systems analysis of storage, hauling and discharge of hot asphalt paving mixtures

napa

QIP-94

prepared for the
National Asphalt Pavement Association
by the

**Civil Engineering Systems Laboratory,
Civil Engineering Department,
Texas Engineering Experiment Station,
Texas A&M University**

a publication of the
Quality Improvement Committee
of the
National Asphalt Pavement
Association

SYSTEMS ANALYSIS OF STORAGE, HAULING, & DISCHARGE OF HOT ASPHALT PAVING MIXTURES

For The

NATIONAL ASPHALT PAVEMENT ASSOCIATION

Prepared By The

CIVIL ENGINEERING SYSTEMS LABORATORY

CIVIL ENGINEERING DEPARTMENT

TEXAS ENGINEERING EXPERIMENT STATION

TEXAS A&M UNIVERSITY

1972

INTRODUCTION

On June 1, 1971, the Civil Engineering Systems Laboratory of Texas A&M University began work on a research project of one year's duration for the National Asphalt Pavement Association. The research performed was to be concerned primarily with the storage, hauling and placement of hot-asphalt paving mixtures. This document constitutes the final report on the work accomplished during the course of the project and is submitted in accordance with the provisions of the project contract.

At the outset of the project, it was envisioned that the work would be concerned almost exclusively with collection and analysis of data pertaining to production, distribution and laydown of hot asphalt paving mixtures. In fact, the major portion of the project effort was expended in this area, and the results of that effort are presented in Part I of this report.

However, as members of the research team went from job to job collecting operational data, they were witness to a variety of hot-mix production problems, efficient and inefficient distribution techniques and good, as well as poor laydown methods — all falling within the general purview of project management.

In more than a few instances ineffective management (or in truth, almost complete lack of overall job control) was resulting in needless expense and consequent loss of profit. Fortunately, there were certain projects on which superior management methods or, at least, certain highly efficient practices were employed, knowledge of which could profit the entire industry. Since the ultimate objective of this research was to achieve improvement of product quality, greater project management efficiency and/or increased profit for the hot-mix industry, it became clear to the research team that the results of their observations in the job management area were at least as important as and were inextricably bound up with the results of the study on production, distribution and laydown operations. Therefore, Part II of the report discusses the most significant of these field observations made of the hot-mix management practices in use at the various projects.

It was NAPA's desire that the research conducted in the project concern itself with determining the following information about hot-mix distribution subsystems:

a. Are the current methods and equipment used to transport hot-mix from the plant to the paver the most feasible, effective and economical means presently available to the industry?

b. If not, what other methods and equipment promise better distribution systems?

c. What other usage is feasible for the hauling units used to transport hot-mix? Can special purpose hot-mix transport vehicles also be used to haul aggregate in periods when they are not hauling hot-mix?

d. How does a unit that discharges mix without raising its bed, such as the Flowboy, measure up as a better system for delivering hot-mix?

e. What methods or means may be used to reduce the turn-around time of a haul unit at the paver?

Findings with regard to the above-listed objectives as well as other conclusions and observations deriving from the investigation, are summarized immediately following this introduction. Discussion of the field data and simulation information upon which these conclusions and observations are based comprises the major portion of the balance of this report.

CONCLUSIONS AND OBSERVATIONS

Specific Conclusions — Based on Field Data and Model Output presented in Part I of the Report:

The Model

Simplified, the model consists of:

a. Time to load unit at the plant

b. Travel time to paver

c. Time to maneuver and unload at the paver

d. Travel time to the plant

A systems analysis of each of these items plus the interaction with production and laydown resulted in the following conclusions regarding equipment.

The distances involved and the physical limitations imposed on hauling equipment (speed, traffic, etc.) are such that only marginal improvement in travel times could be expected from hauling equipment that differs from current equipment.

Improvements can be achieved by decreasing loading time at the plant and at the paver. (Surge bins at the plant and windrows at the paver are current methods.)

For the most part, optimal costs-in-place result from employing the largest possible size hauling equipment with the largest feasible size plant.

Hauling equipment having low unit weight to horsepower ratios outproduces similar equipment with equal horsepowers but higher unit weights inasmuch as the former can carry greater payloads.

The study showed there are limitations on the dollars that can be spent on surge bins and still achieve reductions of in-place costs.

The study showed there are similar limitations on the dollars that can be spent on surge at the paver and still achieve reductions of in-place costs.

Side discharge vehicles would reduce time at the paver but the characteristics studied resulted in no reduction in the in-place cost.

Mechanically unloaded trucks (as opposed to trucks unloaded by gravity from a raised bed) offer no improvement in cycle time. (There are other improvements as noted.)

Thus, the overall conclusion is that the current hauling equipment supplemented by surge at the plant and the paver appears to be the best system of transporting asphalt mix from the plant to the paver.

The model definitely shows there is an optimum number of trucks (based on lowest in-place cost) for any given situation. The optimum number will vary with plant production, travel distance, lawdown capacity, whether or not surge is used, and truck size. The model affords a rapid means of establishing the optimum number of trucks for any given condition.

The observations of actual production rates noted consistent and significant delays in the production, hauling, and laying of hot-mix which could be attributed to poor management. These include lack of aggregate, lack of asphalt, equipment not available or broken down, errors and improper practices on the part of personnel, etc. These external delays were so costly, that the clearest implication of this study is that a bigger reduction in transport costs can be achieved by improving management practices than by any conceivable improvement in equipment.

The following, more specific conclusions, are related to the production and hauling cycles.

1. Hot-mix operations can be improved and unit costs reduced accordingly by decreasing the amount of delay time accumulated, not only by hauling units, but also by plants and laydown machines.

2. In all cases, a large capacity haul unit is superior to a smaller capacity unit, not only from the standpoint

of quantity hauled, but also from the standpoint of the unit hauling cost of the hot-mix — with the possible exception of very short haul distances.

3. In a total production-distribution-laydown operation, haul unit performance is directly dependent upon both plant performance and paver performance.

4. The optimal equipment spread for a particular hot-mix operation based on costs-in-place is that array employing the largest possible haul units with the largest feasible plant.

5. All other factors being equal, a hot-mix operation employing a large plant will outperform an operation employing a smaller plant from the standpoint of unit cost of the hot-mix in place.

6. The greatest hot-mix system economy and efficiency are realized when plant and paver have balanced production rates and a sufficient number of haul units are operating at all times to provide hauling capacity equal to plant and paver production.

7. The productive output of a hot-mix production-distribution-laydown system, which is not in balance, is increased to the greatest degree by corrective action directed at the least productive component of the system.

8. Hot-mix system operations can be improved by decreasing the number of interaction times of haul units with

the plant and with the laydown machine.

9. Surge storage and loading from surge are effective means of improving production performance of a hot-mix system; these operations are economically effective, however, only if sufficient increase in production is realized to outweigh the additional owning and operating costs of the surge storage provided.

10. Windrowing, within its limitations, is an economical and effective means of reducing turn-around time at the paver.

11. A haul unit equipped with a side discharge capability can also improve job production to a limited degree by reducing turn-around time at the paver but does so at the expense of slightly higher unit costs for a ton of hot-mix in place on the road.

12. A haul unit which unloads mechanically out the back of the unit, such as the Flowboy, does not effectively surpass conventional hauling units purely as a means for delivering hot-mix to the laydown machine. However, the lack of necessity to raise the bed is an advantage in paving where there are overhead obstructions, and on superelevations. Also, there is no chance for the truck bed to rest on the paver. The wide range of discharge rates is advantageous in placing fillets and other areas which must be placed by hand.

13. Except for large thermotrailers, no haul unit designed primarily for transporting hot mix, save those similar to the Flowboy, is known to be in wide use at this time. Based on observations of the exposed drag chain driving the horizontal drag conveyor in a Flowboy hauling unit, such a system can be used to haul 1-inch minus, hard-rock aggregate and softer (crushable) aggregates of any desired size; larger hard rock may lock the conveyor. Still based on the Flowboy unit, the discharge rate will depend on aggregate particle shape, particle size uniformity and degree of binder, if present, but will range from 20 to 25 tons per minute for hot-mix down to as low as 10 to 12 tons per minute for aggregate. The unit can also be used to haul wetbatch, portland-cement concrete, but a very high chain maintenance expense can be expected.

14. A hauling unit with either a side discharge or a mechanically-operated end discharge is well-suited for discharging to a traveling surge mechanism at the paver. Provision for surge capacity in the laydown equipment may aid in achieving smoother pavement by decreasing paver stops.

General Observations — Based on Project Management practices observed in the field and discussed in Part II of the Report:

15. Better pre-planning of hot-mix plant location, laydown and facilities is a prime need because of the profound effect which these considerations exert upon materials cost, haul lengths, truck utilization and upon the health, safety and welfare of the plant crew.

16. More attention given to controlling undesirable solid, liquid and gaseous emissions from hot-mix plants will be reflected in smoother riding surfaces and greater profits.

17. Plant crews and, particularly, plant foremen need better instruction concerning the basic characteristics of hot-mix materials as these affect plant operation.

18. Plant foremen need a better appreciation of how a progressive maintenance program affects plant reliability and an understanding of the close interrelationship which exists between the plant, the distribution and the laydown links of a complete hot-mix paving operation.

19. Plant owners must delegate certain construction responsibilities to their lower management. However, owners should not abdicate their own responsibility to control the overall execution of the contract.

20. The practice of using hired trucks to haul hot-mix from the plant to the laydown machine may well be a significant cause of pavement roughness because of the difficulty of controlling a group of independent trucking sub-contractors so as to prevent bunching of trucks and delays between truck arrivals at the plant as well as at the laydown machine.

21. All other factors being equal, owning the largest acceptable hauling units and operating them with a disciplined group of drivers may result in a lower cost per ton of hot-mix in-place on the raod (and in a greater degree of pavement smoothness) even though the price per ton mile offered by the contract trucker may be lower than the comparable owned cost.

TABLE OF CONTENTS

	Page
INTRODUCTION	i
CONCLUSIONS AND OBSERVATIONS	iv
TABLE OF CONTENTS	xii
LIST OF TABLES	xv
LIST OF FIGURES	xvi
PART I - INVESTIGATION OF HOT-MIX DISTRIBUTION SYSTEMS	1
Key Words	1
Abstract	1
Chapter I - Objectives and Approach	2
Objectives	2
Approach	3
Selection of Simulation as an Analysis Technique	6
Chapter II - Data Analysis	9
Cycle Elements	9
Log-Normal Description of Cycle Element Times	12
Travel Times	16
Chapter III - The Model	24
Measures of Effectiveness	24
Input Variables	25
Output	28
Model Technology	29
Chapter IV - Investigation of Basic Systems	37
Definition of Basic Systems	37
Basic Systems Input Variables	40
Simulation of Basic Systems Performances	47

TABLE OF CONTENTS (CONTINUED)

Page

Chapter V - Investigation of Surge Loading and Windrowing 74

Input Variable Values 74
Effects on Systems Performance of Surge Loading and Windrowing 76
Windrowing 77
Surge 79
Combined Surge and Windrowing 82
Effects of Surge and Windrowing on Other Systems Configurations 84
Effects of External Delays 91

Chapter VI - Investigation of Means to Improve Distribution Systems Performance 93

Cost Considerations 93
Production Considerations 97
Overall Systems Considerations 102
Characteristics of Distribution Sub-Systems . . 106
Innovative Concepts With a Potential for Improving Distribution Sub-System Performance 109

Chapter VII - Urban Haul Situations 125

References - Part I 130

PART II - CONSTRUCTION MANAGEMENT PRACTICES 131

Key Words 131
Abstract 131

Chapter I - General Construction Practices Background 132

Interrelationships Within the Total Hot-Mix Production-Laydown System 132

TABLE OF CONTENTS (CONTINUED)

Page

Chapter II - Hot-Mix Production 141

General 141
Aggregate Stockpiles 142
Cold Feed Control 144
The Mixing Process 146

Chapter III - The Distribution of Hot-Mix to the Laydown Machine 148

General 148
The Flowboy Hauling Unit 149

Chapter IV - Hot-Mix Laydown Considerations 152

General 152
Hot-Mix Paver Operation 153

References - Part II 154

APPENDIX I - THE COMPUTER PROGRAM AND PROGRAM LISTING . . I-1

APPENDIX II - COMPILATION OF OWNING AND OPERATING COSTS FOR BASIC SYSTEMS PLANT AND PAVER SPREADS. . II-1

APPENDIX III - FORMS FOR RECORDING PLANT AND PAVER OBSERVATIONS III-1

APPENDIX IV - CONTRACTORS VISITED IV-1

LIST OF TABLES

Table | Page

PART I

1. Distribution of Discharge Times into Paver, X Y Z Construction 15

2. Non-Delay Speed Equations Used in the Model for Rural Haul Situations 20

3. Basic Systems Simulations Performed 39

4. Input Variables 42

5. Hourly Owning and Operating Costs, Plant and Paver Spreads 46

6. Development of a Deterministic Estimate of Haul Unit Production 55

7. Windrow Spreading Time Parameters 76

8. Performances Associated With Production Utilizing Surge Loading and Windrowing . . 80

9. Deterministic Production Estimate 95

10. Deterministic Estimates of Unit Costs 96

11. Contributions of Haul Unit Cycle Time Elements to Per Ton Unit Costs 103

PART II

1. Construction Management Inefficiencies 133

2. Construction Management Efficiencies 137

LIST OF FIGURES

Figure Page

1. The Log-Normal Distribution 12
2. Regression Curve for Speed vs. Distance 18
3. Model Output: Mean Cost and Production 30
4. Model Output: System Performance 31
5. Model Output: Haul Unit Performance 32
6. Model Output: System Information 33
7. Possible System Configurations 35
8. Basic Systems Performances: 200 TPH Plant; 1 Mile Haul 48
9. Basic Systems Performances: 200 TPH Plant; 7.5 Mile Haul 49
10. Basic Systems Performances: 200 TPH Plant; 27.5 Mile Haul 50
11. Basic Systems Optimum Performances: 200 TPH Plant; 1, 7.5 and 27.5 Mile Hauls . 51
12. Basic Systems Performances: 400 TPH Plant; 1 Mile Haul 58
13. Basic Systems Performances: 400 TPH Plant; 7.5 Mile Haul 59
14. Basic Systems Optimum Performances: 400 TPH Plant; 1, 7.5 and 27.5 Mile Hauls . 60
15. Basic Systems Performances: 600 TPH Plant; 1 Mile Haul 61
16. Basic Systems Performances: 600 TPH Plant; 7.5 Mile Haul 62
17. Basic Systems Optimum Performances: 600 TPH Plant; 1, 7.5 and 27.5 Mile Hauls . 63

LIST OF FIGURES (CONTINUED)

Figure Page

18. Basic Systems Performances: 7.5T Haul Unit; 1 Mile Haul 65

19. Basic Systems Performances: 7.5T Haul Unit; 7.5 Mile Haul 66

20. Basic Systems Performances: 15T Haul Unit; 1 Mile Haul 67

21. Basic Systems Performances: 15T Haul Unit; 7.5 Mile Haul 68

22. Basic Systems Performances: 22.5T Haul Unit; 1 Mile Haul 69

23. Basic Systems Performances: 22.5T Haul Unit 7.5 Mile Haul 70

24. Effects of Delays on System Performance 72

25. Effects of Surge and Windrowing 78

26. Effects of Surge and Windrowing on Small Plant. . 85

27. Comparative Effects of Surge and Windrowing; Small, Medium and Large Plants 87

28. Effects of Surge and Windrowing: Long Haul Distances 89

29. Effects of Delays on System Performance 92

30. Performance of 40T Off-The-Road Hauler vs. 22.5T Haul Unit 111

31. Performance of 45T Semi-Trailer, Trailer Combination vs. 22.5T Haul Unit 114

32. Performance of Side Discharge Haul Unit vs. Conventional Haul Unit 116

33. Performance of Mechanically Discharged Haul Unit 119

LIST OF FIGURES (CONTINUED)

Figure | Page

34. Performance of System Employing Traveling Surge Mechanism at Paver. 121

35. Performance of 1000 TPH Plant vs. 400 TPH Plant 124

36. Urban Haul Situation 127

PART I

INVESTIGATION OF HOT-MIX DISTRIBUTION SYSTEMS

PART I - INVESTIGATION OF HOT-MIX DISTRIBUTION SYSTEMS

KEY WORDS: hot-mix operations; production; distribution; laydown; operating parameters; costs; computer modeling; Monte-Carlo simulation

ABSTRACT: Hot-mix paving is carried out by a random time materials handling and transfer system consisting of a plant sub-system, a paving sub-system and a distribution sub-system. To investigate the performances of hot-mix systems, and distribution sub-systems in particular, a model is developed for computer simulation of hot-mix production-distribution-laydown operations. Input values for operating variables of the model are obtained from field observations and cost data. Analyses are made of conventional hot-mix systems using the model. The effects of surge loading and windrowing are investigated. Innovative and/or unconventional systems are also investigated to determine their potentials for use in the field.

PART I - INVESTIGATION OF HOT-MIX DISTRIBUTION SYSTEMS

CHAPTER I

OBJECTIVES AND APPROACH

Objectives

This NAPA sponsored research project has as its major objective the investigation of distribution systems used to convey hot-mix asphaltic concrete from its point of origin at the plant to its point of discharge at the laydown machine. Specifically, it is desired to ascertain whether conventional systems are efficient and economical, which conventional systems are most efficient and most economical, and what innovative systems might prove to be more efficient and more economical if brought into use. In pursuit of this objective, sub-objectives were established consisting of the following:

a. Study thoroughly as many and as varied hot-mix operations as feasible within the limitations of time, distance and the project budget.

b. Analyze hot-mix operations to identify and quantify those particular elements or characteristics which have a significant bearing on the efficiency or economy of operations.

c. Analyze the interactions and performances of various distribution sub-systems within the total hot-mix paving system. Identify and quantify those characteristics of various distribution sub-systems and the environments in which they perform which have a significant bearing on the efficiency or economy of overall operations.

d. Study selected distribution sub-systems with the objective of rating the sub-systems on the basis of efficiency and economy.

In conjunction with the above, it was desired to establish a common basis for evaluating the cost aspects of various distribution sub-systems and for applying these costs in the various analyses performed. This was accomplished in a separate substudy and resulted in the development of a computer model which provides operating cost data for a variety of distribution means. A discussion of this study and documentation of the computer program are to be found in Reference 6.

Approach

The essential elements of the objective stated above for the NAPA research project required (1) data collection and (2) data analysis. Data collection consisted primarily of work carried out in the field at a number of on-going hot-mix operations. Data analysis was accomplished, on the whole, at Texas A&M relying heavily on the services of its IBM 360/65 computer.

Data Collection

Data collection for this project involved numerous trips to the field by members of the project staff to observe hot-mix operations in progress. The data collection team carried with it two super-8 timelapse motion picture cameras (marketed by the Timelapse Corporation of Palo Alto, California) by which operations were recorded at a rate ranging from one frame every four seconds to one frame every one-half second. Generally, the routine followed was the same in that one camera was set up to record operations at the plant, while the other camera followed and recorded paving operations on the road. The team devised a method of attaching numbered signs to haul units so that these vehicles could be identified later when the developed film was analyzed.

Data collection team members supplemented timelapse filming of plant and paver operations by making stopwatch observations at these locations utilizing forms designed for that purpose (forms are presented in Appendix III). Additionally, numerous 35-mm colored slides were made of hot-mix plant and paver activities. Thus, rather thorough documentations of the operations visited were made available for use in the analysis phase of the project.

In addition to data observed and recorded by the collection team, certain information gathered by the Bureau of Public Roads in a research program conducted in the 1950's and 1960's was also utilized. The data consisted of extremely detailed stop-watch observations and time breakdowns of all types of highway construction operations. Through the good offices of the Bureau, valuable data pertaining to hot-mix operations were made available to this project.

Data Analysis

Data analysis for the NAPA project consisted chiefly of two fundamental activities: (1) generation and ordering of raw data resulting from data collection operations, and (2) manipulation or use of the ordered data for overall analysis purposes.

Data generation and ordering for the project was concerned for the most part with developing time distributions for the primary elements making up the production-distribution-laydown cycle of hot-mix operations. All information gathered in the data collection phase of the project was subjected to exhaustive and painstaking review to determine — as precisely as possible — the times associated with the primary operational activities of each job visited. That is, times were determined for each repetition of each cycle element such as haul unit loading at the plant, haul unit maneuvering into position at the paver, haul unit discharging into the paver, etc. These times were then ordered on the basis of ascending values and time distributions developed for each cycle element for each job studied.

The use made of the data generated in the manner described above is the major subject of Part I of this report. The data so generated became the basis for and the input parameters into a computer model designed to analyze hot-mix operations by means of the operations research technique known as Monte-Carlo simulation. Using this technique, it became possible to analyze the performances of a number of differing distribution sub-systems operating within complete hot-mix production-laydown systems. The characteristics of these various means of distributing the hot-mix could be controlled in the computer model to simulate very closely actual, observed performances. This being the case, any observed differences in performances among the various means of hot-mix distribution incorporated in the model simulation could be attributable wholly to the distribution sub-systems.

Selection of Simulation as an Analysis Technique

Hot-mix production-distribution-laydown operations are typical of what Teicholz (4,5) describes as link-node materials handling systems. Such systems are characterized by materials handling units which perform cyclically within their respective links and which interact with other materials handling units at points of transfer or nodes. In the case of a conventional hot-mix operation, there is a three-link, two-node configuration in which the plant, the haul units, and the paver comprise the links, and the points of transfer of the hot-mix from the plant to the haul units to the paver constitute the nodes. Addition of such features as surge bins and windrowing operations affect transfer considerations at the nodes, but the basic system remains three-link. The greatest efficiency within any link-node materials handling system occurs when each link is producing at its maximum and is in balance with the other links, i.e., when the productive capacity of all links are maximum and equal. Only a fully-automated system could be expected to realize its greatest efficiency, and even then, the slightest malfunction or mechanical breakdown would upset the balance and reduce system efficiency. The objective in non-fully-automated systems, such as those for producing, distributing and placing hot-mix, is to achieve the maximum balance and efficiency possible after consideration of the costs involved.

Link-node, materials-handling element times, in general, and hot-mix, link-element times, in particular, are stochastic in nature. This is to say, the times occur randomly as opposed to occurring in some fixed pattern. Our studies showed that even fully automated hot-mix batch plants had some degree of randomness associated with batching times, and when the operators overrode the automated controls to operate manually, the variance of the batching times increased accordingly. This randomness of element times and the interactions of these random times account for the varying production performance of a hot-mix plant or a hot-mix production-distribution-laydown system over a period of time. Any analysis of such a system or of any link or component of such a system must take into account this element of time randomness inherent in the system or link; otherwise, the analysis will give misleading and normally over-optimistic results. Gaarslev (3) showed that non-stochastic or deterministic analyses of a number of construction materials handling systems led, in all cases, to estimates of production rates significantly greater than actual production rates and that these actual rates were more closely approximated through analyses recognizing the stochastic or random natures of the times involved.

Simulation was selected as the analytical technique for this study. This operations research method lends itself extremely well to the type of analysis situation presented by a link-node system such as hot-mix production-distribution-laydown in that a great number of interacting variables (including those random in nature) can be accommodated and their individual or interactive effects incorporated in the analysis. Such a system is so complex that description of the system by a mathematical model is well nigh impossible. Moreover, correct analysis of the model (if it were possible to develop one) would require a level of mathematical sophistication at or beyond the range of most persons attempting such an analysis.

The simulation model developed for this study was written in the FORTRAN IV programming language for use on a digital computer (IBM 360/65). It employs the Monte-Carlo technique for selection of stochastic variate values appearing in the model and can be used to simulate a wide range of production-distribution-laydown situations.

CHAPTER II

DATA ANALYSIS

Cycle Elements

Production Times

To simulate a hot-mix production-distribution-laydown system effectively by means of a computer model, the essential elements within each link or cycle must be determined and their values quantified. This was accomplished in the study using the information gathered during the data collection phase. After study of this information, the following elements were determined to be operationally significant and were quantified for each operation for which data was obtained:

- Plant cycle
  - Batch time
  - Haul unit loading time
- Paver cycle
  - Laydown time
- Haul unit cycle
  - Travel speed loaded
  - Travel speed empty
  - Maneuver time into paver
  - Maneuver time after leaving paver
  - Spreading time (if windrowing is used)

Delay Times

Delay times were found to have a very significant impact on production in the study. Every operation observed had some amount of delay time associated with it, ranging from nominal amounts to times that seemed, at the very least, excessive and unnecessary.

Two general types of delays were noted: (1) internal delays or delays that occurred or were induced within the system when one production, distribution or placing unit had to wait for another before it could continue its cycle, and (2) external delays or delays that were caused by factors that were external to the system.

Internal delays can be further broken down into two types. The majority of internal delays result when one unit of a given link has to wait for another at a transfer point before it can continue its cycle. For example, an internal delay results when a batch plant waits for a haul unit to arrive so that it can continue mixing operations, or when a paver waits for a haul unit to arrive so that it can resume paving operations. This type of delay might be termed a waiting delay. Another type of internal delay results when a haul unit traveling at one rate of speed catches up with but is unable to pass another haul unit proceeding at a slower speed. The faster haul unit then has to slow down and follow the slower unit until such time as it can pass or the remaining distance to the paver or plant has been traversed.

External delays result from a number of factors which occurred fairly commonly on the jobs observed. A partial but certainly not complete listing of external delay factors observed during the study includes:

Weather
Equipment breakdowns (plant, paver and haul unit)
Equipment maintenance
Equipment fueling
Spraying dump beds with diesel fuel
Driver stopping for rest halt, coke, water, etc.

Plant operator inefficiency or error
Paver operator inefficiency or error
Driver inefficiency or error
Inspector halting operations to take sample
Heavy traffic conditions along haul route

Undoubtedly the most significant external delay factor that was observed during this study was weather. Whenever rain begain to fall in any appreciable amount, paving operations and, hence, all operations ceased. Because paver laydown operations cannot continue during periods of rainfall, this factor affects all hot-mix operations equally, regardless of the type, size and characteristics of the haul units transporting the mix. Because all operations are affected in the same manner by rain, because the amount of delay caused by this factor varies so greatly, and because it is the one factor absolutely beyond the control of operations management, weather was not included among the external delay factors considered in this study.

It should be recognized that it is the combined effect of internal and external delay times which accounts for the high degree of variability in the cycle times of the hauling units selected for a given hot-mix paving operation. Some of these delays can be minimized by the contractor. Others lie beyond his sphere of control. Thus, a certain amount of variability will always be present in the production, distribution, and placement of hot-mix. The objective is to hold this variability to the irreducible minimum.

Log-Normal Description of Cycle Element Times

As noted above, those elements of batching, hauling, and lay-down cycle times observed to be significant in the total system operation were timed and their distributions quantified. It then became necessary to find some means of including the element time distributions in the computer model developed for the study short of explicitly feeding in the values for each distribution array each time the model was exercised for a particular situation. In addition to being a laborious process of preparation, the explicit feeding into the model of each element time distribution would prove to be an inefficient process from the standpoint of computer time consumption. Therefore, a simpler and more efficient means of describing element times in the model during computer simulation was sought. The means adopted was use of the log-normal distribution.

A typical log-normal distribution curve is shown in Figure 1.

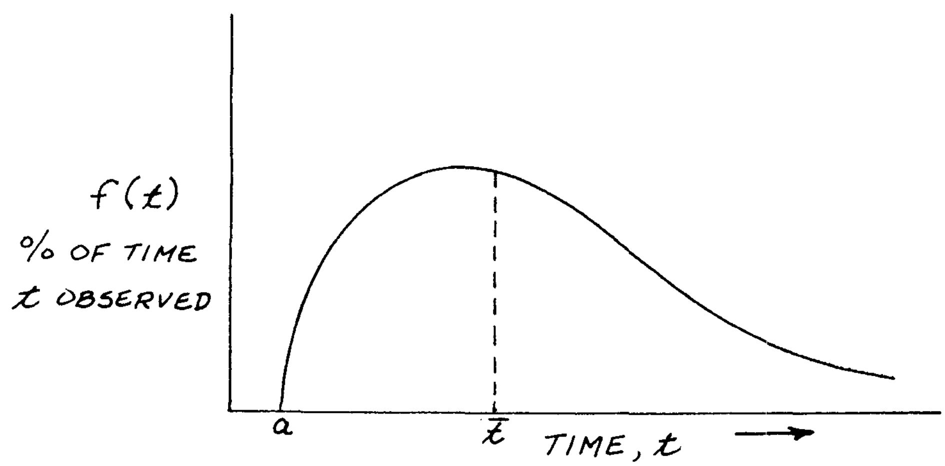

FIGURE 1. - THE LOG-NORMAL DISTRIBUTION

Earlier studies (3,4) have shown that this distribution yields good approximations for times associated with construction operations (the distributions of many other variables such as incomes and annual precipitation are also well approximated by this distribution). The essential features of the log-normal distribution are: (1) it is non-negative; (2) it is skewed to the right, the amount of skew depending upon the ratio of the standard deviation of the distribution to the mean of the distribution (known as the coefficient of variation - the greater the value of the ratio, the more pronounced is the skew); and (3) there is some minimum value, "a", associated with the distribution ("a" may be equal to zero). The name of the distribution derives from the fact that the logarithm (to any base greater than 0) of (t-a) is normally distributed, i.e., $\log_z (t-a)$ is normally distributed for all values of $t>a \geq 0$ and $z>0$.

Distributions of hot-mix cycle element times closely resemble the general shape of log-normal curves. In the case of loading times of haul units at the plant, for example, there is some minimum time (corresponding to "a" in Figure 1) below which no loading times fall. This is the non-delay time required to mix and dump the number of batches loaded into the haul unit. Then, because of external delays (internal delays are not a factor here; they occur between elements but not within element times), the durations of loading times vary increasingly from this minimum value. In the case of a breakdown, one loading time out of a hundred might vary from the non-delay time by as much as 700% or 800%. This corresponds to the tail skewing to the right in Figure 1. The remainder of times are distributed between the maximum and minimum loading times. Because the majority of delay times to be expected are of relatively short duration, the mean loading time is closer in value to the minimum, non-delay time than it is to the maximum time. Again, the shape of the curve depends on the ratio of the standard deviation of the loading times to the mean of the loading times.

Table 1 shows the cumulative distribution function, F(t), of discharge times of haul units into the paver for one of the operations observed during the study. Using the parameters "a" (minimum observed discharge time), "$\bar{t}$" (mean observed discharge time), and "S_t" (standard deviation of observed discharge times), a log-normal cumulative distribution function, G(t), was developed by generating and ordering the results of 200 random samplings of the distribution represented by the equation

$$g(t)= \frac{1}{(t-a)S_x\sqrt{2\pi}} \exp\{-\frac{1}{2}[\frac{\ln(t-a)-\bar{x}}{S_x}]^2\}$$

the normal distribution of the natural logarithm of (t-a). The actual means by which this sampling was accomplished was to run 200 replications on the computer of the equation $t = a+\exp(\bar{x}+S_x \cdot V)$, the expression for a log-normally distributed random variate wherein "$\bar{x}$" is the mean of the normal distribution of ln(t-a), "S_x" is the standard deviation of the distribution and "V" is a normally distributed random variable. "$\bar{x}$" and "S_x" are derived from the observed parameters "a", "$\bar{t}$" and "S_t" by means of the equations:

$$\bar{x} = \ln(\bar{t}-a) - \frac{S_x^{\ 2}}{2}$$

and

$$S_x = \{\ln[1 + (\frac{S_t}{\bar{t}-a})^2]\}^{1/2}$$

The cumulative distribution function, G(t), for the generated values of t also appears in Table 1.

TABLE 1. - DISTRIBUTION OF DISCHARGE TIMES INTO PAVER, XYZ CONSTRUCTION COMPANY

	Observed		Generated		
t(minutes)	f(t)	F(t)	g(t)	G(t)	|G(t)-F(t)|
1.101-1.200	.032	.032	.040	.040	.008
1,201-1.300	.194	.226	.245	.285	.059-D*
1.301-1.400	.388	.614	.325	.610	.004
1.401-1.500	.161	.775	.185	.795	.020
1.501-1.600	.129	.904	.080	.875	.029
1.601-1.700	.064	.968	.050	.925	.043
1.701-1.800	.000	.968	.025	.950	.018
>1.800	.032	1.000	.050	1.000	---

f(t) based on 31 observations of discharge times
$a = 1.15$ minutes
$\bar{t} = 1.41$ minutes
$S_t = 0.18$ minutes

Observation alone reveals the closeness to the observed distribution of the generated log-normal distribution. Moreover, using a Kolmogorov-Smirnov test (an appropriate test in an instance such as this in which the parameters of an hypothesized distribution have been developed from observed data), the "goodness" of the log-normal distribution for describing the observed distribution can be expressed more adequately. This test uses the single parameter "n", the number of observations on which the actual distribution is based (in this case, 31) and the test statistic D*, the maximum of the absolute values of the differences between G(t) and F(t) (critical values for D* are contained in most texts on statistics). In this case, the hypothesis is advanced that the observed data are log-normally distributed with parameters a, $\bar{t}$, and S_t. The hypothesis can be accepted if the test statistic D* (.059 from Table 1) is less than the critical value for D* obtained from an appropriate table (cf. (1)p. 667). At a level of significance of .05, the critical value for D* is 0.24, and the hypothesis cannot be rejected inasmuch as 0.059 is well less than that value.

In a like manner, it could be shown that log-normal distributions based on the three parameters "a", "$\bar{t}$", and "S_t" of observed distributions suitably represent their actual distribution counterparts in the majority of instances. In those cases in which they do not, Teicholz (4) found that the error obtained thereby is relatively small. Therefore, random sampling of log-normal distributions was the method selected to describe all varying cycle element times in the computer model. The lone exception to this is the method used to determine travel times.

Travel Times

Rural Travel Situations

The element times of travel are treated differently than other element times in the model. There are two principal reasons for this. First, because the objective of the study centered on various means of transporting hot-mix, it was desired to devise some method of developing haul unit travel times which recognized the significant characteristics of the units and/or the hauls involved. Second, the data available on travel times allowed a more detailed treatment. In this regard, information was made available to the study by the Bureau of Public Roads which had been collected over a period of some years on a sizable number of construction operations involved in highway construction. Specifically, the Bureau contributed information on hot-mix operations which included detailed time studies on haul unit cycle times as well as descriptive information in many instances on the haul units under observation. The data applied totally to rural haul situations (as opposed to city or urban situations).

From the information received from the Bureau of Public Roads, it was possible to determine values for the following factors involved in travel times for a number of cycles of a varied assortment of hauling situations:

Haul distance
Non-delay time to negotiate the haul distance
Return distance
Non-delay time to negotiate the return distance
Haul unit weight
Haul unit horsepower
Load weight

Multiple regression analysis using the computer was the means by which the correlations between these factors were analyzed, the siginficant factors determined and equations developed to describe rural, non-delay travel speeds which could be used in the computer model.

