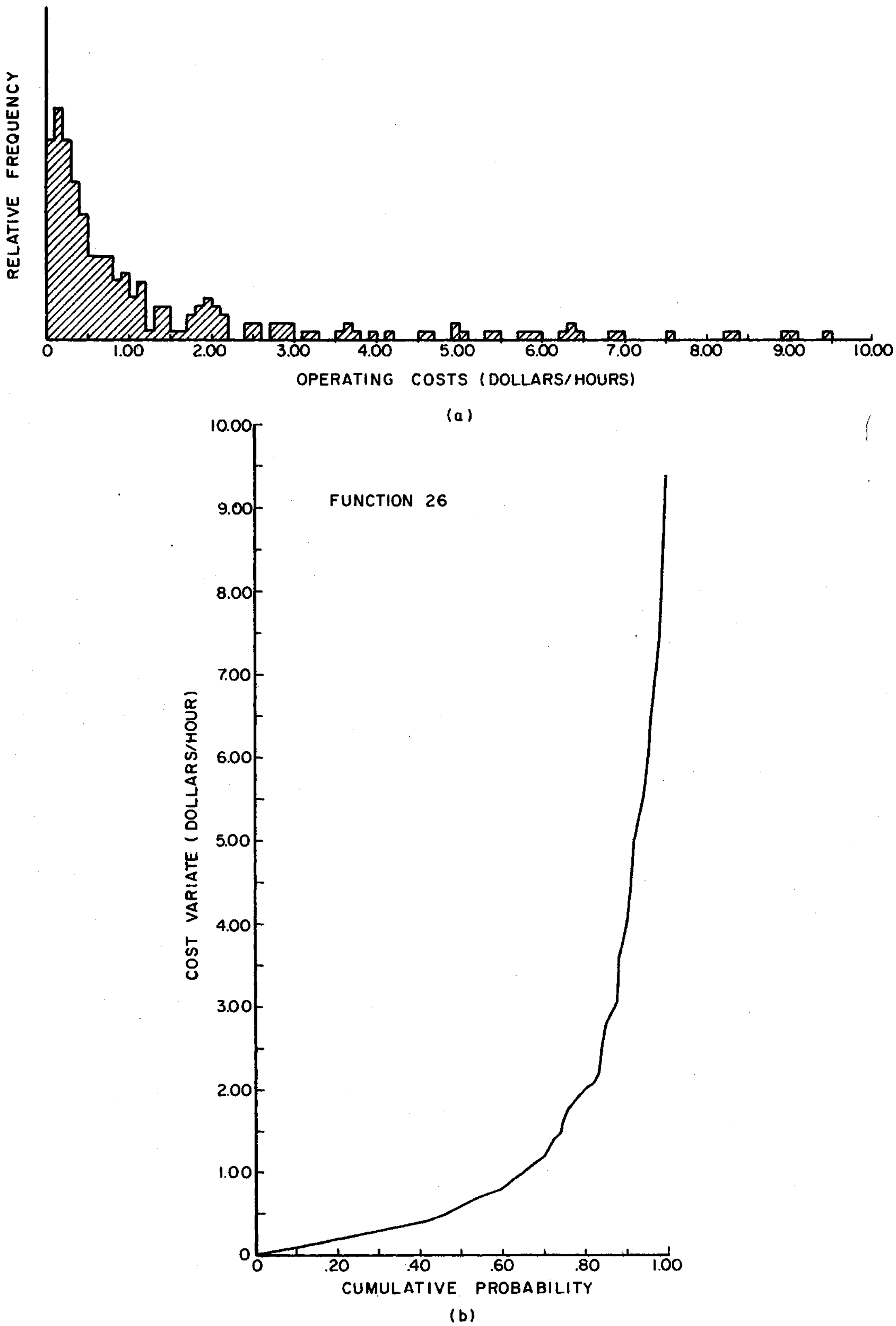


Figure 41. Hourly Operating Costs for Trucks

TABLE XV

FLAIL MOWER OPERATING COSTS
(Dollars/hour)

Year	Equipment Number	Month				
		May	June	July	August	September
		Pennsylvania Turnpike				
1968	36-039	0.24	0.71	0.36	0.20	0.28
1969		0.41	0.76	0.17	0.33	0.48
1968	36-049	1.45	1.24	2.70	0.91	0.74
1969		1.31	3.38	1.54	1.33	1.37
1968	36-059	1.05	1.00	0.92	0.86	0.46
1969		.40	1.56	1.33	0.82	0.66
1968	36-067	0.39	0.35	0.24	0.20	0.17
1969		0.46	0.36	0.51	0.39	0.51
1968	36-077	1.03	2.39	0.87	0.49	1.35
1969		0.80	1.72	1.68	3.45	2.11
1968	36-087	1.17	1.34	2.47	1.16	1.02
1969		2.45	1.74	1.41	0.79	2.22
		Delaware State Highway Department				
1968	NM 301	0.39	0.52	0.40	0.38	0.72
1969		1.35	0.71	0.24	0.66	0.35
1968	NM 302	0.93	1.07	0.88	1.53	1.05
1969		1.19	1.00	0.34	0.87	0.47
1968	NM 304	0.31	0.33	0.21	0.34	0.22
1969		0.41	0.29	0.31	0.53	0.38
1968	NM 322	0.72	0.88	0.93	0.80	0.86
1969		1.08	0.73	1.05	0.52	0.98
1968	NM 323	1.70	0.75	0.62	1.43	0.50
1969		3.48	1.02	1.08	0.88	0.52
1968	NM 386	0.47	0.38	0.34	0.48	-
1969		0.40	0.14	0.27	0.32	0.47
1968	NM 387	1.19	1.46	1.71	0.83	0.51
1969		1.56	0.68	1.48	0.94	1.70
1968	NM 395	0.81	1.30	0.77	0.80	0.92
1969		2.68	1.35	0.83	0.78	2.08
1968	NM 396	1.73	0.88	0.92	0.48	0.81
1969		4.40	1.81	0.87	1.00	0.75

TABLE XV (Continued)

Year	Equipment Number	Month				
		May	June	July	August	September
		Delaware State Highway Department				
1968	TPM 18	0.48	0.40	1.75	0.54	0.15
1969		2.10	0.37	0.22	0.46	0.38
1968	TPM 19	1.37	0.88	0.93	1.51	-
1969		2.43	0.40	0.25	0.78	0.22
1968	TPM 20	0.79	2.14	0.51	0.82	0.66
1969		1.70	0.82	0.57	1.04	1.27

TABLE XVI

TRACTOR OPERATING COSTS
(Dollars/hour)

Year	Equipment Number	Month				
		May	June	July	August	September
		Delaware State Highway Department				
1968	NM 186	1.07	0.58	0.96	0.72	0.73
1969		0.56	0.68	0.88	0.58	0.43
1968	NM 187	1.00	0.47	0.32	0.25	0.35
1969		1.03	0.34	0.40	0.29	0.42
1968	NM 195	0.71	0.75	1.03	0.24	0.33
1969		4.84	0.50	0.24	0.94	0.44
1968	NM 196	1.21	0.96	0.65	1.64	0.75
1969		1.27	0.64	1.34	1.04	1.43
1968	NM 198	6.26	2.31	0.85	0.40	0.29
1969		1.56	0.69	0.60	0.59	0.74
1968	NM 201	3.30	0.22	0.31	0.21	0.24
1969		2.40	0.34	0.54	0.14	0.32
1968	NM 202	0.93	0.31	1.60	0.43	0.52
1969		1.54	0.35	0.90	1.12	1.10
1968	NM 204	1.75	1.07	0.53	0.47	0.38
1969		1.29	1.18	0.50	1.26	0.78
1968	NM 220	0.30	0.33	0.58	3.54	0.27
1969		0.42	0.91	3.40	0.26	0.49
1968	TPM 18	0.26	0.14	0.29	0.17	0.22
1969		1.93	0.33	0.61	0.28	0.35
1968	TPM 19	0.11	0.16	0.22	0.28	1.15
1969		2.94	0.38	0.28	0.21	0.18
		Oklahoma Department of Highways				
1968	82-408	0.24	0.16	0.45	0.22	0.14
1969		0.39	0.22	0.12	1.84	0.95
1968	82-410	1.11	0.96	0.68	0.54	0.56
1969		0.80	0.58	0.44	3.44	1.84
1968	82-411	0.57	0.49	0.20	0.25	0.55
1969		0.53	0.48	0.23	0.70	0.66
1968	82-412	0.72	0.65	0.44	0.25	0.34
1969		1.14	0.96	0.47	0.73	6.23

TABLE XVI (Continued)

Year	Equipment Number	Month				
		May	June	July	August	September
		Oklahoma Department of Highways				
1968	82-413	0.66	0.42	0.59	0.26	0.21
1969		0.58	5.82	2.28	1.27	1.11
1968	82-414	0.45	1.06	0.89	0.43	0.38
1969		1.14	0.84	0.58	0.47	0.25
1968	82-415	0.53	0.47	0.26	1.20	0.93
1969		0.71	0.53	0.31	0.25	4.69
1968	82-416	0.56	0.32	0.58	0.22	0.29
1969		0.44	1.64	0.97	0.67	0.44
1968	82-417	0.68	0.22	0.19	0.49	0.32
1969		1.02	0.52	0.26	4.26	1.14
1968	82-418	0.27	0.31	0.63	0.42	0.14
1969		0.35	7.04	2.26	1.05	0.63
1968	82-419	0.39	0.23	0.37	0.47	0.20
1969		0.67	0.21	0.16	0.81	3.59
1968	82-446	0.46	0.21	0.12	0.30	0.34
1969		0.52	6.28	1.43	0.68	0.43
1968	82-447	0.12	0.22	0.44	0.11	0.54
1969		0.35	0.14	1.81	0.80	0.42
1968	82-448	0.15	0.25	0.14	0.32	0.24
1969		1.72	0.86	0.40	0.17	0.14
1968	82-507	1.44	0.54	0.32	0.28	0.76
1969		4.24	2.07	1.04	0.54	0.85
1968	82-508	1.11	0.33	0.42	2.91	0.69
1969		0.53	0.84	2.23	0.41	0.24
1968	82-509	1.06	0.41	0.37	0.23	0.17
1969		0.83	0.68	1.01	0.44	0.31
1968	82-510	6.40	1.95	0.52	0.68	0.92
1969		0.64	0.55	0.67	1.21	0.39
1968	82-600	0.86	1.13	0.25	0.29	0.41
1969		1.31	0.74	0.53	0.41	0.31
1968	82-601	0.68	0.50	0.59	0.27	0.80
1969		0.61	1.17	0.40	0.33	0.46
1968	82-602	0.87	0.20	0.64	0.17	0.74
1969		0.68	1.03	0.58	0.38	1.27

TABLE XVI (Continued)

Year	Equipment Number	Month				
		May	June	July	August	September
		Oklahoma Department of Highways				
1968	82-603	0.24	0.42	1.84	0.68	0.54
1969		1.58	0.37	7.41	4.42	1.68
1968	82-604	0.50	0.57	0.32	0.15	0.75
1969		0.93	0.20	1.14	0.52	0.70
1968	82-605	0.51	0.60	0.48	0.40	0.59
1969		0.47	1.01	0.37	0.45	2.44
1968	82-606	0.72	0.45	0.86	0.50	0.51
1969		0.64	0.43	0.47	0.74	0.62
1968	82-607	0.54	0.48	0.63	0.39	0.46
1969		1.07	0.76	0.65	0.48	1.36
1968	82-608	0.56	0.70	0.27	0.54	0.18
1969		1.23	0.57	0.39	0.25	0.35
1968	82-609	0.65	0.34	0.47	0.32	0.39
1969		1.44	0.80	0.59	0.56	0.34
1968	82-610	0.94	0.34	0.81	0.38	0.18
1969		1.33	0.58	0.41	1.35	1.02
1968	82-611	0.59	0.34	0.81	0.38	0.18
1969		1.33	0.58	0.41	1.35	1.02
1968	82-612	0.62	0.61	0.39	0.45	0.76
1969		1.86	0.67	0.73	0.72	0.47
1968	82-613	1.25	0.64	0.33	1.11	0.62
1969		1.76	0.65	1.21	0.88	0.56
1968	82-614	0.93	1.23	0.43	0.17	0.34
1969		1.54	0.51	0.14	0.91	0.51
1968	82-615	0.73	0.27	0.38	0.23	0.34
1969		1.93	0.50	0.69	0.32	0.63
1968	82-616	3.44	0.60	0.27	0.28	0.34
1969		2.01	0.65	0.58	0.22	0.26
1968	82-617	1.67	0.85	0.45	0.40	0.47
1969		7.53	2.90	1.55	0.86	0.49