Analyses for loaded haul unit travel from the plant to the paver were run separately from those for return-empty travel from the paver to the plant. Further, analyses in both categories were run for distance classes of 0-1 mile, 1-3 miles, 3-30 miles (the maximum distance for which data was available), 0-3 miles and 0-30 miles. Individual analyses for each mileage class within the haul and return categories developed regression equations for these specific factors:

Dependent Variable		Independent Variables
Speed	vs.	Distance; weight/horsepower ratio
Speed	vs.	Log of distance; log of weight/horsepower ratio
Log of Speed	vs.	Distance; weight/horsepower ratio
Log of Speed	vs.	Log of distance; log of weight/horsepower ratio

The regression analyses performed were of a stepdown variety; that is, independent variables which failed to show a certain level of significance (specified as .05 in every case) were eliminated from further consideration, and the analysis was re-run.

Figure 2 presents a hypothetical illustration of the use made

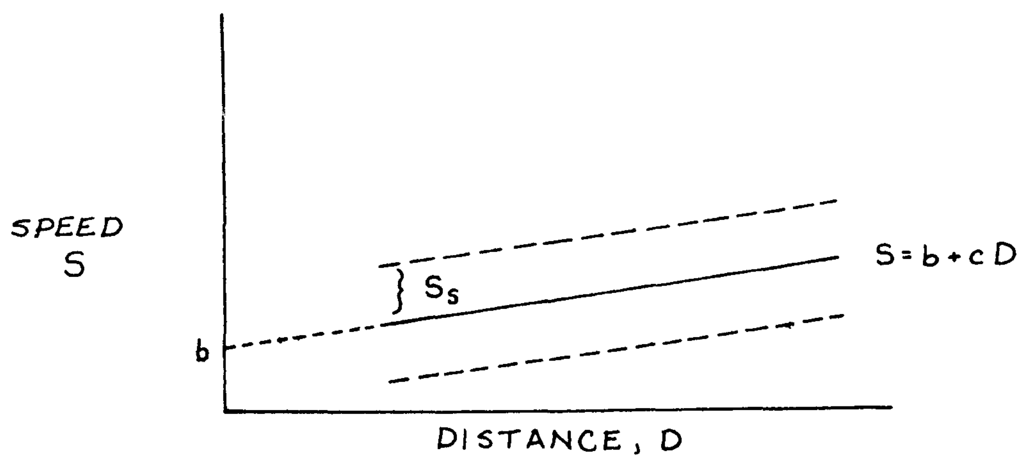

FIGURE 2. REGRESSION CURVE FOR SPEED VS. DISTANCE

in the model of the results of the regression analyses. In this much simplified example, speed is shown to be correlated to the lone independent variable, distance, as expressed by the equation, $S = b+cD$, where the intercept, "b", and the slope of the line, "c" are both products of the regression analysis. The solid line expressing this relationship is the mean of all the sets of speed vs. distance relationships considered in the regression analysis. Differences from this mean are assumed to be normally distributed throughout its range with a standard error (corresponding to a standard deviation) of S_s. This being the case, speeds for the hypothetical example may be generated by drawing from the set of all speeds described by the equation,

$$S = b+cD+S_s \cdot V$$

where V is a normally distributed random variate. In the model, V is generated by a random number process.

Table 2 lists those equations for rural non-delay travel speeds selected for use in the model from the total of all analyses run on BPR data on the basis of the degree of correlation established between the dependent variable (speed or log of speed) and the independent variable or variables. The equations appear as they are used in the model, i.e., with the standard error terms included.

As an example of the use of the speed equations in the model, assume a haul unit with an empty weight of 14,000 pounds hauling a net load of 27,000 pounds. The haul unit rated horsepower is 202. Haul distance and return distance are both equal to 12.5 miles.

TABLE 2. - NON-DELAY SPEED EQUATIONS USED IN THE MODEL FOR RURAL HAUL SITUATIONS

Distance	Equation for Speed
Haul	
0-1 miles	$S = 10^{(1.1081 + .211D + .0995V)}$
1-3 miles	$S = 10^{(1.5126 + .0433D - .000763\ WHP + .2870V)}$
3-30 miles	$S = 70.433 + 15.744 \text{ Log } D - 20.594 \text{ Log } WHP + 2.476V$
Return	
0-3 miles	$S = 10^{(1.668 + .3639 \text{ Log } D - .1640 \text{ Log } EWHP + .3046V)}$
3-30 miles	$S = 10^{(1.3767 + .2847 \text{ Log } D + .0883V)}$

Where:

S = Speed
D = Travel distance in miles
WHP = Total loaded weight (pounds)/horsepower ratio
EWHP = Empty haul weight (pounds)/horsepower ratio
V = Normally distributed random variate

The loaded weight/horsepower ratio is 41,000/202 = 203; the empty weight/horsepower ratio is 14,000/202 = 69.4. For the travel loaded haul, assume a normally distributed random variate equal to + .85 is generated; for the return empty portion of the cycle, the normally distributed random variate assumed generated is -1.20. For these cases, the travel speeds calculated are:

$$\text{Haul Speed} = 70.433 + 15.744 \text{ Log } 12.5 - 20.594 \text{ Log } 203 + 2.476\ (.85) = 42.16 \text{ mph}$$

$$\text{Return Speed} = 10^{[1.3767 + .2847 \text{ Log } 12.5 + .0883\ (-1.20)]} = 38.29 \text{ mph}$$

The complete time for a haul unit to travel from the plant to the paver or return in a rural situation includes not only the travel time resulting from the speed generated by one of the equations in Table 2 but also any external delay time generated for that cycle of the haul unit. Based on the probability that a delay will occur during the haul unit cycle (an input parameter to the program) an external delay time is generated by the computer using a random number process. This time is added to the travel time based on speed to give the total travel time for that phase of the cycle.

Urban Travel Situations

Urban travel times are generated in the model in a manner quite similar to those for rural travel situations. However, the times generated for the urban situation have external delays already included in them. This results from the nature of the data that was available to analyze for urban haul situations.

As indicated earlier, the data received from the Bureau of Public Roads and on which the rural haul speed equations were based included only data on rural haul situations. Therefore, information on urban haul situations had to be gathered by the project data collection team. This was accomplished through the filming and timing of jobs in Houston and Dallas. The data collected on the jobs observed at these locations included travel distances, travel times, load weights, haul unit types, and information about the haul route. Because travel times were based on observations made only at the origin and destination of a cycle travel phase, they included any delays experienced along the route; it was not possible to determine the non-delay travel times as was the case with the

BPR data.

The urban travel data was subjected to the same type of analysis as that performed on the rural haul data; i.e., multiple regression analyses were conducted to determine the correlations among recorded urban haul factors and to develop equations for the generation of urban travel speeds in the model. Specifically, multiple regression analyses were performed to determine the correlations among the following factors for both the haul loaded and return empty phases of the urban haul unit cycle:

Dependent Variable		Independent Variables
Speed	vs.	Distance; weight/horsepower ratio; number of definite stops along route; number of possible stops along route
Speed	vs.	Log of distance; weight/horsepower ratio; number of definite stops; number of possible stops
Log of Speed	vs.	Distance; weight/horsepower ratio; number of definite stops; number of possible stops
Log of Speed	vs.	Log of distance; weight/horsepower ratio; number of definite stops; number of possible stops

As was the case for the rural speeds, the analyses performed were of a stepdown type; independent variables failing to show a specified level of significance of .05 were eliminated, and the analysis was re-run.

Based on the results of the analyses, the following equations were selected to describe urban travel times in the model:

Haul loaded

$$\text{Log Speed} = 1.1733 + .2175 \text{ Log Distance} + .0986V$$

Return empty

$$\text{Log Speed} = 1.3400 + .0931 \text{ Log Distance} + .117V$$

where V is a normally distributed random variate.

It should be noted that neither the vehicle weight, horsepower, or load nor speed reducing factors along the route were determined to have the requisite degree of significance in the urban speed equations. Also, the degree of correlation existing between the dependent and independent variables in the above equations was less than that for the rural haul speed equations. These facts indicate that urban haul situations are unique and individualistic; each must be analyzed on the basis of its own particular contributing factors. Within reason, the above equations can be used to determine haul and return speeds in an urban setting (based on the data analyzed, the equations are valid for distances of from 1 to 10 miles). However, it could possibly be assumed that any size haul unit could be employed in conjunction with the equations inasmuch as the factors of haul unit weight and horsepower and load weight do not appear as factors in the equations. If from no other point of view than that of common sense, this assumption can be recognized as erroneous. The upper limit on haul unit sizes covered by the urban speed equations is therefore considered to be the size of the largest haul units observed while gathering the data, and this was 9.5 tons.

CHAPTER III

THE MODEL

Measures of Effectiveness

The major objective of the NAPA study was to investigate and evaluate various systems for the distribution of hot-mix asphaltic concrete. Therefore, the model developed for this purpose not only had to represent - in a reasonable fashion - the essential characteristics of any system investigated but also had to describe the performance of that system in a manner that facilitated comparison with any other system. It had to ascribe measures of effectiveness to system performance. Such measures of system effectiveness ought to describe performance from the standpoints of both efficiency and economy. The model was therefore constructed to determine the following primary items of information for any system simulated:

a. The average total cost in place of one ton of hot-mix. This cost includes not only the cost of the distribution means involved and the cost of materials, but also the pro-rated share of the total of plant, equipment, labor, and fuel costs involved in the preparation and laydown of the mix.

b. The average production rate of the system in tons per hour over the period of the simulated shift.

In addition to these primary measures of system performance, the model also tabulates and records various other performance data for the plant, paver, and haul system. These are described in the section on program output.

Input Variables

The input to the model for a simulation experiment comprises values for those variables which it was determined most significantly affect system performance. These variables can be classified as belonging to one of three categories, viz., management decision variables, operating variables and environmental variables. In addition, a fourth type of variable is entered which might best be called a program variable.

Management Decision Variables

This type of input variable reflects system configurations and characteristics which are decided upon by management or are directed by the contract and specifications. Specifically, these input variables include:

- Plant operations
  - Shift duration
  - Batch size
  - Batch mixing time (non-delay)
  - Batches per haul unit load
  - Gradation and unit weight of loose mix
  - Surge storage use and capacity
  - Owning and operating costs of total plant spread
- Paving operations
  - Number of pavers
  - Laydown rate of paver(s) (non-delay)
  - Laydown dimensions
  - Distance to paver(s)
  - Density of compacted mix
  - Windrow use
  - Owning and operating costs of total paving spread
- Haul unit operations
  - Number of haul units
  - Haul unit capacity
  - Haul unit horsepower
  - Haul unit weight
  - Owning and operating costs of haul unit

Operating Variables

Included in this category of input variables are parameters describing operating characteristics of the particular system configuration being investigated. Herein are entered the means, standard deviations, and minimum values of the operation cycle elements which are stochastic in nature and which will have particular values generated for them repeatedly during the simulation exercise of the model on the computer. These variables include:

- Actual load mixing and dumping times (delays included)
- Haul unit discharge times at paver
- Paver external delay times and probability of occurrence
- Haul unit external delay times and probability of occurrence
- Haul unit maneuver times at paver -
    - In preparation for discharge
    - Subsequent to discharge
- Windrow spreading times if windrowing used

The operating variables are of prime interest and importance in the model simulation. The parameters entered for them in a simulation run impart to the simulation its realistic, true-to-life aspect. These values and their interactions cause the loading time of a haul unit to have a delay involved, haul units to queue up at the plant or paver, and plant or paver to sit idle waiting for haul units to arrive. For any particular system, the variables are different, and any set of parameter values for the operating variables defines a particular system. If a specific system is to be simulated, the values of these variables can be obtained only by observation and timing of the particular system components in operation.

Although this might appear to be an involved and time-consuming process, the fact is that for most hot-mix operations, one individual can make sufficient observations in one day to suit the needs of the model.

Environmental Variables

Within this category of input variables are those variables which are external to the system configuration but which do affect its operation. Entries in this category include:

- The speed limit along the haul route
- Simple codes which indicate:
  - Whether passing is allowed along the haul and return routes
  - Whether urban or rural conditions prevail

It was mentioned earlier that the factor of weather is not included in the model inasmuch as it affects all hot-mix operations in the same manner, i.e., when it rains, all operations cease. Another factor which logically would be entered in this category of input variables is information pertaining to grades to be found along the haul route. Grades are not considered in the model because time did not permit sufficiently definitive information concerning grades to be obtained during the data collection phase of the study which would have provided any sort of reliable indication of their quantitative effects on haul unit performances. The model, then, assumes essentially level grades along the haul route (this includes grades to about three percent.)

Program Variables

This type of input variable provides information used during simulation runs of the model on the computer. Numerical codes are read in which determine:

The number of replications of a shift to be performed
Data to be printed out on system performance

The number of replications to be performed is an important consideration in a simulation run. Just as shift output or performance varies in the actual case, so it does too in the case of simulation. What is desired is to obtain an average performance figure which has a variance that is within acceptable limits. This is obtained by repeated replications; the greater the number, the more precise the mean value and the smaller the variance. However, this consideration has to be weighed against consideration of the economics of a large number of replications and the knowledge that an extremely precise mean value may be far removed from the true mean if the input data is not sufficiently accurate. In the study, four replications were used and the standard deviation of the mean cost checked. In all cases, the standard deviation was well within acceptable limits (never greater than 3.0%). Had it not been, additional replications would have been made.

Output

The information of primary interest provided by the model through simulation on the computer is that given for the measures of system effectiveness, viz., cost per ton in place of hot-mix and production in tons per hour for the system under investigation. These quantities are averaged for the number of shifts replicated in the simulation and their means and standard deviations summarized in a separate output table. Figure 3 presents an example of this output.

Additional information about the system under investigation is also included in the output. For each shift replication performed, output information is provided on efficiency, delay time and idle time for the haul units (figures given are averages). Figure 4 shows this output for one shift replication.

Information is also available on the performance of each haul unit in each shift replication. This output information is optional and can be obtained by the programmer by use of a coded input variable. Figure 5 presents an example of haul unit performance information for one shift replication.

The program also provides an output summary of the variables read into the computer to define the system for any computer simulation run. Figure 6 is an example of this system summarization output.

Model Technology

The computer simulation model developed for the study incorporates a great deal of flexibility. It was designed to handle a variety of hauling sub-systems operating within an equally varied assortment of total system configurations. The range of these

MEAN COST AND PRODUCTION

4 REPLICATIONS

NUMBER OF HAUL UNITS	PRODUCTION TONS/HOUR MEAN	STD DEV	UNIT COST DOLLARS/TON MEAN	STD DEV	PCT DEV
6	207.0	4.47	6.34	0.030	0.47
7	227.0	16.41	6.28	0.060	0.96
8	259.7	3.56	6.19	0.018	0.29
9	280.0	1.85	6.18	0.016	0.25
10	291.3	3.43	6.20	0.020	0.31
11	293.9	2.75	6.27	0.021	0.34
12	298.3	5.52	6.32	0.027	0.43

FIGURE 3. - MODEL OUTPUT: MEAN COST AND PRODUCTION

REPLICATION 1

SYSTEM PERFORMANCE - TIMES ARE PERCENTS OF TOTAL TIMES

NO OF HAUL UNITS	AVG UNIT EFF	AVG UNIT EXT DELAY	AVG UNIT INT DELAY	AVG UNIT IDLE TIME PLANT	AVG UNIT IDLE TIME PAVER	AVG UNIT TIME IN TRAVEL	PLANT EFF	PLANT DELAY	PLANT IDLE TIME	PAVER EFF	PAVER DELAY	PAVER IDLE TIME	TOTAL LOADS	MILES LAID	TONS LAID	TONS PER HOUR	COST PER TON
2	87.07	6.53	0.00	2.21	4.19	29.07	39.67	7.05	53.28	47.22	7.22	45.57	46	0.64	966.0	92.5	6.68
3	81.95	9.29	0.10	3.87	4.80	28.47	53.63	11.60	34.77	64.21	9.24	26.56	62	0.86	1302.0	125.5	6.37
4	72.13	8.89	0.79	7.10	11.08	26.38	61.48	13.01	25.51	73.46	11.94	14.60	71	0.98	1491.0	143.6	6.31
5	59.84	12.71	0.74	16.71	10.01	22.72	62.42	13.82	23.75	73.14	10.96	15.89	73	1.01	1533.0	143.1	6.46
6	55.81	6.44	2.99	21.61	13.15	23.97	68.65	14.40	16.96	81.48	11.94	6.58	79	1.09	1659.0	159.3	6.42
7	50.09	3.90	1.15	13.94	30.92	19.79	73.87	17.15	8.98	85.20	13.03	1.77	85	1.17	1785.0	166.9	6.48
8	46.89	3.14	0.61	16.21	33.15	19.42	73.45	16.72	9.83	85.80	14.12	0.08	84	1.16	1764.0	168.1	6.58

FIGURE 4. - MODEL OUTPUT: SYSTEM PERFORMANCE

REPLICATION 1

HAUL UNIT PERFORMANCES - TIMES ARE IN MINUTES

HAUL UNIT NO	TOTAL OPERATING TIME	DELAY TIME AT PLANT	DELAY TIME AT PAVER	TOTAL EXTERNAL DELAYS	TOTAL INTERNAL DELAYS	TIME SPENT IN TRAVEL	NUMBER OF CYCLES
2 HAUL UNITS OPERATING							
1	603.72	13.41	21.95	53.83	0.00	169.46	22
2	632.94	13.90	29.89	26.92	0.00	190.04	24
3 HAUL UNITS OPERATING							
1	637.58	13.50	39.93	40.45	0.00	192.84	22
2	600.79	30.36	19.91	15.17	1.88	189.22	22
3	625.23	28.18	29.52	117.56	0.00	148.43	18
4 HAUL UNITS OPERATING							
1	650.84	20.62	56.74	40.40	13.95	220.78	19
2	611.05	36.38	72.33	30.19	3.65	170.94	19
3	605.05	50.97	66.03	59.02	0.00	139.70	17
4	616.75	68.48	80.09	91.27	2.10	123.78	16
5 HAUL UNITS OPERATING							
1	621.82	91.23	38.62	134.41	4.74	143.90	13
2	609.34	95.16	47.71	45.46	1.63	158.27	16
3	637.45	116.84	49.31	68.68	16.15	158.49	15
4	650.94	94.65	103.70	127.31	0.00	106.34	14
5	607.27	124.46	73.77	21.44	0.51	143.27	15
6 HAUL UNITS OPERATING							
1	602.61	102.72	88.94	20.38	31.27	154.30	15
2	622.09	123.19	83.55	59.90	3.11	141.65	13
3	609.23	133.96	69.10	13.12	10.10	155.43	14
4	629.22	147.08	91.56	18.43	37.80	169.11	13
5	628.02	138.50	66.11	101.80	6.27	130.06	11
6	601.58	152.73	86.33	24.13	21.85	134.70	13
7 HAUL UNITS OPERATING							
1	625.15	88.35	153.54	29.06	12.86	146.21	13
2	635.30	69.53	205.22	36.41	12.28	137.03	12
3	641.79	92.84	208.81	25.27	2.50	105.31	13
4	596.58	86.79	178.63	28.10	0.00	107.75	12
5	648.52	82.77	206.10	19.98	22.33	143.65	12
6	607.50	94.88	187.16	16.06	0.00	108.29	12
7	598.17	91.73	206.44	14.81	0.00	111.09	11
8 HAUL UNITS OPERATING							
1	588.53	94.45	197.46	18.37	0.00	118.52	10
2	610.47	73.74	221.35	30.61	1.85	114.77	11
3	602.16	91.61	197.20	7.90	15.45	126.70	11
4	625.04	101.52	205.18	19.13	0.02	119.12	11
5	633.49	113.81	217.45	12.52	0.00	107.59	11
6	605.09	96.44	188.54	24.19	12.35	124.74	10
7	618.38	110.77	193.57	10.71	0.00	140.62	10
8	589.67	107.56	194.39	29.62	0.00	94.02	10

FIGURE 5. - MODEL OUTPUT: HAUL UNIT PERFORMANCE

SYSTEM INFORMATION

JOB NO 22.5/200/1.0

PLANT
BATCH SIZE - 6000. POUNDS
SURGE LOADING USED - 0
SURGE CAPACITY - 0. TONS
SURGE AVAILABLE AT START - 0. TONS
SPECIFICATION BATCH TIME - 0.75 MIN
MEAN BATCHING TIME - 6.419 MIN FOR 7 BATCHES
BATCH TIME STANDARD DEVIATION - 1.60
TOTAL PLANT SPREAD O&O COST -$ 188.89 PER HOUR
MIX DENSITY AT PLANT - 105. PCF
MIX MATERIALS COST -$ 3.80

HAUL UNITS
LOAD WEIGHT - 42000. POUNDS
HORSEPOWER - 221.
VEHICLE WEIGHT - 24000. POUNDS
EXTERNAL DELAY PROBABILITY - 50.0 PCT
DELAY MEAN - 5.000 MIN, STD DEV - 10.000 MIN
FIRST MANEUVER MEAN - 0.920 MIN, STD DEV - 0.920 MIN
FIRST MANEUVER MINIMUM TIME - 0.400 MIN
SECOND MANEUVER MEAN - 2.379 MIN, STD DEV - 1.283 MIN
SECOND MANEUVER MINIMUM TIME - 0.700 MIN
HAUL UNIT O&O COST -$ 21.57 PER HOUR

PAVER
NUMBER OF PAVERS - 1
PAVEMENT WIDTH - 12.0 FEET
PAVEMENT DEPTH - 4.0 INCHES
WINDROWING USED - 0
MAX WINDROW LOADS AHEAD OF PAVER - 0
SPREADER BOX USED - 0
SPREADER BOX HOOKUP TIME - 0.00 MIN
SPREADER BOX UNHOOK TIME - 0.00 MIN
MEAN WINDROW DISCHARGE TIME - 0.00 MIN
WINDROW DISCHARGE STD DEV - 0.00 MIN
MINIMUM WINDROW DISCHARGE TIME - 0.00 MIN
NON-DELAY PAVER LAYDOWN RATE -11.5 FPM
EXTERNAL DELAY PROBABILITY - 83.3 PCT
DELAY MEAN - 1.208 MIN,STD DEV - 0.864 MIN
MINIMUM DELAY TIME - 0.500 MIN
TOTAL PAVER SPREAD O&O COST -$ 140.49 PER HOUR
MIX DENSITY IN PLACE - 144. PCF

HAUL ROUTE
HAUL DISTANCE AT START - 1.00 MILES
RETURN DISTANCE AT START - 1.00 MILES
LAYDOWN DIRECTION - 1
PASSING PERMITTED - 0,SPEED LIMIT - 60. MPH
URBAN HAUL - 0

PROGRAM INFORMATION

APPROXIMATE SIMULATED SHIFT DURATION - 10. HOURS
NUMBER OF REPLICATIONS - 1

FIGURE 6. - MODEL OUTPUT: SYSTEM INFORMATION

system configurations is illustrated in Figure 7. By properly selecting values for the parameters of the haul unit operating variables, any conventional haul unit can be simulated and its performance investigated by means of the model. Likewise, the performances of unique, unconventional, and/or innovative haul unit concepts can also be simulated using the model if the values of their operating variable parameters can be estimated to a reasonable degree of accuracy.

Rules and Assumptions

The model operates under a set of simple rules and assumptions. These may be divided into two groups, those controlling loading and discharge phases of the operations cycle and those controlling the travel phase of the cycle. The rules and assumptions under which the model operates are these:

Loading and discharge

1. A plant delivers a constant batch size.
2. A haul unit loading from either plant or surge takes on a full load.
3. Haul units are handled on a first-come-first-serve basis at both plant and paver. If plant or paver is occupied, units form a waiting line.
4. If five or more units are hauling and none of the units is within twenty seconds of the plant, the plant shuts down and does not resume operations until two haul units are waiting to be loaded.
5. External delays experienced by the plant occur during loading. (While this does not conform totally to reality, insufficient data was available to determine the percent of plant external delays that occurred when a haul unit was not in the loading position. The possible error introduced affects only one haul unit, the one being loaded; any others

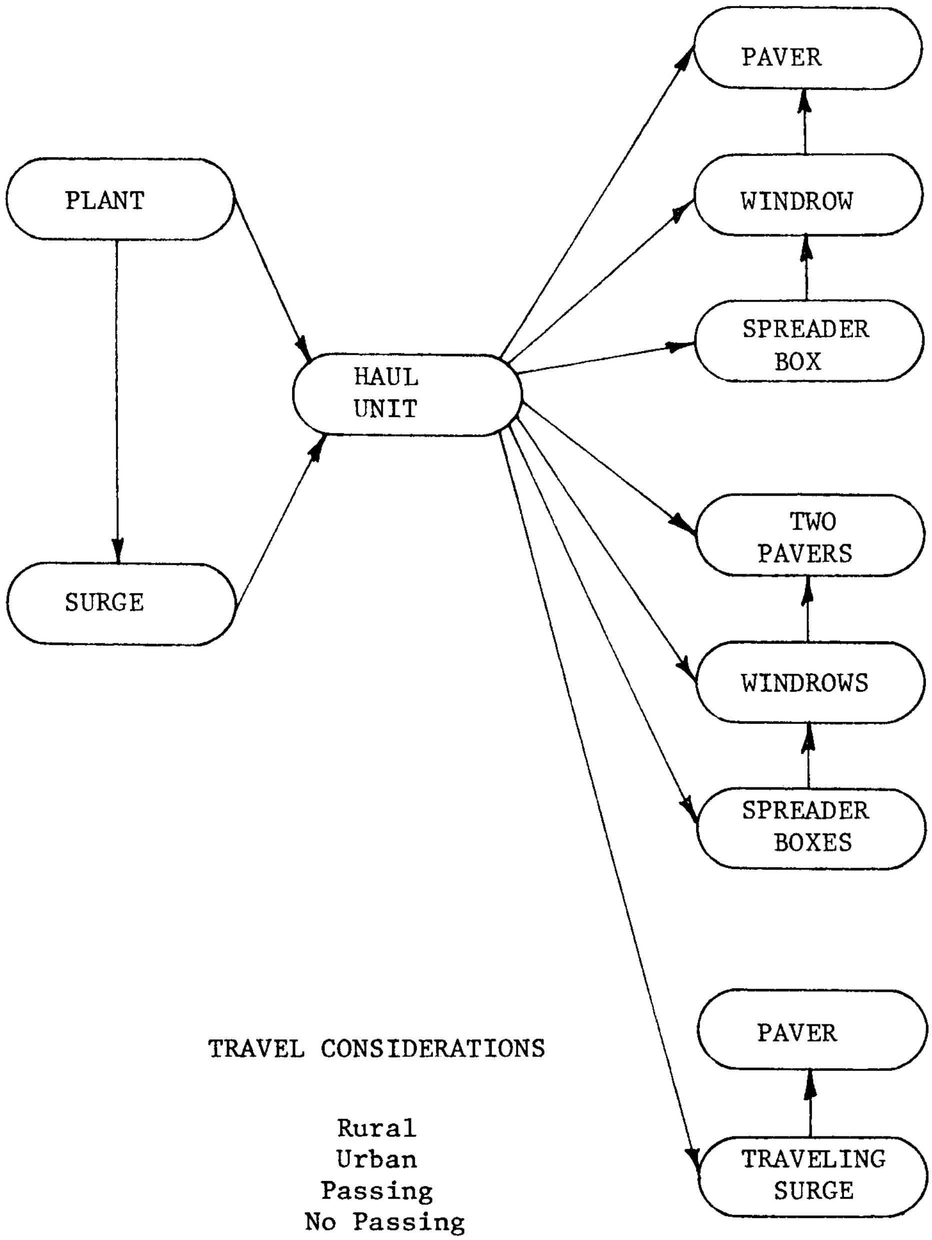

FIGURE 7. - POSSIBLE SYSTEM CONFIGURATIONS

waiting in line would be affected anyway.)

Travel

1. External delays experienced by haul units occur during the travel phase. (Again, data available was insufficient to determine the percentages of delays occurring at various points in the haul unit cycle.)

2. External delays may occur during the haul loaded phase and during the return phase of haul unit travel. The probability of a delay occurring during either the haul loaded phase or the return phase is equal to one-half the probability of a delay occurring during the haul unit cycle.

3. Haul units can pass only while in the travel portion of the cycle.

4. If the condition of no passing is specified, faster units must follow slower units to their destination. In the event a slower unit suffers an external delay, it may be passed.

Logic of the Model

The logic of the model as well as discussion of its flow and flow diagrams of the program are contained in Appendix I.

CHAPTER IV

INVESTIGATION OF BASIC SYSTEMS

This chapter and those that follow in Part I of the report are concerned with applications of the computer simulation model described in Chapter III. This chapter describes experiments performed using the model to investigate basic hot-mix operating systems. That is, the experiments conducted were concerned with systems in which the haul units were loaded directly from the plant and discharged directly to the paver. The haul units were all end dumping. Chapter V discusses experiments performed to investigate systems employing surge storage and windrowing operations. Chapter VI describes experiments performed in the investigation of innovative concepts. Urban haul experiments are discussed briefly in Chapter VII.

Definition of Basic Systems

The difficulty in investigating construction systems comprising two or more materials handling links lies in the fact that there is an almost infinite set of possible system combinations, each having its own peculiar defining parameters and operating characteristics. The initial problem becomes one of settling on those particular system combinations to be investigated which are reasonably representative of the total set of all possible systems and the investigation of which will provide meaningful information generally applicable to the major portion of those systems.

In this study, an array of basic hot-mix production-distribution-laydown systems was selected for investigation which it was believed would provide good general information about the total array of possible systems and, of equal importance, would serve as a basis of comparison for the investigations of particular systems. The basic systems array consisted of:

a. Three haul unit sizes

   1. Small - 7.5 tons capacity

   2. Medium - 15 tons capacity

   3. Large - 22.5 tons capacity

b. Three nominal plant sizes

   1. 200 tons per hour

   2. 400 tons per hour

   3. 600 tons per hour

c. Three initial haul distances

   1. 1.0 mile

   2. 7.5 miles

   3. 27.5 miles

d. A fixed paving operation

   1. Pavement dimensions 12 feet by 4 inches

   2. Paver laydown rates governed by plant production rates

With regard to d. 1. above, the 4" pavement thickness was selected as representative of all possible pavement depths. Had two differing pavement depths been investigated, this would have doubled the number of computer runs required; three pavement depths would have tripled the number of runs, etc.

Initially, it was envisioned that simulation experiments would be run for a haul unit of each capacity loading from each plant and traveling over each distance to the paver. However, a few basic calculations revealed that in some instances, the number of hauls involved would probably be quite large (e.g., on the order of 90 units in the case of 7.5·ton haul units loading from a 600 TPH plant and traveling over a 27.5 mile haul route to the paver). Since about 30 units were thought to be the maximum number that could be considered as feasible on a job, this figure was selected as the cutoff in determining whether a basic system simulation experiment would be run. Table 3 indicates the basic system simulations conducted based on this cutoff criterion.

TABLE 3. - BASIC SYSTEMS SIMULATIONS PERFORMED

Haul Unit	Plant	Distance 1.0 Mile	7.5 Miles	27.5 Miles
7.5T	200 TPH	Yes	Yes	Yes
15T	200 TPH	Yes	Yes	Yes
22.5T	200 TPH	Yes	Yes	Yes
7.5T	400 TPH	Yes	Yes	No
15T	400 TPH	Yes	Yes	No
22.5T	400 TPH	Yes	Yes	Yes
7.5T	600 TPH	Yes	No	No
15T	600 TPH	Yes	Yes	No
22.5T	600 TPH	Yes	Yes	No

Basic Systems Input Variables

The input variables for the basic systems simulated, although based on field observations, actually consisted of values representing composite haul units which in turn reflected significant characteristics of and differences among the three haul unit size categories comprising the basic systems array. To state it differently, the variable values input for the 7.5 ton haul unit category reflected a composite 7.5 ton haul unit, those for the 15 ton haul unit category a composite 15 ton unit and those for the 22.5 ton category a composite 22.5 ton unit. While the 7.5 ton unit was a single axle bobtail dump and the 15 ton haul unit was a tandem axle bobtail dump, the 22.5 ton haul unit was a tandem axle, end dumping, semi-trailer. Average operating variable parameters were used to describe the performance characteristics of the haul units in their cycle operations. In each case, the haul unit cycle consisted of:

Load directly from plant

Travel loaded to paver

Maneuver into position for discharge (first maneuver time)

Discharge to paver

Turn around for return trip (second maneuver time)

Return empty to plant

The physical characteristics of the haul situation remained the same for the three haul distances considered in the simulations. In each case, the haul situation had these characteristics:

An initial haul distance of 1.0, 7.5 or 27.5 miles

A return distance equal to the haul distance

The increment of distance realized from each load discharged extending away from the plant (i.e., increasing the haul and return distances)

A rural setting

A haul unit speed limit of 60 miles per hour

Passing not possible at the 1.0 mile haul distance but possible at the 7.5 and 27.5 mile distances

Input Variable Values

Table 4 presents the input variable values used to describe the basic systems in the simulations performed for these systems. Several comments concerning these values are in order. First, note that the batch size varies for the 200 TPH and 400TPH plants whereas it remains the same for each haul unit at the 600 TPH plant. In the case of the 200 TPH plant, this occurs for the reason that the plant is capable of producing a maximum batch size of 3 tons which is a common denominator of the 15T haul unit capacity but not of the 7.5T and 22.5T units. For these units, two options are open: (1) use the maximum batch size and not make full use of the haul unit capacity (i.e., load 2 batches or 6 tons in the 7.5T unit and 7 batches or 21 tons in the 22.5T unit); or (2) reduce the batch size and fill the units to capacity (in which case the 7.5T haul unit would haul 3 batches of 2.5 tons and the 22.5T unit would haul 9 batches of 2.5 tons). Option (2) was used for the 7.5T haul unit while option (1) was selected for the 22.5T unit. The same problem and corresponding options are present in the cases of the 400 and

TABLE 4. - INPUT VARIABLES

Variables	Plant Size / Haul Unit	200 TPH			400 TPH			600 TPH		
		7.5T	15T	22.5T	7.5T	15T	22.5T	7.5T	15T	22.5T
Plant Spread										
Shift duration, hrs		10	10	10	10	10	10	10	10	10
Batch size, tons		2.5	3	3	6	5	5.625	7.5	7.5	7.5
No. of batches/ load		3	5	7	1	3	4	1	2	3
Non-delay batch time, min		0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Mean plant time/ load, min		2.751	4.585	6.419	0.917	2.751	3.668	0.917	1.843	2.751
Standard deviation, min		0.686	1.144	2.050	0.229	0.686	0.916	0.229	0.485	0.686
Owning and operating cost, $/hr		188.89	188.89	188.89	360.33	360.33	360.35	513.59	513.59	513.59
Paver Spread										
Non-delay laydown rate, fpm		9.5	11.5	11.5	23.0	20.0	22.9	34.5	34.5	34.5
Probability of external delay, %		83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3	83.3
Mean delay, min		1.208	1.208	1.208	1.208	1.208	1.208	1.208	1.208	1.208
Standard deviation, min		0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864	0.864
Minimum delay, min		0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Owning and operating cost, $/hr		140.49	140.49	140.49	152.19	152.19	152.19	162.24	162.24	162.24
Haul unit										
Load weight, tons		7.5	15	21	6	15	22.5	7.5	15	22.5
Vehicle weight, tons		4.90	6.78	12.00	4.90	6.78	12.00	4.90	6.78	12.00
Horsepower		202	215	221	202	215	221	202	215	221
Probability of external delay, %		50	50	50	50	50	50	50	50	50
Mean delay, min		5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Standard deviation, min		10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0
Minimum delay, min		0	0	0	0	0	0	0	0	0
First maneuver mean, min		0.111	0.111	0.920	0.111	0.111	0.920	0.111	0.111	0.920
Standard deviation, min		0.054	0.054	0.920	0.111	0.111	0.920	0.111	0.111	0.920
Minimum time, min		0.033	0.033	0.400	0.033	0.033	0.400	0.033	0.033	0.400
Second maneuver mean, min		1.106	1.106	2.379	1.106	1.106	2.379	1.106	1.106	2.379
Standard deviation, min		0.436	0.436	1.283	0.436	0.436	1.283	0.436	0.436	1.283
Minimum time, min		0.25	0.25	0.7	0.25	0.25	0.7	0.25	0.25	0.7
Owning and operating cost, $/hr		11.92	19.84	21.57	11.92	19.84	21.57	11.92	19.84	21.57

600 TPH plants. The 400 TPH plant can produce a maximum batch size of 6 tons which is a common denominator of none of the haul unit capacities. The decisions made here were: to load 1 batch of 6 tons in the 7.5T haul unit; to load 3 batches of 5 tons in the 15T unit; and to load 4 batches of 5.625 tons in the 22.5T haul unit. The 600 TPH plant can produce a maximum batch size of 9 tons which is likewise a common denominator of none of the haul unit capacities. In this case, the decisions made were: to load one batch of 7.5 tons in the 7.5T haul unit; to load two batches of 7.5 tons in the 15T haul unit; and to load 3 batches of 7.5 tons in the 22.5T haul unitl

The haul unit weights and horsepowers are those of three chassis and bed combinations commonly used in hot-mix transport. As indicated above, the 7.5T and 15T units are, respectively, single axle and tandem axle bobtail dumps while the 22.5T unit is a tandem axle semi-trailer combination with an end dump capability. Maneuver time parameters for the 7.5T and 15T haul units were selected the same inasmuch as it was observed during the data analysis phase that these types of units have about the same degree of maneuverability regardless of their capacities. The semi-trailer, on the other hand, is less maneuverable, a fact reflected in the parameters of its maneuver times.

External delay time parameters for the haul units reflect the highly varying nature of these cycle time factors. In each case, parameters were selected which reflect values determined from the data obtained from the Bureau of Public Roads. The same haul unit mean delay and standard deviation were used regardless of the haul distances involved. This was done because data available from the data collection phase was not adequate to determine the effect of haul distance on delay time. However, since any possible error introduced by adopting this procedure should affect the haul units equally, it is not believed that this decision invalidates the results to any significant degree, particularly with respect to their comparability.

In the case of the plants simulated, a non-delay batching time of 45 seconds was used throughout. This corresponds to the minimum mixing time required for a batch by specifications plus discharge time and a lag factor (short period of time between the clearing of the pug-mill of an old batch and the charging of the ingredients for a new batch). Investigation of plants currently in use showed no correlation between batch size and mixing time; in fact, a large batch may require less mixing time than a smaller batch. This requirement is established in the specifications for a particular job. The mean mixing time and standard deviation reflect an average of values observed for batching and loading times.

Paver laydown rates were based on the average production of the plant which in turn was based on the batch size and mean time per batch. The parameters defining paver delay indicate the great amount of external delay time which was observed on paver operations by the data collection team. As was the case for the other system components, these parameters are essentially average values of all the values observed and recorded.

Owning and Operating Costs

Since one of the two measures of effectiveness of the results obtained in the use of the model is cost per ton of hot-mix in place, it was essential to the study of the basic systems that realistic and similarly prepared owning and operating costs for system components be used. To this end, separate project sub-studies were accomplished to develop the owning and operating costs required for the haul units and for the plant and paver spreads.

The study resulting in haul unit costs is documented in Reference 6*. The specific costs for haul unit chassis-bed combinations selected for inclusion in the basic systems were:

7.5 Ton Unit - $11.92/hour

15 Ton Unit - $19.84/hour

22.5 Ton Unit - $21.57/hour

The studies resulting in the plant and paver owning and operating costs are summarized in Appendix II. In all cases, the costs developed comprise the sum of all equipment, labor, fuel and maintenance costs required for hourly operation of the particular system component, e.g., the plant spread. Equipment costs, in turn, are based on a number of factors and assumptions such as size of job, annual equipment utilization, insurance rates, move-in

*Copies of this reference are available on a loan basis from NAPA.

costs, etc., to name only a few. Table 5 lists the hourly plant and paver spread owning and operating costs developed for use in the model.

TABLE 5. - HOURLY OWNING AND OPERATING COSTS, PLANT AND PAVER SPREADS

	Plant Spread		Paver Spread	
Plant Size	w/o Surge	w/Surge*	w/o Windrowing	w/Windrowing**
200 TPH	$188.89	$211.91	$140.49	$143.21
400 TPH	$360.33	$383.35	$152.19	$154.91
600 TPH	$513.59	$536.61	$162.24	$164.96
1000 TPH	$605.44	$628.46	$311.88***	$317.32***
1000 TPH Continuous mix, screenless	$474.00	$497.02	$311.88***	$317.32***

*100 tons of surge storage capacity; for each additional 100 tons of capacity, add $11.51/hour

**Includes two additional equipment items, a spreader box and Ko-Cal attachment for picking up windrow

***Two pavers and related supporting equipment used

One other cost developed for use in the simulation of the basic systems was that of the hot-mix materials. A mix design comprising 37.6% by weight of sand, 56.4% stone and 6% asphalt was used for which the materials cost was calculated to be $3.80 per ton (based on prices prevailing in the Texas Gulf Coast region).

Simulation of Basic Systems Performances

Using the input variables set forth in Table 4, model simulations were performed for the system configurations appearing in Table 3. The following is a discussion of the simulated basic systems performances.

200 TPH Plant

Figures 8, 9, 10 and 11 depict the performances of the three basic systems haul units at the 1.0, 7.5 and 27.5 miles initial haul ranges. With the exception of very short haul distances, the performance of the 22.5T haul unit is clearly superior from the standpoints of both optimal cost per ton of hot-mix in place on the road and production in tons per hour. This may seem surprising since intuitively it might appear that the smaller haul units would perform more economically operating in conjunction with a small plant, particularly at the lesser haul distances. This is not, however, borne out by the model studies.

The large haul unit outperforms the small and medium size units hauling from a small plant in spite of the fact that it has a slower average travel speed (see speed equations in Table 2) and requires more maneuver time at the paver. The primary reasons for this are: (1) the large haul unit carries more tons of hot-mix per load; and (2) for the tonnage hauled, there are fewer interactions between the haul unit and plant, between the haul unit and paver and between the haul unit and other haul units. With regard to (2), the 22.5T haul

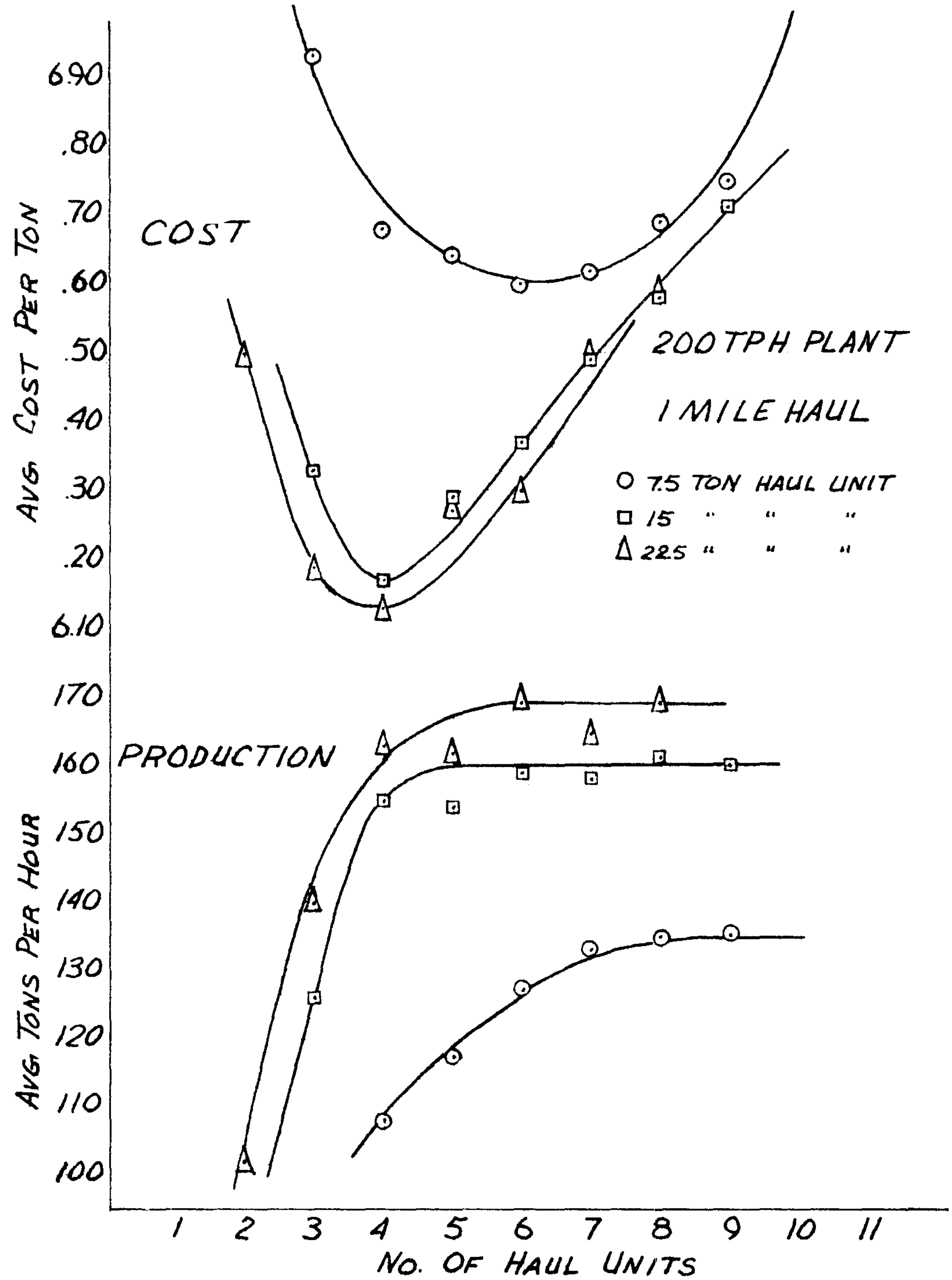

FIGURE 8. - BASIC SYSTEMS PERFORMANCES: 200 TPH PLANT; 1 MILE INITIAL HAUL DISTANCE

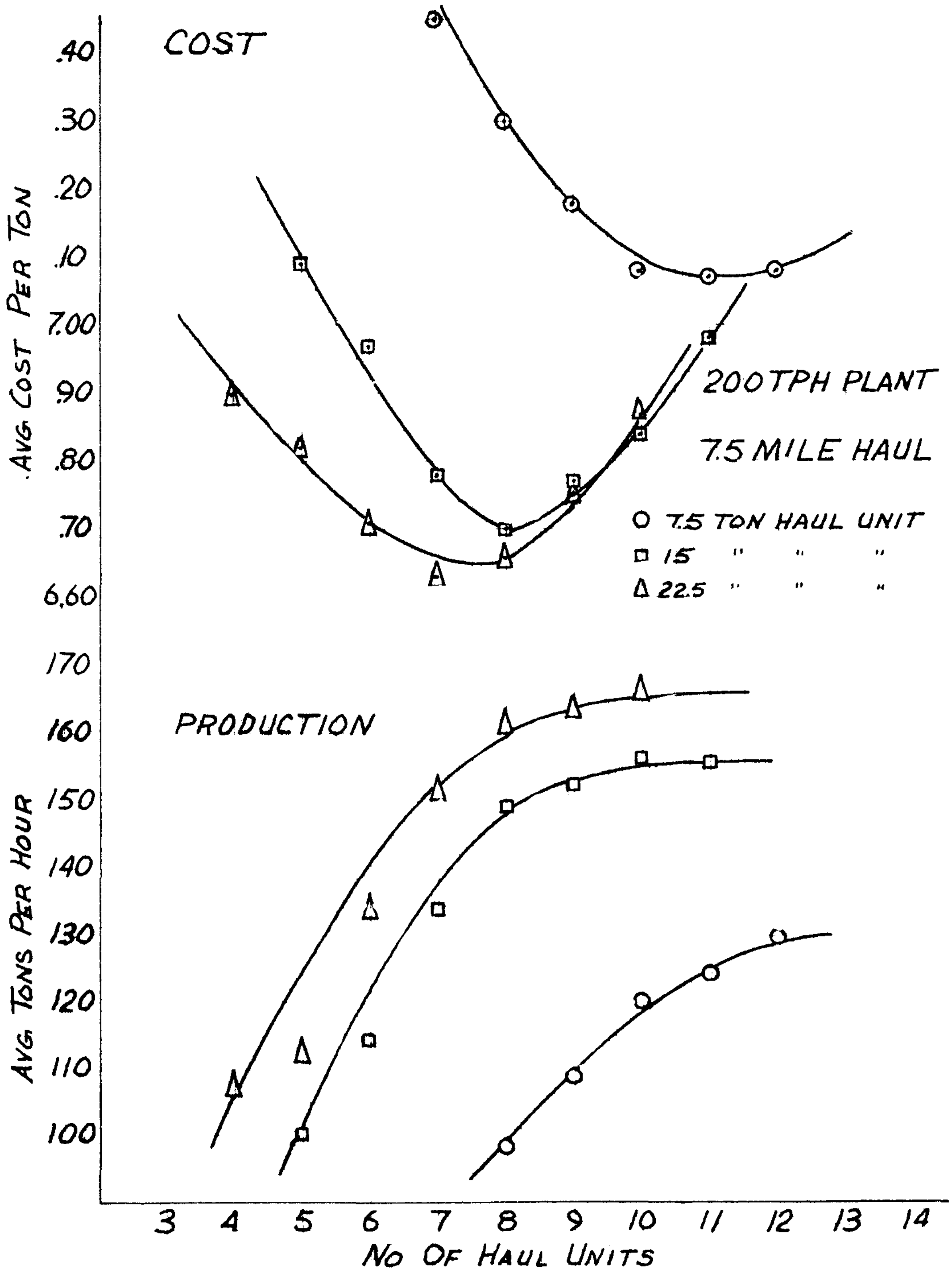

FIGURE 9. - BASIC SYSTEMS PERFORMANCES: 200 TPH PLANT; 7.5 MILES INITIAL HAUL DISTANCE

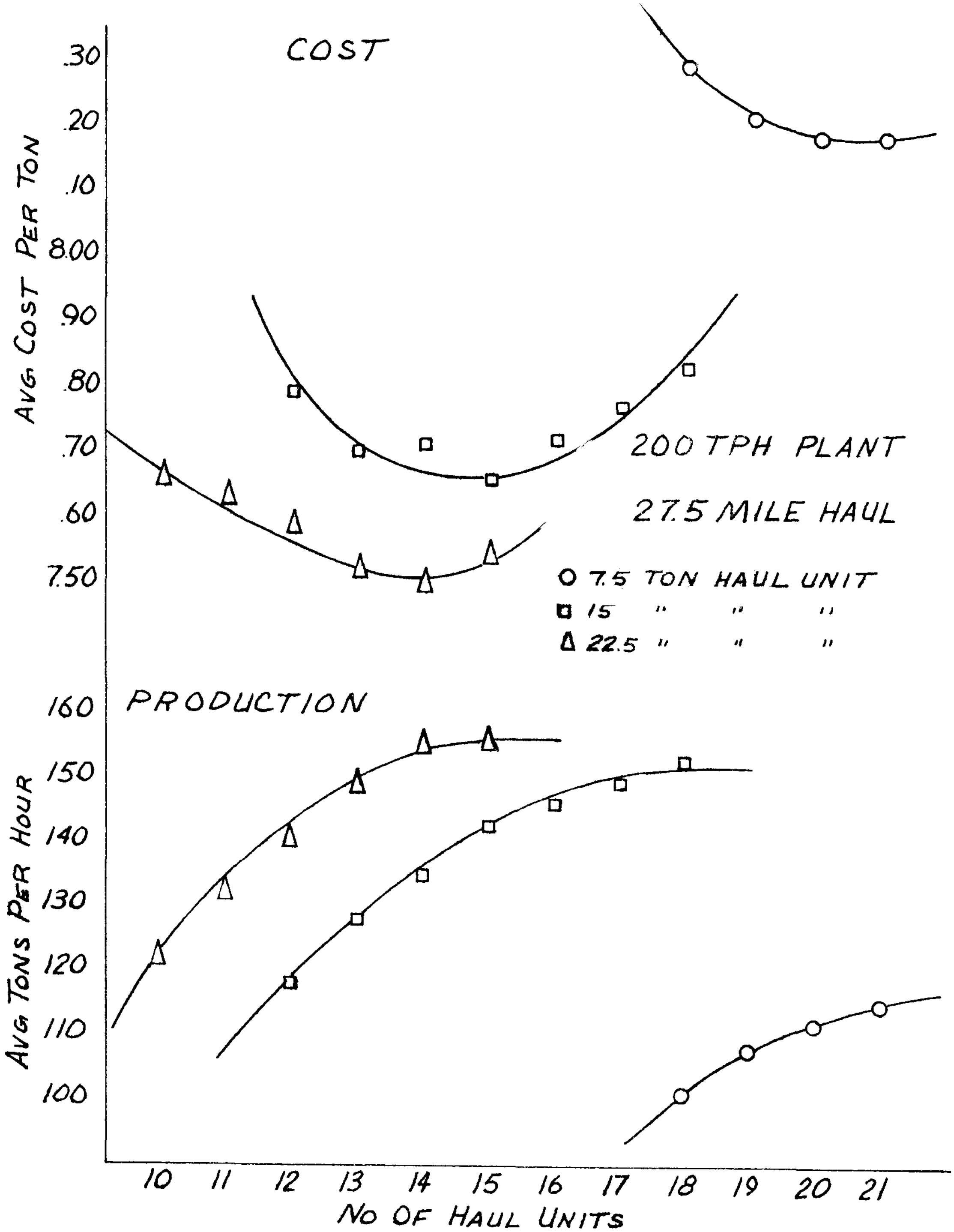

FIGURE 10. - BASIC SYSTEMS PERFORMANCES: 200 TPH PLANT; 27.5 MILES INITIAL HAUL DISTANCE

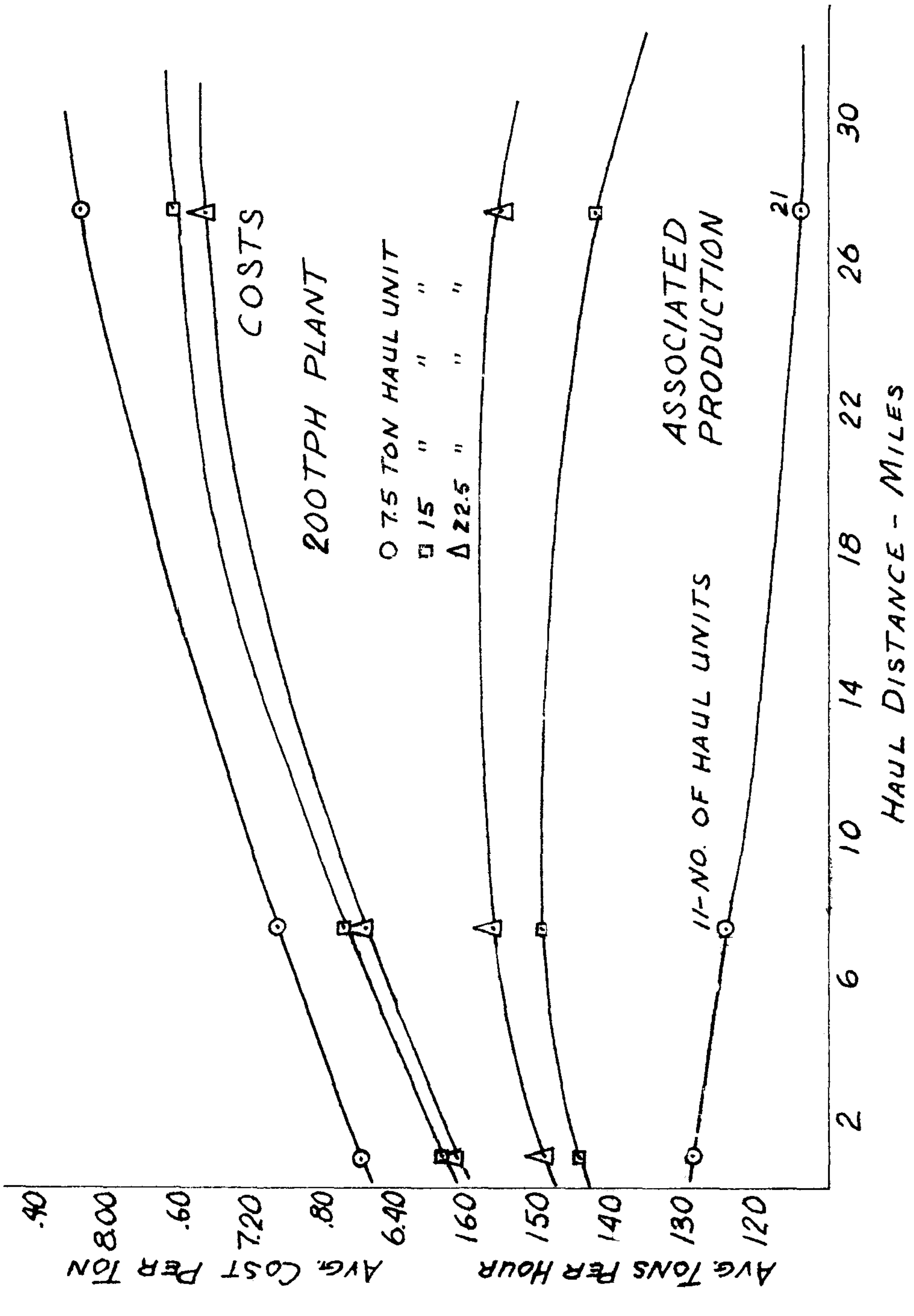

FIGURE 11. - BASIC SYSTEMS OPTIMUM PERFORMANCES:
200 TPH PLANT; 1.0, 7.5 and 27.5 MILES
INITIAL HAUL DISTANCES

unit interacts 10 times with the plant in hauling a total of 225 tons of hot-mix; in delivering an equal amount of mix the 15T unit interacts 15 times and the 7.5T unit interacts 30 times with the plant. Generally, the greater the number of interactions between the links of a distribution system the less efficient the overall performance of the system becomes. This is because of the variable or stochastic nature of the interaction times between the links. For example, in the model simulation of the 200 TPH plant, the plant had a mean batching and loading time for one 5 batch load (15 tons) of 4.585 minutes, with a standard deviation of 1.144 minutes and a minimum time value of 3.75 minutes (the minimum non-delay batch time of 0.75 minutes times five). In terms of the log-normal distribution used to represent these plant parameters in the model, 95 +% of the loading times would have values which range anywhere from 3.8 minutes to 7.6 minutes. This time variation, along with the numbers of haul units involved, causes queuing at the plant and a resultant reduction of performance. The same holds true at the paver which, in the case of simulation of the basic systems, had an amount of deviation about the mean external delay time even greater than that of the batching time deviation about the mean batching time at the plant. The result is that queuing can and does develop at both the plant and the paver, bringing about a resultant production decrease.

In illustration of the foregoing, consider the performances of the 7.5T and 15T haul units as depicted in Figure 8. Specifically, note that the production of six 7.5T units is about equal to the production of three 15T units. Roughly, this is to be expected, since the 15T unit is hauling twice the load of the 7.5T unit, the optimum number of units (from a unit cost standpoint) has not been exceeded, and the haul distance is a short one (there is no great difference in average travel speeds). However, additional output data provided by the model shows the following for the numbers of each type of unit being examined:

Size	No.	Idle Time at Plant	Idle Time at Paver	Average Unit Efficiency*
7.5T	6	12.9%	15.5%	.574
15T	3	2.7%	5.6%	.800

*Portion of time that haul unit is either loading, traveling, maneuvering or discharging

The six 7.5T units accumulate approximately five times as much waiting time at the plant and three times as much waiting time at the paver as the three 15T units. Furthermore, the six 7.5T units are about 70% as efficient, overall, as the 15T units. Thus, the point is made that as the number of haul units increases, the number of interactions at nodes or material transfer points increases also, with the consequent result that the potential for idle or waiting time in queues also increases.

As the haul distance increases, two things happen: the number of haul units increases and travel speeds have a greater influence on system and individual unit performances. Faster units overtake slower units. If passing cannot be accomplished, internal delays result as the faster units trail the slower units to their destination. With or without passing, speed variations account for two or more units arriving at the plant or paver within a short period of time. Again, queuing and decreased performance is the result. The greater the number of haul units involved, the greater becomes this possibility of performance loss because of haul unit interactions resulting from speed variations. Thus, there is the decrease in peak production performance between the 1.0 and 7.5 mile haul distances and between the 7.5 and 27.5 mile haul distances for all three haul unit categories operating from the 200 TPH plant.

Optimal production for each haul unit is that production associated with the low point on the cost curve for the unit. This point corresponds to that point in a conventional or deterministic estimate of haul unit production at which the governing factor of production transfers from the haul unit to the plant. Table 6 develops figures for the 22.5T unit, 200 TPH plant, 1.0 mile haul system which illustrate this point. The deterministic, non-stochastic estimate of haul unit production is 48.2 TPH per unit; plant production is 196 TPH. Using four haul units or less, system production is governed by the haul units; using five or more haul units, system production is governed by the plant and is equal to 196 TPH regardless of the number of haul units. Therefore, it does not pay to use more than five haul units since it only results in driving up unit costs. An optimal cost per ton of $5.96 is realized using four haul units; five haul units give a unit cost of $6.03 per

TABLE 6. - DEVELOPMENT OF A DETERMINISTIC ESTIMATE OF HAUL UNIT PRODUCTION

22.5 Haul unit hauling 21T load

200 TPH Plant

1 Mile initial haul distance

Assume all stochastic variables having 0 variances

Assume 1.5 mile average haul distance

Determine cycle time for one haul unit

Travel Time -

Weight/HP = (42,000 + 24,000) ÷ 221 = 229

Empty Weight/HP = 24,000 ÷ 221 = 108.5

From equations for speed:

Avg Haul Speed $= 10^{(1.513 + .065 - .228)} = 10^{(1.35)}$
$= 22.4$ mph

Avg Return Speed $= 10^{(1.668 + .064 - .333)} = 10^{(1.40)}$
$= 25.0$ mph

Avg Round Trip Speed = (22.4 + 25.0) ÷ 2 = 23.7 mph

Travel = (3.0 x 60.) ÷ 23.7 =	7.60 min.
Load* =	6.42 min.
First Maneuver* =	0.92 min.
Discharge* = 42,000 ÷ (11.5 x 12. x .33 x 144) =	6.34 min.
Second Maneuver* =	2.38 min.
Delay* = 0.5 x 5.0 =	2.50 min.
Cycle time =	26.16 min.

*These are means of values appearing in Table 4

Cycles/hour = 60 ÷ 26.16 = 2.29

Production = 2.29 x 21 = 48.2 TPH/unit

Expected production of plant = (21 x 60) ÷ 6.42 = 196 TPH = Expected number of loads per hour times weight of load in tons

Expected production of paver = (21 x 60) ÷ (6.34 + .833 x 1.208) = 172 TPH = Expected number of loads placed per hour times weight of load in tons (here 6.34 is the non-delay laydown time in minutes per load and .833 x 1.208 is the expected external delay time per load) ton (total cost of plant and materials per hour using four and five haul units divided by hourly production for these two systems).

The figures arrived at deterministically above bear resemblance to like figures arrived at by means of the simulation model. Still referring to the 22.5T, 200 TPH, 1.0 mile system, note that the optimal cost is also realized with four haul units; however, the unit costs for four and five haul units are greater than the deterministically developed costs. Those costs, based on deterministic or non-stochastic times, are overly optimistic; the variations in times and interactions among system components are not considered. But correlations do exist between the optimum numbers of haul units of the two solutions and the consequences of employing additional haul units beyond the optimum number.

While the deterministic solution indicates a system production rate of 196 TPH for five or more units, the model solution falls well short of this figure, leveling off at about 175 TPH for eight or more haul units. This is due partially to the influence of the paver which, deterministically, has a production rate of 172 TPH. The plant does govern production for five or more haul units but not in quite the same fashion as it does in the deterministic solution. In the model solution and in the real world situation, the addition of haul units beyond the number giving the optimal cost serves only to decrease the amount of time that the plant or paver sits idle waiting for haul units to arrive, and it does so at no small cost. Model output showed that by increasing the number of

22.5T haul units from four to eight, plant idle time decreased from 17.4% of shift time to 6.7% and paver idle time from 7.4% to 0.1% (the paver non-delay laydown rate was 11.5 fpm), and system output increased from 155 TPH to 175 TPH. The cost of this production increase is quite significant. In this instance it amounts to [175 (\$6.85 - \$3.80) - 155(\$6.17 - \$3.80)] ÷ (175-155) = \$5.95 per ton of increase (175 and \$6.85 are the production in TPH and final cost per ton for eight haul units; 155 and \$6.17 are like values for four haul units; \$3.80 is the hot-mix materials cost per ton). This is the amount of penalty paid for producing each ton in excess of the tonnage associated with the optimal cost. In conjunction with the above, two points should be made:

a. Regardless of the system to be used for distribution, the optimal number of haul units to be included in the haul fleet should be determined and used.

b. Paver(s) should be operated at a rate geared to the optimal production rate of the system. For the situation discussed, the paver effective laydown rate should be:

   (155 TPH x 2000) ÷ (60 x 12 x .33 x 144) = 9 fpm

   External delays would have to be considered in achieving this rate.

<u>400 and 600 TPH Plants</u>

The performances of basic systems employing 400 and 600 TPH plants are graphically illustrated in Figures 12 through 17. As in the case of basic systems incorporating the 200 TPH plant, those utilizing the large, 22.5T haul unit are clearly superior from the standpoints of both cost and production. The reasons for this superiority advanced above in the section on the 200 TPH plant are