TABLE XVII

TRUCK OPERATING COSTS
(Dollars/hour)

Year	Equipment Number	Month				
		May	June	July	August	September
		Oklahoma State Highway Department				
1968	77-0070	0.97	1.09	0.67	0.87	1.43
1969		2.03	0.53	0.81	0.66	0.85
1968	77-0071	0.79	2.20	0.33	0.63	0.10
1969		1.06	0.23	0.40	3.66	0.34
1968	77-0072	0.54	0.68	6.22	1.45	0.79
1969		1.25	0.37	0.93	0.39	0.42
1968	77-0082	0.38	0.48	1.92	0.69	0.96
1969		0.52	0.80	0.67	1.37	0.86
1968	77-0083	0.23	0.39	0.08	0.52	5.85
1969		0.34	0.23	9.06	2.28	0.54
1968	77-0087	0.22	0.12	5.18	2.10	1.38
1969		1.22	0.30	0.14	0.95	7.62
1968	77-0088	0.38	6.32	1.38	0.29	0.20
1969		0.22	2.47	0.10	0.34	0.41
1968	77-0089	0.27	0.33	0.26	0.93	1.17
1969		0.29	2.11	0.38	1.52	0.43
1968	77-0090	0.78	8.35	2.24	0.97	0.67
1969		1.16	0.50	0.90	0.66	3.97
1968	77-0091	0.09	0.43	0.27	3.29	0.12
1969		0.29	2.50	0.61	0.80	0.21
1968	77-0101	0.63	0.36	0.44	4.16	0.27
1969		3.56	0.21	2.15	0.29	0.10
1968	77-0112	5.77	1.60	0.48	0.72	0.55
1969		0.19	5.41	0.58	0.54	0.29
1968	77-0122	0.42	0.17	0.83	8.28	0.20
1969		0.65	0.24	4.43	0.83	1.12
1968	77-0123	0.48	0.11	0.63	3.73	0.25
1969		1.50	0.72	0.43	0.37	2.04
1968	77-0124	0.86	0.20	3.78	1.12	0.17
1969		2.09	0.18	1.04	1.20	0.27
1968	77-0125	0.40	1.19	0.56	6.92	1.46
1969		1.76	0.44	5.95	1.37	0.56

TABLE XVII (Continued)

Year	Equipment Number	Month				
		May	June	July	August	September
		Oklahoma State Highway Department				
1968	77-0126	0.16	0.23	0.15	1.73	0.51
1969		4.64	0.29	0.20	0.47	0.27
1968	77-0127	1.97	0.57	0.40	0.98	2.95
1969		5.05	1.14	0.30	0.34	0.33
1968	77-0128	0.31	1.87	0.91	3.22	1.90
1969		1.14	0.55	4.72	1.48	1.02
1968	77-0129	6.44	1.14	0.79	1.12	0.45
1969		2.04	0.97	1.81	0.53	0.58
1968	77-0160	0.25	2.64	0.21	0.15	9.37
1969		2.93	1.06	0.27	5.01	2.14
1968	77-0162	1.58	0.20	6.97	1.17	2.97
1969		0.14	1.51	0.29	2.75	0.48
1968	77-0185	1.04	0.24	0.15	5.31	0.76
1969		2.90	0.21	0.29	1.19	0.36
1968	77-0186	0.54	1.96	0.22	0.31	1.18
1969		1.87	0.55	5.02	1.15	0.38

APPENDIX F

RANDOM NUMBERS GENERATED FOR THE RAINFALL

PROBABILITY FUNCTION 25

TABLE XVIII

RANDOM NUMBERS GENERATED FOR THE RAINFALL PROBABILITY FUNCTION 25

Sample	Observation 1 Cycle												Observation 2 Cycle												Observation 3 Cycle												Observation 4 Cycle											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	4	60	74	73	9	29	17	57	67	24	42	80	88	54	43	44	80	20	30	76	32	4	7	82	38	41	31	25	80	13	11	66	48	77	34	37	99	42	52	89	91	33	14	72	84	62	88	82
2	0	34	6	4	32	20	9	42	15	5	9	77	8	3	83	45	97	96	57	55	73	30	81	32	43	91	28	35	18	78	73	38	30	75	28	43	92	32	98	49	69	69	79	15	3	5	50	86
3	3	17	9	49	89	97	43	12	9	3	15	51	60	60	86	72	77	31	29	57	69	98	74	54	46	4	89	69	40	5	26	77	13	14	54	95	0	19	37	11	74	86	43	2	50	57	15	82
4	0	83	15	82	1	15	0	13	68	39	17	75	70	2	18	22	1	74	86	17	36	93	48	84	65	36	42	93	48	28	76	2	19	69	0	75	74	15	4	38	29	66	45	96	28	84	3	62
5	3	94	84	86	79	88	14	69	43	60	78	30	96	76	9	38	46	93	4	9	48	39	54	46	73	15	49	24	35	8	14	54	27	95	14	78	54	16	39	28	88	75	55	50	89	9	26	5

Sample	Observation 5												Observation 6												Observation 7												Observation 8											
1	75	48	54	35	81	48	35	51	72	6	43	12	56	18	72	6	35	70	66	3	56	46	88	40	64	60	29	12	74	77	5	68	72	4	17	35	27	73	70	8	17	24	97	79	10	28	82	45
2	89	72	9	74	82	3	40	88	35	91	15	22	37	40	79	83	74	97	92	75	84	30	51	24	3	77	28	86	15	35	98	23	61	7	93	75	6	76	48	65	37	54	71	17	48	48	7	4
3	5	71	26	71	7	90	79	81	52	27	41	91	15	7	11	92	78	75	84	32	3	68	50	99	12	17	97	42	17	7	11	75	41	39	83	17	36	29	37	74	71	35	87	70	16	93	79	41
4	48	23	4	87	56	4	79	77	67	75	2	82	59	1	31	41	50	43	40	64	10	42	54	45	16	2	44	8	46	99	49	29	81	14	80	85	57	74	79	6	47	57	1	78	43	17	49	5
5	2	86	8	50	5	82	6	34	26	77	39	56	86	40	84	30	11	78	55	8	33	9	42	94	5	11	94	48	10	83	36	48	3	59	51	60	29	37	72	60	11	55	58	57	24	67	78	6

Sample	Observation 9												Observation 10												Observation 11												Observation 12											
1	65	21	45	39	44	71	96	46	34	73	16	66	5	39	21	33	96	71	61	43	63	32	78	28	32	5	95	44	64	24	70	91	57	97	49	10	59	11	46	90	96	7	67	97	28	8	86	92
2	16	10	48	55	76	58	78	91	20	29	26	68	65	18	48	11	16	25	63	53	14	40	74	2	35	77	21	72	68	5	25	22	82	90	57	28	5	7	1	32	97	85	22	51	91	76	70	20
3	49	8	5	93	79	41	85	21	28	58	78	74	94	26	22	46	63	92	74	58	16	84	52	77	3	14	75	58	13	89	37	92	38	73	97	14	16	57	9	98	49	30	72	69	76	67	25	4
4	77	60	28	14	82	45	65	73	61	40	25	27	22	70	41	51	58	36	3	0	34	1	94	44	30	9	6	94	41	69	86	49	43	37	56	89	52	97	32	67	61	52	2	68	57	22	66	26
5	10	38	12	31	16	84	62	11	43	23	87	14	62	67	74	92	54	39	52	90	24	12	3	23	37	67	47	5	19	30	40	85	22	55	52	64	66	55	20	34	72	88	86	98	16	29	52	50

Sample	Observation 13												Observation 14												Observation 15												Observation 16											
1	1	36	4	32	44	16	27	55	38	45	41	94	5	70	42	59	60	57	62	88	8	65	97	95	12	14	17	40	7	5	83	10	43	79	97	12	52	39	75	88	33	51	23	25	76	27	72	44
2	25	49	77	5	88	3	50	65	98	63	35	50	45	30	57	4	68	77	7	85	46	52	15	26	43	86	59	12	53	66	15	58	76	42	59	36	75	42	61	16	45	36	46	41	51	87	21	75
3	9	38	62	8	86	99	16	42	75	30	45	98	51	47	36	44	99	88	64	12	73	89	46	22	95	57	90	53	46	27	73	17	98	31	80	76	23	96	21	98	91	52	34	83	83	76	25	51
4	84	93	86	22	1	8	82	32	6	24	40	40	74	46	26	12	48	4	97	41	61	6	60	4	33	20	82	76	31	77	43	82	24	22	1	97	54	19	17	54	11	78	96	90	44	91	8	73
5	53	20	85	60	87	90	89	34	9	97	13	74	23	52	57	52	5	27	81	63	65	42	50	79	48	30	15	21	16	87	50	74	75	78	66	90	95	37	68	41	23	41	30	82	10	87	95	6

Sample	Observation 17												Observation 18												Observation 19												Observation 20											
1	24	92	53	34	62	3	56	6	57	42	73	94	64	64	27	12	35	7	16	53	98	58	20	15	97	60	39	79	14	96	37	62	56	6	5	90	25	36	80	36	98	64	27	98	14	83	85	15
2	70	47	7	76	23	60	16	94	10	68	3	95	68	99	61	5	24	75	84	94	75	85	80	76	43	13	67	81	42	38	68	11	84	65	9	81	35	45	42	40	33	10	58	56	20	25	5	96
3	76	75	88	12	73	18	57	72	26	11	44	20	6	15	7	18	52	65	54	67	93	41	72	84	65	9	12	90	69	43	76	80	94	75	83	94	5	6	56	90	64	35	88	4	76	55	12	40
4	39	84	96	51	80	38	96	20	49	22	14	2	99	37	17	14	28	62	15	63	20	73	96	70	23	77	18	66	31	92	40	64	87	16	48	97	40	18	15	71	31	59	43	36	24	79	42	55
5	31	94	38	10	99	68	33	34	74	71	62	44	32	73	7	53	88	22	49	65	40	23	57	55	79	40	29	10	66	58	88	4	76	40	64	58	9	44	35	54	65	72	75	30	8	54	18	25

APPENDIX G

PROJECT TIMES, PROJECT COSTS, AND RAINFALL INFORMATION FOR 5 SAMPLES OF THE SOUTHBOUND LANE

TABLE XIX

SOUTHBOUND LANE - 360/75
(Sample 1)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Product Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	2582	43.03	2582	43.03	1.00	1472	24.53
2	3544	59.07	2584	43.07	1.37	1378	22.97
3	3060	51.00	2580	43.00	1.19	1406	23.43
4	3840	64.00	2400	40.00	1.60	1359	22.65
5	3506	58.43	2546	42.43	1.38	1388	23.15
6	2604	43.40	2604	43.40	1.00	1434	23.90
7	2705	45.08	2705	45.08	1.00	1447	24.12
8	2814	46.90	2814	46.90	1.00	1544	25.73
9	2535	42.25	2535	42.25	1.00	1399	23.32
10	3987	66.45	2547	42.45	1.57	1387	23.12
11	2969	49.48	2489	41.48	1.19	1429	23.82
12	4095	68.25	2655	44.25	1.54	1432	23.87
13	2648	44.13	2648	44.14	1.00	1461	24.35
14	2582	43.03	2582	43.03	1.00	1435	23.92
15	2605	43.42	2605	43.41	1.00	1384	23.07
16	3095	51.58	2615	43.58	1.18	1452	24.20
17	3240	54.00	2760	46.00	1.17	1442	24.03
18	2583	43.05	2583	43.05	1.00	1443	24.05
19	3994	66.57	2554	42.56	1.56	1388	23.11
20	4286	71.43	2366	39.43	1.81	1408	23.47
Mean	3164	52.73	2588	43.14	1.23	1424	23.47
Std. Dev.	603	10.05	104	1.74	0.26	42	0.70