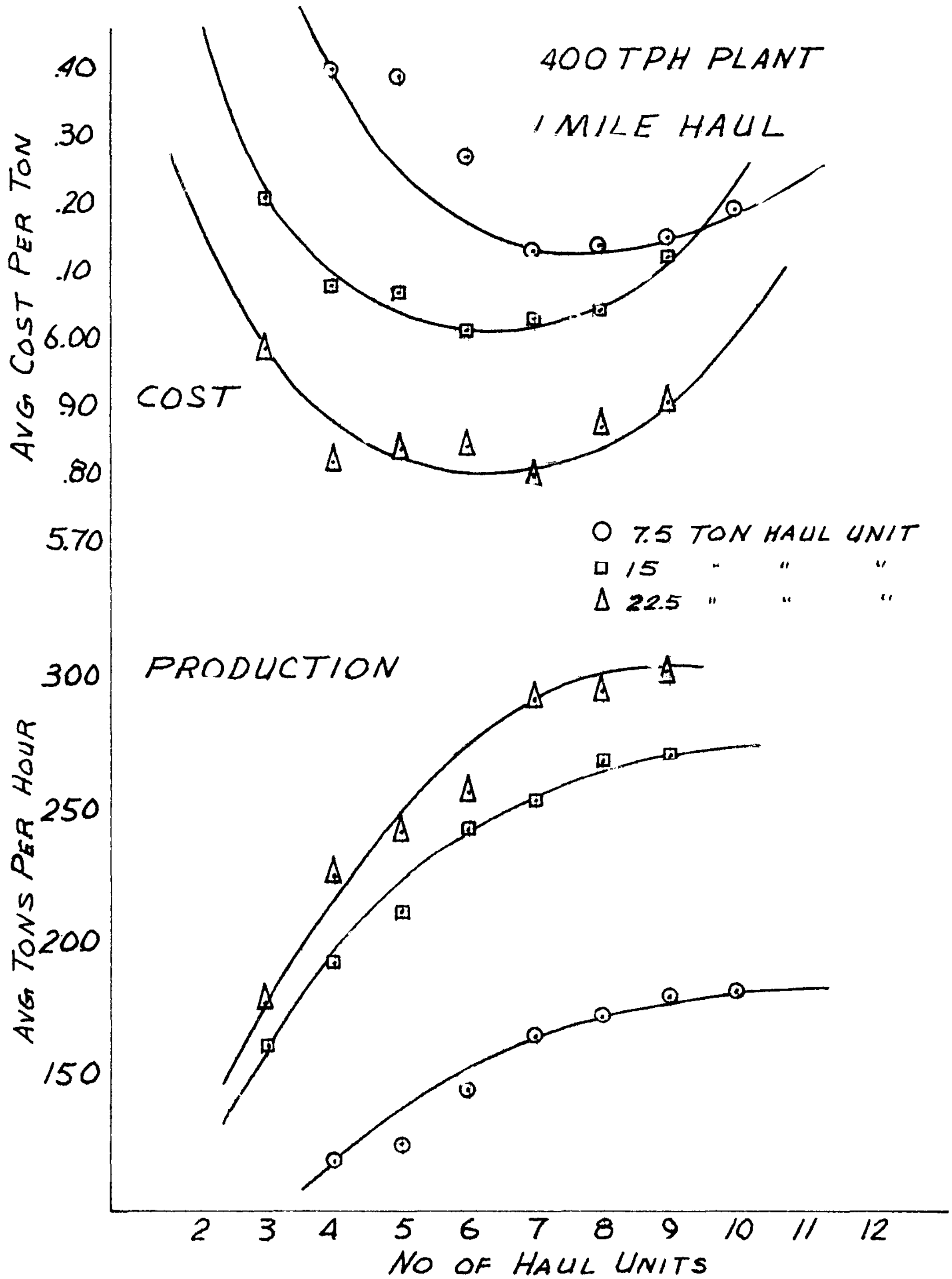

FIGURE 12. - BASIC SYSTEMS PERFORMANCES: 400 TPH PLANT; 1.0 MILE INITIAL HAUL DISTANCE

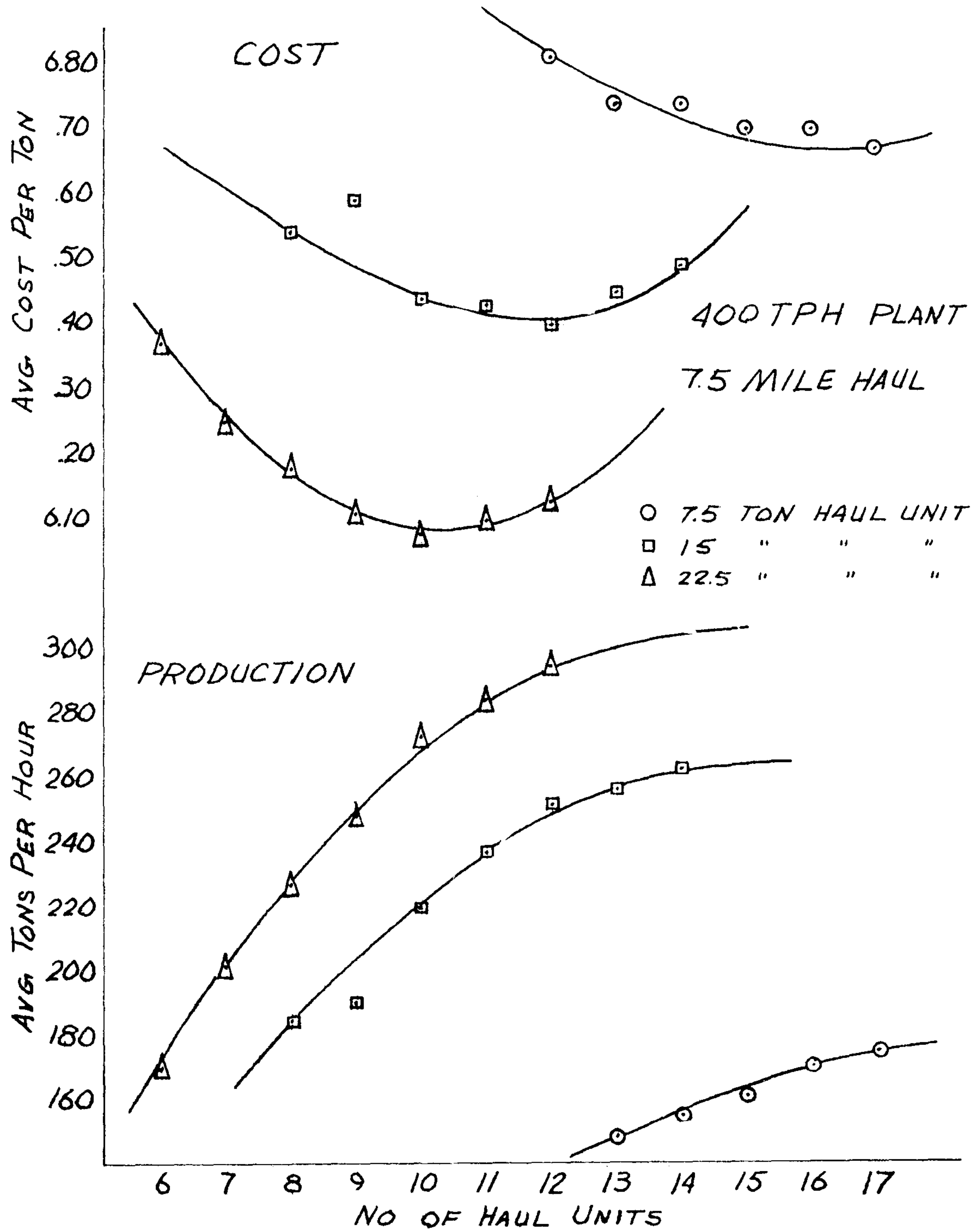

FIGURE 13. - BASIC SYSTEMS PERFORMANCES: 400 TPH PLANT; 7.5 MILES INITIAL HAUL DISTANCE

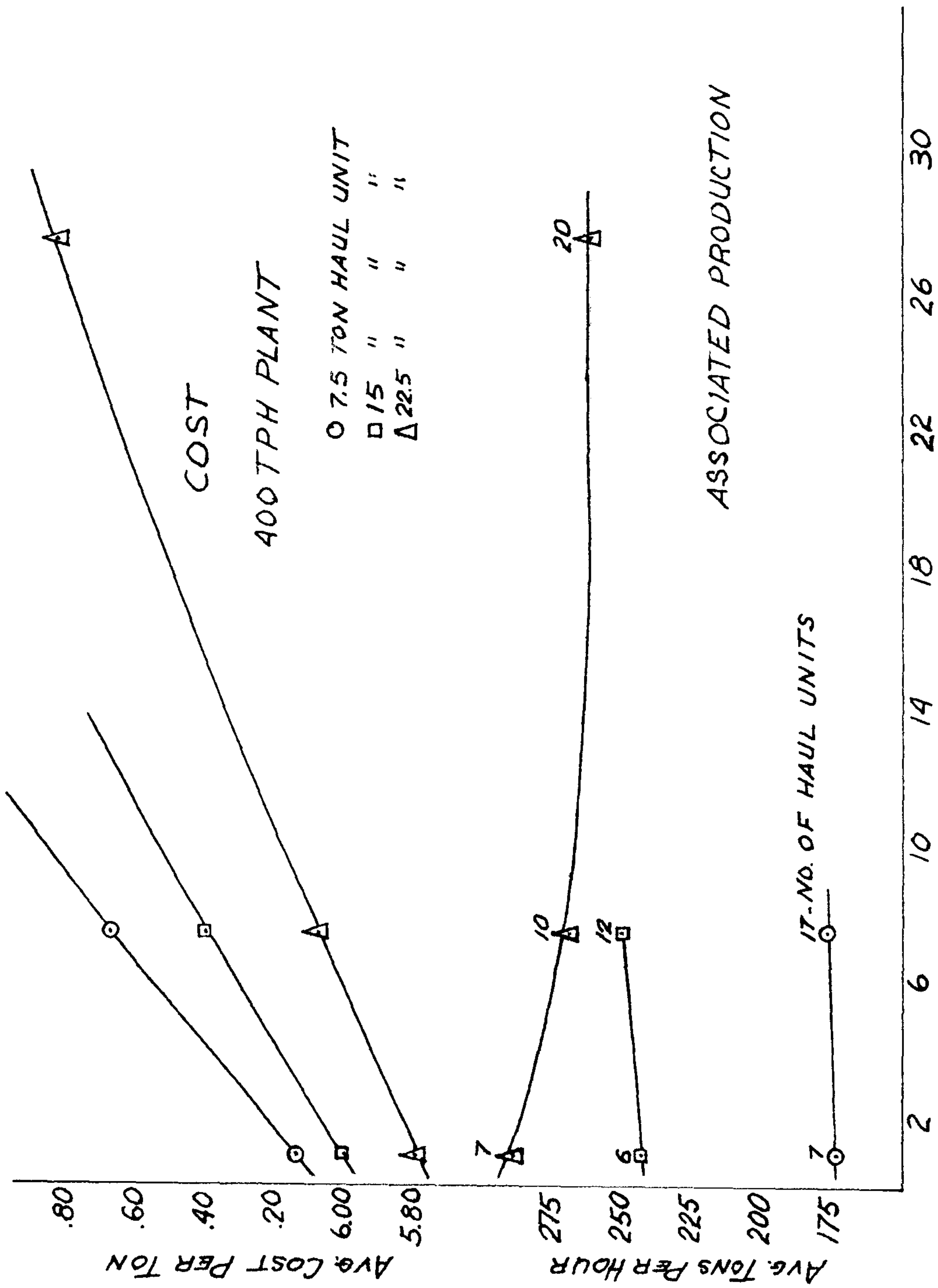

FIGURE 14. - BASIC SYSTEMS OPTIMUM PERFORMANCES: 400 TPH PLANT; 1.0, 7.5 and 27.5 MILES INITIAL HAUL DISTANCES

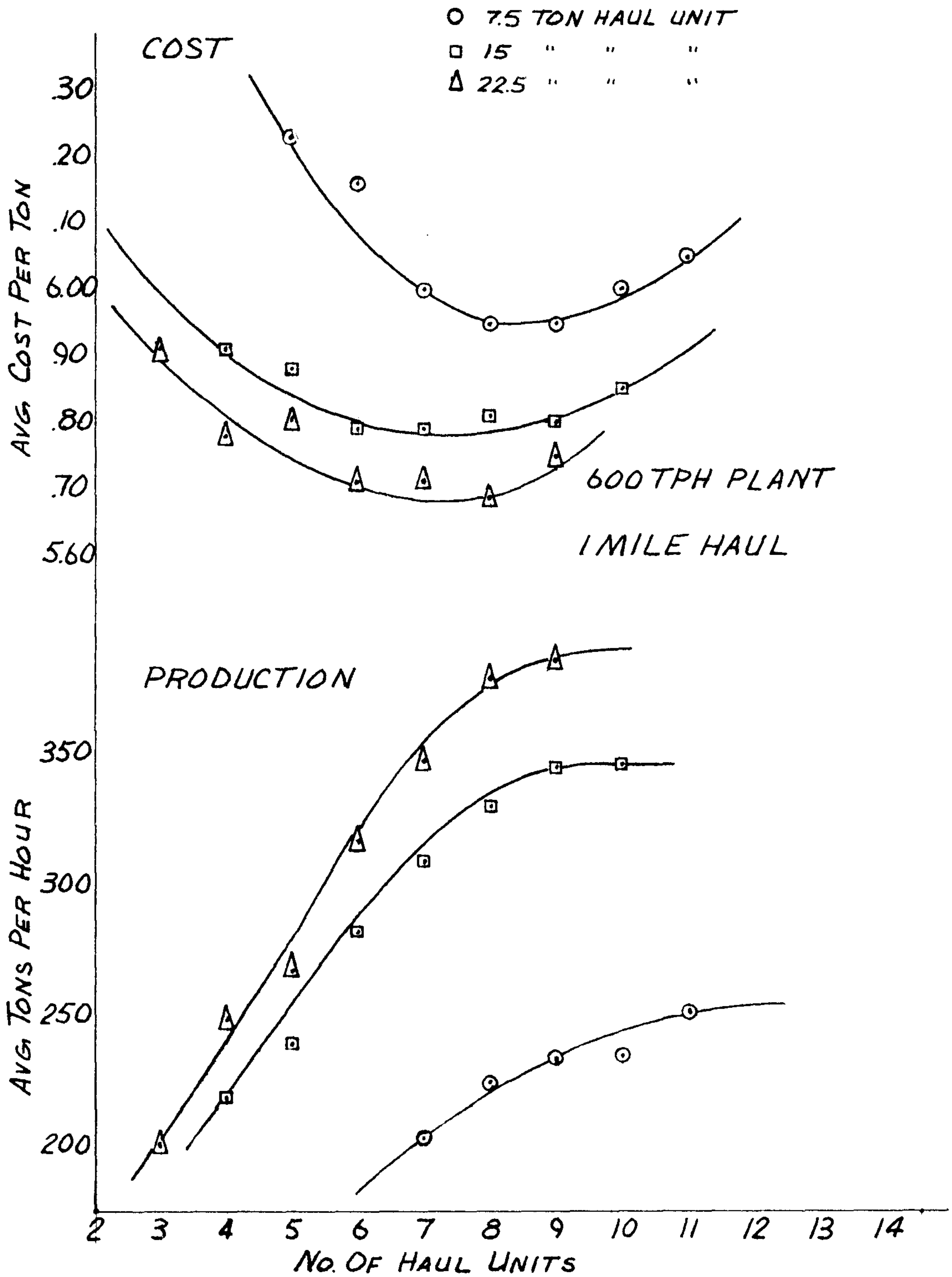

FIGURE 15. - BASIC SYSTEMS PERFORMANCES: 600 TPH PLANT; 1.0 MILE INITIAL HAUL DISTANCE

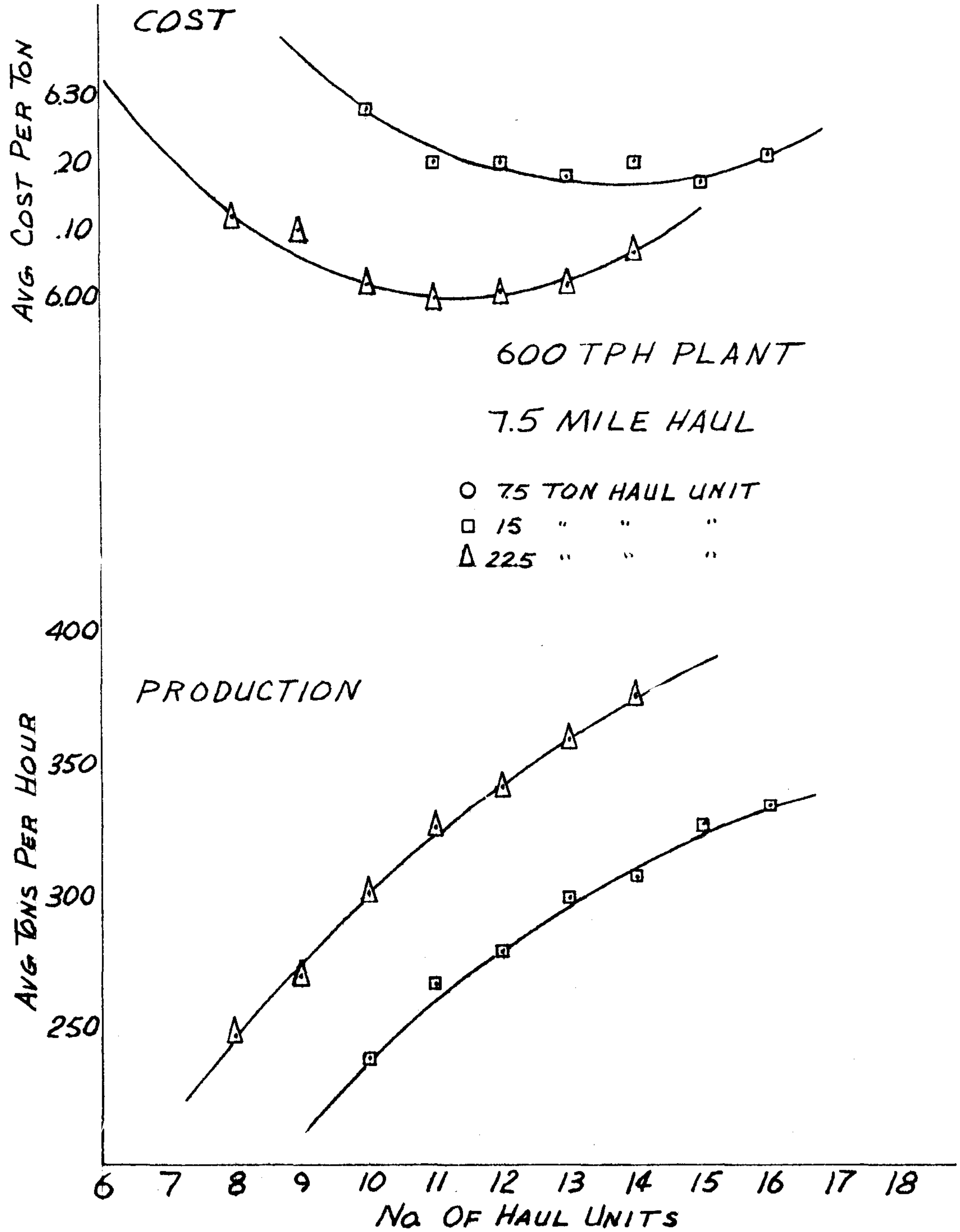

FIGURE 16. - BASIC SYSTEMS PERFORMANCES: 600 TPH PLANT; 7.5 MILES INITIAL HAUL DISTANCE

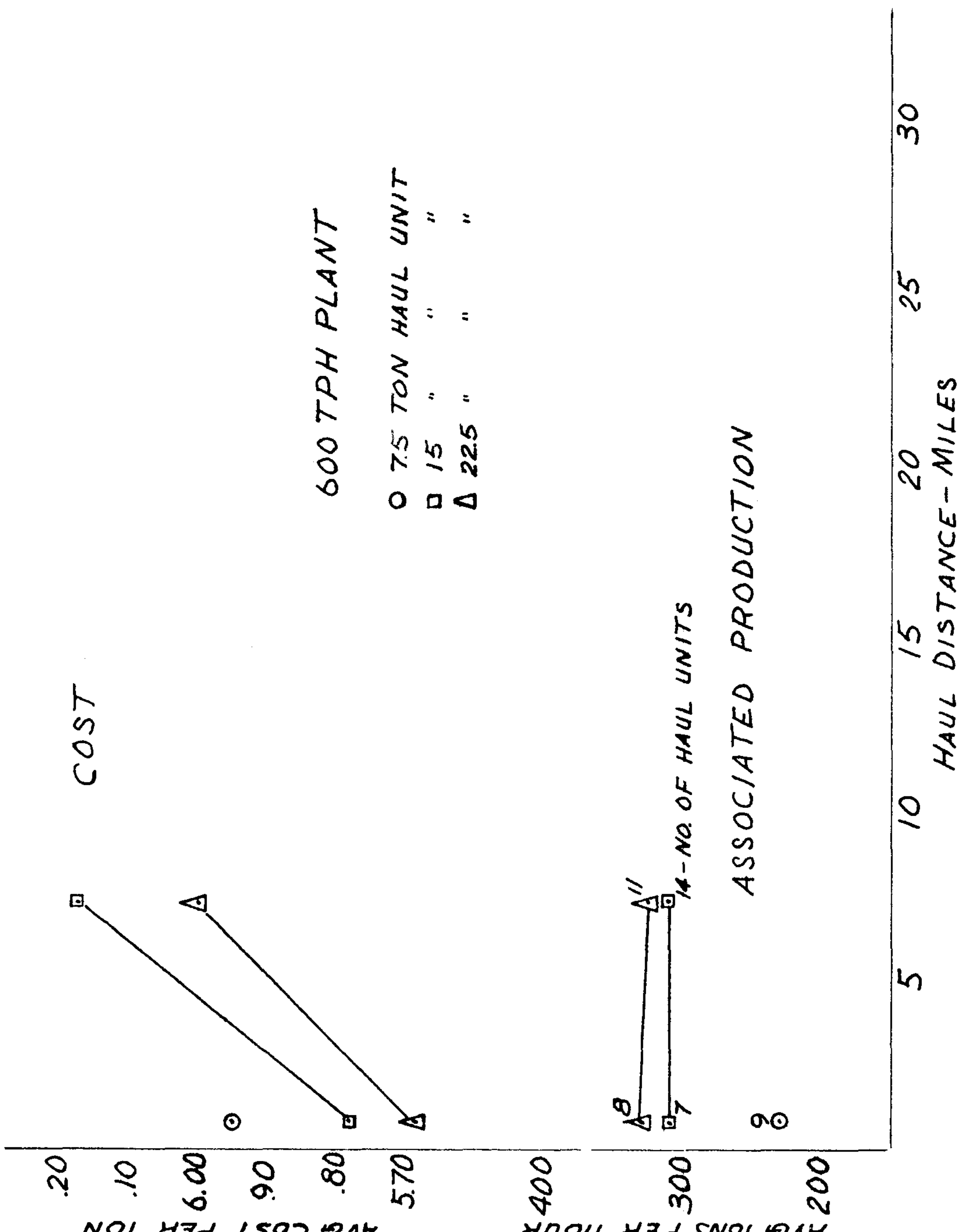

FIGURE 17. - BASIC SYSTEMS OPTIMUM PERFORMANCES: 600 TPH PLANT; 1.0, 7.5 and 27.5 MILES INITIAL HAUL DISTANCES

valid here also.

Effect of Plant Size on Haul Unit Performance

Figures 18 through 23 present the performance data for the basic systems configurations grouped by size of haul unit for the 1.0 and 7.5 mile initial haul distances. Presented in this fashion, the effect of increasing the size of plant production capacity becomes strikingly evident. As the size of the plant increases, haul unit productivity increases also. For example, Figure 22 indicates that four 22.5T haul units hauling from a 200 TPH plant result in about 164 TPH of hot-mix in place on the road. However, four 22.5T units hauling from a 400 TPH plant account for some 225 TPH and from a 600 TPH plant, 245 TPH (it should be kept in mind that the production figures quoted are based on a particular set of input variable values to the computer model - results are relative and comparable, however). Further, as the production rate increases, optimum unit costs decrease, falling from $6.13/ton for the 200 TPH plant to $5.80/ton for the 400 TPH plant and to $5.69/ton for the system employing the 600 TPH plant.

The primary explanation for the effect that plant size has on performance is evident. Larger plants produce larger size batches, thus decreasing loading times and increasing the number of cycles a haul unit (regardless of size) can make in an hour or during a shift. Since paver laydown rates are (or should be) geared to plant production, the haul unit discharges more rapidly at the paver for a large plant than it does for a smaller plant. Thus, for a given