TABLE XX

SOUTHBOUND LANE - 360/65
(Sample 2)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	2585	43.08	2585	43.08	1.00	1393	23.22
2	4043	67.38	2603	43.38	1.55	1416	23.60
3	3208	53.47	2728	45.47	1.18	1394	23.23
4	3690	61.50	2730	45.50	1.35	1443	24.05
5	4044	67.40	2604	43.40	1.55	1404	23.40
6	5760+	(Work not completed - 124,166 sq. ft. of Section 36 remains.)					
7	3496	58.26	2536	42.27	1.38	1397	23.28
8	2831	47.18	2831	47.18	1.00	1433	23.88
9	2613	43.55	2613	43.55	1.00	1474	24.57
10	2552	42.53	2552	42.53	1.00	1426	23.77
11	3066	51.10	2586	43.10	1.19	1346	22.43
12	3587	59.78	2627	43.78	1.37	1454	24.23
13	3234	53.90	2754	45.90	1.17	1483	24.72
14	2594	43.23	2594	43.23	1.00	1409	23.48
15	3254	54.23	2774	46.23	1.17	1472	24.53
16	2996	49.93	2516	41.93	1.19	1384	23.07
17	2521	42.01	2521	42.01	1.00	1397	23.28
18	5760+	(Work not completed - 176,462 sq. ft. of Section 36 remains.)					
19	3112	51.86	2631	43.85	1.18	1446	24.10
20	2637	43.87	2632	43.87	1.00	1379	23.28
Mean	3114	51.90	2634	43.90	1.18	1419	23.67
Std. Dev.	501	8.35	92	1.53	0.19	37	0.61

TABLE XXI

SOUTHBOUND LANE - 360/65
(Sample 3)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	3490	58.17	2530	42.17	1.38	1398	23.30
2	3993	66.55	2553	42.55	1.56	1390	23.17
3	3108	51.80	2631	43.85	1.18	1428	23.80
4	3115	51.92	2635	43.92	1.18	1409	23.48
5	4179	69.65	2739	45.65	1.53	1510	25.17
6	4654	77.57	2734	45.57	1.70	1367	22.78
7	3121	52.02	2641	44.02	1.18	1513	25.22
8	2564	42.73	2564	42.73	1.00	1440	24.00
9	4545	75.75	2655	44.25	1.71	1420	23.67
10	4041	67.35	2601	43.35	1.55	1461	24.35
11	3024	50.40	2544	42.40	1.19	1412	23.53
12	3116	51.93	2636	43.93	1.18	1441	24.02
13	3546	59.10	2586	43.01	1.37	1469	24.48
14	5013	83.55	2613	43.55	1.92	1423	23.72
15	3595	59.92	2635	43.92	1.36	1480	24.67
16	5467	91.12	2587	43.12	2.11	1405	23.42
17	4069	67.82	2629	43.82	1.55	1489	24.82
18	2521	42.02	2521	42.02	1.00	1390	23.17
19	4012	66.87	2572	42.87	1.56	1473	24.55
20	3092	51.53	2612	43.53	1.18	1391	23.18
Mean	3714	61.89	2611	43.51	1.42	1435	23.92
Std. Dev.	797	13.29	59	0.98	0.30	43	0.71

TABLE XXII

SOUTHBOUND LANE - 360/65
(Sample 4)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	3572	59.53	2612	43.53	1.37	1468	24.47
2	2566	42.77	2566	42.77	1.00	1415	23.58
3	3019	50.32	2539	42.32	1.19	1441	24.02
4	3271	54.52	2791	46.52	1.17	1489	24.82
5	5042	84.03	2642	44.03	1.91	1431	23.85
6	2790	46.50	2790	46.50	1.00	1484	24.73
7	3030	50.50	2550	42.50	1.19	1434	23.90
8	3096	51.60	2616	43.60	1.18	1490	24.83
9	3603	60.05	2643	44.05	1.36	1427	23.78
10	2528	42.14	2528	42.14	1.00	1389	23.15
11	3513	58.55	2553	42.55	1.38	1445	24.08
12	3075	51.25	2595	43.25	1.18	1449	24.15
13	4518	75.30	2598	43.30	1.74	1441	24.02
14	3529	58.82	2569	42.82	1.37	1469	24.48
15	4027	67.12	2587	43.12	1.57	1416	23.55
16	3212	53.53	2732	45.53	1.18	1445	24.02
17	4974	82.90	2574	42.90	1.93	1488	24.80
18	3106	51.77	2626	43.77	1.18	1447	24.12
19	2741	45.68	2741	45.68	1.00	1430	23.83
20	3077	51.28	2597	43.28	1.18	1414	23.57
Mean	3423	57.05	2622	43.71	1.32	1446	24.09
Std. Dev.	728	12.14	80	1.33	0.25	29	0.48

TABLE XXIII

SOUTHBOUND LANE - 360/65
(Sample 5)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	5433	90.55	2553	42.55	2.13	1395	23.25
2	4090	68.17	2650	44.17	1.54	1428	23.80
3	3242	54.03	2762	46.03	1.17	1427	23.78
4	3613	60.22	2653	44.22	1.36	1447	24.12
5	3582	59.77	2622	43.70	1.37	1474	24.57
6	4078	67.97	2638	43.97	1.54	1428	23.80
7	3463	57.72	2503	41.72	1.38	1422	23.70
8	2585	43.05	2583	43.05	1.00	1414	23.57
9	2617	43.62	2617	43.62	1.00	1403	23.38
10	3089	51.48	2609	43.48	1.18	1411	23.52
11	2566	42.77	2566	42.77	1.00	1440	24.00
12	3987	66.45	2547	42.45	1.57	1463	24.38
13	4554	75.90	2634	43.90	1.73	1416	23.60
14	3101	51.68	2621	43.68	1.18	1410	23.50
15	3580	59.67	2620	43.67	1.37	1431	23.85
16	3743	62.38	2783	46.38	1.34	1439	23.98
17	4543	75.72	2623	43.72	1.73	1422	23.70
18	3087	51.45	2607	43.45	1.18	1451	24.18
19	3108	51.80	2628	43.80	1.18	1417	23.62
20	2785	46.42	2785	46.42	1.00	1464	24.40
Mean	3542	59.04	2630	43.84	1.35	1430	23.84
Std. Dev.	748	12.47	74	1.23	0.30	21	0.35

TABLE XXIV

SOUTHBOUND LANE - TOTAL PROJECT COST
(Dollars)

Observation	Sample 2 360/65	Sample 3 360/65	Sample 4 360/65	Sample 5 360/65
1	$223.13	$226.97	$201.39	$204.98
2	264.66	194.05	186.66	252.93
3	244.35	238.93	187.19	239.21
4	218.30	216.35	196.85	220.23
5	198.24	246.76	192.51	230.69
6	*	226.46	239.45	280.63
7	215.26	214.39	194.27	225.32
8	222.82	196.20	233.01	214.20
9	215.94	303.64	217.23	238.42
10	212.13	206.09	247.49	261.24
11	204.10	211.83	207.29	208.27
12	234.45	239.83	219.27	229.74
13	336.32	244.23	220.76	239.50
14	221.31	223.63	236.21	207.42
15	208.49	230.30	206.02	207.42
16	213.87	221.74	226.40	207.80
17	191.90	236.68	244.78	200.67
18	*	227.15	205.90	192.35
19	199.63	196.82	208.12	199.48
20	229.68	202.32	217.47	237.50
Mean	$219.14	$225.22	$214.41	$224.81
Std. Dev.	$ 17.39	$ 24.54	$ 18.92	$ 23.06

*Job not completed in 12 cycles.

TABLE XXV

RAINFALL

Observation	Cycles to Complete Project (N)	Rain Days During Project (N_s)	Rain Frequency per Work Week			Observation	Cycles to Complete Project (N)	Rain Days During Project (N_s)	Rain Frequency per Work Week			Observation	Cycles to Complete Project (N)	Rain Days During Project (N_s)	Rain Frequency per Work Week		
Sample 1						Sample 2						Sample 3					
1	6	0	0/5	0/1		1	6	0	0/5	0/1		1	8	2	1/5	1/3	
2	8	2	2/5	0/3		2	9	3	2/5	1/4		2	9	3	3/5	0/4	
3	7	1	1/5	0/2		3	7	1	1/5	0/2		3	7	1	1/5	0/2	
4	8	3	3/5	0/3		4	8	2	2/5	0/3		4	7	1	0/5	1/2	
5	8	2	2/5	0/3		5	9	3	2/5	1/4		5	9	3	0/5	3/4	
6	6	0	0/5	0/1		6	12	7	3/5	4/5	0/2	6	10	4	2/5	2/5	
7	6	0	0/5	0/1		7	8	2	1/5	1/3		7	7	1	1/5	0/2	
8	6	0	0/5	0/1		8	6	0	0/5	0/1		8	6	0	0/5	0/1	
9	6	0	0/5	0/1		9	6	0	0/5	0/1		9	10	4	3/5	1/5	
10	9	3	1/5	2/4		10	6	0	0/5	0/1		10	9	3	1/5	2/4	
11	7	1	1/5	0/2		11	7	1	1/5	0/2		11	7	1	0/5	1/2	
12	9	3	2/5	1/4		12	8	2	1/5	1/3		12	7	1	1/5	0/2	
13	6	0	0/5	0/1		13	7	1	1/5	0/2		13	8	2	1/5	1/3	
14	6	0	0/5	0/1		14	6	0	0/5	0/1		14	11	5	2/5	3/5	0/1
15	6	0	0/5	0/1		15	7	1	1/5	0/2		15	8	2	2/5	0/3	
16	7	1	1/5	0/2		16	7	1	1/5	0/2		16	12	6	3/5	3/5	0/2
17	7	1	1/5	0/2		17	6	0	0/5	0/1		17	9	3	3/5	0/4	
18	6	0	0/5	0/1		18	12	7	1/5	4/5	2/2	18	6	0	0/5	0/1	
19	9	3	2/5	1/4		19	7	1	1/5	0/2		19	9	3	1/5	2/4	
20	9	4	2/5	2/4		20	6	0	0/5	0/1		20	7	1	1/5	0/2	
Sample 4						Sample 5											
1	8	2	2/5	0/3		1	11	5	4/5	1/5	0/1						
2	6	0	0/5	0/1		2	9	3	2/5	1/4							
3	7	1	1/5	0/2		3	7	1	1/5	0/2							
4	7	1	1/5	0/2		4	8	2	1/5	1/3							
5	11	5	1/5	4/5	0/1	5	8	2	2/5	0/3							
6	6	0	0/5	0/1		6	9	3	3/5	0/4							
7	7	1	0/5	1/2		7	8	2	1/5	1/3							
8	7	1	1/5	0/2		8	6	0	0/5	0/1							
9	8	2	2/5	0/3		9	6	0	0/5	0/1							
10	6	0	0/5	0/1		10	7	1	1/5	0/2							
11	8	2	1/5	1/3		11	6	0	0/5	0/1							
12	7	1	1/5	0/2		12	9	3	0/5	3/4							
13	10	4	3/5	1/5		13	10	4	1/5	3/5							
14	8	2	1/5	1/3		14	7	1	1/5	0/2							
15	9	3	2/5	1/4		15	8	2	1/5	1/3							
16	7	1	1/5	0/2		16	8	2	2/5	0/3							
17	11	5	3/5	2/5	0/1	17	10	4	2/5	2/5							
18	7	1	1/5	0/2		18	7	1	0/5	1/[illegible]							
19	6	0	0/5	0/1		19	7	1	1/5	0/2							
20	7	1	1/5	0/2		20	6	0	0/5	0/1							

APPENDIX H

PROJECT COMPLETION TIMES FOR THE NORTHBOUND LANE AND SOUTHBOUND LANE (CALCULATED WITH THE IBM 360/75 COMPUTER)

TABLE XXVI

NORTHBOUND LANE - 360/75*

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	3970	66.17	2530	42.17	1.57	1404	23.40
2	3025	50.42	2545	42.41	1.19	1395	23.25
3	4996	83.27	2596	43.27	1.92	1448	24.13
4	3029	50.48	2549	42.48	1.18	1383	23.05
5	3053	50.88	2573	42.88	1.19	1389	23.15
6	4064	67.73	2624	43.73	1.55	1413	23.55
7	3260	54.33	2780	46.33	1.17	1459	24.32
8	2740	45.67	2740	45.67	1.00	1405	23.42
9	4436	73.93	2516	41.93	1.76	1361	22.68
10	3039	50.65	2559	42.65	1.19	1365	22.75
11	3025	50.42	2545	42.41	1.19	1371	22.85
12	3075	51.25	2595	43.25	1.18	1411	23.51
13	4457	74.28	2537	42.28	1.76	1337	22.28
14	3532	58.87	2572	42.87	1.37	1380	23.00
15	2604	43.40	2604	43.40	1.00	1422	23.70
16	3447	57.45	2487	41.45	1.39	1379	22.98
17	3109	51.82	2629	43.81	1.18	1371	22.85
18	3558	59.30	2598	43.30	1.37	1444	24.07
19	4089	68.15	2649	44.15	1.54	1433	23.88
20	4277	71.28	2357	39.28	1.81	1358	22.63
Mean	3539	58.99	2579	42.99	1.38	1396	23.27
Std. Dev.	663	11.05	88	1.47	0.28	33	0.55

*Random number generator sequence same as Southbound Lane 360/75 (Sample 1).

TABLE XXVII

SOUTHBOUND LANE - 360/75
(Sample 1)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Product Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	2582	43.03	2582	43.03	1.00	1472	24.53
2	3544	59.07	2584	43.07	1.37	1378	22.97
3	3060	51.00	2580	43.00	1.19	1406	23.43
4	3840	64.00	2400	40.00	1.60	1359	22.65
5	3506	58.43	2546	42.43	1.38	1388	23.15
6	2604	43.40	2604	43.40	1.00	1434	23.90
7	2705	45.08	2705	45.08	1.00	1447	24.12
8	2814	46.90	2814	46.90	1.00	1544	25.73
9	2535	42.25	2535	42.25	1.00	1399	23.32
10	3987	66.45	2547	42.45	1.57	1387	23.12
11	2969	49.48	2489	41.48	1.19	1429	23.82
12	4095	68.25	2655	44.25	1.54	1432	23.87
13	2648	44.13	2648	44.14	1.00	1461	24.35
14	2582	43.03	2582	43.03	1.00	1435	23.92
15	2605	43.42	2605	43.41	1.00	1384	23.07
16	3095	51.58	2615	43.58	1.18	1452	24.20
17	3240	54.00	2760	46.00	1.17	1442	24.03
18	2583	43.05	2583	43.05	1.00	1443	24.05
19	3994	66.57	2554	42.56	1.56	1388	23.11
20	4286	71.43	2366	39.43	1.81	1408	23.47
Mean	3164	52.73	2588	43.14	1.23	1424	23.47
Std. Dev.	603	10.05	104	1.74	0.26	42	0.70

APPENDIX I

PROJECT COMPLETION TIMES FOR THE NORTHBOUND LANE AND SOUTHBOUND LANE (CALCULATED WITH THE IBM 360/65 COMPUTER)

TABLE XXVIII

NORTHBOUND LANE - 360/65*

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	4480	74.67	2560	42.67	1.75	1388	23.14
2	3982	66.37	2542	42.37	1.57	1373	22.88
3	2509	41.82	2509	41.82	1.00	1402	23.37
4	3049	50.82	2569	42.82	1.19	1364	22.73
5	3017	50.28	2537	42.28	1.24	1389	23.15
6	3122	52.03	2642	44.03	1.18	1428	23.80
7	4928	82.13	2528	42.13	1.95	1341	22.35
8	3691	61.52	2731	45.52	1.35	1416	23.60
9	2738	45.63	2738	45.63	1.00	1364	22.73
10	2580	43.00	2580	43.00	1.00	1412	23.53
11	3056	50.93	2576	42.93	1.19	1394	23.23
12	5423	90.38	2543	42.38	2.13	1374	22.90
13	4050	67.50	2610	43.50	1.55	1391	23.18
14	3095	51.58	2615	43.58	1.18	1414	23.57
15	2821	47.02	2821	47.02	1.00	1387	23.12
16	5539	92.32	2659	44.32	2.08	1393	23.22
17	3500	58.33	2540	42.33	1.38	1445	24.08
18	2854	47.57	2854	47.57	1.00	1359	27.65
19	3509	58.48	2549	42.48	1.38	1370	22.83
20	2841	47.35	2841	47.35	1.00	1370	22.86
Mean	3534	58.94	2627	43.79	1.36	1389	23.15
Std. Dev.	919	15.32	111	1.85	0.37	26	0.43

*Random number generator sequence same as Southbound Lane - 360/65 (Sample 2).

TABLE XXIX

SOUTHBOUND LANE - 360/65
(Sample 2)

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	2585	43.08	2585	43.08	1.00	1393	23.22
2	4043	67.38	2603	43.38	1.55	1416	23.60
3	3208	53.47	2728	45.47	1.18	1394	23.23
4	3690	61.50	2730	45.50	1.35	1443	24.05
5	4044	67.40	2604	43.40	1.55	1404	23.40
6	5760+	(Work not completed - 124,166 sq. ft. of Section 36 remains.)					
7	3496	58.26	2536	42.27	1.38	1397	23.28
8	2831	47.18	2831	47.18	1.00	1433	23.88
9	2613	43.55	2613	43.55	1.00	1474	24.57
10	2552	42.53	2552	42.53	1.00	1426	23.77
11	3066	51.10	2586	43.10	1.19	1346	22.43
12	3587	59.78	2627	43.78	1.37	1454	24.23
13	3234	53.90	2754	45.90	1.17	1483	24.72
14	2594	43.23	2594	43.23	1.00	1409	23.48
15	3254	54.23	2774	46.23	1.17	1472	24.53
16	2996	49.93	25.16	41.93	1.19	1384	23.07
17	2521	42.01	2521	42.01	1.00	1397	23.28
18	5760+	(Work not completed - 176,462 sq. ft. of Section 36 remains.)					
19	3112	51.86	2631	43.85	1.18	1446	24.10
20	2637	43.87	2632	43.87	1.00	1379	23.28
Mean	3114	51.90	2634	43.90	1.18	1419	23.67
Std. Dev.	501	8.35	92	1.53	0.19	37	0.61

APPENDIX J

PROJECT COMPLETION TIMES FOR THE MEDIAN

(CALCULATED WITH THE IBM 360/75

COMPUTER)

TABLE XXX

MEDIAN - 360/75

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	3970	66.17	3010	50.17	1.32	1557	25.95
2	4281	71.35	2841	47.35	1.51	1523	25.38
3	3506	58.43	3026	50.43	1.16	1624	27.07
4	3120	52.00	2640	44.00	1.18	1442	24.03
5	2999	49.98	2999	49.98	1.00	1555	25.92
6	3697	61.62	2737	45.62	1.35	1542	25.70
7	3780	63.00	2820	47.00	1.34	1524	25.40
8	4461	74.35	3021	50.35	1.48	1565	26.08
9	3605	60.08	2645	44.08	1.36	1524	25.40
10	2761	46.02	2761	46.02	1.00	1541	25.68
11	5397	89.95	2997	49.95	1.80	1593	26.55
12	4085	68.08	2645	44.08	1.54	1527	25.45
13	2735	45.58	2735	45.58	1.00	1581	26.35
14	4707	78.48	2787	46.45	1.69	1593	26.55
15	5238	87.30	2838	47.30	1.85	1594	26.57
16	3771	62.85	2811	46.85	1.34	1591	26.52
17	3210	53.50	2730	45.50	1.18	1520	25.33
18	2987	49.78	2987	49.78	1.00	1559	25.98
19	4757	79.28	2837	47.28	1.68	1545	25.75
20	4204	70.07	2764	46.07	1.52	1572	26.20
Mean	3864	64.39	2832	47.19	1.36	1554	25.90
Std. Dev.	784	13.07	132	2.21	0.27	40	0.67

APPENDIX K

PROJECT COMPLETION TIMES AND COSTS FOR THE
NORTHBOUND LANE AND SOUTHBOUND LANE
WITHOUT CLASS D (3:1 SIDE SLOPE)
CUTTING (CALCULATED WITH THE
IBM 360/75 COMPUTER)

TABLE XXXI

NORTHBOUND LANE WITHOUT CLASS D - 360/75

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	3275	54.58	1835	30.58	1.78	1018	16.97
2	2972	49.53	2012	33.53	1.48	1028	17.13
3	1832	30.53	1832	30.53	1.00	1009	16.82
4	3286	54.93	1846	30.77	1.79	1035	17.25
5	2271	37.85	1791	29.85	1.27	1027	17.12
6	1818	30.30	1818	30.30	1.00	962	16.03
7	1763	29.38	1763	29.38	1.00	1010	16.83
8	1826	30.43	1826	30.43	1.00	994	16.57
9	2298	38.30	1818	30.30	1.26	1058	17.63
10	2022	33.70	2022	33.70	1.00	1038	17.30
11	2490	41.50	2010	33.50	1.24	1016	16.93
12	2282	38.03	1802	30.03	1.27	993	16.55
13	2622	43.70	1662	27.70	1.58	947	15.78
14	2843	47.38	1883	31.38	1.51	1015	16.92
15	2823	47.05	1863	31.05	1.52	1015	16.92
16	2314	38.57	1834	30.57	1.26	1045	17.42
17	3233	53.88	1793	29.88	1.80	1020	17.00
18	2150	35.83	2150	35.83	1.00	997	16.62
19	2041	34.02	2041	34.02	1.00	1019	16.98
20	2832	47.20	1872	31.20	1.51	1022	17.03
Mean	2450	40.83	1874	31.23	1.31	1013	16.89
Std. Dev.	509	8.50	116	1.93	0.29	26	0.43

TABLE XXXII

SOUTHBOUND LANE WITHOUT CLASS D - 360/75

Observ.	Total Project Time With Rain (A) (min)	(hrs)	Total Project Time Without Rain Effect (B) (min)	(hrs)	Rain Factor A/B	Total Production Time in Project (min)	(hrs)
1	2315	38.58	1835	30.58	1.26	1094	18.23
2	2352	39.20	1872	31.20	1.26	1103	18.38
3	3076	51.27	2116	35.27	1.45	1177	19.62
4	3068	51.13	2108	35.13	1.46	1101	18.35
5	2123	35.38	2123	35.38	1.00	1101	18.35
6	2764	46.07	2284	38.07	1.21	1130	18.83
7	3781	63.02	1861	31.02	2.03	1056	17.60
8	4480	74.67	2080	34.67	2.15	1111	18.52
9	2827	47.12	1867	31.12	1.51	1089	18.15
10	3549	59.15	2109	35.15	1.68	1099	18.32
11	2046	34.10	2046	34.10	1.00	1079	17.98
12	2540	42.33	2060	34.33	1.23	1059	17.65
13	3106	51.77	2146	35.77	1.45	1087	18.12
14	3980	66.33	2060	34.33	1.93	1091	18.18
15	2618	43.63	2138	35.63	1.22	1144	19.07
16	2045	34.08	2045	34.08	1.00	1086	18.10
17	3999	66.65	2079	34.65	1.92	1088	18.13
18	2534	42.23	2054	34.23	1.23	1085	18.08
19	3052	50.87	2092	34.87	1.46	1100	18.33
20	2558	42.63	2078	34.63	1.23	1090	18.17
Mean	2941	49.01	2053	34.21	1.43	1099	18.31
Std. Dev.	702	11.69	112	1.87	0.35	27	0.45