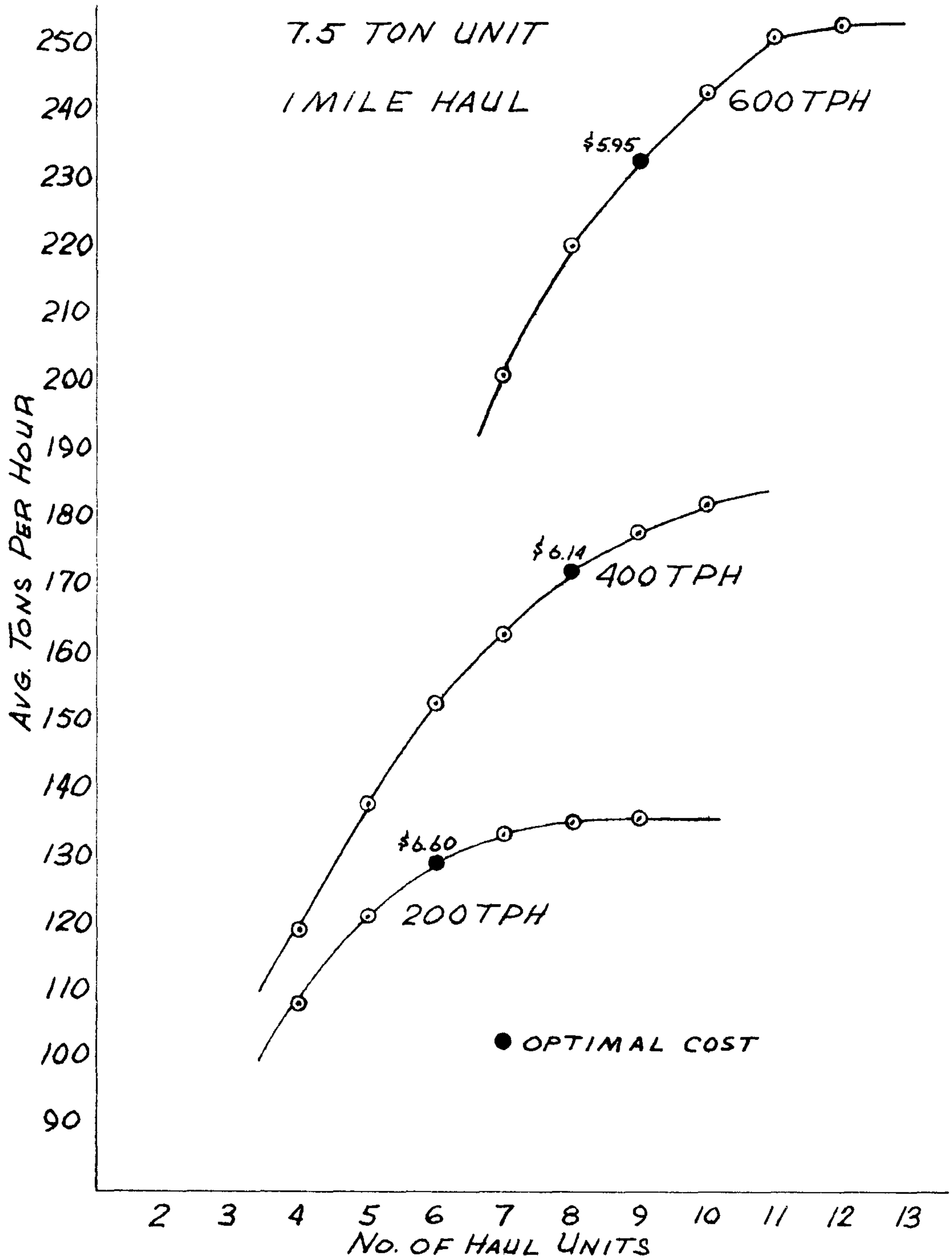

FIGURE 18. - BASIC SYSTEMS PERFORMANCES: 7.5T HAUL UNIT; 1.0 MILE INITIAL HAUL DISTANCE

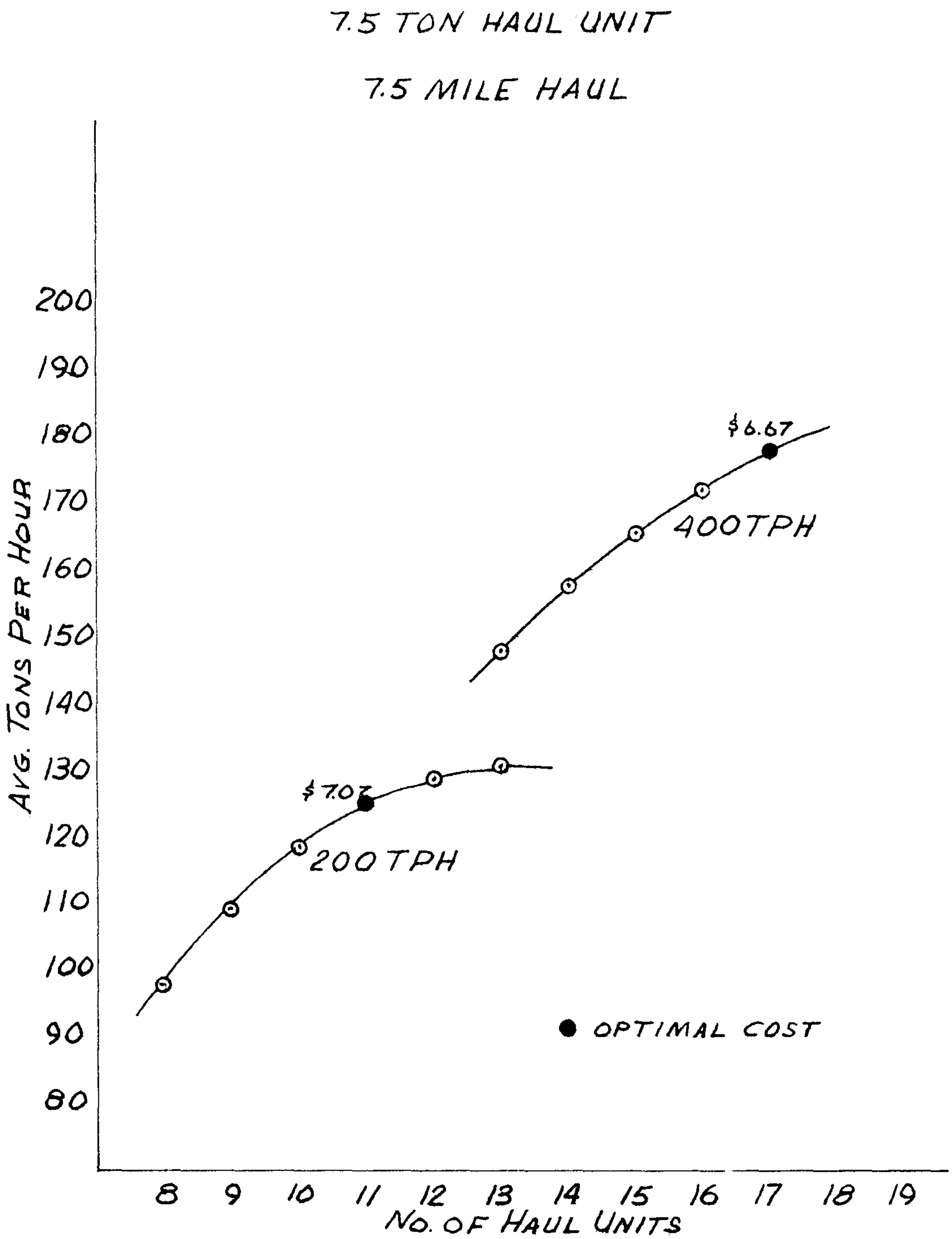

FIGURE 19. - BASIC SYSTEMS PERFORMANCES: 7.5T HAUL UNIT;
7.5 MILES INITIAL HAUL DISTANCE

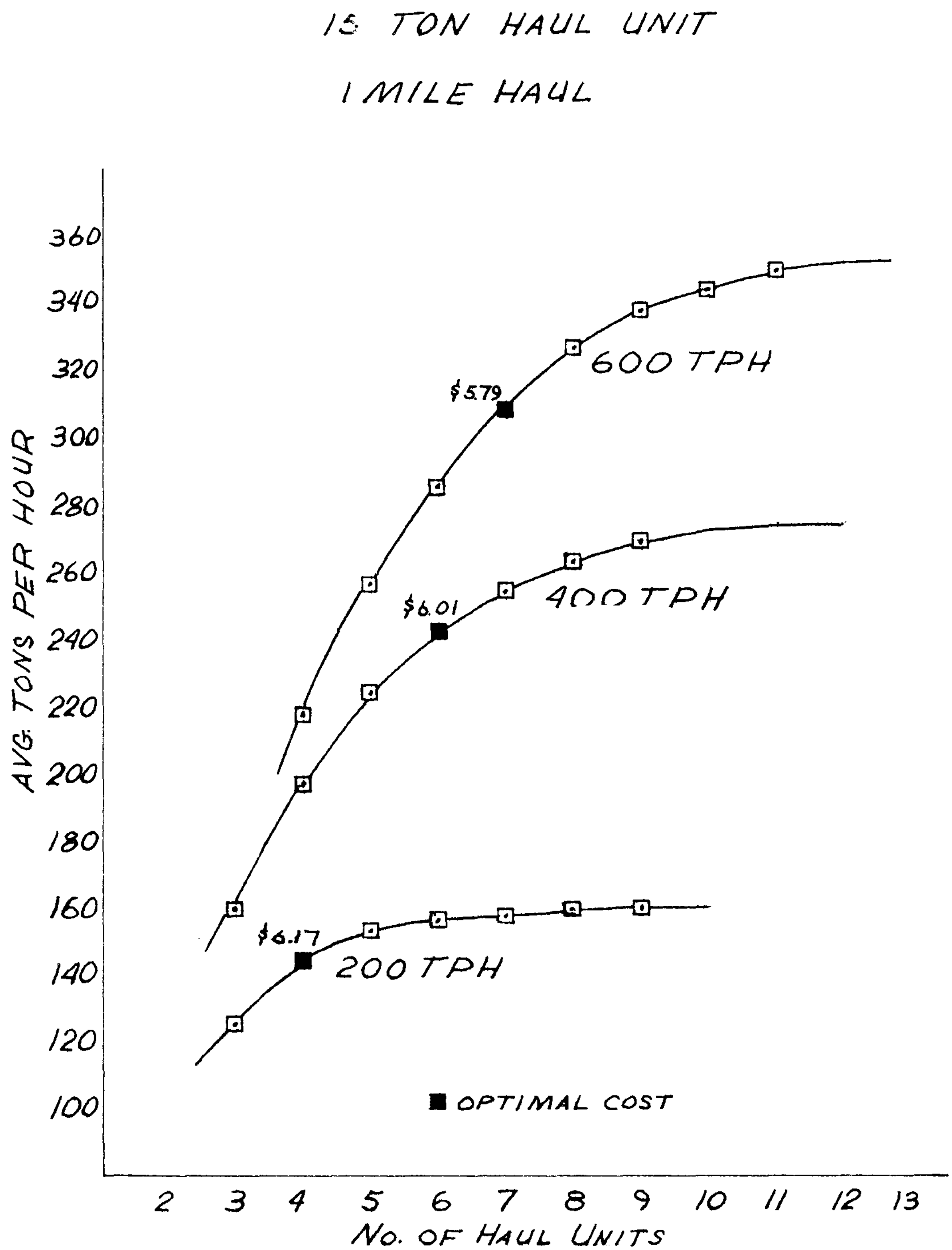

FIGURE 20. - BASIC SYSTEMS PERFORMANCES: 15T HAUL UNIT; 1.0 MILE INITIAL HAUL DISTANCE

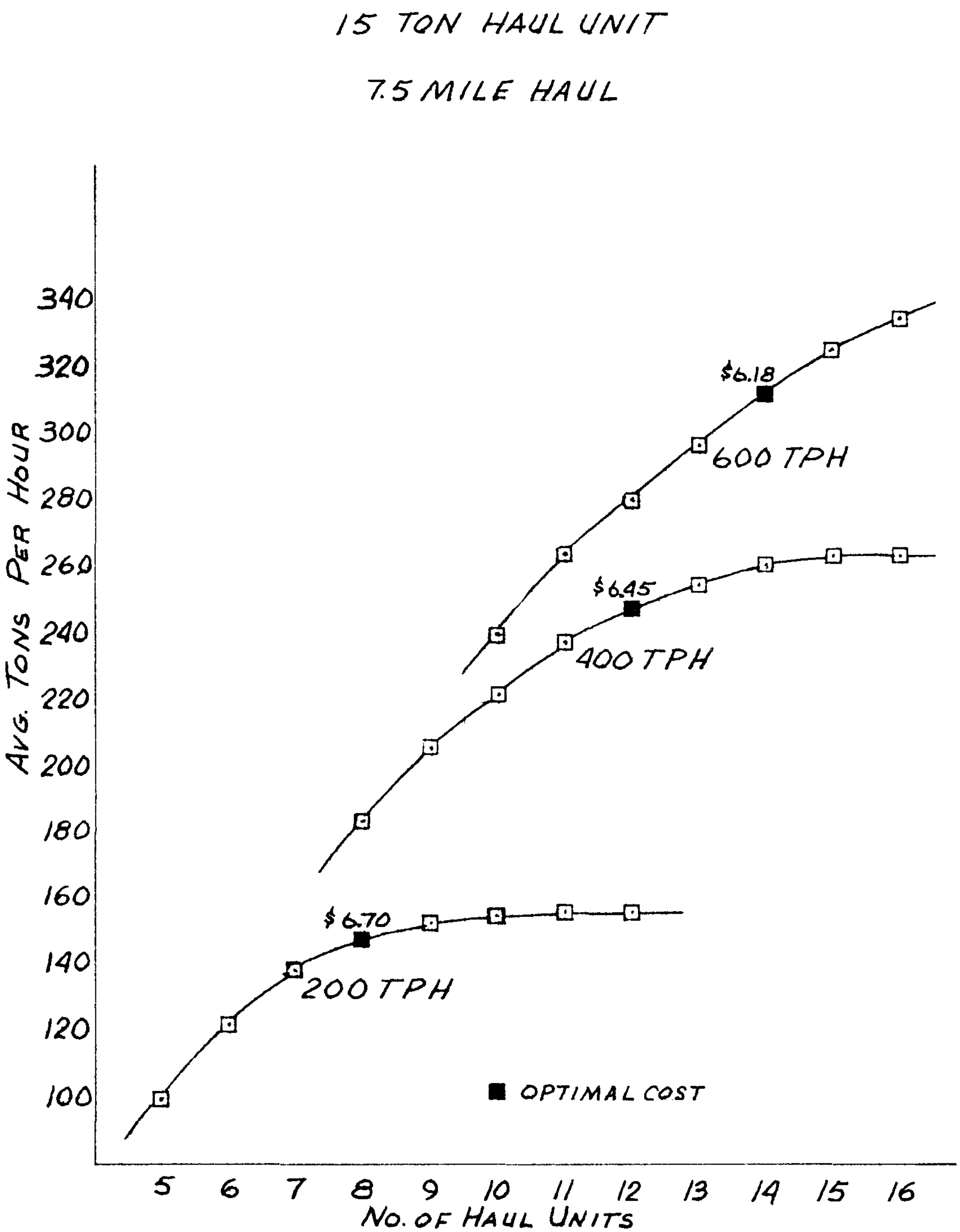

FIGURE 21. - BASIC SYSTEMS PERFORMANCES: 15T HAUL UNIT; 7.5 MILES INITIAL HAUL DISTANCE

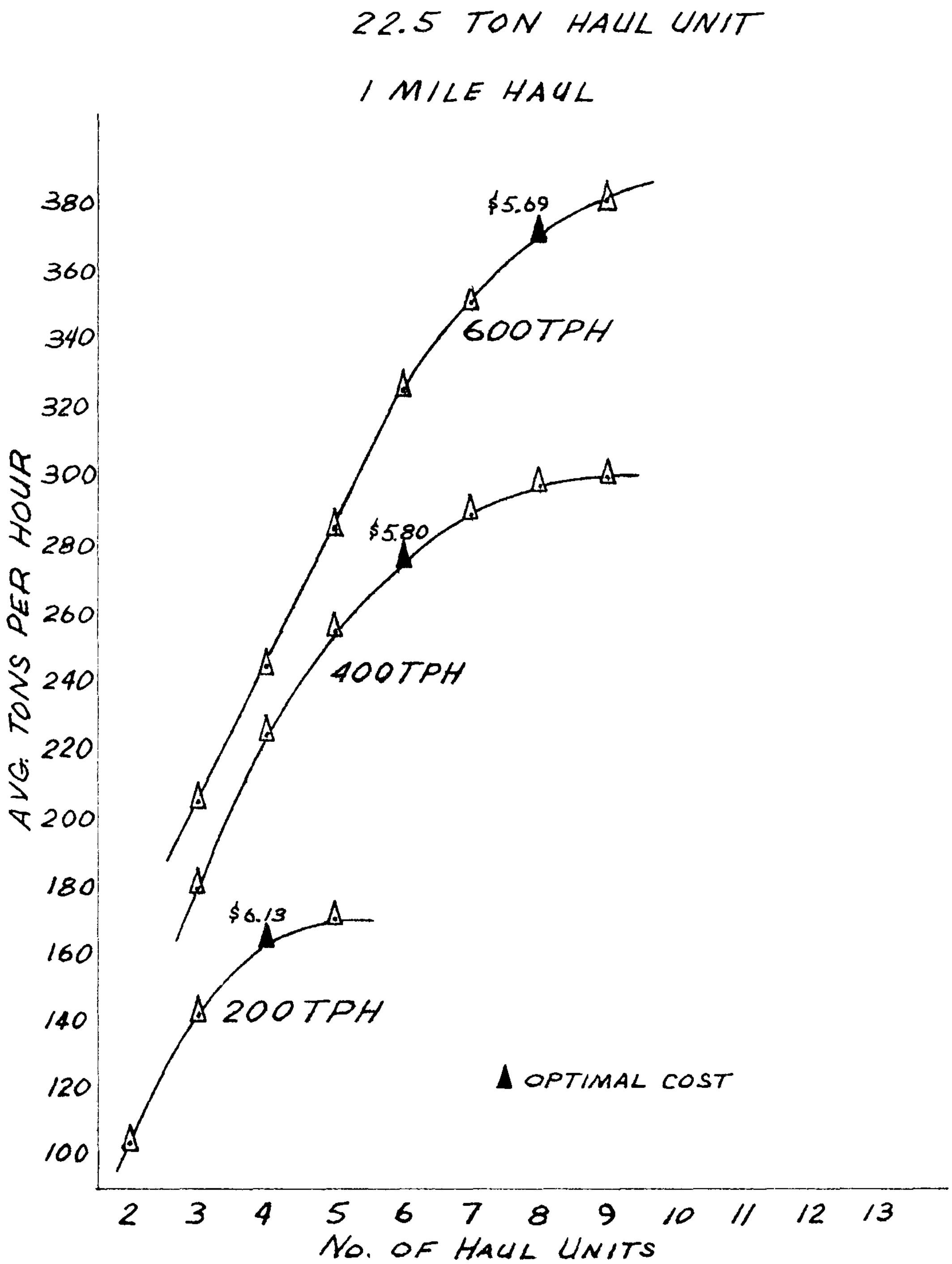

FIGURE 22. - BASIC SYSTEMS PERFORMANCES: 22.5T HAUL UNIT
1.0 MILE INITIAL HAUL DISTANCE

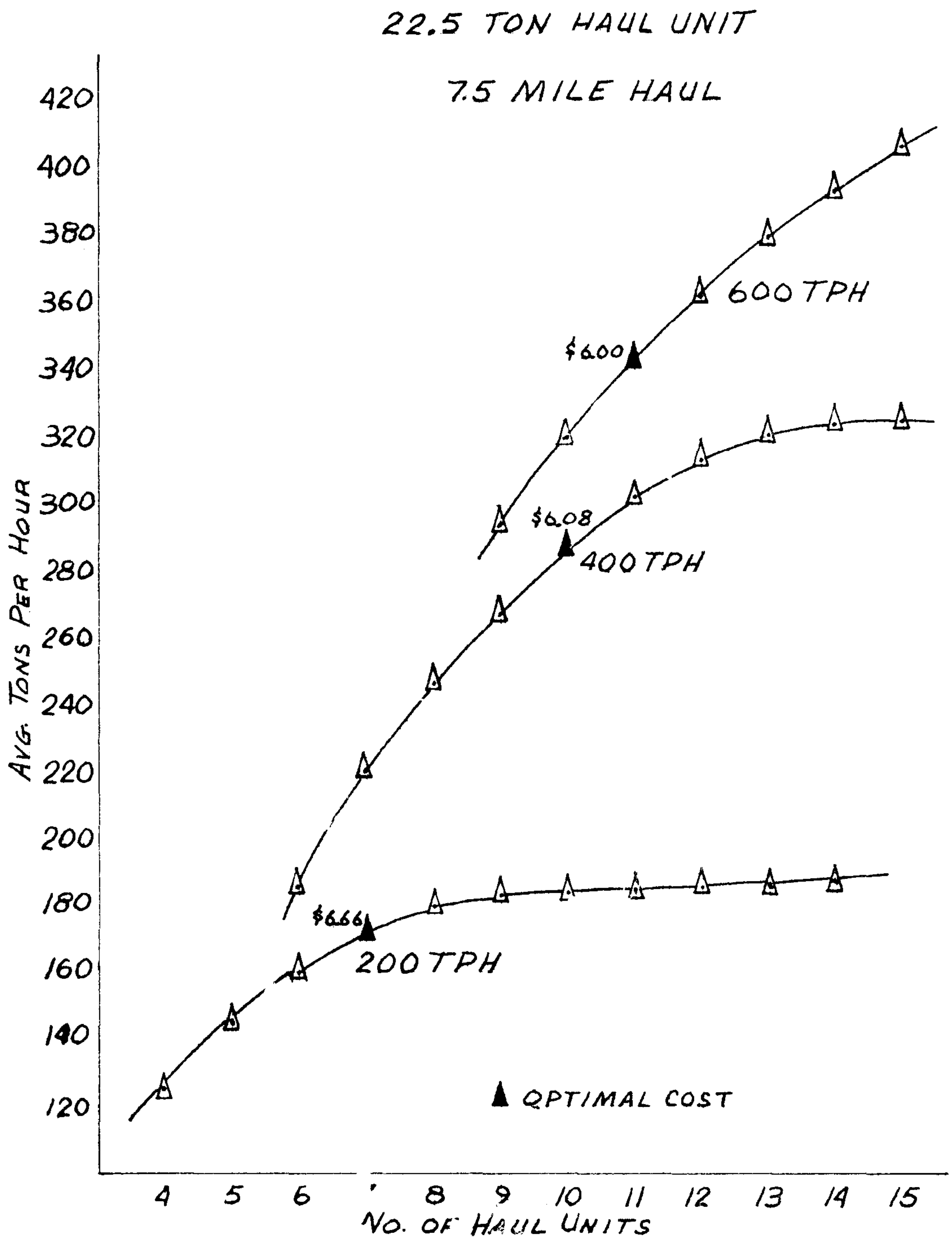

FIGURE 23. - BASIC SYSTEMS PERFORMANCES: 22.5T HAUL UNIT; 7.5 MILES INITIAL HAUL DISTANCE

haul distance, the cycle time of a haul unit is decreased at both the plant and paver and production is increased by an increase in plant size.

In the case of the basic systems, unit costs decreased without exception with an increase in plant size (note that this is true for the three haul unit capacities considered, for the three plant sizes and for the distances for which runs were made). This would not necessarily always be the result. An increase in plant size would normally be associated with an increase in plant owning and operating costs. Unless the increased cost of owning and operating the larger plant is offset by a sufficiently increased rate of production, unit costs of the hot-mix produced will be higher for the larger plant, even with the increased production.

Effect of External Delays on System Performance

One very noticeable fact evident in the figures which have been presented to this point is that in no instance has the average production achieved by a particular system come close to equaling the nominally rated output of the plant for that system. The explanation for this is that the outputs shown reflect the effects on system productivities of external delays experienced by the plants, pavers and haul units within the systems investigated. As was noted earlier, the input parameters for all operating variables, including those for external delays, were essentially average values of those observed in the data collection phase of the project.

Figure 24 depicts the results obtained by simulating a production-

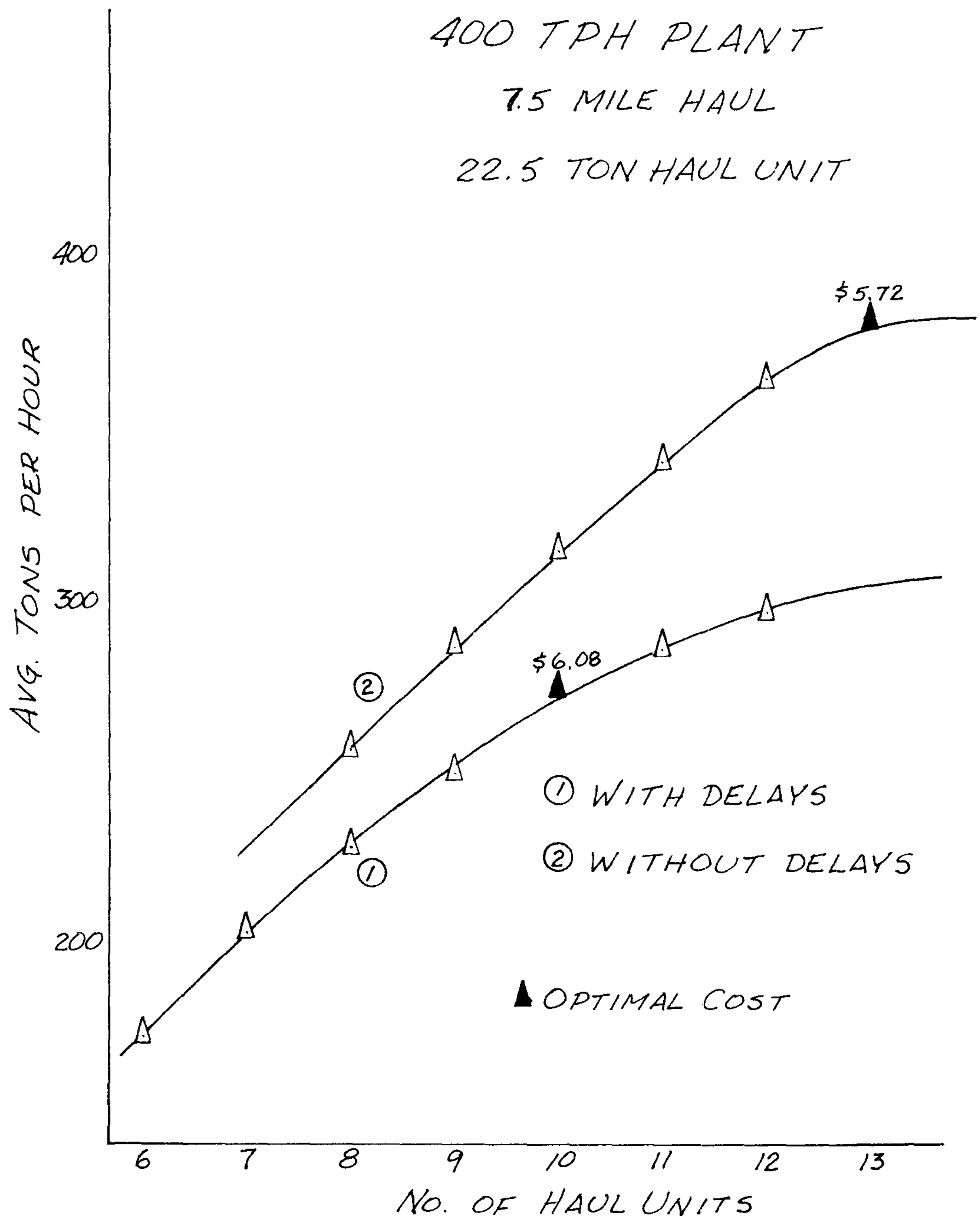

FIGURE 24. - EFFECTS OF DELAYS ON SYSTEM PERFORMANCE

distribution-laydown system operating with no external delays. In this case, a system employing a 400 TPH plant, a 22.5T haul unit fleet, and a 7.5 mile initial haul distance is simulated. For the sake of comparison, the simulation results for this system incorporating external delays is also shown. Very obviously, the delays experienced within a system significantly affect the output of that system. In this particular case, system productivity is increased, on the average, by about 18% and unit costs benefit accordingly when external delays are eliminated. Rated production is still not attained for the reason that idle time still occurs in the system because of the variable or stochastic natures of sub-system cycle times (e.g., because of their varying cycles, haul units queue up at the plant or paver, or plant or paver sits idle waiting for a haul unit to arrive).

CHAPTER V

INVESTIGATION OF SURGE LOADING AND WINDROWING

Input Variable Values

The use of surge loading and windrowing techniques has a decided effect on hot-mix distribution operations. The model was used to analyze the effects of the use of these techniques when incorporated into several of the basic systems configurations discussed in Chapter IV.

To describe surge and windrowing in the computer model, values have to be assigned to the following variables:

Surge loading -

- Surge storage capacity in tons
- Amount of hot-mix in surge storage at the beginning of a shift simulation
- Exchange time for one haul unit to replace another under the surge loading hopper (taken note of in the model only when queuing occurs at the surge hopper)
- Additional owning and operating costs accruing to the plant spread

Windrowing -

- Maximum number of loads which may be windrowed ahead of the paver
- Mean, standard deviation and minimum value of the time required for a haul unit to discharge into the windrow
- If a spreader box is used, the times required to engage and disengage the spreader box
- Additional owning and operating costs accruing to the paver spread

The effects of three sizes of surge capacity, viz., 100 tons, 200 tons and 300 tons, were simulated. The additional plant spread costs assumed as a result of adding surge capacity appear in Table 5.

Exchange times used were 12 seconds for small and medium sized units and 30 seconds for large units. Although not totally realistic, it was assumed in all cases that no hot-mix was in a surge bin at the beginning of a shift. All surge operations, therefore, started on the same basis. The assumption of no surge at the start of a shift represents the worst possible case from the standpoint of an efficient operation and production and cost values resulting thereby can thus be considered as being on the conservative side. In the actual case, of course, a contractor employing surge storage and loading would start his plant producing hot-mix prior to the beginning of a normal shift and have the surge bins full or nearly so when the first haul unit was ready to load. Assume, hypothetically, that a plant is started up thirty minutes prior to the beginning of a shift. Assume, also, that the plant continues to produce at its regular rate throughout the shift. This being the case, the plant will theoretically cease shift operations thirty minutes prior to the last load being loaded from surge. Essentially, the operating costs do not change in the hypothetical case, and they would not change a great deal in the actual case for the same reason.

In the case of windrowing, six loads were assumed to be the maximum number that could be deposited ahead of the paver. If six loads were already windrowed when a haul unit arrived, the haul unit could not discharge its load into the windrow until the paver had laid a load from the windrow. Windrow load spreading time parameters were selected based on observations made in the field during the data collection phase of the project. Table 7 lists the parameters used in the simulations. Spreader box engage and disengage times were each assumed to be 30 seconds for all sizes of haul units. If a belly dump unit were to be simulated, these times would be entered as 0.

TABLE 7. - WINDROW SPREADING TIME PARAMETERS

Plant Size TPH	Load Size in Tons	Windrow Spreading Mean	Windrow Spreading Std. Dev.	Windrow Spreading Min. Time
200	7.5	1.00	0.15	0.68
200	15	2.00	0.30	1.36
200	22.5	3.00	0.46	2.04
400	7.5	1.00	0.15	0.68
400	15	2.00	0.30	1.36
400	22.5	3.00	0.46	2.04
600	7.5	0.74	0.12	0.50
600	15	1.51	0.23	1.00
600	22.5	2.25	0.35	1.50
1000*	7.5	0.74	0.12	0.50
1000*	15	1.51	0.23	1.00
1000*	22.5	2.25	0.35	1.50

*Two pavers used

Effects on Systems Performance of Surge Loading and Windrowing

Both surge loading and windrowing have the same general effect on hot-mix distribution operations of decreasing the interdependencies of system components at material transfer points and of smoothing and/or decreasing transfer times at these points. With surge storage available, a plant can continue to batch hot-mix regardless of whether haul units are available for loading; the only constraint is the capacity of the surge storage bin. Also, using surge storage, a haul unit can be loaded more rapidly (particularly in the cases of plants producing small batch sizes) and can load even if the plant is temporarily shut down; the constraint here, of course, is the amount of hot-mix in surge storage at the time of loading. Using windrowing operations, haul units can discharge their loads at the paver regardless of whether the paver is ready to lay that particular load; here the constraint is the limitation on the number of loads that can be windrowed ahead of the paver. Also, using windrowing, a paver can continue to lay hot-mix whether a loaded hual unit is present or not; the constraint is the amount of hot-mix in the windrow.

Windrowing

Figure 25 illustrates the effects of both surge and windrowing when incorporated into the basic system configuration of a 22.5T haul unit loading from a 400 TPH plant and negotiating an initial haul distance of 7.5 miles. Curve 1 of the figure indicates the production of varying numbers of haul units loading directly from the plant and discharging directly to the paver. Line 1 (no surge - no windrow situation) of Table 8 gives the associated efficiencies and

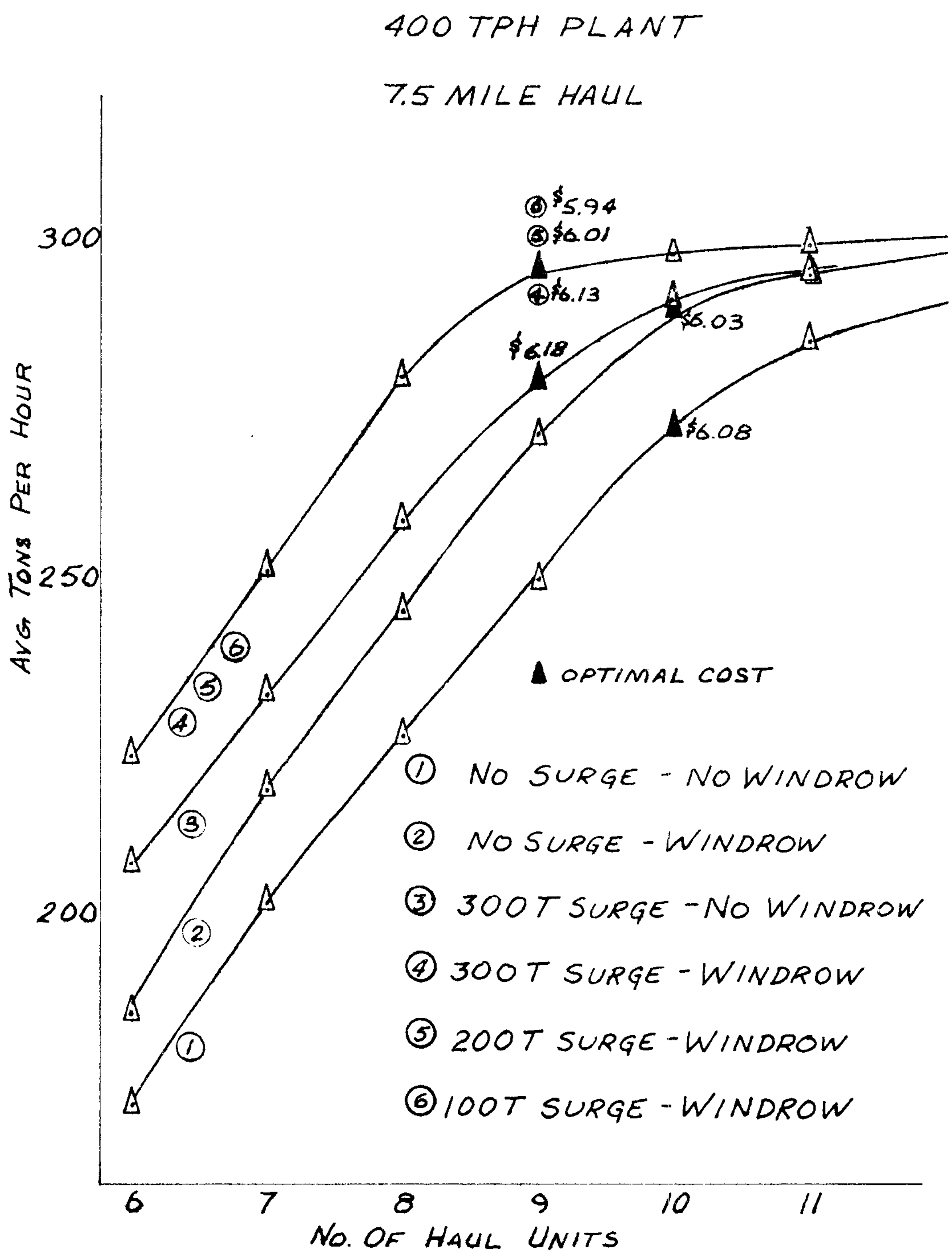

FIGURE 25 - EFFECTS OF SURGE AND WINDROWING

idle times for this system configuration. Curve 2 of Figure 25 shows the effect of using windrowing in conjunction with the paving operation. Optimal production is still obtained with 10 haul units, but it has increased by about 16 tons per hour, an increase of almost 6%. At the same time, the unit cost of optimal production has decreased by $.05, a decrease of about 0.8% (a savings of roughly $150.00 per shift). Line 2 of Table 8 shows how production increased. Paver efficiency rose by some 4.3% as a result of the smoothing effect on material transfer operations of adding windrowing. The increased paver production allowed more hot-mix to be hauled (haul unit efficiency rose from 76.1% to 77.3% overall) and, consequently, more hot-mix to be produced at the plant (plant efficiency rose from 62.8% to 66.1%). Simply by using what amounts to a horizontal form of surge storage at the paver, production increased sufficiently that unit costs decreased, in spite of the increased costs brought about by additional equipment items in the paver spread (a spreader box and a Ko-Cal feeder to pick up the windrow and feed it to the paver).

Surge

Curve 3 of Figure 25 indicates the effect of adding a surge storage and loading operation to the plant component of the system. In this case, 300 tons of storage capacity were provided. Comparing curve 3 with curve 1, it can be seen that the addition of surge increased system production in every instance for the numbers of haul

TABLE 8. - PERFORMANCES ASSOCIATED WITH PRODUCTION UTILIZING SURGE LOADING AND WINDROWING

400 TPH Plant - 7.5 Mile Haul

Situation	Optimal No. of Units	Avg. System Prod. TPH	Avg. Unit Eff. %	Haul Unit Idle Time at Plant %	Haul Unit Idle Time at Paver %	Plant Eff. %	Plant Idle Time %	Paver Eff. %	Paver Idle Time %	Cost per Ton $
1. No surge - no windrow	10	273.8	76.1	9.7	10.1	62.8	24.2	70.8	8.5	6.08
2. No surge - windrow	10	290.8	77.3	8.9	8.1	66.1	18.3	75.1	3.1	6.03
3. 300T surge - no windrow	9	290.8	80.4	2.4	11.4	67.1	20.2	72.3	7.5	6.18
4. 300T surge - windrow	9	295.4	81.7	2.5	9.6	71.2	13.0	76.0	0.4	6.13
5. 200T surge - windrow	9	294.7	81.5	2.6	11.8	69.6	14.9	76.5	0.4	6.01
6. 100T surge - windrow	9	295.4	81.0	2.7	10.3	67.3	18.7	76.4	0.5	5.95

units shown and that optimal production (from the standpoint of unit cost) was obtained with one less haul unit (9 haul units as opposed to 10 in the case of no surge or windrowing). Line 3 of Table 8 shows how this increased production was achieved. Plant efficiency rose from 62.8% to 67.8% since plant batching was no longer tied directly to the availability of haul units. Haul units were able to load more quickly and uniformly and thus spent less time loading at the plant and waiting to be loaded (as indicated by the reduction in haul unit idle time at the plant from 9.7% of shift time to 2.4%). Haul units were thus in a position to haul more hot-mix. The production bottleneck in the system was the paver. Although its efficiency rose from 70.8% to 72.3% of shift time, it could not handle the total production increase which could have been realized by the addition of surge storage and loading. In this regard, note that haul unit waiting time at the paver increased from 10.1% to 11.4% with the addition of surge.

Although system production increased with the incorporation of 300 tons of surge loading, unit costs did not go down. On the contrary, they rose by a significant amount (from the optimal cost of \$6.08/ton for the no surge-no windrowing optimum situation to \$6.18/ton for the optimum situation using 300 tons of surge). The explanation for this is that the additional owning and operating costs of the surge capacity added to the system outweighed the additional production realized. Either the cost of the surge storage was too great for this situation or too much surge capacity was used.

Combined Surge and Windrowing

Lines 4, 5 and 6 of Table 8 and the single curve representing these three situations in Figure 25 indicate the production, unit costs and efficiencies to be realized by combining varying amounts of surge capacity with windrowing operations for the particular basic system under investigation. In all three situations, production increased by close to 8% over that of the basic system employing no surge loading and no windrowing. The production realized approaches very closely the maximum possible for this system configuration and its particular loading time, laydown time, and delay time parameters.

The unit costs for these three situations indicate the necessity of selecting the proper amount of surge capacity for a particular system configuration. In situation 4 (300 tons of surge) the unit cost of the optimum production rate is still greater than the optimum unit cost of the no surge - no windrow operation. Again, this indicates that the cost of the surge is too great or that too much surge capacity is being used. The latter is proved to be the case by situation 5 in which 200 tons of surge capacity are provided. While plant efficiency falls off slightly (and haul unit efficiency even less slightly) and system production decreases by less than a ton per hour, the optimum unit cost falls to a level below that of the optimum cost for the no surge-no windrow situation. Thus, using 200 tons of surge capacity and windrowing, production is increased by about 8% and unit costs are decreased by about 1.2%. Situation 6, in which 100 tons of surge capacity and windrowing are utilized, improves unit costs even more while not seriously affecting production and efficiencies. Here, unit costs are decreased by about 2.1% over the no surge-no windrow situation. In situation 6, plant efficiency drops from 71.2% of shift time to 67.3% because surge capacity is less. It is possible for the plant to keep the surge capacity almost constantly filled; therefore, it occasionally has to stop batching until haul units arrive to begin emptying the full surge bin. This is indicated in Table 8 by the fact that plant idle time increases from 13% for situation 4 (300 tons surge capacity) to 18.7% for situation 6 (100 tons surge capacity).

It should be noted at this point that windrowing can be an effective means of increasing production at the paver component of the system only if one condition is met. The combined times of haul unit discharge into the windrow, maneuver time of the haul unit into windrowing position, and engage and disengage times for the spreader box (if used) must be equal to or less than the time required for the paver to lay one haul unit load plus any external delay time occurring during the laydown operation for one load. If this condition is not met, there will be occasions when the paver will run out of windrow and will sit idle waiting for a haul unit to arrive.

There are, however, at the present time, certain limitations to the use of windrowing. For one thing, the windrow loading device required to elevate the hot-mix into the paver does introduce an additional expense. Also, there is a limitation on the capacity of the loading device to feed the paver from the windrow. Further, there is a limitation on the size of the windrow that can be deposited from the gates of bottom dump haul units. Greater acceptance of this technique, however, should result in equipment changes which eliminate these physical limitations. A final limitation is the exposure of the windrowed mix to sudden changes in the weather and to the possibility of mechanical failure of the windrow loading device and/or the hot-mix paver.

Effects of Surge and Windrowing on Other Systems Configurations

In Chapter IV it was shown that the larger the haul unit, the better the performance from the viewpoints of both cost and production, whether the unit was hauling from a small, medium or large production capacity plant. Model simulations were performed to see if this were still the case for a small plant when surge and windrowing operations were included in the system. Figure 26 graphically illustrates the results of these simulations. Curves 1, 2 and 3 of Figure 26 depict the performance of 7.5 ton haul units hauling from a 200 TPH plant. Curve 1 is the basic system situation; i.e., no surge or windrowing is used. Curve 2 shows the results of incorporating 100 tons of surge storage. Curve 3 illustrates the effects of including windrowing as well as 100 tons of surge storage. The addition of surge loading does improve performance; the further addition of windrowing improves performance even more (optimum production increased by 5.5%; optimum unit cost

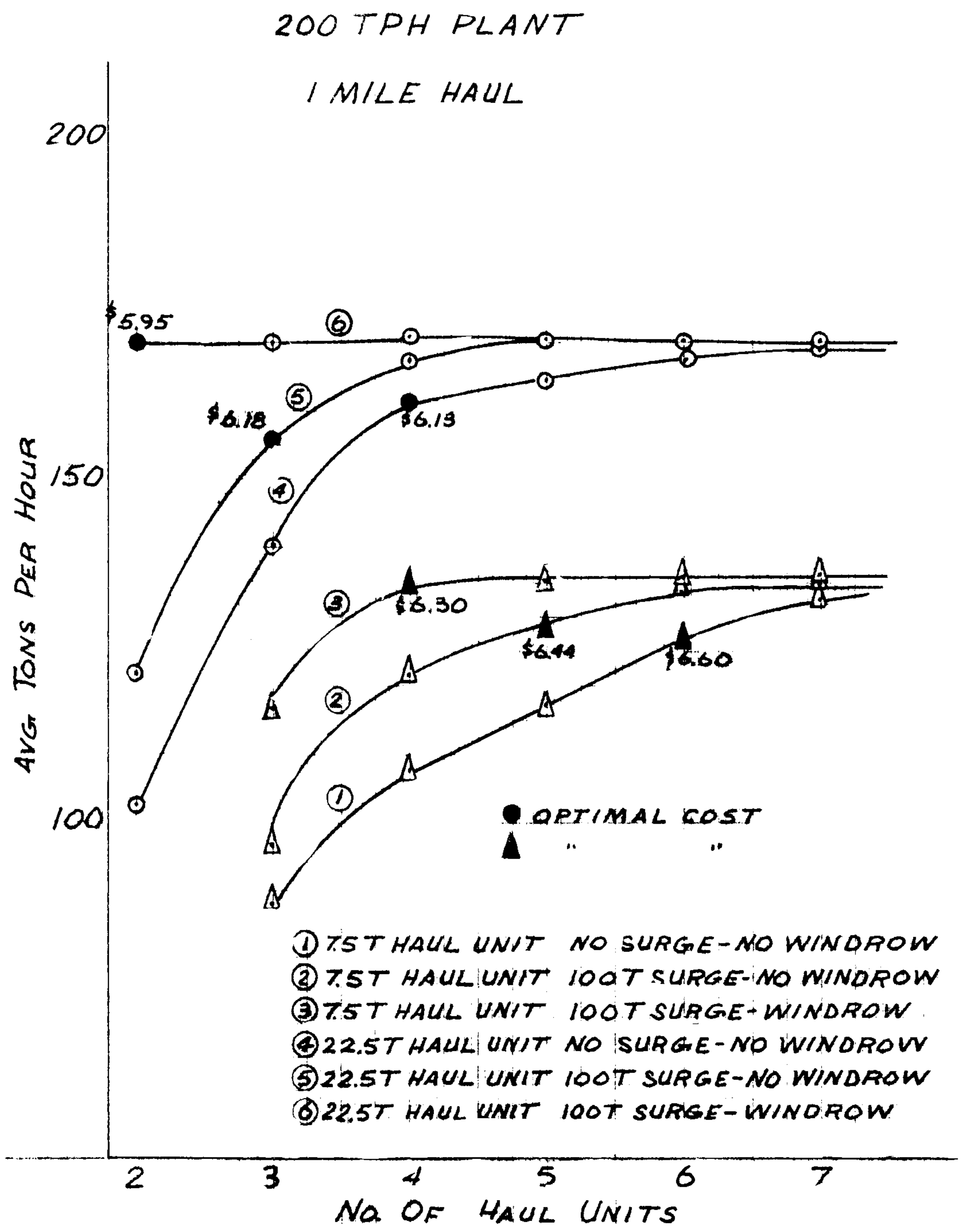

FIGURE 26. - EFFECTS OF SURGE AND WINDROWING ON SMALL PLANT

decreased by 4.5%). However, even using surge and windrowing, the small haul unit is not as effective a performer as the large haul unit loading directly from the plant and discharging directly to the paver (see Curve 4, Figure 26). And with the addition of both surge loading and windrowing operations (see Curve 6), the large haul unit becomes even more effective (optimum production increased by 26.8% and optimal unit cost decreased by 5.6% over the small haul unit employing surge and windrowing). Surge and windrowing do improve the performance of a small unit hauling from a small plant. However, they also improve the performance of a large unit hauling from a small plant. The large unit retains its relative performance edge and remains the overall superior unit.

Figure 27 depicts the performances of a large haul unit operating in systems utilizing 200, 400 and 600 TPH plants, all employing both surge and windrowing operations. The amount of surge capacity employed by each size plant is equal to one-half the nominal hourly output rating of the plant. As was true of the basic systems configurations employing no surge or windrowing, the large plant not only produces the greatest output (as expected), but also produces at the lowest unit cost. Surge and windrowing serve to improve the production performance of any size of plant; if the amount of surge capacity is properly selected, cost performance may well be improved also.