TABLE XXXIII

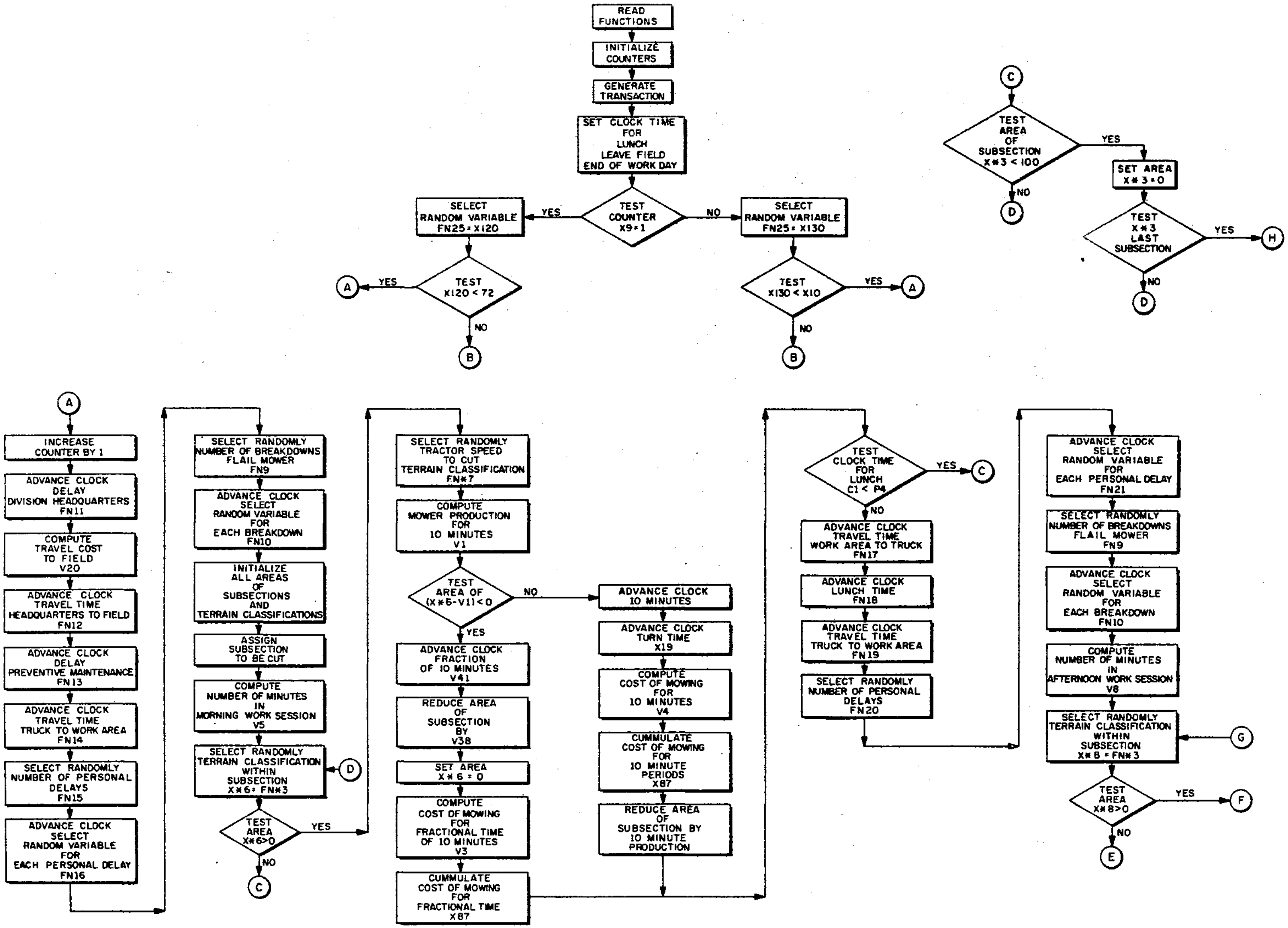
PROJECT COSTS

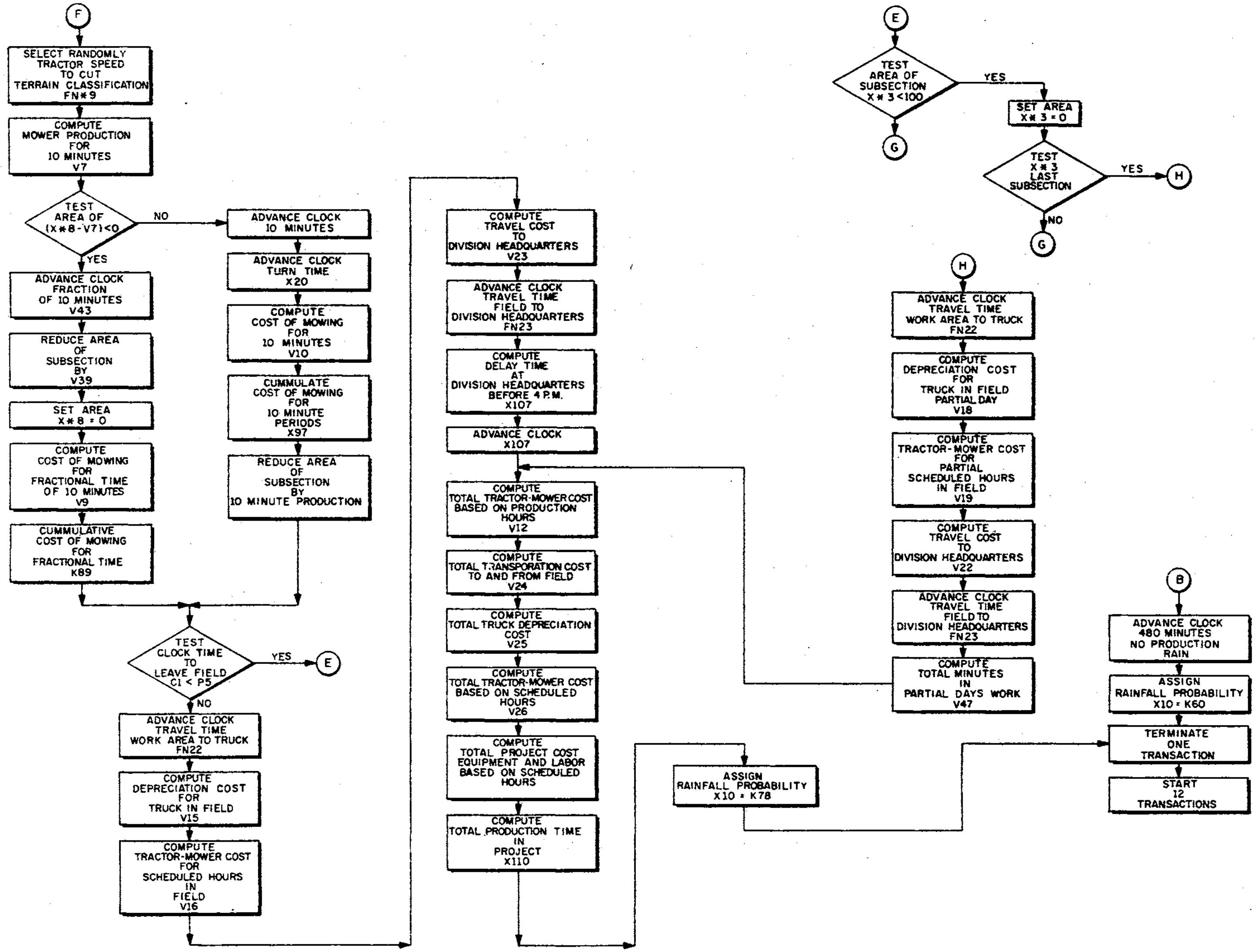
Northbound - Southbound Lanes Without Class D - 360/75 Total Production Cost With Transportation and Labor			Northbound - Southbound Lanes With Class D - 360/75 Total Production Cost With Transportation and Labor		
Observ.	North	South	Observ.	North	South
1	$76.36	$79.34	1	$102.75	$101.13
2	80.78	82.80	2	105.35	103.56
3	84.25	91.42	3	102.60	106.12
4	82.83	84.50	4	107.85	104.10
5	85.55	90.82	5	98.96	102.45
6	79.90	87.31	6	109.23	106.10
7	77.90	83.57	7	105.62	106.49
8	81.16	87.70	8	104.52	105.11
9	80.89	82.67	9	95.59	100.00
10	79.75	84.35	10	107.64	103.09
11	83.93	87.59	11	101.85	103.71
12	81.51	83.66	12	104.28	104.54
13	76.09	87.08	13	101.22	106.31
14	83.01	83.17	14	104.44	109.07
15	78.53	93.02	15	103.78	106.69
16	78.49	83.36	16	99.60	106.47
17	76.97	90.95	17	104.61	104.36
18	76.94	83.65	18	101.94	107.12
19	83.11	88.33	19	111.16	102.45
20	84.54	85.95	20	97.42	96.57
Mean	$80.62	$86.06		$103.52	$104.27
Std. Dev.	$ 2.95	$ 3.57		$ 3.88	$ 2.86

APPENDIX L

FLOW DIAGRAM AND GPSS/360 COMPUTER PROGRAM FOR

THE MOWING SIMULATION MODEL


READ FUNCTIONS
INITIALIZE COUNTERS
GENERATE TRANSACTION
SET CLOCK TIME FOR LUNCH LEAVE FIELD END OF WORK DAY
TEST COUNTER X9=1
YES
NO
SELECT RANDOM VARIABLE FN25=X120
SELECT RANDOM VARIABLE FN25=X130
TEST X120 < 72
TEST X130 < X10
YES
NO
A
B
C
TEST AREA OF SUBSECTION X*3 < 100
SET AREA X*3=0
TEST X*3 LAST SUBSECTION
D
H
INCREASE COUNTER BY 1
ADVANCE CLOCK DELAY DIVISION HEADQUARTERS FN11
COMPUTE TRAVEL COST TO FIELD V20
ADVANCE CLOCK TRAVEL TIME HEADQUARTERS TO FIELD FN12
ADVANCE CLOCK DELAY PREVENTIVE MAINTENANCE FN13
ADVANCE CLOCK TRAVEL TIME TRUCK TO WORK AREA FN14
SELECT RANDOMLY NUMBER OF PERSONAL DELAYS FN15
ADVANCE CLOCK SELECT RANDOM VARIABLE FOR EACH PERSONAL DELAY FN16
SELECT RANDOMLY NUMBER OF BREAKDOWNS FLAIL MOWER FN9
ADVANCE CLOCK SELECT RANDOM VARIABLE FOR EACH BREAKDOWN FN10
INITIALIZE ALL AREAS OF SUBSECTIONS AND TERRAIN CLASSIFICATIONS
ASSIGN SUBSECTION TO BE CUT
COMPUTE NUMBER OF MINUTES IN MORNING WORK SESSION V5
SELECT RANDOMLY TERRAIN CLASSIFICATION WITHIN SUBSECTION X*6=FN*3
TEST AREA X*6>0
SELECT RANDOMLY TRACTOR SPEED TO CUT TERRAIN CLASSIFICATION FN*7
COMPUTE MOWER PRODUCTION FOR 10 MINUTES V1
TEST AREA OF (X*6-V1)<0
ADVANCE CLOCK FRACTION OF 10 MINUTES V41
REDUCE AREA OF SUBSECTION BY V38
SET AREA X*6=0
COMPUTE COST OF MOWING FOR FRACTIONAL TIME OF 10 MINUTES V3
CUMMULATE COST OF MOWING FOR FRACTIONAL TIME X87
ADVANCE CLOCK 10 MINUTES
ADVANCE CLOCK TURN TIME X19
COMPUTE COST OF MOWING FOR 10 MINUTES V4
CUMMULATE COST OF MOWING FOR 10 MINUTE PERIODS X87
REDUCE AREA OF SUBSECTION BY 10 MINUTE PRODUCTION
TEST CLOCK TIME FOR LUNCH C1 < P4
ADVANCE CLOCK TRAVEL TIME WORK AREA TO TRUCK FN17
ADVANCE CLOCK LUNCH TIME FN18
ADVANCE CLOCK TRAVEL TIME TRUCK TO WORK AREA FN19
SELECT RANDOMLY NUMBER OF PERSONAL DELAYS FN20
ADVANCE CLOCK SELECT RANDOM VARIABLE FOR EACH PERSONAL DELAY FN21
SELECT RANDOMLY NUMBER OF BREAKDOWNS FLAIL MOWER FN9
ADVANCE CLOCK SELECT RANDOM VARIABLE FOR EACH BREAKDOWN FN10
COMPUTE NUMBER OF MINUTES IN AFTERNOON WORK SESSION V8
SELECT RANDOMLY TERRAIN CLASSIFICATION WITHIN SUBSECTION X*8=FN*3
G
TEST AREA X*8>0
F
E


F
SELECT RANDOMLY TRACTOR SPEED TO CUT TERRAIN CLASSIFICATION FN*9
COMPUTE MOWER PRODUCTION FOR 10 MINUTES V7
TEST AREA OF (X*8-V7)<0
NO
YES
ADVANCE CLOCK 10 MINUTES
ADVANCE CLOCK TURN TIME X20
COMPUTE COST OF MOWING FOR 10 MINUTES V10
CUMMULATE COST OF MOWING FOR 10 MINUTE PERIODS X97
REDUCE AREA OF SUBSECTION BY 10 MINUTE PRODUCTION
ADVANCE CLOCK FRACTION OF 10 MINUTES V43
REDUCE AREA OF SUBSECTION BY V39
SET AREA X*8 = 0
COMPUTE COST OF MOWING FOR FRACTIONAL TIME OF 10 MINUTES V9
CUMMULATIVE COST OF MOWING FOR FRACTIONAL TIME K89
TEST CLOCK TIME TO LEAVE FIELD C1 < P5
YES
E
NO
ADVANCE CLOCK TRAVEL TIME WORK AREA TO TRUCK FN22
COMPUTE DEPRECIATION COST FOR TRUCK IN FIELD V15
COMPUTE TRACTOR-MOWER COST FOR SCHEDULED HOURS IN FIELD V16
COMPUTE TRAVEL COST TO DIVISION HEADQUARTERS V23
ADVANCE CLOCK TRAVEL TIME FIELD TO DIVISION HEADQUARTERS FN23
COMPUTE DELAY TIME AT DIVISION HEADQUARTERS BEFORE 4 P.M. X107
ADVANCE CLOCK X107
COMPUTE TOTAL TRACTOR-MOWER COST BASED ON PRODUCTION HOURS V12
COMPUTE TOTAL TRANSPORATION COST TO AND FROM FIELD V24
COMPUTE TOTAL TRUCK DEPRECIATION COST V25
COMPUTE TOTAL TRACTOR-MOWER COST BASED ON SCHEDULED HOURS V26
COMPUTE TOTAL PROJECT COST EQUIPMENT AND LABOR BASED ON SCHEDULED HOURS
COMPUTE TOTAL PRODUCTION TIME IN PROJECT X110
ASSIGN RAINFALL PROBABILITY X10 = K78
E
TEST AREA OF SUBSECTION X*3<100
YES
G
SET AREA X*3 = 0
TEST X*3 LAST SUBSECTION
YES
H
NO
G
H
ADVANCE CLOCK TRAVEL TIME WORK AREA TO TRUCK FN22
COMPUTE DEPRECIATION COST FOR TRUCK IN FIELD PARTIAL DAY V18
COMPUTE TRACTOR-MOWER COST FOR PARTIAL SCHEDULED HOURS IN FIELD V19
COMPUTE TRAVEL COST TO DIVISION HEADQUARTERS V22
ADVANCE CLOCK TRAVEL TIME FIELD TO DIVISION HEADQUARTERS FN23
COMPUTE TOTAL MINUTES IN PARTIAL DAYS WORK V47
B
ADVANCE CLOCK 480 MINUTES NO PRODUCTION RAIN
ASSIGN RAINFALL PROBABILITY X10 = K60
TERMINATE ONE TRANSACTION
START 12 TRANSACTIONS

```
************************************************************************
                         SIMULATION MODEL
                                OF
        A MOWING OPERATION ON A SECTION OF INTERSTATE HIGHWAY
                            WRITTEN IN
          THE GENERAL PURPOSE SIMULATION SYSTEM LANGUAGE
                             GPSS/360
                          PROGRAMMED BY
                         ROBERT J. STONE
                    OKLAHOMA STATE UNIVERSITY
                               1971
************************************************************************
***
*   INPUT DATA
***
**
*      DATA PACK (MOWER SPEEDS)
**
       1 FUNCTION    RN1,C45     FLAIL SPEED 0-8 SLOPE MI/HR
.007 2.4   .023 2.5   .030 2.6   .040 2.7   .070 2.8   .083 2.9
.123 3.0   .146 3.1   .186 3.2   .236 3.3   .334 3.4   .413 3.5
.499 3.6   .569 3.7   .627 3.8   .673 3.9   .699 4.0   .725 4.1
.741 4.2   .761 4.3   .768 4.4   .775 4.5   .785 4.6   .815 4.7
.828 4.8   .838 4.9   .841 5.0   .844 5.1   .851 5.2   .854 5.3
.870 5.4   .880 5.5   .887 5.6   .907 5.7   .917 5.8   .927 5.9
.950 6.0   .964 6.1   .967 6.2   .970 6.3   .980 6.4   .987 6.7
.994 6.8   .997 6.9   1.00 7.1
       2 FUNCTION    RN2,C33     FLAIL SPEED 9-12 SLOPE MI/HR
.009 2.3   .018 2.6   .036 2.7   .063 2.8   .072 2.9   .090 3.0
.126 3.1   .149 3.2   .203 3.3   .279 3.4   .369 3.5   .410 3.6
.455 3.7   .509 3.8   .563 3.9   .644 4.0   .698 4.1   .716 4.2
.748 4.3   .780 4.4   .812 4.5   .844 4.6   .862 4.7   .876 4.8
.912 4.9   .921 5.0   .944 5.1   .953 5.2   .976 5.3   .985 5.4
.990 5.6   .995 5.7   1.00 5.8
       3 FUNCTION    RN3,C24     FLAIL SPEED 13-16 SLOPE MI/HR
.005 1.9   .031 2.0   .052 2.1   .083 2.2   .124 2.3   .155 2.4
.191 2.5   .222 2.6   .268 2.7   .359 2.8   .435 2.9   .497 3.0
.548 3.1   .589 3.2   .651 3.3   .677 3.4   .749 3.5   .795 3.6
.821 3.7   .883 3.8   .934 3.9   .975 4.0   .985 4.1   1.00 4.2
       4 FUNCTION    RN4,C27     FLAIL SPEED 17-22 SLOPE MI/HR
.007 1.3   .014 1.4   .021 1.5   .035 1.6   .063 1.7   .084 1.8
.105 1.9   .119 2.0   .140 2.1   .168 2.2   .196 2.3   .224 2.4
.294 2.5   .308 2.6   .385 2.7   .448 2.8   .546 2.9   .602 3.0
.651 3.1   .749 3.2   .860 3.3   .888 3.4   .944 3.5   .979 3.6
.986 3.7   .993 3.9   1.00 4.0
       5 FUNCTION    RN5,C33     OBSTACLE MOWING SPEED MILES/HOUR
0.00 0.0   .004 .40   .015 .50   .019 .60   .035 .70   .039 .80
.050 .90   .082 1.0   .130 1.1   .183 1.2   .236 1.3   .295 1.4
.359 1.5   .407 1.6   .466 1.7   .514 1.8   .526 1.9   .605 2.0
.679 2.1   .727 2.2   .770 2.3   .802 2.4   .834 2.5   .855 2.6
.876 2.7   .892 2.8   .903 2.9   .930 3.0   .946 3.1   .957 3.2
.978 3.3   .989 3.4   1.00 3.8
       6 FUNCTION    RN6,C18     ROADING SPEED MILES/HOUR
0.00 1.0   .056 2.0   .153 3.0   .295 4.0   .402 5.0   .483 6.0
.569 7.0   .635 8.0   .696 9.0   .767 10.   .813 11.   .874 12.
.910 13.   .940 14.   .970 15.   .985 16.   .990 17.   1.00 18.
**
*      DATA PACK (EQUIPMENT COSTS)
**
       7 FUNCTION    RN7,C32     HOURLY OPERATING COST OF MOWER CENTS/HR
.023 10    .090 20    .146 30    .224 40    .291 50    .342 60
.387 70    .471 80    .550 90    .617 100   .656 110   .684 120
.723 130   .757 140   .802 150   .813 160   .841 170   .863 180
.869 190   .875 200   .892 210   .903 220   .909 230   .920 240
.937 250   .948 260   .965 270   .971 290   .977 340   .988 350
.994 410   1.00 440
       8 FUNCTION    RN8,C39     HOURLY OPERATING COST OF TRACTOR CENTS/HR
.038 10    .130 20    .277 30    .411 40    .539 50    .626 60
.709 70    .750 80    .778 90    .812 100   .844 110   .861 120
.880 130   .891 140   .902 150   .919 160   .927 170   .935 180
.942 190   .946 200   .948 210   .955 220   .962 230   .966 240
.970 290   .972 340   .974 360   .976 420   .978 430   .980 440
.982 470   .984 480   .986 580   .990 620   .992 630   .994 640
.996 650   .998 740   1.00 750
**
***    SEE FUNCTION 26 FOR TRUCK COSTS
**
*      DATA PACK (DELAY FUNCTIONS)
**
       9 FUNCTION    RN1,D5      NUMBER OF BREAKDOWNS FOR FLAIL MOWER
.29  0     .54  1     .82  2     .93  3     1.0  4
      10 FUNCTION    RN2,C7      TIMES PER BREAKDOWN FOR FLAIL MOWER MIN.
0.0  1.0   .56  3.0   .71  6.0   .80  9.0   .84  12.0  .96  15.0
1.0  18.0
      11 FUNCTION    RN3,C6      DELAY TIME AT DIVISION HQ. MINUTES
0.0  14.   .33  15.   .44  20.   .67  25.   .89  30.   1.0  35.
      12 FUNCTION    RN4,C6      TRAVEL FROM SHOP TO MOWER MINUTES
0.0  13.   .11  14.   .33  16.   .67  20.   .78  26.   1.0  28.
      13 FUNCTION    RN5,C5      PREVENIVE MAINTENANCE MINUTES
0.   4.    .09  5.    .36  10.   .91  15.   1.0  20.
      14 FUNCTION    RN6,C4      TRAVEL FROM TRUCK TO SITE A.M. MINUTES
.3   0.    .4   4.    .6   6.    1.0  8.
      15 FUNCTION    RN7,D7      NUMBER OF PERSONAL DELAYS IN A.M.
.11  0     .22  1     .33  2     .66  3     .77  5     .88  7
1.0  10
      16 FUNCTION    RN8,C7      PERSONAL DELAY TIMES IN THE A.M. MINUTES
0.0  1.0   .39  2.0   .70  4.0   .79  6.0   .88  8.0   .94  10.
1.0  12.
      17 FUNCTION    RN1,C5      TRAVEL FROM SITE TO TRUCK AT LUNCH MINUTES
0.   1.    .2   2.    .8   4.    .9   6.    1.   10.
      18 FUNCTION    RN2,C5      LUNCH PERIOD MINUTES
0.0  41.   .11  45.   .33  50.   .55  55.   .89  60.   1.0  75.
      19 FUNCTION    RN3,C5      TRAVEL FROM TRUCK TO SITE P.M. MINUTES
0.0  1.0   .22  2.0   .78  4.0   .89  6.0   1.0  10.
      20 FUNCTION    RN4,D5      NUMBER OF PERSONAL DELAYS IN THE P.M.
.11  2     .55  4     .66  5     .88  6     1.0  8
      21 FUNCTION    RN5,C7      PERSONAL DELAY TIMES IN THE P.M. MINUTES
0.0  1.0   .51  2.0   .68  4.0   .86  6.0   .91  8.0   .93  10.
```

```
1.0   12.
     22 FUNCTION    RN6,C5        TRAVEL FROM SITE TO TRUCK P.M. MINUTES
0.0   1.0   .22   2.0   .78   4.0   .89   8.0   1.0   12.
     23 FUNCTION    RN7,C6        TRAVEL FROM FIELD TC HQ. MINUTES
0.0   17.   .22   20.   .56   25.   .78   30.   .89   35.   1.0   38.
**
***
     25 FUNCTION    RN8,C11       RANDOM NUMBER FOR RAINFALL PROBABILITY
0     0     .1    10    .2    20    .3    30    .4    40    .5    50
.6    60    .7    70    .8    80    .9    90    1.0   100
***
**
     26 FUNCTION    RN1,C58       HOURLY OPERATING COST OF TRUCK CENTS/HR
0.00  00    .100  10    .217  20    .317  30    .397  40    .460  50
.503  60    .546  70    .589  80    .618  90    .651  100   .672  110
.701  120   .705  130   .722  140   .739  150   .743  160   .747  170
.760  180   .777  190   .798  200   .815  210   .828  220   .836  250
.844  260   .852  280   .860  290   .868  300   .872  320   .876  330
.880  360   .888  370   .892  380   .896  400   .900  420   .904  440
.908  460   .912  470   .920  500   .924  510   .928  520   .932  530
.936  540   .940  580   .944  590   .948  600   .952  620   .960  630
.964  640   .968  690   .972  700   .976  720   .980  760   .984  830
.988  840   .992  900   .996  910   1.00  940
**
***
     27 FUNCTION    RN2,C37       TURN TIMES 1/100 OF A MINUTE
0.00  .02   .011  .04   .035  .06   .087  .08   .162  .10   .252  .12
.340  .14   .425  .16   .508  .18   .591  .20   .666  .22   .731  .24
.775  .26   .804  .28   .831  .30   .846  .32   .858  .34   .870  .36
.882  .38   .901  .40   .916  .42   .927  .44   .935  .46   .946  .48