The performances discussed in the preceding paragraph and depicted in Figure 27 illustrate another salutary effect of surge

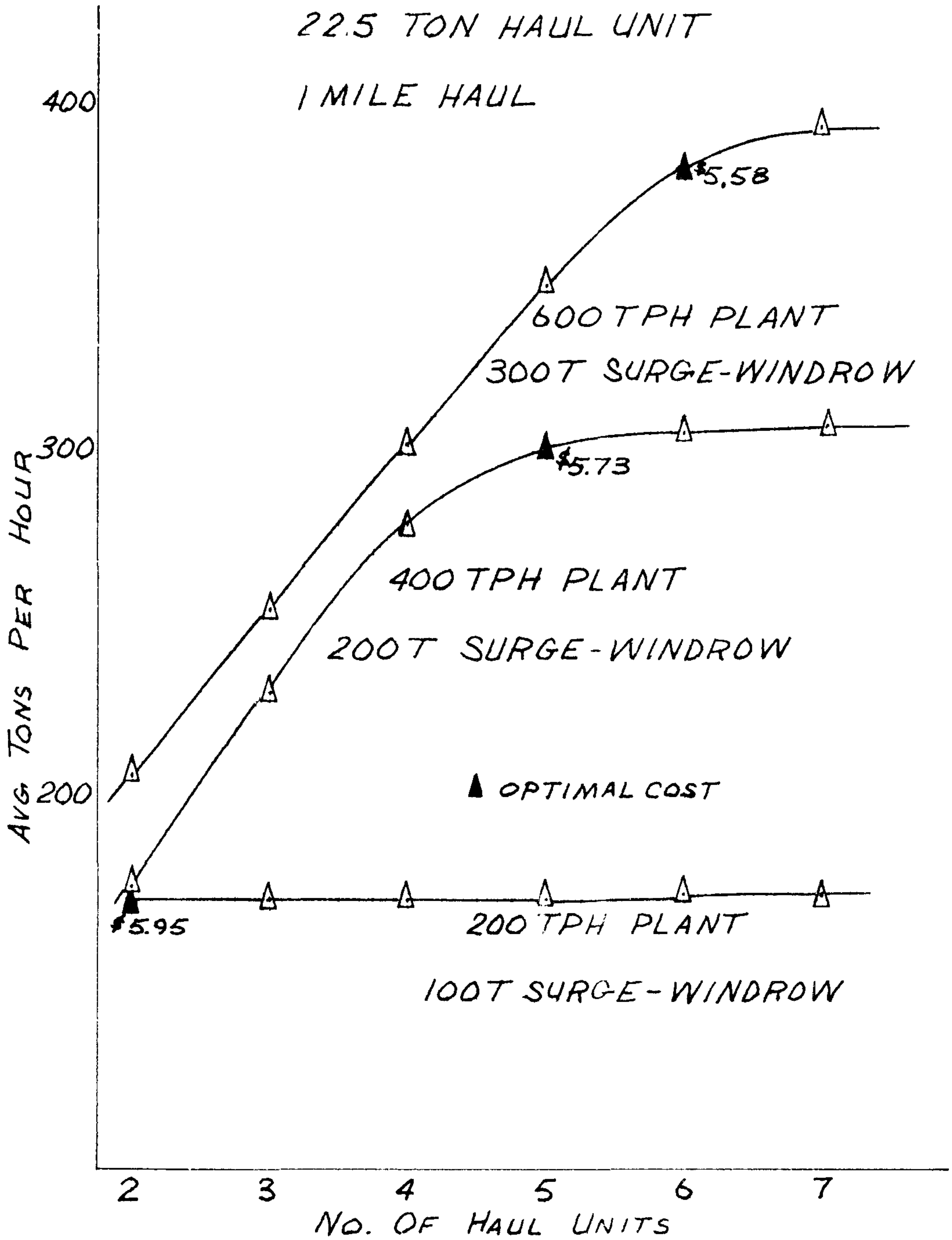

FIGURE 27. - COMPARATIVE EFFECTS OF SURGE AND WINDROWING; SMALL, MEDIUM AND LARGE PLANTS

loading operations. Because plant and haul units are no longer directly dependent on one another for the material transfer operation, each can operate at its maximum capacity. That is, the plant can produce a maximum batch size and the haul can carry its maximum load limit. Whereas the 22.5T haul unit carried only 21 tons of hot-mix loading directly from the 200 TPH plant, it can carry its full rated load of 22.5 tons loading from surge. And whereas the 600 TPH plant produced only 7.5 ton batches when loading the 22.5T haul unit directly, it can produce the maximum batch size of 9 tons loading into surge.

Figure 28 demonstrates the effect of surge and windrowing on operations involving a long haul distance. Two situations are depicted. Curves 1 illustrate the unit cost and production performance of the basic 22.5T haul unit, 400 TPH plant system operating with initial haul distances of 1, 7.5 and 27.5 miles. Curves 2 represent the cost and production performance of this same system employing 200 tons of surge storage and windrowing operations. It is evident that surge and windrowing do improve performance at the longer haul distances as opposed to operating systems not employing these techniques. At the 7.5 mile initial haul distance, utilization of surge and windrowing improves production performance by better than 9.5% and decreases unit costs by 1.3%. At the 27.5 mile haul distance, utilization of surge and windrowing operations improved production performance by 8% and decreased unit costs by 1.3% in comparison with the basic system employing neither

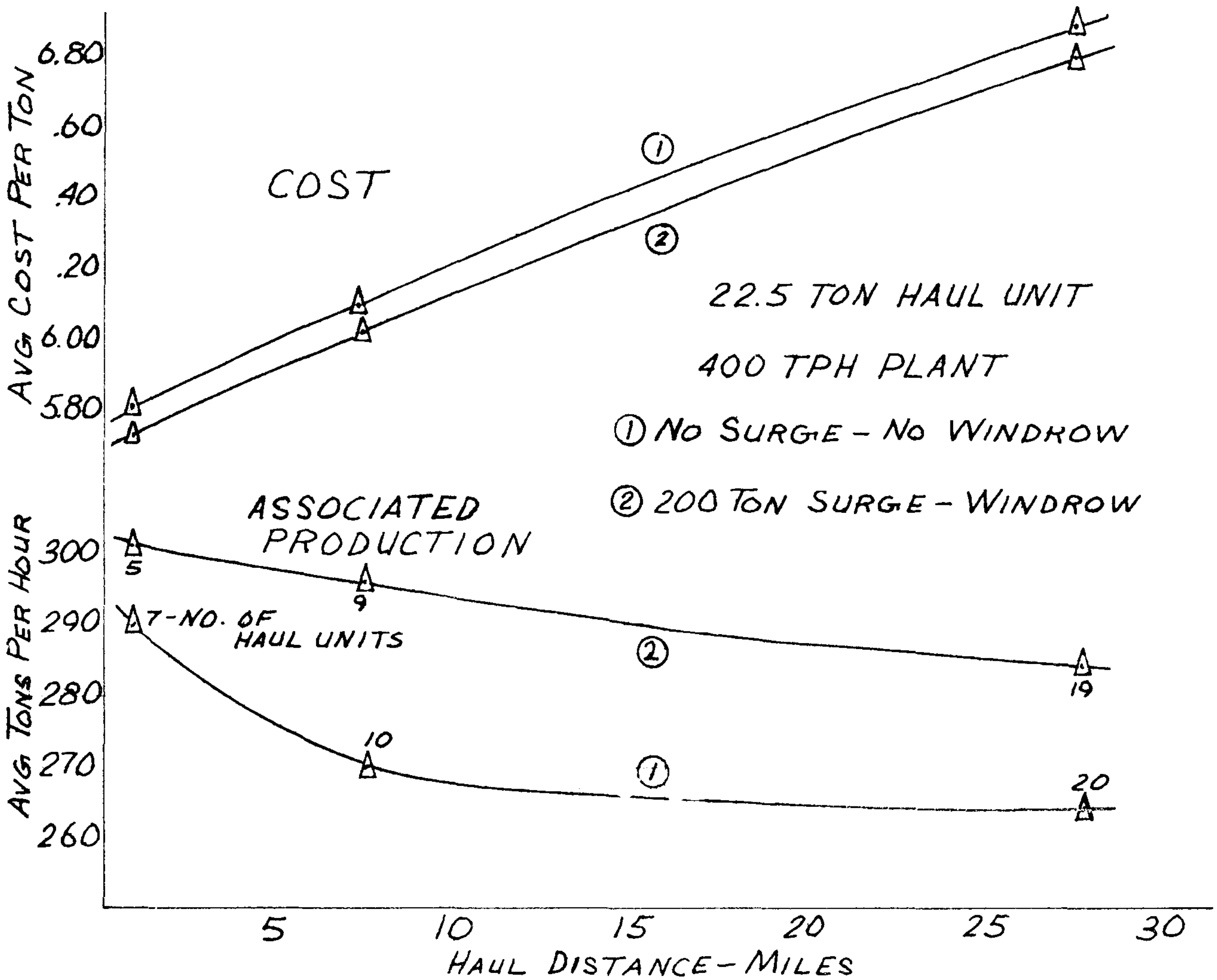

FIGURE 28. - EFFECTS OF SURGE AND WINDROWING; LONG-HAUL DISTANCES

of these operations. Because of the increased numbers of haul units required for greater haul distances, these results are not surprising. More haul units result in a greater potential for haul unit idle time spent in queues at the plant and paver. Surge loading at the plant and windrow discharging at the paver smooth and, on the average, reduce the times of these material transfer operations, resulting in increased production and a possible improvement in unit costs.

Again, a decrease in unit costs is dependent upon the selection of a proper amount of surge capacity. On the basis of observation of model output, it appears that the absolute maximum amount of surge capacity economically desirable at a hot-mix plant is that equal to one-half of the hourly output of the plant. Depending on the situation, less than this amount may be entirely adequate from a production standpoint, and this, of course, would have an even greater beneficial effect on unit costs. It should be kept in mind that this refers to surge storage intended to smooth the material transfer operation at the plant and the operating efficiency of the plant in a continuous haul situation. It does not apply to surge storage used in a situation such as that in which a plant is run for a short period each day to load surge storage to full capacity in order that units may then haul from that surge storage for the remainder of the day's operations (a technique employed in urban operations).

Effects of External Delays

Figure 29 indicates the effects on a system employing both surge and windrowing of eliminating external delays. As was the case when delays were eliminated in a system employing no surge and no windrowing, the absence of external delays has a significant impact on system productivity. In this case, system productivity is increased, on the average, by about 23% by eliminating external delays from the cycles of the plant, paver, and haul units.

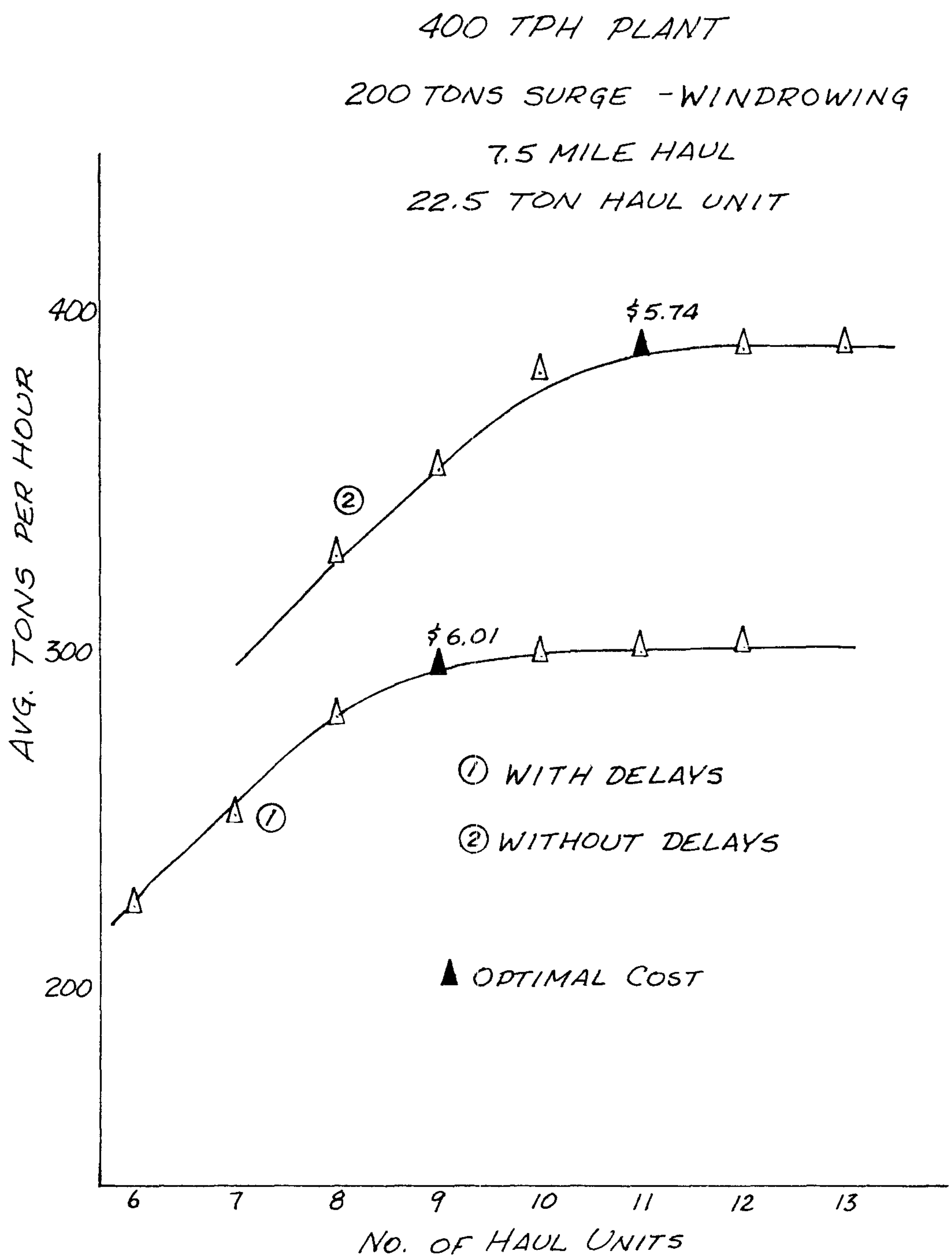

FIGURE 29. - EFFECTS OF DELAYS ON SYSTEM PERFORMANCE

CHAPTER VI

INVESTIGATION OF MEANS TO IMPROVE DISTRIBUTION SYSTEMS PERFORMANCE

The purpose of this chapter is to explore hot-mix distribution systems configurations possessing characteristics which hold potential for improving unit costs and/or production performances. Certain of the ideas to be advanced are innovative while others have been used before but apparently on only a small scale. Prior to discussing these concepts, it is necessary to take a look at those characteristics of any system which significantly influence its cost and production performance. Systems configurations improving on these performance measures will do so only as a result of optimizing those characteristics.

Cost Considerations

In the discussion and analysis which have thus far been presented in this report four major costs can be identified which contribute to the final unit cost of a ton of hot-mix in place on the road. These costs are: (1) the cost of the hot-mix ingredients; (2) the owning and operating costs of the plant spread; (3) the owning and operating costs of the paver spread; and (4) the owning and operating costs of the haul units. This section will examine the sensitivity of final costs to a significant change in any one of these costs excluding that of materials.

As a means of examining the effects on unit costs of changes in owning and operating costs of the plant, of the paver and of haul units, the system configuration of the 22.5T haul unit loading from the 400 TPH plant and having an initial haul distance of 7.5 miles (as presented in Chapter IV) will be used. Also, the sensitivity examination will be accomplished using deterministic calculations rather than stochastic simulation results, even though the deterministic results are always over-optimistic. For the purposes of this sensitivity analysis, the relative values of the results are of more interest than the actual values; therefore, analysis using deterministically derived results will suffice.

Table 9 develops deterministic production estimates for the 22.5 T haul unit, 400 TPH plant, 7.5 mile initial haul system. Table 10 develops unit costs for a ton of hot-mix in place based on these estimates. Note that to bring the unit costs more closely into line with true-to-life costs, the mean of the production rates of the plant and the paver has been used as the governing production rate for the ten and eleven haul units computations. An optimal figure of ten haul units is selected based on these deterministic results (which agrees with the stochastic results depicted in Figure 13).

The sensitivity of unit costs to changes in owning and operating costs of plant, paver and haul units will be examined utilizing the figures developed in Table 10 for the optimal number of ten haul units. First, consider the effect on these costs of a

TABLE 9. - DETERMINISTIC PRODUCTION ESTIMATE

22.5T haul unit

400 TPH plant

7.5 mile initial haul distance

Assume all variable having 0 variances

Assume 8.25 mile average haul distance

Determine cycle time for one unit:

Average travel times -

Weight/Horsepower = (45,000 + 24,000) ÷ 221 = 312.2

From Table 2,

Avg Haul Speed = 70.433 + 15.744 Log 8.25 - 20.594 Log 312.2 = 33.49 mph

Avg Return Speed = $10^{(1.3767 + .2847 \text{ Log } 8.25)}$ = 43.41 mph

Avg Round Trip Speed = (33.49 + 43.41) ÷ 2 = 38.45 mph

Travel = (16.5 x 60) ÷ 38.45 =	25.75 min.
Load =	3.67 min.
First maneuver =	.92 min.
Discharge = 45,000 ÷ (22 x 12 x .33 x 144) =	3.55 min.
Second maneuver =	2.38 min.
Expected delay = 0.5 x 5 =	2.50 min.
Cycle Time =	38.77 min.

Cycles/hour = 60 ÷ 38.77 = 1.55

Haul unit average production = 1.55 x 22.5 = 34.8 TPH/unit

Plant average production = (22.5 x 60) ÷ 3.67 = 367.8 TPH

Paver average production = (22.5 x 60) ÷ (3.55 + .833 x 1.208) = 296.7 TPH significant change in the owning and operating costs of a plant spread brought about for any reason (e.g., development of a new process for producing hot-mix utilizing a less expensive plant). Assume plant costs are increased or decreased by a figure of 25% or $90.08 per hour. The effects on unit costs are:

Total costs, ten haul units	$1990.06	$1990.96
± 25% plant costs	+90.08	-90.08
New Total	$2081.04	$1900.88
Revised unit costs	6.263	5.720
difference	+0.272	-0.271
% difference	+4.53%	-4.52%

In other words, a ± 25% variation in the owning and operating costs of the plant spread in this system configuration results in a change

TABLE 10. - DETERMINISTIC ESTIMATES OF UNIT COSTS

22.5T Haul Unit/400 TPH plant/7.5 Mile Initial Haul

	Number of Haul Units				
	7	8	9	10	11
Production, TPH	243.6	278.4	313.2	332.3*	332.3*
Haul unit cost, $/hr**	150.99	172.56	194.13	215.70	237.27
Plant spread cost, $/hr	360.33	360.33	360.33	360.33	360.33
Paver spread cost, $/hr	152.19	152.19	152.19	152.19	152.19
Total cost, $/hr	663.51	685.08	706.65	728.22	749.79
Materials cost, $/hr	925.68	1058.92	1190.16	1262.74	1262.74
Total	$1589.19	$1744.00	$1896.81	$1990.96	$2012.53
Unit cost, $/hr	6.52	6.26	6.06	5.99	6.06

*mean of plant and paver production rates

**$21.57 per hour per unit

in unit costs of hot-mix produced and laid on the order of ± 4.5%. The relative changes in unit costs in the actual case or based on the stochastic model would be of this magnitude also.

In a like manner, it can be shown that a ± 25% variance in owning and operating costs of the paver spread in this situation would result in a change in hot-mix unit costs on the order of ± 1.9%. Likewise, a ± 25% variance in haul unit owning and operating costs would bring about a change in the unit cost of hot-mix in place on the road of ± 2.7%. Thus, the net effect on unit costs of minor changes in owning and operating costs of system components will be relatively slight (a relatively slight change can be significant, of course; a slight change of 0.5% in unit costs on a $2,000,000 contract is $10,000). Unless significant changes in component owning and operating costs are affected in a system, little change will be brought about in the unit cost of the hot-mix product on the road.

Production Considerations

Production output of a hot-mix distribution system is at its maximum and unit costs are at the optimum when plant, paver and haul units are as closely in balance as possible and producing at the maximum rate of the least productive element. Referring again to Table 9 which develops deterministic production estimates for the 22.5T/200 TPH/7.5 mile system, certain production considerations can be illustrated. Table 9 indicates that the plant for this system can produce at an average rate of 367.8 tons per hour, and each haul unit at an average of 34.8 tons per hour. Using the optimal number of ten haul units, it is evident that this system is not in balance; on the average, the plant is capable of producing at a rate 5.5% greater than the haul units and 23.5% greater than the paver. Obviously, system production can be increased by increasing paver production, and unless paver production is improved, there is little to be gained in attempting to improve productive output of the haul units or plant. In the example at hand, several possibilities exist for improving paver performance: (1) increase paver laydown rate; (2) decrease external delay time; and (3) employ windrowing to smooth performance and improve efficiency of the paver. Possibility (1) would increase production, but it would also increase the probability of stops made by the paver to wait for haul units which, in turn, would tend to increase pavement roughness. Possibility (3) would also increase production somewhat, but only because it would eliminate most of the idle time the paver would otherwise spend waiting for haul units. Possibility (2) holds the greatest promise for increasing paver production at this point. Assume it is possible to decrease the probability of paver external delay by half and to decrease the mean delay time by half also. Deterministically, the expected paver external delay per load of hot-mix laid would now be (.5) x (.833) x (.5) x (1.208) = .25 minutes, and paver production would now be:

$$(22.5 \times 69) \div (3.55 + .25) = 355 \text{ tons per hour.}$$

The system now approaches a balanced condition (plant production

367.8 TPH, paver production 355 TPH and haul unit production, ten haul units, 348 TPH). Unit costs would adjust accordingly. Again assuming the maximum production to be the mean of plant and paver production, unit costs for ten, eleven and twelve haul units would now be:

	10 Haul Units	11 Haul Units	12 Haul Units
Production, TPH	348	361.4	361.4
Haul unit cost, $/hr	215.70	237.27	258.84
Plant and paver cost, $/hr	512.52	512.52	512.52
Total cost, $/hr	728.22	749.79	771.36
Materials cost, $	1322.40	1373.32	1373.32
Total	$2050.62	$2131.11	$2144.68
Unit cost, $/ton	5.89	5.87	5.93

Thus, by reducing expected delays at the paver by 75%, the system is brought more closely into balance, system production is increased and unit costs are decreased. Once again it is emphasized that although this is a deterministically developed illustration, correlative changes would occur in the stochastic model and real life situations if external delays were to be reduced at the paver.

Once a system has been fairly well brought into balance any further increases in productivity can be brought about only by improving the performances of all of the components of the system, i.e., by balancing any production increase at the plant by like increases in the haul units and at the paver. Therefore, to continue the above example, assume that the mean loading time at the plant were to be reduced from 3.67 minutes per load to 3.50 minutes by eliminating certain of its external delays. Plant average production would now be:

$$(22.5 \times 60) \div 3.50 = 386 \text{ TPH}$$

This reduction in plant loading time will slightly decrease the average cycle times of the haul units but not sufficiently to raise their production rate to the plant rate. Some means of increasing haul unit productivity must be implemented. Referring to Table 9, the possibilities for accomplishing this can be seen: (1) decrease travel time by maintaining a higher average rate of travel; (2) decrease loading time (already accomplished); (3) decrease maneuver times; (4) decrease discharge times into the paver (accomplished by increasing paver laydown rate); and (5) decrease external delays. Assume that paver laydown rate is increased to 24 fpm to keep pace with plant production. Paver laydown time for one load becomes: $45{,}000 \div (24 \times 12 \times .33 \times 144) = 3.25$ minutes. This results in a 0.3 minute decrease in haul unit cycle time. Haul unit cycle time is now equal to $38.77 - .17 - .3 = 38.3$ minutes, and haul unit production becomes:

$$(60 \div 38.3) \times 22.5 = 35.2 \text{ TPH/unit.}$$

Paver production is now equal to: $(22.5 \times 60) \div (3.25 + .25) = 386$ TPH. Unit costs based on these new production rates become:

	10 Haul Units	11 Haul Units	12 Haul Units
Production, TPH	352	386	386
Haul unit cost, $/hr	215.70	237.27	258.84
Plant and paver cost, $/hr	512.52	512.52	512.52
Total cost, $/hr	728.22	749.79	771.36
Materials cost, $	1337.60	1466.80	1466.80
Total	$2065.82	$2216.59	$2238.16
Unit cost, $/ton	5.87	5.74	5.80

Thus, production is increased and unit costs are decreased by first bringing the system into balance. Production is further increased and unit costs are reduced still more by improving the performance of each component of the system. The major points to be made based on this illustration are these: (1) a hot-mix production-distribution-laydown system is at its most efficient when plant, paver(s) and haul units are essentially balanced in their respective productive outputs; (2) if a system is not in balance, the most significant contribution to system output can be made by bringing the production rate of the lowest producing component into balance with the other components; (3) resources are to a large extent wasted if they are expended in an effort to improve the performance of a system component which is already performing better than another component: (4) the performance of a system which is balanced can be improved only by improving in a balanced manner the performances of its individual components.

The subject of this study is concerned primarily with the distribution component of hot-mix production-distribution-laydown systems. However, the above serves to illustrate the fact that the performance of a hot-mix system (from either a cost or a production viewpoint) is dependent on the performances of its plant, paver and haul unit sub-systems and that the performances of the sub-systems are interdependent. In short, the most advanced and technically superior distribution sub-system will never realize its full potential if the production rates of the plant and paver are not maintained essentially balanced and at a maximum.

Overall Systems Considerations

In conjunction with the foregoing discussions on cost and production considerations, Table 11 presents information pertaining to both cost and productivity of the distribution component of hot-mix systems. It presents a breakout of haul unit cycle times into their individual cycle elements for the cases of the 22.5 ton haul unit loading from 200, 400 and 600 TPH plants and initially traversing a 7.5 mile haul distance. Costs are then developed for the time breakouts showing the composition of unit costs for a ton of hot-mix delivered from each of the plants. Analyzing the information appearing in Table 11, a number of general observations can be made concerning the potential for cost savings with regard to total system performance and distribution sub-system performance in particular:

TABLE 11. - CONTRIBUTIONS OF HAUL UNIT CYCLE TIME ELEMENTS TO PER TON UNIT COSTS

22.5 Ton Haul Unit; 7.5 Mile Initial Haul Distance

	Plant Size							
	200 TPH		400 TPH		400 TPH S-W*		600 TPH	
No. of Units	8		10		9		11	
Optimal Production	160 TPH		270 TPH		290 TPH		324 TPH	
Cycle Elements	% Time	Cost/ton	% Time	Cost/ton	% Time	Cost/ton	% Time	Cost/ton
1. Plant queue	11.6	$.114	9.7	$.065	2.7	$.015	7.7	$.044
2. Loading	11.4	.112	7.4	.050	1.2	.007	6.4	.037
3. Paver queue	10.5	.103	10.1	.068	10.1	.057	4.3	.025
4. Maneuver to paver	1.6	.016	1.9	.013	1.4	.008	2.1	.012
5. Discharge to paver	11.2	.110	7.2	.049	6.2**	.035	5.2	.030
6. Maneuver for return	4.2	.041	4.8	.032	3.7	.021	5.5	.031
7. Travel	45.6	.449	54.7	.369	68.5	.386	63.0	.360
8. Delay	3.9	.039	4.2	.028	6.2	.035	5.8	.033
	100.0	$.984	100.0	$.674	100.0	$.564	100.0	$.572
Plant Cost/ton		1.076		1.130		1.112		1.237
Paver Cost/ton		0.800		0.476		0.464		0.391
		$2.86		$2.28		$2.14		$2.20
Materials Cost/ton		3.80		3.80		3.80		3.80
Total Cost/ton		$6.66		$6.08		$5.94		$6.00

*100 tons of surge storage; windrowing
**Includes times for engaging and disengaging spreader box

1. From the cost standpoint, the greatest savings can be realized by reducing or eliminating the non-productive element of queuing time at the plant. This can be at least partially accomplished by:

    a. Employing a larger plant with correspondingly larger batch sizes (if this is a feasible alernative).

    b. Employing surge storage and loading.

    c. Reducing plant down-time to an absolute minimum.

    d. Reducing variability of batching times to an absolute minimum.

2. A second area of significant cost savings is the non-productive element of queuing time at the paver. Reduction or elimination of this element can be accomplished by:

    a. Hauling the largest possible size loads.

    b. Adjusting paver laydown rate to keep pace with average plant production.

    c. Employing some form of surge storage at the paver (windrowing is a primary form).

    d. Reducing down time and other delays to the absolute minimum.

3. The non-productive element of haul unit delay offers a third area of potential cost savings. Certain delays (traffic conditions, unavoidable stops, etc.) are inevitable. However, those resulting primarily from the human element could very likely be reduced by exerting more control over haul unit operator performance by such means as:

    a. Providing rest stop accommodations at the plant.

    b. Establishing production goals and standards.

    c. Implementing and maintaining schedules for both operator and organizational maintenance of hauling equipment.

4. The time haul units spend in travel is a highly important cost consideration. As the haul distance increases, of course, the cost contribution of this element should increase also. However, this element may increase or be too high because haul units are not maintaining the greatest feasible average rate of travel. If this is the case, the portion of total unit cost contributed by this element is too high. Transportation of hot-mix is the objective of the distribution sub-system. Optimal costs are achieved when the percent of time devoted to this cycle element is at a maximum and the rate of travel of haul units is at the feasible maximum also.

5. The cost contribution of loading time at the plant can be reduced by reducing this element. The means to accomplish this are the same as those advanced to reduce haul unit queuing time at the plant (see observation 1). In addition of course, reduction of batching time to the minimum required by specifications will also contribute to the reduction of this cost contributing item.

6. The cost contributing element of discharge time at the paver can be reduced only if haul units can discharge at the paver at a rate greater than the rate of paver laydown. This can be accomplished by utilizing some means of surge storage at the paver, either in the form of windrowing or some other type of storage as yet not devised.

7. The final cost contributing element of the haul unit cycle is that of haul unit maneuver times at the paver. Haul unit maneuvers at the paver (or at a windrow) are affected by two considerations, (1) the mechanical configuration of the haul unit (the ease or difficulty with which it can be backed into a paver or windrow or can be turned around, its mode of discharge (end dumping, belly dumping, etc.) and the consequent maneuvering this mode entails); and (2) the physical layout at the paving site (the traffic pattern for approach to and departure from paver or windrow; surface space available for maneuvering into paver or turning around). Generally, as haul units increase in hauling volume, maneuver times and space required for maneuvering increase, thereby increasing the contribution to unit costs of these cycle elements. Particularly in the case of large hauling units, the best layout at the paver site would be one in which the haul unit could perform all maneuvers in a forward gear, i.e., the unit could pull abreast of a paver, surge hopper or windrow, discharge while moving forward and then turn around for the

return trip (or could turn around prior to discharge if this is the way the job is set up) by making a series of ninety degree (or less) angle turns while moving forward.

Of the foregoing observations concerning the contributions of haul unit cycle elements to unit costs, those concerning non-productive time (observations 1, 2 and 3) possess the greatest potential for increasing system performance and efficiency and decreasing unit costs. Only observations 3, 4 and 6 are directly concerned with hauling systems, and of these, only 4 and 6 directly relate to the technical performance aspects of haul units. In other words, the performance and cost considerations of distribution sub-systems can be improved at least as much (if not more) by changes made to operations and equipment configurations at the plant and paver sites and by the control exerted by management as by improvements made to the operations or technical aspects of the distribution sub-systems themselves. It is not intended that this discount the improvements which could be made to distribution sub-systems, but it is certainly a fact which should be recognized by hot-mix contractors.

Characteristics of Distribution Sub-Systems

If it were possible to design an ideal distribution sub-system for transportation of hot-mix from the plant to the paver, the system would possess these characteristics:

1. Large load capacity
2. Low weight to load ratio
3. Sufficient power to rapidly achieve and maintain a fairly high rate of movement

4. A high degree of maneuverability (assuming that conditions at the paver site will not always be favorable)
5. A means of rapidly initiating and effecting discharge at the paver
6. No delays
7. A reasonable cost

No such distribution sub-system currently exists, and it is doubtful that one fulfilling all of these requisites could ever be brought into being. If 1 through 6 were incorporated in one unit or system, then surely 7 would not be. The achievement of 6 implies the elimination of the human element and movement of hot-mix by some means such as electronically controlled haulers moving on tracks or a tramway. Although this sort of system might be economically feasible on certain specific jobs, it hardly seems likely that it could justify itself from an economic standpoint on most hot-mix asphalt paving work. The attainment of 1, a large load capacity, makes it difficult to achieve 4, high maneuverability. In short, certain of the characteristics of the ideal distribution sub-system are at odds with one or more of the others, and the entire package taken as a whole appears to call for technology beyond the present state of the art.

Present distribution sub-systems, for the most part, make use of what is available in the way of hauling equipment for hot-mix. Although manufacturers of hauling equipment allow fleet purchasers to more or less tailor their haul units (buyers can select chassis, body, engine, etc.), no known haul unit exists that is designed and sold solely for the hauling of hot-mix from plant to paver. At least one such specialized haul unit exists for concrete paving, however, and it was observed in action on a highway job in Mississippi during the course of this study. Haul units for hot-mix, whether contractor owned or sub-contracted, normally are used for other hauling purposes and particularly for hauling aggregate to the plant. This is probably one reason why specialized haul units for hot-mix are not on the market - they wouldn't provide the versatility required though they would do an excellent job of transporting hot-mix. So, it seems fair to say that units for hauling hot-mix are selected with other uses in mind, and the purchaser makes what he considers to be the best choice possible from the selection of hauling equipment available. He selects that unit he feels will fulfill the majority of his requirements and does not require specialized equipment designed only for the job of getting hot-mix from the plant to the paver. For this reason, then, it is necessary to rig a bobtail dump with a spreader box before it can discharge to a windrow and to maneuver a haul unit backward into a paver before the unit can discharge. For this reason, some belly dumps can't be used for windrowing, inasmuch as their clearances won't allow a windrow of sufficient height and volume to be deposited. Designed for general usage, virtually all haul units, when used to transport hot-mix, have certain drawbacks. However, it appears that general purpose haul units will continue to be used for transporting hot-mix until such time that asphalt pavement contractors become convinced of the profitability of specialized equipment. When that time comes, equipment manufacturers will make the specialized equipment available.

Innovative Concepts With a Potential for Improving Distribution Sub-System Performance

Aluminum Body Haul Units

It would appear that certain equipment items are available or could be made available rather easily at the present time which, if used for or in conjunction with transporting hot-mix, have the potential for improving distribution sub-system performances. One such item is aluminum body haul units. Haul units with aluminum beds have been shown to withstand the rigors of rock hauling operations (6), and it appears that they could be used in hot-mix operations. Aluminum haul bodies, of course, improve on the characteristic of the haul unit weight to load ratio. All other characteristics of an aluminum body haul unit relative to a steel body haul unit remain the same with the possible exception of owning and operating costs. If the costs of owning and operating an aluminum body haul unit are greater than those for a comparable steel body haul unit (as would normally be expected) then an analysis must be performed to determine if the marginal increase in production more than offsets the increased costs incurred. Such an analysis was not performed for the study inasmuch as several instances were found (using the program described in Reference 6) of haul units utilizing aluminum haul bodies capable of carrying greater pay loads at lesser owning and operating costs than comparable steel body units. This being the case, final unit costs of hot-mix would obviously be improved, no matter how slightly.

Off-the-Road Haulers

Another category of equipment presently available and which holds promise of improving hot-mix distribution performance is off-the-road haulers. These equipment items are available in load capacities ranging up to 100 tons, and it appears that they might be used for hot-mix transportation involving short haul distances. The computer model was used to determine the performance of a 40T rear-dump, off-the-road hauler loading from a 600 TPH plant and traveling an initial haul distance of 1.0 mile (the plant had 300 tons of surge storage and the unit was discharging into a spreader box for windrowing). The parameters assumed to describe the haul unit in the program were:

Load weight - 80,000 pounds
Horsepower - 450
Vehicle weight - 79,460 pounds
Mean time into windrowing position - 13.5 seconds;
standard deviation - 6.5 seconds
Mean dsicharge time into windrow - 4.0 minutes;
standard deviation - 0.62 minute
Mean maneuver time for return to plant - 2.2 minutes;
standard deviation - 0.5 minute
Owning and operating cost $44.28 per hour

The performance of the off-the-road hauler as determined by the computer simulation model and based on the assumed parameters is presented in Figure 30. Figure 30 also depicts the performance of the 22.5T haul unit operating in the same system configuration. The model results indicate that the off-the-road hauler surpasses the 22.5 ton haul unit in production performance but that the increased production is not sufficient to offset the increased owning and operating costs assumed. Several observations are pertinent, however.

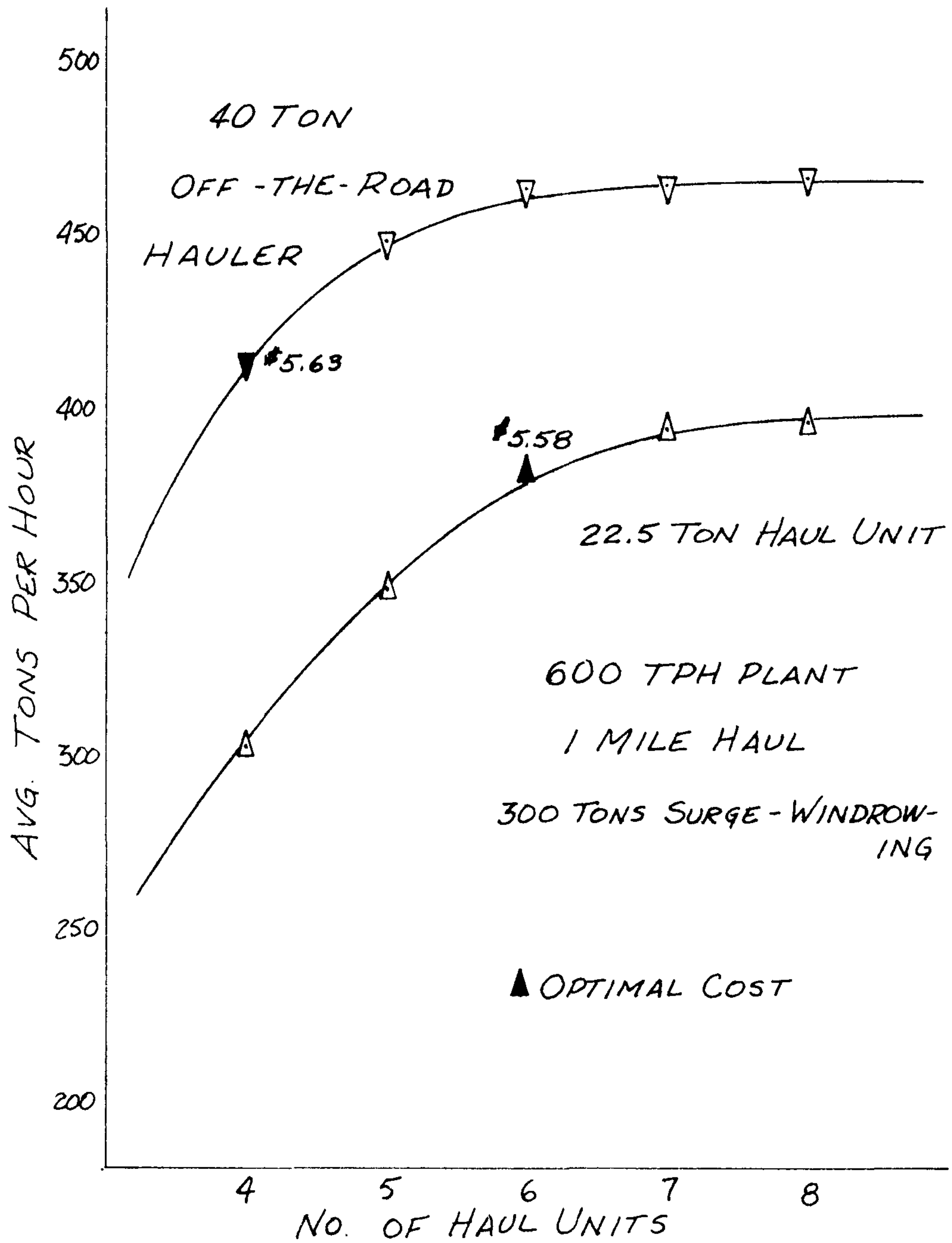

FIGURE 30. - PERFORMANCE OF 40T OFF-THE-ROAD HAULER VS. 22.5T HAUL UNIT

One, in an actual situation, the circumstances dictating owning and operating cost development might well result in a lower cost figure and consequent lower unit costs for the off-the-road haul unit. Two, if volume of production were of primary importance, the higher producing haul unit might well be the choice in spite of the higher resulting unit costs (within reason). And three, the model results are evidence that off-the-road haulers might profitably be considered for certain hot-mix hauling situations.

Semi-Trailer, Trailer Combinations

Another hot-mix distribution concept studied was one employing semi-trailers pulling full trailers. The haul unit characteristic exploited in this concept is that of moving the largest possible load from plant to paver at one time. This is not a new concept, the idea having been employed in California for some years (though to what extent is not known). The semi-trailer, trailer combination visualized is one utilizing belly dump trailers; the assumption is made that clearance between the discharge gates and the roadway surface is sufficient to allow the requisite quantity of hot-mix to be windrowed for the particular paving operation being conducted. The computer model was used to determine the performance of a tractor hauling a 22.5T semi-trailer and a 22.5T trailer. Assumptions and estimates made for this combination were:

Load weight - 45 tons
Horsepower - 238
Vehicle weight - 38,500 pounds
Mean time into windrowing position - 1.4 minutes;
standard deviation - 1.4 minutes

Mean discharge time into windrow - 5.0 minutes;
standard deviation - 0.5 minute
Mean maneuver time for return to plant - 2.46 minutes;
standard deviation - 1.35 minutes
Maximum windrow loads allowed ahead of paver - 3
Owning and operating costs - $30.51 per hour

It should be noted that some information pertaining to the operating parameters of this type of haul unit combination was obtained from the Bureau of Public Roads.

Performance of this haul unit was simulated for the situation in which the unit was loading from a 400 TPH plant (200 tons of surge storage) and discharging into a windrow at a single paver after traversing a haul distance which initially was 7.5 miles. Figure 31 presents the results of this simulation. Figure 31 also presents the performance of the 22.5T haul unit operating in the same system configuration for comparison purposes. Based on the results as depicted, the semi-trailer, trailer combination appears to be a distribution sub-system offering great promise for improving production and cost performances.

Side Discharge Haul Unit

Another distribution concept investigated by means of the computer model was one employing a haul unit with a side discharge capability. In this situation, the haul unit pulls alongside the paver, makes connection with a conveyor mechanism lowered from the paver hopper to the rear of the haul unit, and discharge to the conveyor which in turn transfers the hot-mix to a skip traveling back and forth across the hopper, depositing the hot-mix evenly

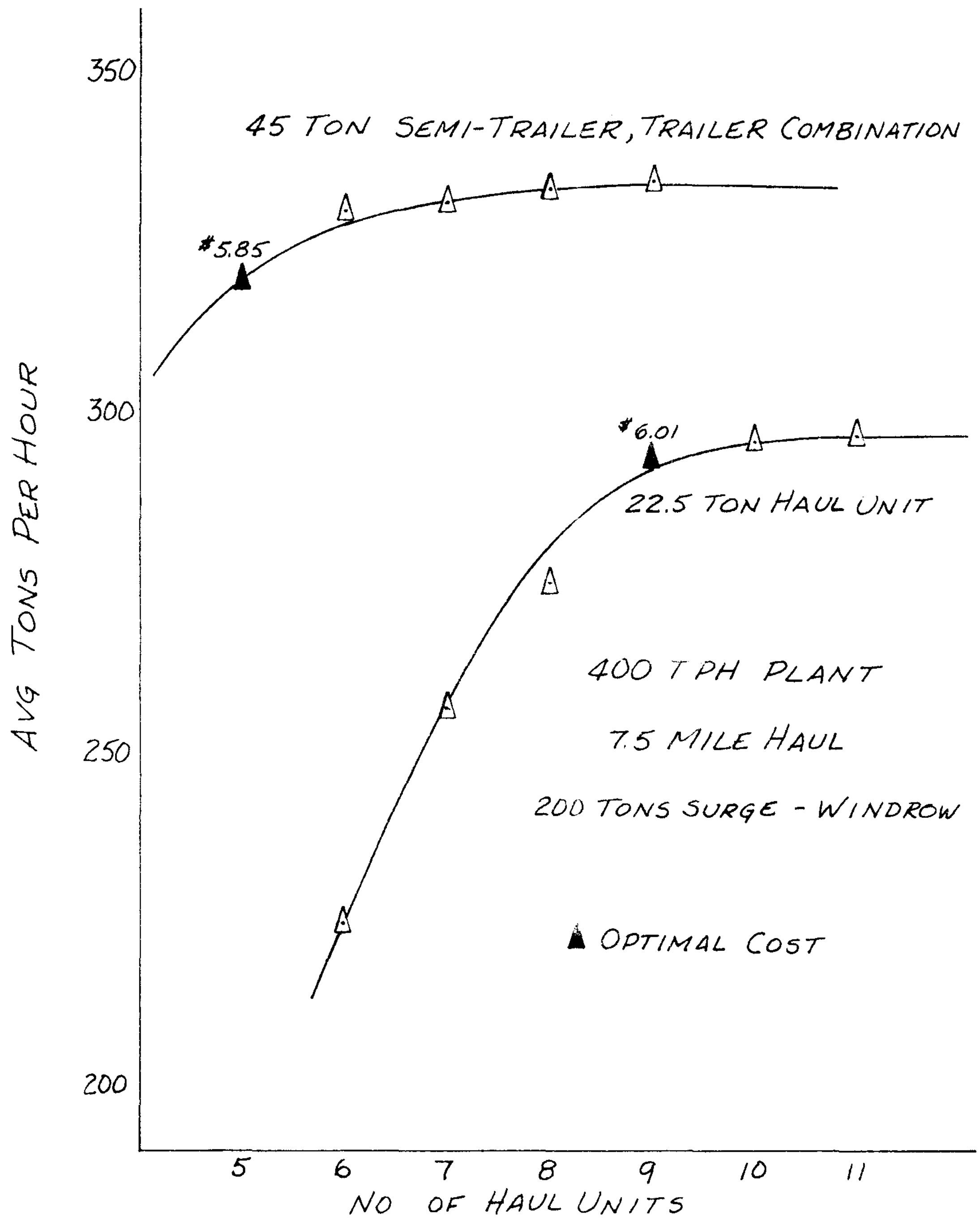

FIGURE 31. - PERFORMANCE OF 45T SEMI-TRAILER, TRAILER COMBINATION VS. 22.5T HAUL UNIT

ahead of the screed. The objective here is to eliminate or reduce haul unit maneuver time prior to discharge. In the simulation of this situation, the parameters used to describe the haul unit maneuver time prior to discharge were based on observations made of a similar operation used in the placement of concrete on a highway project in Mississippi. Although the maneuver time to discharge is substantially reduced, a certain amount of time is still required for the haul unit to assume the correct position beside the paver hopper and for the conveyor connection to be made. The simulation was conducted for a 22.5T haul unit loading from a 400 TPH plant (220 tons of surge storage) and traversing an initial 7.5 mile haul distance to the paver. Estimates and or assumptions made for this particular system simulation were:

Mean maneuver time prior to discharge - 0.25 minute; standard deviation - 0.125 minute; minimum time - 0.083 minute

Owning and operating cost of paver spread - $152.19 per hour

Additional paver owning and operating cost of conveyor equipment and skip - $5.00 per hour

Figure 32 presents the performance results for the side discharge situation as determined by the computer model. For comparison purposes, the performance curve for a 22.5T haul unit operating in the same system configuration but discharging into a windrow is also presented. As can be seen, the use of a side discharge mechanism results in system production performance very nearly equal to that of a system employing windrowing, although one less haul unit is required. Furthermore, the unit cost of the hot-mix in place

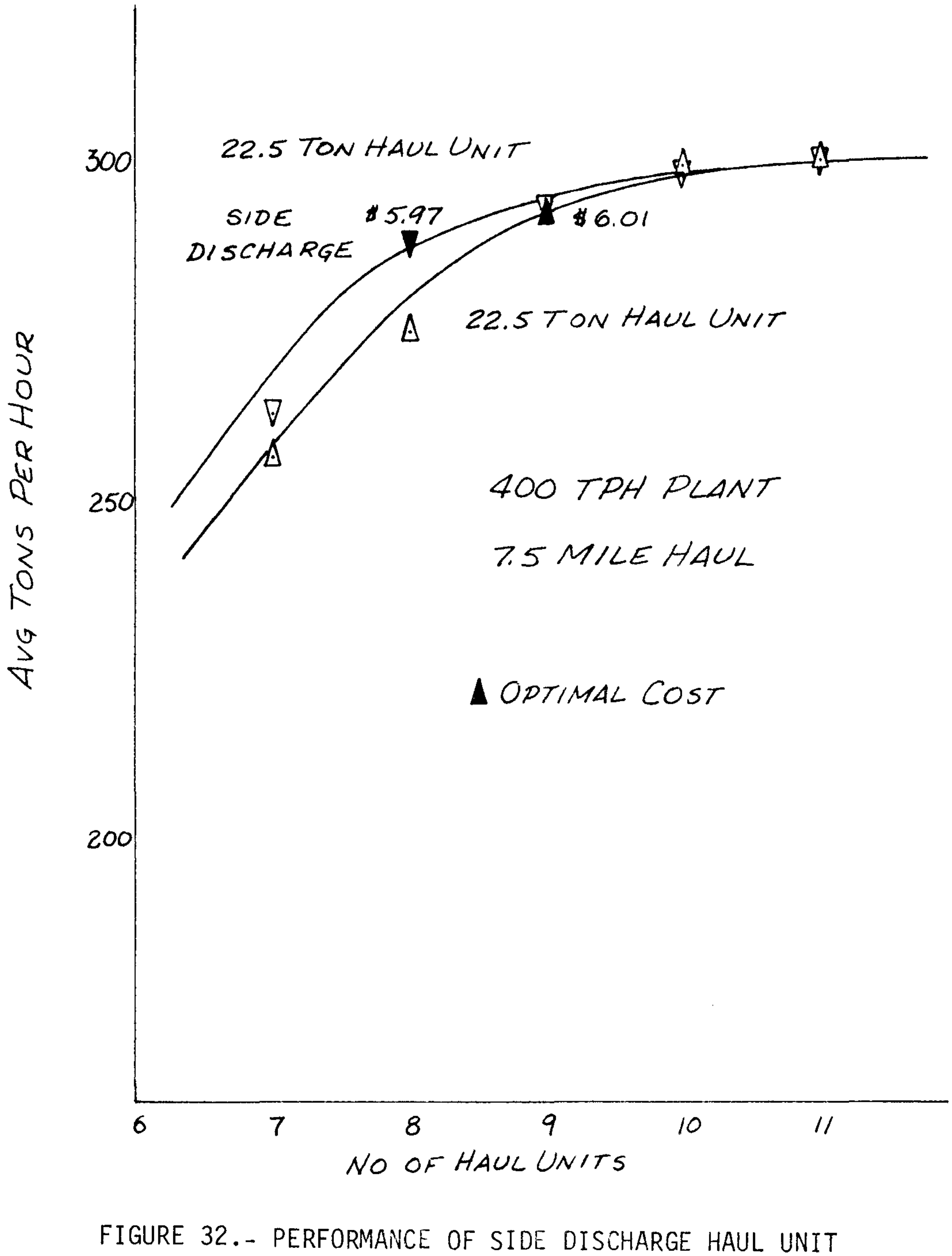

FIGURE 32.- PERFORMANCE OF SIDE DISCHARGE HAUL UNIT VS. CONVENTIONAL HAUL UNIT

on the road is decreased by \$.04 per ton using the input parameter values assumed. This is accomplished utilizing a side discharge arrangement for which the additional owning and operating costs are assumed to be \$5.00 per hour. For this particular situation, the total owning and operating costs of a mechanism or mechanisms (in the event that haul units might have to be modified to achieve side discharge) for effecting side discharge could amount to as much as \$.04 x 288 = \$11.52 + \$5.00 (the additional owning and operating cost assumed for side discharge in the simulation) = \$16.52 per hour without exceeding the figure of \$6.01 per ton of hot-mix in place.

The results of the simulation indicate that the concept of side discharge of hot-mix has merit and warrants further investigation.

Mechanically Discharged Haul Unit

A mechanically discharged hauling unit was investigated by means of the computer model. This idea is not entirely new and envisions a hauling unit discharging to the rear by some means such as a conveyor running the length of the haul bed. Versions of this discharge concept are in existence at the present time.

During the data collection phase, information was recorded on several operations utilizing Flowboy hauling units which employ a form of mechanical discharge consisting of an hydraulically operated flight and drag chain running the length of the load-carrying bed. Input data for the computer simulation was based on the observations of Flowboy performance. Pertinent input values for the simulation (surge and windrowing used) were:

Plant size - 400 TPH; 200T surge at the plant
Mean time of haul unit first maneuver to windrow - 0.845 minute; standard deviation - 0.328 minute; minimum time - 0.250 minute
Mean time of haul unit discharge into windrow - 2.260 minutes; standard deviation - 0.150 minute; minimum time - 1.95 minutes
Mean time of haul unit second maneuver - 1.377 minutes; standard deviation - 0.490 minute; minimum time - 0.733 minute
Load weight - 22.9 tons
Weight of haul unit - 26,100 pounds
Horsepower - 221
Owning and operating cost of unit - $22.85 per hour

Figure 33 presents the simulation results.

Traveling Surge at the Paver

This concept of discharging hot-mix provides haul units a means of rapidly initiating and effecting discharge at the paver as well as divorcing the discharge operation from dependency on paver lay-down operations. The concept is, as far as is known, completely unique and envisions providing a moving surge bin ahead of the paver into which haul units can discharge. Further, the traveling surge provides three points which can be used simultaneously for hot-mix discharge. Haul units discharge to the traveling surge by pulling alongside of, ahead of or ahead of and across the surge unit and backing into one of the three discharge points. Using this mechanism, haul units can move rapidly into discharge position, discharge at their maximum discharge rates and can also discharge simultaneously with one or two other units (a feature not true of windrowing).

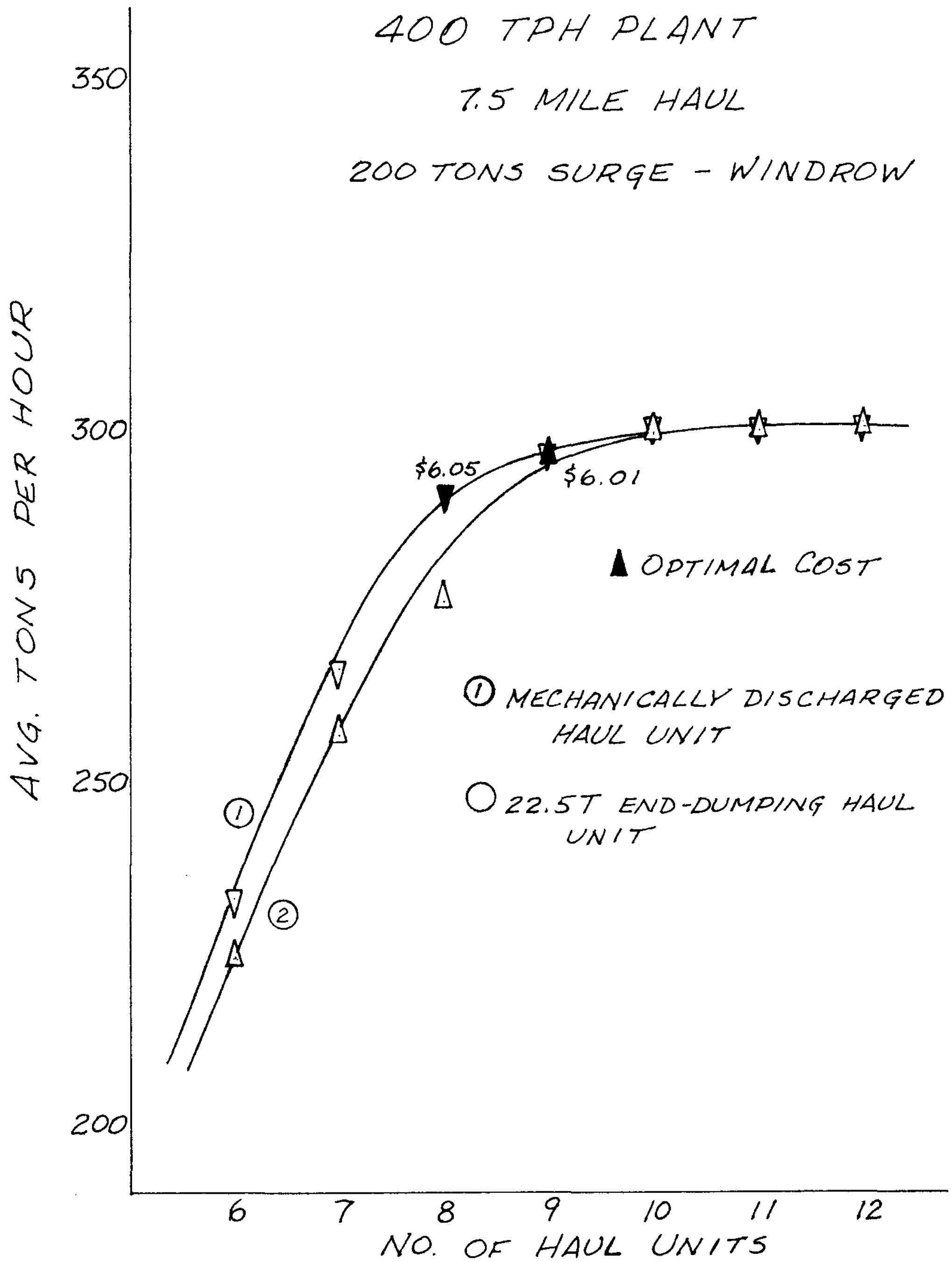

FIGURE 33. - PERFORMANCE OF MECHANICALLY DISCHARGED HAUL UNIT

In order to investigate the potential of this discharge concept, use was made of the traveling surge subprogram developed for the computer model. The model was exercised for a distribution sub-system employing a nominally rated 100T traveling surge capacity and mechanically discharged hauling units of the type discussed in the preceding section. Significant input values developed or assumed and provided to the program for the simulation were:

Plant size - 400 TPH; 200T surge provided at the plant
Traveling surge capacity - 4 haul unit loads
Owning and operating cost per hour of traveling surge - $35.00
Mean time of haul unit first maneuver to discharge point - 0.700 minute; standard deviation - 0.400 minute; minimum time - 0.300 minute
Mean time of haul unit discharge to traveling surge - 1.200 minutes; standard deviation - 0.200 minute; minimum time - 0.900 minute

Results of the computer simulation of a system employing traveling surge appear in Figure 34. For comparison purposes, the performance of a 22.5T haul unit operating in a similar system not employing traveling surge is also shown. In addition to the obvious fact that use of traveling surge allowed optimum production to increase by 15 tons per hour over the system not employing traveling surge (using the same number of hauling units), the results of the simulation run indicated that overall haul unit efficiency increased by about 5% (from 81% to 86.2%); plant efficiency increased from 69.6% to 78.9%; paver efficiency increased from 76.5% to 80.8%; paver idle time decreased to 0% from an already low 0.5%; and haul unit

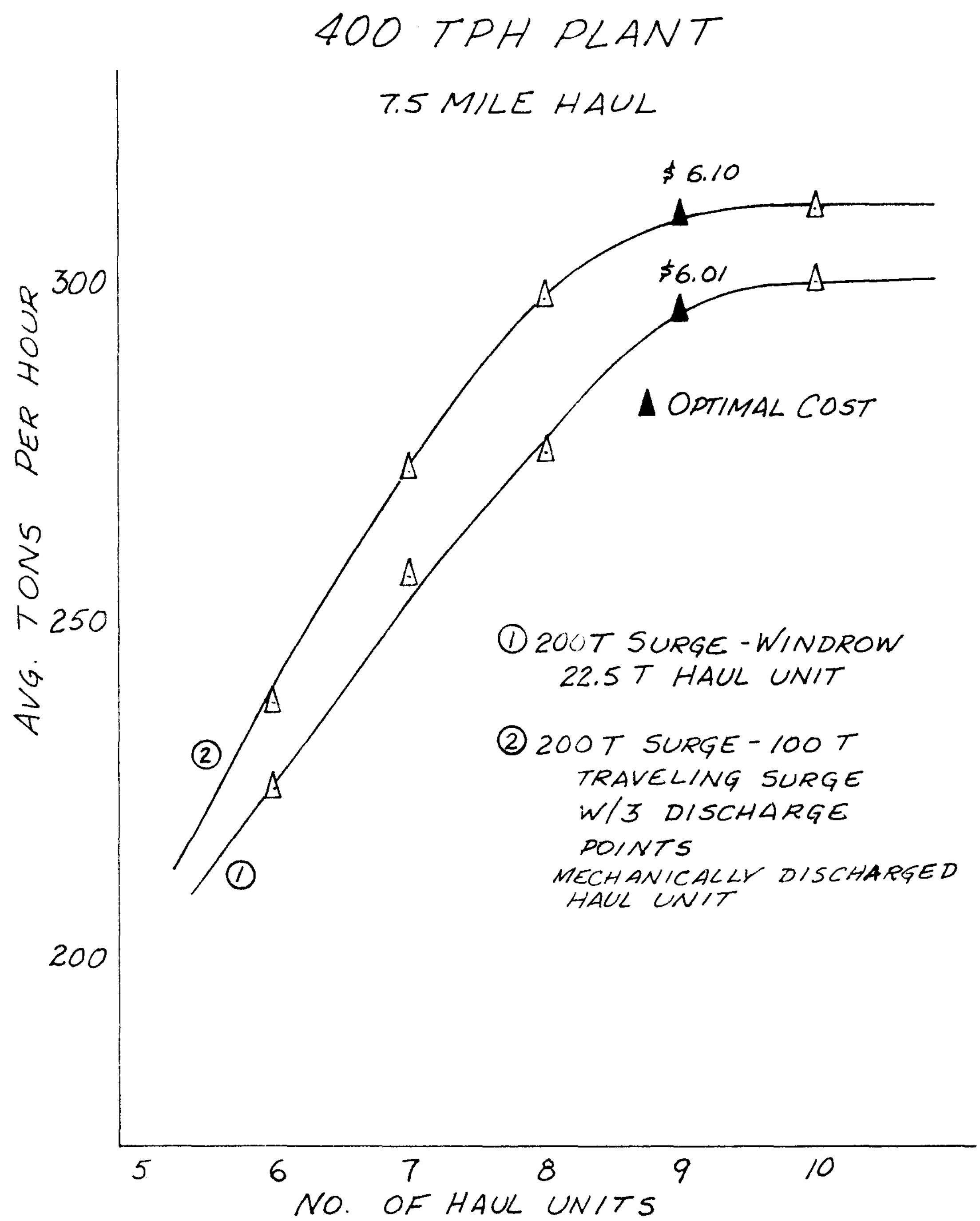

FIGURE 34. - PERFORMANCE OF SYSTEM EMPLOYING TRAVELING SURGE MECHANISM AT PAVER

idle time at the paver decreased from 11.8% to 0%. Use of traveling surge improved on production performance and operating efficiency of the system. In spite of the fact that Figure 34 indicates unit costs of the resultant production are higher using the traveling surge (as a result of owning and operating cost developed for it), the simulation results do establish the fact that traveling surge is a valid hot-mix distribution concept which appears to warrant further investigation.

1000 TPH Plants

One final concept was investigated relative to improving cost and production performance of the total hot-mix system utilizing a 1000 TPH rated plant. This is not a new concept, although the use of such a high capacity plant has certainly not been adopted on a wide scale by the hot-mix industry. Two versions of such a plant were simulated, one employing a conventional dryer to hot bin to pug mill configuration and the other employing a screenless, continuous batch concept in which heating, drying and mixing all take place in the dryer (modified for this purpose). The difference between the two plants from a simulation standpoint is that their owning and operating costs are different (the continuous plant has the lesser cost inasmuch as the pugmill and hot bins are eliminated). Otherwise, the operating parameters for these plants are the same and were assumed or estimated to be:

Batch size - 30,000 pounds
Minimum batch time - .75 minute
Mean batch time - 0.917 minute; standard deviation - 0.23 minute
Owning and operating cost of conventional plant including 500 tons of surge storage - $674.50 per hour
Owning and operating cost of the screenless, continuous batch plant including 500 tons of surge storage - $543.06 per hour

Simulations were performed for systems employing these plants in which 22.5T haul units loaded from surge at the plant, traveled over an initial 7.5 mile haul distance and discharged into windrows laid down ahead of two pavers operating at the laydown site. Figure 35 depicts the performances of these two plants in comparison with a 400 TPH plant operating in the same system configuration (employing only one paver, however). As can be readily seen, on large jobs, large plants, adequately maintained and efficiently operated, would prove to be the most economical producers of hot-mix.

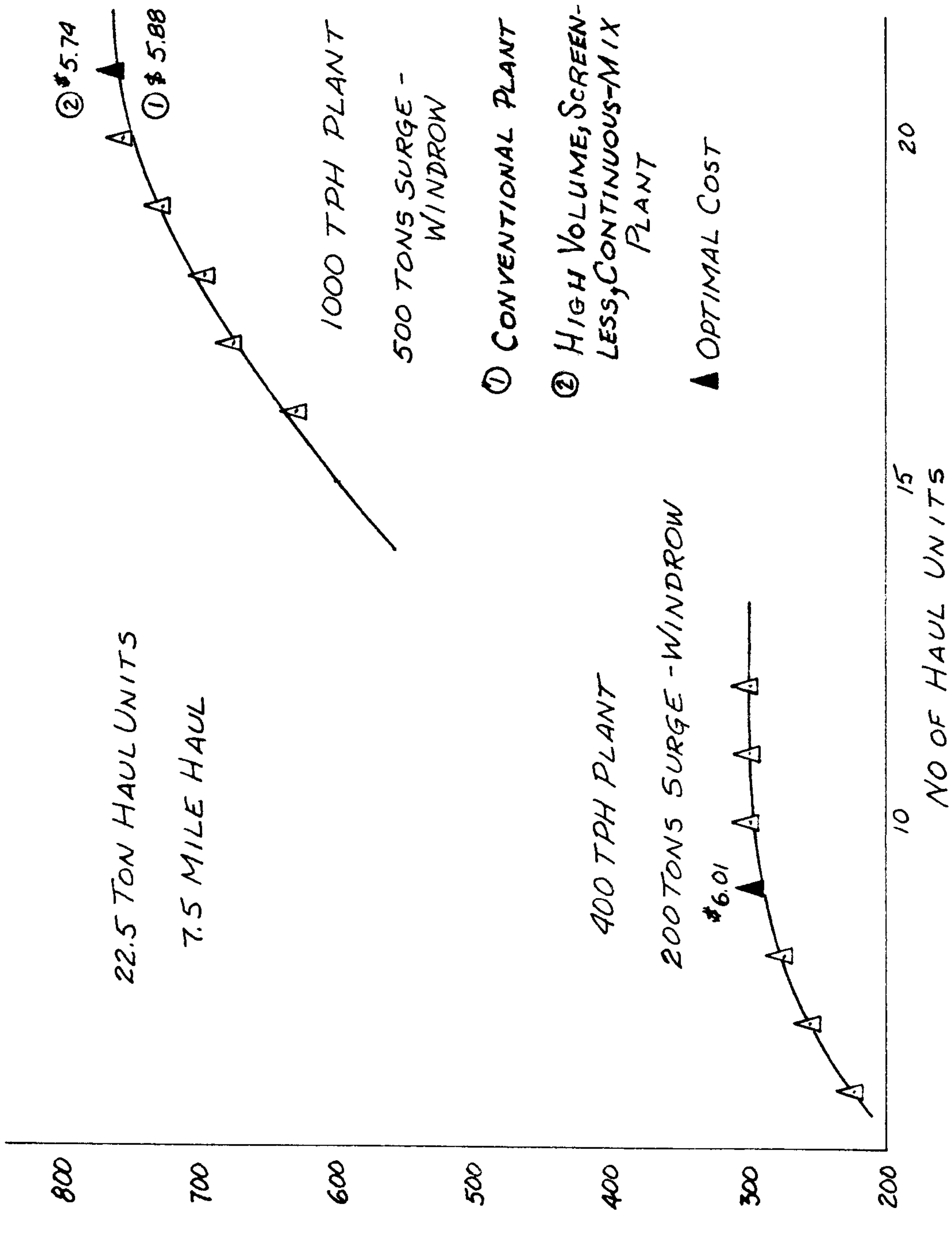

FIGURE 35. - PERFORMANCE OF 1000 TPH PLANT
VS. 400 TPH PLANT

CHAPTER VII

URBAN HAUL SITUATIONS

With the exception of the speed equations developed for this situation in Chapter II, nothing has been said concerning hot-mix distribution operations taking place in an urban setting. As was noted in the discussion of the development of the urban speed equations for the model, urban hauling situations are unique and individualistic; each must be investigated considering the conditions under which the hot-mix system is to operate. This is particularly true with respect to the route, for it is in this area, the travel phase of the haul unit cycle, that the primary differences between rural and urban haul situations exist which affect system performance.

Rural haul routes, generally, have less traffic than urban routes, require fewer haul unit stops and allow haul units to achieve and maintain greater travel speeds. Urban haul routes, on the other hand, are subject to numerous speed varying factors in the forms of traffic congestion and more numerous required or possible stops in the forms of stop signs, traffic lights, railroad crossings and yield situations. These conditions make it exceedingly difficult for haul units to maintain a high rate of speed (approaching the legal speed limit) and, equally important, make it virtually impossible to maintain a uniform rate of travel. Consequently, haul unit travel times in the majority of urban distribution situations are marked by relatively low average speeds and high speed variabilities.

The effect of low hauling speeds on hot-mix operations is to increase cycle times which, in turn, means that more haul units are required to haul a given tonnage of hot-mix over any time period than would be the case if haul unit speeds were greater. The effect of high travel speed variabilities on urban hot-mix systems is that arrival rates of haul units are more highly variable at plant and paver resulting in: (1) more waiting or idle time for plant, paver and haul units (the probability increases that plant and paver sit idle waiting for haul units to arrive or haul units sit in line waiting to load or discharge); (2) correspondingly lower efficiencies for plant, paver and haul units; and (3) greater cost contributions of plant, paver and haul units to the final costs of the hot-mix. In short, unit costs of hot-mix are greater in urban hauling situations than in comparable rural situations (same system configuration except for a rural setting) because more haul units are required to haul the hot-mix produced by the plant and because plant, paver and haul units are less efficient in the urban setting.