.958  .50   .962  .52   .966  .54   .970  .56   .974  .58   .980  .60
.984  .62   .986  .64   .988  .66   .990  .70   .992  .78   .996  .86
1.00  .90
***
**
*       DATA PACK(SUBSECTIONS AND CLASSIFICATIONS)
**
     30 FUNCTION    RN3,D6        NAAMANS INTERCHANGE SOUTHBOUND
.45   11    .56   12    .70   13    .86   14    .98   15    1.0   16
     31 FUNCTION    RN4,D5        NAAMANS TO HARVEY SOUTHBOUND
.28   21    .49   22    .73   23    .94   24    1.0   26
     32 FUNCTION    RN5,D6        HARVEY INTERCHANGE SOUTHBCUND
.33   41    .45   42    .54   43    .72   44    .85   45    1.0   46
     33 FUNCTION    RN6,D5        HARVEY TO MARSH SOUTHBOUND
.14   51    .33   52    .65   53    .96   54    1.0   56
     34 FUNCTION    RN7,D2        MARSH INTERCHANGE SOUTHBOUND
.81   65    1.0   66
     35 FUNCTION    RN8,D5        MARSH TO RTE 202 SCUTHBCUND
.46   71    .55   72    .78   73    .93   74    1.0   76
     36 FUNCTION    RN1,D6        RTE 202 INTERCHANGE SOUTHBOUND
.41   81    .65   82    .82   83    .94   84    .98   85    1.0   86
****
*       CORE PROGRAM
****
          INITIAL     X7,K0
          INITIAL     X8,K1
          GENERATE    500,,,12,,40,F
          ASSIGN      4,C1
          ASSIGN      5,C1
          ASSIGN      12,C1
          ASSIGN      30,C1
          ASSIGN      4+,K220
          ASSIGN      5+,K425
          ASSIGN      12+,480
*         C1 IS THE CLOCK TIME THAT THE TRANSACTION ENTERS THE CHAIN
*         P4+K230 IS THE CLOCK TIME BEFORE QUITTING WORK FOR LUNCH
*         P5+K435 IS THE CLOCK TIME TO STOP MOWING IN THE AFTERNOON
*         P12+480 IS THE CLOCK TIME AT END OF WORKING DAY (4PM)
       30 VARIABLE    X7+X8
          SAVEVALUE   9,V30
          TEST E      X9,K1,BAYES
          SAVEVALUE   120,FN25
          TEST LE     X120,K72,DEND      RAINFALL PROBABILITY FIRST DAY
          TRANSFER    ,BEGWK
    BAYES SAVEVALUE   130,FN25
          TEST LE     X130,X10,DEND
    BEGWK SAVEVALUE   8+,K1
          SEIZE       1
          ADVANCE     FN11         DELAY TIME AT DIVISION HEADQUARTERS
          RELEASE     1
          ASSIGN      16,FN12
       20 FVARIABLE   (FN26+225)*P16/60       COST OF TRAVEL TO FIELD
*         225 CENTS/HR DEPRECIATION CHARGE FOR TRUCK
          SAVEVALUE   1+,V20
          SEIZE       2
          ADVANCE     P16          TRAVEL TIME FROM HEADQUARTERS TO FIELD
          RELEASE     2
          ASSIGN      33,C1
          SEIZE       3
          ADVANCE     FN13         PREVENTIVE MAINTENANCE TIME
          RELEASE     3
          SEIZE       4
          ADVANCE     FN14         TRAVEL TIME FROM TRUCK TO WORK SITE
          RELEASE     4
*         PERSONAL DELAYS IN THE MORNING
          ASSIGN      1,FN15       PARAMETER 1, NUMBER OF DELAYS
          TEST G      P1,K0,TEABK
    DELAM SEIZE       5
          ADVANCE     FN16         TIME PER PERSONAL DELAY
          RELEASE     5
          ASSIGN      1-,K1        SUBT. 1 FROM ASSIGNED VALUE TO P1 BY FN 15
          TEST E      P1,K0,DELAM
*         TEST DETERMINES IF ALL DELAYS ASSIGNED BY FN15 HAVE TIMES
    TEABK ASSIGN      14,FN9       NUMBER OF BREAKDOWNS OF FLAIL MOWER
          TEST G      P14,K0,AREAP
    BRKAM SEIZE       25
          ADVANCE     FN10         BREAKDOWN TIMES PER BREAKDOWN
          RELEASE     25
```

```
        ASSIGN      14-,K1
        TEST LE     P14,K0,BRKAM
**
*       MORNING PRODUCTION
**
*       SUBSECTIONS AND TERRAIN CLASSIFICATIONS
*       SOUTHBOUND LANE PRESENT CUTTING ASSIGNMENT
        INITIAL     X30,K307485
        INITIAL     X11,K141285
        INITIAL     X12,K36360
        INITIAL     X13,K40460
        INITIAL     X14,K48650
        INITIAL     X15,K36850
        INITIAL     X16,K3880
        INITIAL     X31,K489965
        INITIAL     X21,K139875
        INITIAL     X22,K102180
        INITIAL     X23,K116300
        INITIAL     X24,K104000
        INITIAL     X25,K0
        INITIAL     X26,K27610
        INITIAL     X32,K86610
        INITIAL     X41,K28150
        INITIAL     X42,K10065
        INITIAL     X43,K8200
        INITIAL     X44,K15980
        INITIAL     X45,K11620
        INITIAL     X46,K12595
        INITIAL     X33,K399085
        INITIAL     X51,K56185
        INITIAL     X52,K76130
        INITIAL     X53,K127800
        INITIAL     X54,K122745
        INITIAL     X55,K0
        INITIAL     X56,K16225
        INITIAL     X34,K13510
        INITIAL     X61,K0
        INITIAL     X62,K0
        INITIAL     X63,K0
        INITIAL     X64,K0
        INITIAL     X65,K10980
        INITIAL     X66,K2530
        INITIAL     X35,K497215
        INITIAL     X71,K229355
        INITIAL     X72,K46380
        INITIAL     X73,K112150
        INITIAL     X74,K76770
        INITIAL     X75,K0
        INITIAL     X76,K32560
        INITIAL     X36,K596680
        INITIAL     X81,K243810
        INITIAL     X82,K140130
        INITIAL     X83,K103955
        INITIAL     X84,K78830
        INITIAL     X85,K25335
        INITIAL     X86,K4620
  AREAI ASSIGN      3,K30
        ASSIGN      24,C1
      5 FVARIABLE   (P4-P24)
        SAVEVALUE   108,V5
        SAVEVALUE   118+,X108
*       CLASSIFICATION TO BE MOWED IN ASSIGNED SUBSECTION
  WKAM  ASSIGN      6,FN*3
*       TEST IF ALL THE AREA OF THE CLASSIFICATION HAS BEEN CUT.
*       IF SO, RETURN FOR ANOTHER CLASSIFICATION WITHOUT ADVANCING TIME
        TEST G      X*6,K0,ATEST
*       SELECT SPEED FUNCTION AS SPECIFIED BY A SINGLE NUMBERED FUNCTION
        ASSIGN      7,V40
     40 VARIABLE    P6/1210
*       MOWER PRODUCTION FOR 10 MIN. EXPRESSED IN SQ. FT. (VARIABLE 1)
*       EFFECTIVE MOWER WIDTH EQUALS 5.5 FEET (55/10)
      1 FVARIABLE   FN*7(5280/60)*(55/10)*10
        SAVEVALUE   77,V1
*       AREA REMAINING IN THE CLASSIFICATION SPECIFIED BY P6
        SAVEVALUE   *6-,X77
*       CHECK IF 10MIN. PRODUCTION CUT MORE GRASS THAN ACTUALLY REMAINED
*       IN THE CLASSIFICATION
        TEST L      X*6,K0,NORMA
*       ADJUST CUTTING TIME FOR LESS THAN 10MIN PRODUCTION
*       VARIABLE 41 IS EXPRESSED IN MINUTES
     41 FVARIABLE   (X*6+X77)/(X77)*10
        ASSIGN      27,V41
*       CUMULATIVE TIME FOR FRACTIONAL PRODUCTION (MORNING)
        SAVEVALUE   80+,P27
        SEIZE       16
        ADVANCE     P27
        RELEASE     16
     38 FVARIABLE   X*6+X77
        SAVEVALUE   *3-,V38
        SAVEVALUE   *6,K0
*       MOWING COST FOR FRACTIONAL TIME CALCULATED IN CENTS
*       120 CENTS/HR DEPRECIATION CHARGE FOR TRACTOR/MOWER UNIT
      3 FVARIABLE   (FN7+FN8+120)/60*P27
*       CUMULATIVE COST FOR FRACTIONAL MOWING IN THE A.M. (CENTS/HR)
        SAVEVALUE   79+,V3
        TRANSFER    ,NEXT1
  NORMA SEIZE       6
        ADVANCE     10              STANDARD 10 MIN. PRODUCTION INTERVAL
        RELEASE     6
      2 FVARIABLE   3*FN27
        SAVEVALUE   19,V2
        SEIZE       15
        ADVANCE     X19             TURN TIME
        RELEASE     15
*       MOWING COST FOR 10 MIN. INTERVAL CALCULATED IN CENTS
*       120 CENTS/HR DEPRECIATION CHARGE FOR TRACTOR/MOWER UNIT
      4 FVARIABLE   (FN7+FN8+120)/60*10
*       CUMULATIVE COST OF 10 MINUTE MOWING INTERVALS IN THE MORNING
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        SAVEVALUE  87+,V4
        SAVEVALUE  *3-,X77
*       TEST FOR LUNCH TIME
 NEXT1  TEST L     C1,P4,LUNCH
*       TEST IF ALL THE AREA OF THE SUBSECTION HAS BEEN CUT, IF NOT,
*       CONTINUE CUTTING
 ATEST  TEST LE    X*3,K100,WKAM
        SAVEVALUE  *3,K0
*       TEST IF ALL SUBSECTIONS HAVE BEEN CUT, IF NOT, CONTINUE
*       CUTTING
        ASSIGN     3+,K1
        TEST G     P3,K36,WKAM
*       K__ VARIES WITH THE NUMBER OF SUBSECTIONS IN THE HIGHWAY
*       MAINTENANCE SECTION
*       K36 IS THE SAVEVALUE NUMBER OF THE LAST SUBSECTION IN THE
*       ILLUSTRATIVE  EXAMPLE
        TRANSFER   ,PJEND
 LUNCH  SEIZE      7
        ADVANCE    FN17         TRAVEL TIME TO TRUCK AT LUNCH
        RELEASE    7
        ASSIGN     17,FN18
     21 FVARIABLE  (FN26*P17/60)*(20/100)
        SAVEVALUE  2+,V21
        SEIZE      8
        ADVANCE    P17              LUNCH TIME
        RELEASE    8
        SEIZE      9
        ADVANCE    FN19         TRAVEL TIME FROM TRUCK TO WORK SITE
        RELEASE    9
*       PERSONAL DELAYS IN THE AFTERNOON
        ASSIGN     2,FN20       PARAMETER 2, NUMBER OF DELAYS
        TEST G     P2,K0,TEPBK
 DELPM  SEIZE      10
        ADVANCE    FN21         TIME PER PERSONAL DELAY
        RELEASE    10
        ASSIGN     2-,K1        SUBT. 1 FROM VALUE ASSIGNED TO P2 BY FN20
        TEST LE    P2,K0,DELPM
*       TEST DETERMINES IF ALL DELAYS ASSIGNED BY FN20 HAVE TIMES
 TEPBK  ASSIGN     15,FN9       NUMBER OF BREAKDOWNS OF THE FLAIL MOWER
        TEST G     P15,K0,PMTIM
 BRKPM  SEIZE      26
        ADVANCE    FN10         BREAKDOWN TIMES PER BREAKDOWN
        RELEASE    26
        ASSIGN     15-,K1
        TEST LE    P15,K0,BRKPM
 PMTIM  ASSIGN     26,C1
      8 FVARIABLE  (P5-P26)
        SAVEVALUE  109,V8
        SAVEVALUE  119+,X109
**
*       AFTERNOON PRODUCTION
**
 WKPM   ASSIGN     8,FN*3
        TEST G     X*8,K0,PTEST
        ASSIGN     9,V42
     42 VARIABLE   P8/1010
*       MOWER PRODUCTION FOR 10 MIN. EXPRESSED IN SQ. FT. (VARIABLE 7)
      7 FVARIABLE  FN*9(5280/60)*(55/10)*10
        SAVEVALUE  78,V7
*       AREA REMAINING IN CLASSIFICATION SPECIFIED BY P8
        SAVEVALUE  *8-,X78
        TEST L     X*8,K0,NORMP
     43 FVARIABLE  (X*8+X78)/(X78)*10
        ASSIGN     28,V43
*       CUMULATIVE TIME FOR FRACTIONAL PRODUCTION (AFTERNOON)
        SAVEVALUE  90+,P28
        SEIZE      21
        ADVANCE    P28
        RELEASE    21
     39 FVARIABLE  X*8+X78
        SAVEVALUE  *3-,V39
        SAVEVALUE  *8,K0
*       MOWING COST FOR FRACTIONAL TIME CALCULATED IN CENTS
*       120 CENTS/HR DEPRECIATION CHARGE FOR TRACTOR/MOWER UNIT
      9 FVARIABLE  (FN7+FN8+120)/60*P28
*       CUMULATIVE COST FOR FRACTIONAL MOWING IN THE P.M. (CENTS/HR)
        SAVEVALUE  89+,V9
        TRANSFER   ,NEXT2
 NORMP  SEIZE      11
        ADVANCE    10           STANDARD 10 MIN. PRODUCTION INTERVAL
        RELEASE    11
      6 FVARIABLE  3*FN27
        SAVEVALUE  20,V6
        SEIZE      17
        ADVANCE    X20          TURN TIME
        RELEASE    17
*       MOWING COST FOR CUTTING FOR 10 MIN. CALCULATED IN CENTS
     10 FVARIABLE  (FN7+FN8+120)/60*10
*       CUMULATIVE COST OF 10 MINUTE MOWING INTERVALS IN THE AFTERNOON
        SAVEVALUE  97+,V10
        SAVEVALUE  *3-,X78
*       TEST FOR TIME TO STOP MOWING IN THE AFTERNOON
 NEXT2  TEST L     C1,P5,GOHOM
*       TEST IF ALL AREA IN THE SUBSECTION HAS BEEN CUT, IF NOT,
*       CONTINUE CUTTING
 PTEST  TEST LE    X*3,K100,WKPM
        SAVEVALUE  *3,K0
        ASSIGN     3+,K1
        TEST G     P3,K36,WKPM
*       K__ VARIES WITH THE NUMBER OF SUBSECTIONS IN THE HIGHWAY
*       MAINTENANCE SECTION
        TRANSFER   ,PJEND
 GOHOM  SEIZE      12
        ADVANCE    FN22         TRAVEL TIME FROM WORK SITE TO TRUCK
        RELEASE    12
        ASSIGN     34,C1
     14 FVARIABLE  P34-P33
        SAVEVALUE  129,V14
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*          DEPRECIATION CHARGE FOR TRUCK WHILE IN THE FIELD
      15 FVARIABLE  (225)*(X129/60)
         SAVEVALUE  137+,V15
*          COST OF TRACTOR/MOWER UNIT FOR SCHEDULED HOURS IN THE FIELD
      16 FVARIABLE  (FN7+FN8+120)/60*X129
         SAVEVALUE  138+,V16
         ASSIGN     19,FN23
      23 FVARIABLE  (FN26+225)*P19/60       COST OF TRAVEL TO HQ. (GOHOM)
*          CUMULATIVE COST OF RETURNING TO HQ. (GOHOM)
         SAVEVALUE  4+,V23
         SEIZE      13
         ADVANCE    P19          TRAVEL TIME FROM FIELD TO HEADQUARTERS
         RELEASE    13
         ASSIGN     11,C1
      45 FVARIABLE  P12-P11
         SAVEVALUE  107,V45
         SEIZE      14
         ADVANCE    X107         DELAY AT SHOP BEFORE QUITTING
         RELEASE    14
         ASSIGN     31,C1
      46 FVARIABLE  P31-P30
*          TOTAL MINUTES FOR A STANDARD WORK DAY
         SAVEVALUE  127,V46
         TRANSFER   ,NEXT3
   PJEND SEIZE      22
         ADVANCE    FN22         TRAVEL TIME FROM WORK SITE TO TRUCK
         RELEASE    22
         ASSIGN     35,C1
      17 FVARIABLE  P35-P33
         SAVEVALUE  139,V17
*          DEPRECIATION CHARGE FOR TRUCK (PARTIAL DAYS WORK)
      18 FVARIABLE  (225)*(X139/60)
         SAVEVALUE  140,V18
*          COST OF TRACTOR/MOWER UNIT FOR PARTIAL DAYS WORK
      19 FVARIABLE  (FN7+FN8+120)/60*X139
         SAVEVALUE  147,V19
         ASSIGN     18,FN23
      22 FVARIABLE  (FN26+225)*P18/60       COST OF TRAVEL TO HQ. (PJEND)
*          ACCUMULATIVE COST OF RETURNING TO HEADQUARTERS (PJEND)
         SAVEVALUE  3+,V22
         SEIZE      23
         ADVANCE    P18          TRAVEL TIME FROM FIELD TO HEADQUARTERS
         RELEASE    23
         ASSIGN     32,C1
*          TOTAL MINUTES IN A PARTIAL DAY
      47 FVARIABLE  P32-P30
         SAVEVALUE  128,V47
**
*          CALCULATIONS OF TOTAL COSTS IN THE MOWING PROJECT
**
*          X99 TOTAL COST OF TRACTOR/MOWER UNIT BASED ON PRODUCTION  TIME
   NEXT3 SAVEVALUE  99,V12
      12 FVARIABLE  X79+X87+X89+X97
*          X5 TOTAL PROJECT COST OF TRANSPORTATION TO AND FROM THE FIELD
         SAVEVALUE  5,V24
      24 FVARIABLE  X1+X3+X4
*          X6 TOTAL TRUCK DEPRECIATION CHARGE
         SAVEVALUE  6,V25
      25 FVARIABLE  X137+X140
*          X148 TOTAL COST FOR TRACTOR/MOWER UNIT BASED ON SCHEDULED
*          WORK HOURS
         SAVEVALUE  148,V26
      26 FVARIABLE  X138+X147
*          X149 TOTAL EQUIPMENT AND LABOR COST BASED ON SCHEDLUED
*          WORK HOURS
      27 FVARIABLE  X5+X6+X148+(261*8)
         SAVEVALUE  149,V27
*          CUMULATIVE PRODUCTION TIME IN THE PROJECT FOR FULL WORK DAYS
      11 FVARIABLE  X118+X119
         SAVEVALUE  110,V11
         SAVEVALUE  10,K78       SET RAINFALL PROBABILITY
         TRANSFER   ,NEXT4
    DEND SEIZE      24
         ADVANCE    480          ADVANCE CLOCK 480 MINUTES FOR RAIN DAY
         RELEASE    24
         SAVEVALUE  8+,K1
         SAVEVALUE  10,K60       SET RAINFALL PROBABILITY
   NEXT4 TERMINATE  1            END OF DAY HURRAY
         START      12,,1
**
*          END OF FIRST OBSERVATION OF PROJECT COMPLETION TIME AND COSTS
**
***
*          BEGIN SECOND OBSERVATION
***
*          SOUTHBOUND LANE PRESENT CUTTING ASSIGNMENT
         INITIAL    X8,K1
         INITIAL    X30,K307485
         INITIAL    X11,K141285
         INITIAL    X12,K36360
         INITIAL    X13,K40460
         INITIAL    X14,K48650
         INITIAL    X15,K36850
         INITIAL    X16,K3880
         INITIAL    X31,K489965
         INITIAL    X21,K139875
         INITIAL    X22,K102180
         INITIAL    X23,K116300
         INITIAL    X24,K104000
         INITIAL    X25,K0
         INITIAL    X26,K27610
         INITIAL    X32,K86610
         INITIAL    X41,K28150
         INITIAL    X42,K10065
         INITIAL    X43,K8200
         INITIAL    X44,K15980
         INITIAL    X45,K11620
         INITIAL    X46,K12595
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        INITIAL     X33,K399085
        INITIAL     X51,K56185
        INITIAL     X52,K76130
        INITIAL     X53,K127800
        INITIAL     X54,K122745
        INITIAL     X55,K0
        INITIAL     X56,K16225
        INITIAL     X34,K13510
        INITIAL     X61,K0
        INITIAL     X62,K0
        INITIAL     X63,K0
        INITIAL     X64,K0
        INITIAL     X65,K10980
        INITIAL     X66,K2530
        INITIAL     X35,K497215
        INITIAL     X71,K229355
        INITIAL     X72,K46380
        INITIAL     X73,K112150
        INITIAL     X74,K76770
        INITIAL     X75,K0
        INITIAL     X76,K32560
        INITIAL     X36,K596680
        INITIAL     X81,K243810
        INITIAL     X82,K140130
        INITIAL     X83,K103955
        INITIAL     X84,K78830
        INITIAL     X85,K25335
        INITIAL     X86,K4620
        CLEAR       X8,X11-X16,X21-X26,X30-X36,X41-X46,X51-X56,X61-X66
        CLEAR       X71-X76,X81-X86
        START       12,,1
**
*       END SECONO OBSERVATION OF PROJECT COMPLETICN TIME AND COSTS
**
******* CONTINUE OBSERVATIONS OF PROJECT COMPLETICN TIME AND COSTS
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VITA

Robert James Stone

Candidate for the Degree of

Doctor of Philosophy

Thesis: SIMULATION MODELING OF HIGHWAY MAINTENANCE OPERATIONS APPLIED TO ROADSIDE MOWING

Major Field: Engineering

Biographical:

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Education: Attended grade school in Lansdowne, Pennsylvania; was graduated from Lansdowne High School in 1948; received the Bachelor of Science degree from the College of William and Mary, with a major in Mathematics, in June, 1952; received the Bachelor of Science degree with a major in Civil Engineering from Swarthmore College in June 1957; received the Master of Science in Engineering degree from the University of Michigan, with a major in Civil Engineering, in June, 1957; completed requirements for the Doctor of Philosophy degree from the Oklahoma State University, with a major in Civil Engineering, in May, 1972.

Professional Experience: From 1952 to 1954 was an officer in the Field Artillery of the United States Army; from 1954 to 1958 was employed summers with the Pennsylvania Department of Highways as an assistant project engineer, with Modjeski and Masters Consulting Engineers as a detailer, with Turner Construction Company as an assistant officer engineer, and with the Soil Conservation Service as a GS-9 structural designer; from September 1957 to June 1958 was employed by Swarthmore College as an Instructor of Civil Engineering; from September, 1958 to June, 1959 was employed by the University of Denver as an Assistant Professor of Civil Engineering; from September, 1959 to September, 1966 was employed by Drexel Institute of Technology as an Assistant Professor of Civil Engineering; from September, 1966 to September, 1968 was a National Science Faculty Fellow at Oklahoma State University; presently employed as an Assistant Professor of Civil Engineering by Drexel University.

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