The addition of surge capacity at the plant can improve the performance of an urban system. Figure 36 demonstrates the improvement realized by adding 100 tons of surge storage to a 200 TPH plant in simulations run using the computer model. For the situations depicted, the haul distance was assumed to be five miles and simulations were performed utilizing 7.5T and 15T haul units. The 15T

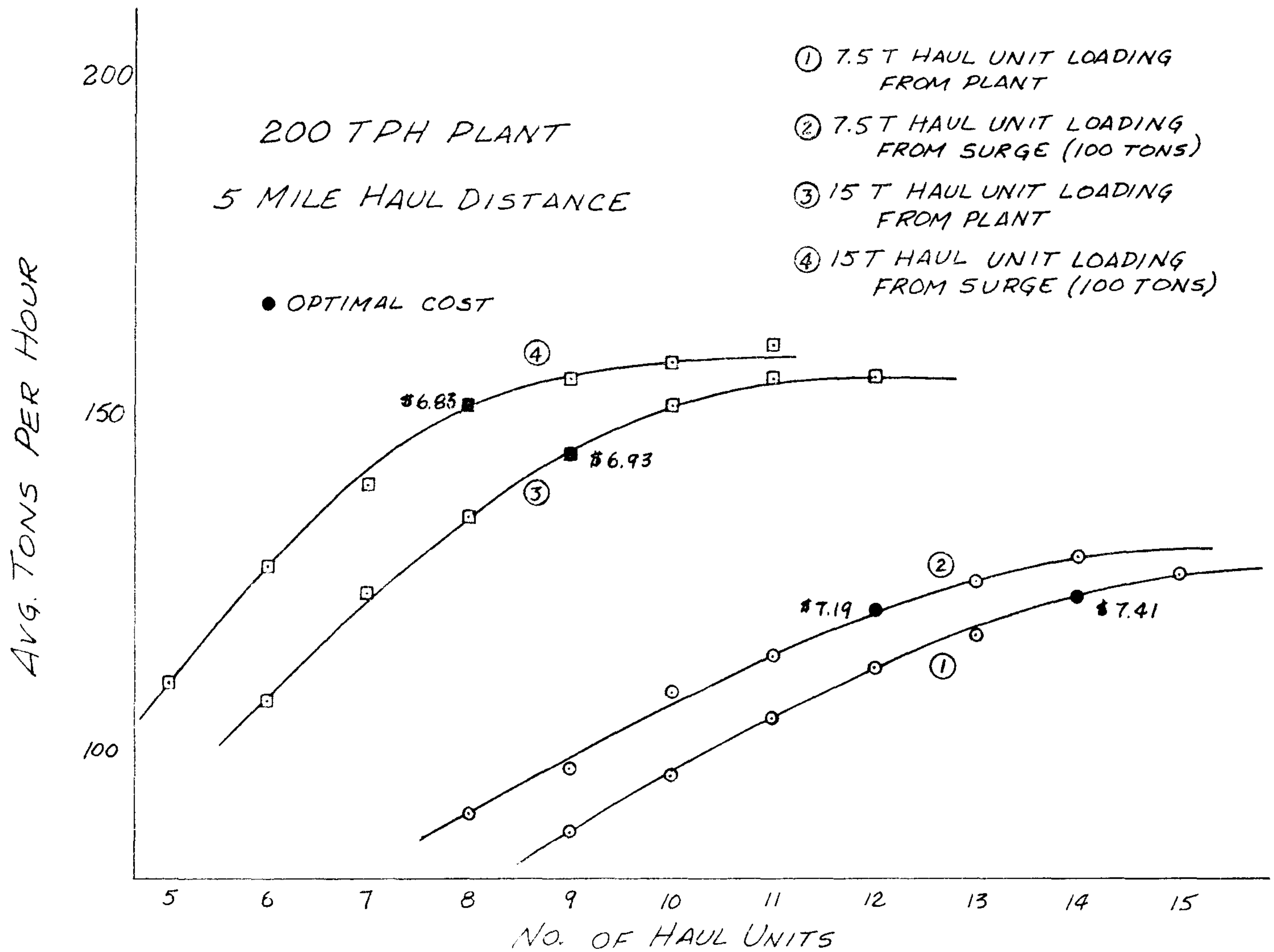

FIGURE 36. - URBAN HAUL SITUATION

haul unit performance was simulated despite the fact that the unit exceeds the 9.5T limitation given for the urban speed equations in Chapter II. The use of the 15T unit is believed justified in this case since the assumption is still made that the 7.5T and 15T units are similar in their operating characteristics and vary markedly only in their haul capacities. The simulated performance of the 15T unit was desired inasmuch as this appears to be about the maximum size unit feasible for the major portion of urban haul situations.

As was the case for rural haul situations, the larger haul unit outperformed the smaller unit in production and resultant unit costs (refer to Figure 36). This, again, is a case of more tons being hauled per cycle of the 15T unit and fewer interactions taking place between haul units and plant and between haul units and paver for the total tons hauled during a shift. The addition of surge storage reduces the waiting time of haul units at the plant and allows the plant to produce when haul units are not available. This, in turn, increases efficiencies of both the haul units and the plant, increases total production and, in these particular situations, reduces unit costs (the added costs of the surge storage are more than compensated for by production increases). By adding some form of surge storage at the paver, production performance could be increased still further (particularly if this tended to balance plant and paver efficiencies), and unit costs would again be subject to potential improvement.

The foregoing comments are a condensation of those presented in discussing surge and windrowing in rural haul situations. This is to say, urban systems operations are no different from rural systems operations at the plant and paver. The provision of some form of surge at either plant or paver or both is as effective a means of improving production performance in urban settings as it is in rural. The potential of the surge provided to lower unit costs, however, depends upon the amount of increased production realized, the number of haul units now required for optimal production, and the system owning and operating cost increase resulting from addition of the surge feature.

Individual urban haul situations, then, are unique because of the high degree of variability that is to be found in the cycle times of their distribution sub-systems. This characteristic, along with the lower average travel speeds possible under urban conditions, dictates the use of more hauling equipment to service plant and paver which is the major factor in the increased costs of urban hot-mix. Operations at urban plants and pavers, for the most part, have little to differentiate them from those taking place in rural system situations.

REFERENCES - PART I

1. Benjamin, Jack R. and Cornell, C. Allin, _Probability, Statistics and Decision for Civil Engineers_, McGraw Hill, New York. 1970.

2. Esmonde, R. A., "How Aluminum Bodies Trim Pit Costs," _Engineering and Mining Journal_, vol. 164, pp. 84-6, March 1967.

3. Gaarslev, Axel, "Stochastic Models to Estimate the Production of Material Handling Systems in the Construction Industry," Technical Report No. 111, Department of Civil Engineering, Stanford University, Stanford, California, 1969.

4. Teicholz, Paul M., "A Simulation Approach to the Selection of Construction Equipment," Ph.D. dissertation (published as Technical Report No. 26), Department of Civil Engineering, Stanford University, 1963.

5. Teicholz, Paul M., "An Analysis of Two-Link Material Handling Systems With One Carrier in One of the Links," Technical Report No. 29, Department of Civil Engineering, Stanford University, 1963.

6. Wenners, Edward B., "A Computer Solution for Estimating Owning and Operating Costs for Over-the-Road Hauling Units," unpublished Master's Thesis, Department of Civil Engineering, Texas A&M University, 1972.

PART II - CONSTRUCTION MANAGEMENT PRACTICES

KEY WORDS: construction management; hot-mix paving system interrelationships; hot-mix production; distribution of hot-mix; hot-mix laydown; planning; scheduling; resource allocation; delegation of responsibility; end-product specifications; statistical sampling; statistical quality control; gradation control; system reliability; drum mixing; truck driver discipline; Flowboy; pavement smoothness; hardening; viscosity; compaction; surge storage; windrowing; thick lift; rolling surge bin

ABSTRACT: The interrelationships which exist between the production, distribution and laydown links of a total hot-mix paving system demand a much higher level of construction management efficiency than presently exists within the hot-mix industry. In the face of this situation, an argument is made in support of end-product specifications complemented with statistical methods of sampling and product control. Given this, industry would then be free to use its collective ingenuity to improve control of aggregate gradation at the cold feeder; to investigate innovative drying and mixing systems calculated to reduce unwanted plant emissions and improve plant reliability and to experiment with certain hot-mix laydown procedures on the road. In general, all of these suggested operating procedures are directed toward producing quality mix at a lower cost. A specific short-term goal of these measures, however, is to find a solution to the problem of hot-mix pavement roughness.

CHAPTER I

GENERAL CONSTRUCTION PRACTICES BACKGROUND

During the course of this research twenty-one hot-mix plants were visited. The hot-mix producers included in this array of plants represented contractors producing a wide variety of hot-mix tonnages each year. These plants were located in Arkansas, Louisiana, Mississippi, and Texas. Six of these plants were visited several times making a total of thirty-three visitations over a period of eleven months from June, 1971 through April, 1972. This time span provided a variety of weather conditions and the four state area covered provided a broad range of operating conditions as well as an array of construction specifications and procedures. On each visitation timelapse motion pictures were taken simultaneously at the plant and at the laydown machine on the road. These films were supplemented with slides taken of plant and road operations and with detailed truck logs as well. The various elements comprising the total cycle time for each truck, viz., loading, hauling, maneuvering, waiting to be unloaded, unloading, returning empty, and waiting to be loaded again were noted to the nearest second. In addition, both efficient and inefficient construction management practices were also noted in these logs.

Interrelationships Within the Total Hot-Mix Production-Laydown System

Although the primary purpose of this research was to investigate the distribution systems used to convey hot-mix asphalt from its point of origin at the plant to its point of discharge at the laydown machine, it is not possible to divorce the distribution link from the influences of the production and laydown links of this total system. Management efficiencies or inefficiencies existing in the production or laydown sub-systems operate inescapably and in like manner upon the distribution sub-systems as well. Accordingly, it is thought appropriate to present first a tabulation of general operating inefficiencies and a tabulation of general operating efficiencies which were noted in the course of the visitations. These tabulations are presented below as Tables 1 and 2. Each entry in these tables played a part in establishing the total cycle time of the hauling units utilized in the various distribution systems studied or, alternatively, exerted a profound effect on the morale of the truckers employed. Obviously, it is the mission of the Construction Manager to eliminate or, at the least, minimize such inefficiencies by striving to obtain the optimal level of efficiency which can be realized under existing conditions.

TABLE 1. - CONSTRUCTION MANAGEMENT INEFFICIENCIES

1. There is need to give more attention to better pre-planning for location of truck scales — particularly when trucks must be weighed empty each time they are loaded. (See Mississippi specifications.) In general, planning for adequate sight distance, maneuvering room and traffic control at the hot-mix plant left much to be desired.
2. In one instance the 25-ton trailers selected to haul hot-mix could be loaded to only two-thirds capacity because of a soft subgrade condition existing during the winter months.

3. On a private job being constructed during the winter months, the hot-mix aggregate was heated to such a level that the mix caught fire when the asphalt cement was introduced into the mixer.

4. A mineral filler silo supported on a slab designed for the total load of the silo filled with limestone filler, was filled with portland cement at a time when the regular filler was not available. The slab and silo punched into the foundation soil; rotated into the batch tower and caused extensive damage to the plant.

5. The sludge drain from a wet-type dust collector was laid out to pass beneath the haul road leading under the plant mixer. Unfortunately, the grade selected for this drain was not sufficient to keep the sludge flowing and a lengthy interruption in hauling resulted.

6. Dust leaks from the batch tower resulted in a series of complications.

(1) Dust leakage into the aggregate scales:

(a) Caused an unacceptable variation between plant, batch weight and truck-scale weights on a job in Mississippi.

(b) Produced a random failure of the aggregate scales to return to zero when the weigh box was emptied. Consequently, when the next batch was weighed in an automated plant, too little aggregate was batched to match the design quantity of asphalt cement and a wet batch resulted.

(2) Dust leakage from the tower and from the plant in general, caused the haul trucks to hang back some distance away, thus increasing truck exchange time. Some drivers preferred to back under the tower in an effort to preserve vision through their windshields. Others headed under the tower; drove out blind after loading and then stopped to clean their windshields. This situation, however, made for a very hazardous operation and complete disruption of orderly traffic flow.

7. Numerous instances were noted where it was necessary for the truck driver to dismount and enter the control trailer to obtain his load ticket.

8. On a few jobs the haul price paid for hired trucks was too low. On these jobs, the hauling speeds were characteristically excessive, resulting in numerous traffic citations from the state highway patrols. In spite of these, a hazardous hauling situation persisted and in one case a tandem truck threw an outside wheel onto the porch of a farmhouse some distance from the highway, severely injuring a woman.

9. Many instances of plant delay (and, thus, of truck delay) were noted, which resulted from maintenance after the fact. Typical of such delays were:

(1) Loose chain on a hot-elevator bucket line

(2) Paver hung in gear on the road until a mechanic could be summoned from the plant to free it.

10. A laydown crew suffered the loss of one roller, but the rate of laydown was maintained. The pavers soon outdistanced the remaining rollers and the road inspector shut down the job.

11. Gravel was being crushed to supply a nearby hot-mix plant. During the lunch hour the operator of a Caterpillar off-road hauler left his machine parked uphill from the crusher and set only his air brakes. The air leaked off; the off-road hauler rolled down the hill into the flywheel of the roll crusher and disabled the whole crushing operation. This also resulted in shutting down the hot-mix plant as well.

12. Each of three long-haul trailers were delivering three loads of coarse sand daily to a hot-mix plant. As each round of sand arrived, the plant was fired up; run for two hours and then shut down.

13. A tandem-axle haul truck with side boards was loaded with an extra batch on the front end of the bed. Upon reaching the paver, the trucker could not dump the load.

14. Creek gravel was being crushed and washed from a mountain stream to supply a hot-mix plant some distance away. Both plants were owned by the same company. The discharge of muddy wash water into the stream resulted in an injunction to cease and desist. This was ignored; the plant foreman was arrested and the job was temporarily shut down for lack of aggregate.

15. Many projects had no radio communication between the plant and the road.

16. Numerous instances were noted in which the noise of certain unshielded burner blowers was deafening. This will inevitably lead to difficulty with OSHA inspectors.

17. Several plants were arranged in such a manner that haul trucks were required to back under a surge bin to load.

18. At one plant, loaded trucks must climb a 6 percent grade from a standing start as they leave the truck scales. Then they must make a right hand turn and climb a 10 percent grade for several hundred feet to the top of a hill. Immediately to the left of this haul road is a valley. The loaded trucks could have been provided a much easier haul route by building a road to a lesser grade up and across the head of the valley. Empty trucks could still use the existing road.

TABLE 2. - CONSTRUCTION MANAGEMENT EFFICIENCIES

1. A number of plants were set up at material deposits and were employing crushing sections to produce the majority of their materials. Several plants incorporated a single crusher in the hot-mix production system to reduce the oversize scalped off by the hot-bin screen.

2. Pre-planning of the total hauling operation was used to very good effect on one contract which involved placing black base under a four lane, slip-formed, portland cement concrete slab and which also required the construction of black base shoulders. This particular project ran east and west. Two 12-ft. lanes lay either

side of the median. Since the sources of hot-mix aggregate lay west of the job, the hot-mix plant was erected at the west end and because the concrete aggregate sources lay east of the job, the central-mix concrete batch plant was placed nearer the east end but at a carefully pre-calculated location. This location was determined in such a manner that as black base was placed in the south driving lanes — beginning at the east end of the job and proceeding west and followed close behind by the 24-ft. wide, slip-form concrete slab, the unneeded hot-mix trucks could drop back east to sufficiently aged concrete slab and begin placing black base shoulder material toward the east end of the job. As the slip-form placement approached the central-mix, concrete plant, unneeded concrete haul trucks could join the extra hot-mix trucks in placing long-haul shoulder material at the extreme east end of the project. In this manner the entire truck fleet was kept busy during the whole project.

3. On one project a gravel pit near the job contained material with a P.I. above that permitted by the black base specifications. The use of lime slurry mixed into each 2-ft. lift of a layered stockpile permitted this pit to be used successfully.

4. At a remote, rural location the secondary, wet dust collector unit was omitted and excess minus 200 mesh material was wasted out the stack of the exhauster. This permitted the use of a fine blow sand pit immediately adjacent to the plant site though, admittedly, to the detriment of the surrounding countryside.

5. One resourceful hot-mix producer mounted a hudraulic backhoe at the top of a cold feeder bin containing damp blow sand. This unit was provided with a long steel tooth instead of a conventional backhoe bucket. When the blow sand began to bridge, the backhoe operator manipulated the tooth to keep the sand flowing through the bin.

6. Another efficiency-minded contractor improved plant production with:

(1) A small motor grader which constantly broad-bladed the stockplie unloading area and all haul roads at the plant site.

(2) Two flagmen who directed and controlled high-volume truck traffic into and out of the plant area.

(3) A laborer who carried load tickets out to the haul trucks so that the drivers did not have to dismount.

7. Certain good construction procedures were noted at permanent plants visited in Corpus Christi and Dallas:

(1) At a plant supplying maintenance mix to city and county trucks throughout the day, a hot-storage silo was filled with the proper mixture before 8:00 AM. Then for the remainder of the day, the plant was free to produce hot-mix for private work.

(2) A plant located in an urban area employed a water wagon and a vacuum-type street sweeper to control haul road dust emissions from the site.

(3) Tunnel-conveyor systems running beneath material stockpiles separated by concrete partition walls were used to improve cold feed efficiency. In one permanent plant on a large site, the stockpiles were dozed over a long reclaiming tunnel from both sides and dead storage material was utilized to partition between stockpiles of different materials.

(4) Hot asphalt storage tanks were buried underground to reduce heat losses and to provide unobstructed sight distances and maneuvering room for very heavy truck traffic.

The majority of the examples cited in Tables 1 and 2 above, however, serve to point out a fundamental failing of top management in the whole of the construction industry. After investing very large sums in complicated and sophisticated equipment and after spending additional thousands of dollars to bid and obtain construction (paving) contracts, many owners deliver this most expensive equipment into the hands of men who have no vested interest in maintaining it and little real motivation to make it produce to its capacity. In addition, such owners seemingly abdicate their rightful functions of planning and scheduling, allocation of resources and execution of construction works, some of which involve very substantial sums of money and most of which demand the utmost in construction management skills. Although there are arguments in support of this potentially perilous delegation of the owner's responsibility to execute the jobs his company bids, the financial consequences are often disastrous. Procedures and methods of reducing the severity of these hot-mix construction business risks are discussed in the chapters which follow.

CHAPTER II

HOT-MIX PRODUCTION

General

In the discussion of hot-mix construction operations presented thus far, more than ninety percent of the general operating inefficiencies noted occurred at — or were associated with — the hot-mix plant proper. This bespeaks the very real necessity of improving the level of construction management efficiency in the production process itself. Any interruption within the production link inevitably results in a corresponding delay within the distribution link. Obviously, trucks cannot haul while the plant is down unless surge storage is available. Even this expedient hedge of the production manager cannot protect him from the consequences of basic inefficiencies for long. If the hot-mix plant stays idle for any appreciable length of time, the whole system grinds to a halt.

Under the existing system of paving specifications, which also control equipment and work methods, the hot-mix production and laydown systems generally employed in this country are, in certain respects, basically inefficient and too vulnerable to random interruption from many sources. In the face of this situation, there exists a growing body of opinion which holds that the hot-mix paving industry would be better served by end-product specifications complemented with statistical methods of sampling and product control. Then, indeed, the production manager would be placed squarely upon his own reliances. No longer would there be division of authority and responsibility within the hot-mix production process. True, the testing of aggregates and the tests needed to monitor the production of hot-mix would, necessarily, be performed by the contractor's own forces. However, with the contracting agency's inspection force confining itself to truly effective acceptance testing of the final product, all "work type" references could be eliminated from construction specifications and the hot-mix industry would be free to use its collective ingenuity "to produce quality mix at lower cost" (1).

Aggregate Stockpiles

Even with a multiple deck hot-bin screen, it is not possible to balance the hot bins of a conventional batch-type hot-mix plant if the gradation of the various aggregates employed varies at the cold feed. When a particular hot bin runs short, completion of the batching operation is delayed and truck loading time is increased. At many of the plants observed in the course of this study, coarse aggregates were dumped at the bottom of an inclined wedge-shaped stockpile, dozed to the top and allowed to tumble down the steep front face — thus, producing segregation and potential batching delay. The consequences of this time-honored method of stockpiling are minimal so far as the sand-sized materials are concerned. However, if this practice is followed in handling the coarse aggregate, some measure of hot-bin imbalance will result, in spite of using a front-end loader to cave down the steep face of the pile before filling the loader bucket.

In contrast to the stockpiling method discussed above, a series of Interstate jobs visited in Texas employed a more effective method of stockpiling materials for nearly 1.1 million tons of black base, and thereby, eliminated the need for all but a scalping screen at the hot-bins of three, fully automated, hot-mix plants. Good advance planning between representatives of the contractor and the state resulted in an agreement to build the stockpile of the single material used for both the untreated base and the hot black base in horizontal lifts not to exceed 2 feet in thickness. Furthermore, these piles were to be not less than 12 feet nor more than 20 feet in height. The stockpiles were sampled by coring in a statistical pattern when one-third completed. Certain corrections in material gradation indicated by the initial set of cores were accomplished at that time and stockpiling was continued to the two-thirds level. Statistical coring of the whole area of each pile then indicated very minor additional corrections in gradation were still required. These corrections were made and the stockpiles were completed to their full height. At this point, a final statistical coring operation — drilled full depth over the whole area of the piles — revealed satisfactory compliance with the untreated base specifications had been achieved and no gradation testing of this untreated material was made after it left the stockpile area except for occasional field checks (2).

True, the gradation requirements for the hot black base were minimal indeed, but this was not the case for the untreated base, itself. Furthermore, it must be emphasized that for the hot-mix industry to realize the benefits deriving from the elimination of all hot-bin screens, it must first set its house in order with regard to controlling the variability of materials introduced at the cold feeder. Perceptive contractors can appreciate the significance to the industry of a project completed in the spring of 1972 at Winnemucca, Nevada. This $5,735,430.00 contract included approximately 248,000 tons of hot-mix base and surfacing which was produced with a Cedar Rapids Stabilized Base Mixer operating as a continuous hot-mix plant with pugmill jacketed. Effective control of hot-mix aggregate gradation enabled this contractor to feed the hot-mix aggregates over a 5 x 16 ft. Cedar Rapids vibrating grizzly to a Kolberg conveyor which conveyed the aggregate to a Cedar Rapids drier from which the aggregate was delivered to the pugmill at approximately 500 tons per hour. From the pugmill, the hot-mix was delivered by radial stacker to a six-bin, hot-storage facility which was used to flood load a fleet of eight Flowboy trailers (3). The economies inherent in such an operation are clearly evident.

Cold Feed Control

In addition to controlling the gradation of aggregates fed into the cold feeder, there exists another source of variation in cold aggregate feed which must be overcome before screenless hot-mix plants can become a reality in this country. This variation in feed arises from the variation of moisture within the individual material stockpiles themselves. The water contained within and upon a given hot-mix aggregate varies with the weather conditions which have existed and are existing at the plant site.

Obviously, then, a truly effective cold feeder must incorporate moisture sensors in each cold feed bin. Without them no hot-mix plant can be considered truly automated. These sensors, furthermore, must have the capability of transmitting continuously to an electronic control circuit which can in turn transmit the necessary signals to the individual variable speed motor driving the feeder at the offending cold bin. This control circuit feed-back loop would then increase or decrease the speed of that particular cold feeder to maintain the number of pounds of dry material desired from that cold bin. One proprietary German hot-mix production system features this type of control system (4). In addition, such moisture sensing devices would be of great value in the development of full automatic sampling and testing systems for verification of hot-mix gradation control. Such devices could be used by the contractor's forces operating under end-product specifications. Effective control of gradation insures increased production as well as lower hauling and laying costs.

The Mixing Process

There is much discussion in the paving industry today concerning the relative merits of various types of hot-mix plants. All of today's plants, however, have one feature in common. They all depend on some type of dust collector to stay in operation. The effect of uncontrolled dust upon the efficiency of the distribution link has already been discussed.

In addition to this consideration, however, all such dust collecting systems represent a considerable capital investment and a continuing source of operating expense to the industry. Furthermore, as OSHA inspectors gain knowledge and experience, dust control requirements will become more and more stringent because plant dust emissions exert such a profound effect on the health, well-being and safety of every workman and truck driver in the hot-mix production operation. Inevitably, then, the sophistication and expense of dust control equipment will increase.

As a result of this situation, equipment manufacturers are investigating "drying systems (drum mixers) in which the fine particles are wetted and agglomerated with the asphalt binder before or shortly after the cold, wet aggregates are introduced into the dryer drum .... Since the fine aggregate particles (dust) are wetted and agglomerated with the asphalt before they are dry, the quantity entrained in the flow of gases is reduced; consequently, the work (and expense) required to recapture the emitted particulate matter is reduced. (5)"

Environmental considerations aside, in a batch-type pug mill a certain number of operations are required to be performed in succession. These include a dry-mix cycle (in some situations), introduction of the asphalt, a wet-mix cycle, a pug-mill-dumping cycle and a batching cycle to assemble the materials required for the next batch to follow. All of these operations increase the operating complexity and initial expense of the batch-type, hot-mix plant. This in turn, reduces the reliability of the production system.

The relative complexity of the typical, batch-type, hot-mix plant — in comparison to the simplicity of the high-capacity, continuous-mix, screenless plant in which the drying <u>and</u> mixing operations are performed in the dryer drum — make the batch-type hot-mix plant vulnerable to still another operating difficulty. This particular problem arises from the extreme sensitivity of the batch-type, hot-mix plant to low voltage. Sufficient generating capacity or power supply must be provided to make certain that line voltage and current cycles of a hot-mix batch plant remain within very narrow limits. Otherwise, the numerous electrical components comprising this system do not operate at their design speeds. Then, mix gradations vary because hot-bin gradations change; hot-bins become unbalanced and overflow, thus, resulting in wasted material, lost production and poor utilization of the distribution system. Reliability of the production link is absolutely essential if efficient distribution of the product is to be achieved.

CHAPTER III

THE DISTRIBUTION OF HOT-MIX TO THE LAYDOWN MACHINE

General

Knowledgeable contractors interviewed during the course of this research asserted, time after time, that it was less expensive for them to sub-contract their hot-mix hauling than to attempt to operate and maintain their own truck fleet. No doubt, when viewed from only the single cost of transporting the mix to the laydown machine, this opinion is true. But what effect does the use of hired trucks have upon the production and distribution links of the total construction system? Are these two major operations adequately served?

There is, in fact, considerable evidence to the contrary. For example, inexperienced drivers were observed dumping their loads in front of the paver. Long haul trailers with front mounted telescopic hoists were seen to bear on the front of the paver hopper when fully raised, despite the fact that the trailers were equipped with snubbers designed to prevent this. Under excessive pressure from the hoist, the snubbers merely raised the front axle of the trailer tandem off the ground until the rear of the trailer was supported by the paver.

The most serious problem resulting from the use of hired trucks, however, was the lack of discipline among the drivers. Each trucker was a law unto himself. He gassed and serviced his truck when it was convenient for *him*. If he broke down, it was his own responsibility to effect repairs and get back into service and often this required several hours. Every trucker established his own rate of speed and, thus, his own cycle time. If he felt like stopping for coffee, he did so and hearing the end of a good story while waiting in line was sufficient excuse for delaying loading or unloading for a few seconds more. This lack of control over the hired trucks naturally resulted in their bunching up, with consequent delays between arrivals of groups of trucks. This, in turn, led to shutting down the plant and, of even more concern, it made steady operation of the paver almost impossible which, in turn, resulted in rough pavement and loss of riding quality.

The Flowboy Hauling Unit

In addition to conventional full width paving operations, two widening-resurfacing projects were observed on three different occasions. These projects involved the placing of hot-mix to full depth in one pass in a previously constructed trench on either side of the existing concrete slab. The trench widening material was placed with a side delivery paver attached to the front of a motor grader. The configuration and capacity of this paver was such that it could accommodate and quickly unload any size of truck from a single-axle bobtail to a large semi-trailer. The Flowboy unit which incorporates a flight conveyor along the length of the bottom of the trailer and which discharges material into the paver at a controlled rate (up to a maximum of 23 tons per minute) without the necessity of raising a bed, would, of course be an ideal selection for this type of operation.

Flowboy trailers were observed in operation on two projects. At one job south of Mena, Arkansas, these units were being used over steep mountain roads — with numerous super-elevated curves — to haul materials to the plant from a distant source and to haul hot-mix from the plant to the paver, some 15 miles away. Both of these assignments were performed with the utmost effectiveness. These 23 ton truck-trailer units are just as fast as conventional semi-trailers. If anything, they are more maneuverable and on steep, super-elevated curves, their low center of gravity gives them a superior measure of resistance to overturning. Paver operators report the Flowboy easier to push than conventional trucks because the load is not concentrated on the rear axle or rear tandem by hoisting a bed. On the Winnemucca project in Nevada — See reference (3) — eight Flowboys operating over flat terrain under desert conditions, delivered and unloaded over 500 tons of hot-mix per hour.

Using five Flowboys, pulled with International F 2000 D tractors, a Minnesota contractor hauled 4500 tons per day on an average 5.6 mile haul from a hot-mix plant with a self-contained 200 ton surge system and eliminated plant and laydown bunching as well. The construction manager in charge of the project stated that "we were able to make better use of everything involved in the job, including accessory equipment. And, we did it with fewer hauling units. Our opportunity hours loss was reduced because we were able to keep equipment and crews operating on a consistent schedule (6)." This is not to say that the same good trucking management practices applied to properly designed tractor-trailers of a competitive type could not have produced similar results. Furthermore, it is true that five Flowboys and the tractors to pull them (or five competitive tractor-trailer units) represent a capital investment in excess of $100,000. However, in view of the demonstrated efficiency of these units and, particularly, in view of their contribution to the overall efficiency of the whole hot-mix construction operation, this extra investment in contractor's hauling equipment will be repaid after a few jobs optimizing the much larger investment already made in plant and laydown equipment.

CHAPTER IV

HOT-MIX LAYDOWN CONSIDERATIONS

General

A recent article in Engineering News Record quoted Robert Hunt, president of the National Asphalt Paving Association, concerning a primary objective which NAPA will have to accomplish, and quickly, viz., finding the cause of and solution to riding quality roughness in asphalt paving. "It's something fairly new," says Hunt, "and it's a national problem, cropping up all over. We're getting poorer riding quality than we did 10 years ago. Many states have gone to electronic screed leveling devices and we feel that has a certain bearing on this (7)." There are however, other factors that contribute to pavement roughness which are not generally appreciated by hot-mix plant operating personnel. These factors include variations in the gradation of the mix, as well as variations in the temperature of the mix. Unduly high mix temperatures may very well harden the asphalt binder, increasing its viscosity to such a level that the layability and, especially, the durability of the mix are affected in a most adverse fashion. Projects into which overheated hot-mix has been incorporated often exhibit severe ravelling, particularly if the mix was laid during the winter months and had no chance to knit together under warm weather traffic. One of the principal factors, however, contributing to pavement roughness is failure to keep the plant operating continuously which situation demands, in turn, that an adequate number of hauling units and/or adequate surge storage be available.

Hot-Mix Paver Operation

Still other operating problems which contribute to riding quality roughness must be overcome at the laydown machine itself. It is axiomatic that starting and stopping the paver frequently, results in a poor riding surface. This comes about because of certain basic operating characteristics of hot-mix pavers. As paver speed varies during start-up, the compaction achieved by the machine itself varies. Furthermore, as the amount of material in front of a paver equipped with an electronic screed leveling device varies, machine power requirements vary. Again, the material head in the hopper and in the screw area of conventional pavers must be maintained at a near constant level to insure uniform thickness control. Another factor which must be considered is truck size. A medium size hot-mix paver may not handle semi-trailers (with exception of Flowboys) unless the paver is provided with hydrostatic controls. Smaller class pavers cannot handle 10-wheel trucks at all (8). Once again, then, it is seen that the solution of operating problems at the paver and the construction of smooth hot-mix pavements demands the utmost reliability of the plant and distribution links as well.

REFERENCES - PART II

1. Foster, C. H., Problems Encountered by Contractors in Constructing Hot-Mix Asphalt Pavements Under Quality Assurance Programs, 51st Annual Meeting, Highway Research Board, January, 1971.

2. Personal communication with Walter E. Ehlers, Supervising Resident Engineer, Texas Highway Department, Seguin, Texas.

3. "Winnemucca Project Will Be Completed Soon By Parson," Rocky Mountain Construction, January 25, 1972.

4. Layman, A. H., New Concepts in Mixing, Annual Convention, National Asphalt Pavement Association, Las Vegas, Nevada, February, 1971.

5. Beaty, R. W., Asphalt Paving For the Seventies — Equipment. Annual Meeting, Association of Asphalt Paving Technologists, Oklahoma City, Oklahoma, February, 1971.

6. "Five Trailers Move 4500 Tons of Blacktop Per Day," Roads And Streets, January, 1972.

7. "Asphalt Pavers Turn Activist to Battle Regulators," Engineering News Record, January 27, 1972.

8. Notes from Barber-Greene Paving Conference, Aurora, Illinois, April, 1972.

APPENDIX I

THE COMPUTER PROGRAM

AND PROGRAM LISTING

THE COMPUTER PROGRAM AND PROGRAM LISTING

The Computer Program

The computer program for the model consists of a main program and twelve subprograms whose functions are described in the following sections.

The logic of the program is based on the continuous repetition of the cycle elements of load, haul, discharge and return by a fleet of haul units transporting hot-mix. After input variable values describing the particular system to be investigated have been entered into the computer, a starting number of haul units for which a shift will be simulated is determined. Each haul unit in the starting fleet is then carried through a continuous round of load at the plant, travel to the paver, maneuver at the paver, discharge, and return to the plant for the next load. At each step in the cycle a performance time for the specific cycle element is determined and its duration added to a cumulative, time-keeping clock for the individual haul unit. A master plant clock keeps track of total cumulative shift time for the entire system and terminates operations when the end of the shift has been reached. Upon completion of the shift, performance data for the haul units, plant, and paver are calculated and stored in memory.

When a complete shift has been simulated for the starting number of haul units and the performance data calculated, the number of haul units in the fleet is increased by one, the time-keeping mechanisms are re-set to zero, and another shift operation is simulated for the new number of haul units. When this shift has been completed, performance data are again calculated and stored in memory. Once again, the number of haul units in the hauling fleet is increased by one, a shift simulated and performance data calculated and stored. This process is repeated until shifts have been simulated for a set number of haul unit fleets beginning with the starting number of haul units through the starting number plus six (a total of 7 shift simulations). The objective is to obtain data for a sufficient number of haul unit fleets to define a cost curve for operations using this type of haul unit from which the optimum cost and the associated number of haul units can be determined. It is also possible to have shifts simulated and performance data calculated for a specified number of haul units (the model can accommodate as few as one and as many as fifty haul units).

When the requisite numbers of haul unit fleets have had shifts simulated for them, the number of shift replications upon which average performance data are to be based is checked. If only one replication is specified, the data stored in memory are printed out. If more than one replication is directed, the entire process described in the foregoing is repeated as many times as is required to satisfy the replication requirement. When this has been accomplished, the means and standard deviations for unit cost and hourly production are calculated for each haul unit fleet for which shifts were replicated. These data, along with data on system performance for each replication and individual haul unit performance for each replication (if this option is selected), are then printed out by the computer.

Main Program

The function of the main program in the model is to act as the control element for the overall simulation, coordinate the functions of the subprograms and accumulate, manipulate into proper form and output summary information on system performance.

Basically, the control and coordinating function is accomplished by examining an array in memory in which are stored cumulative time information and the event to be performed next (as well as other performance data) for each haul unit in that particular shift simulation. The haul unit having the lowest cumulative time figure is selected and its next event (loading, travel, discharge) simulated. The cumulative time total of the haul unit is updated by the duration of the event just simulated, and its event counter is set to the event it should perform next in sequence. If the event simulated was loading or discharge, cumulative time clocks for the plant or paver are updated also. One of the cumulative time clocks for the plant acts as the master clock for the simulation. When it indicates that a shift is complete, no further loading is simulated, and any haul units already loaded are run through the discharge event at the paver. When the last load for the shift has been discharged, cost, tonnage and other performance data for the shift are calculated.

Figure I-1 presents a detailed picture of the logic flow of the main program.

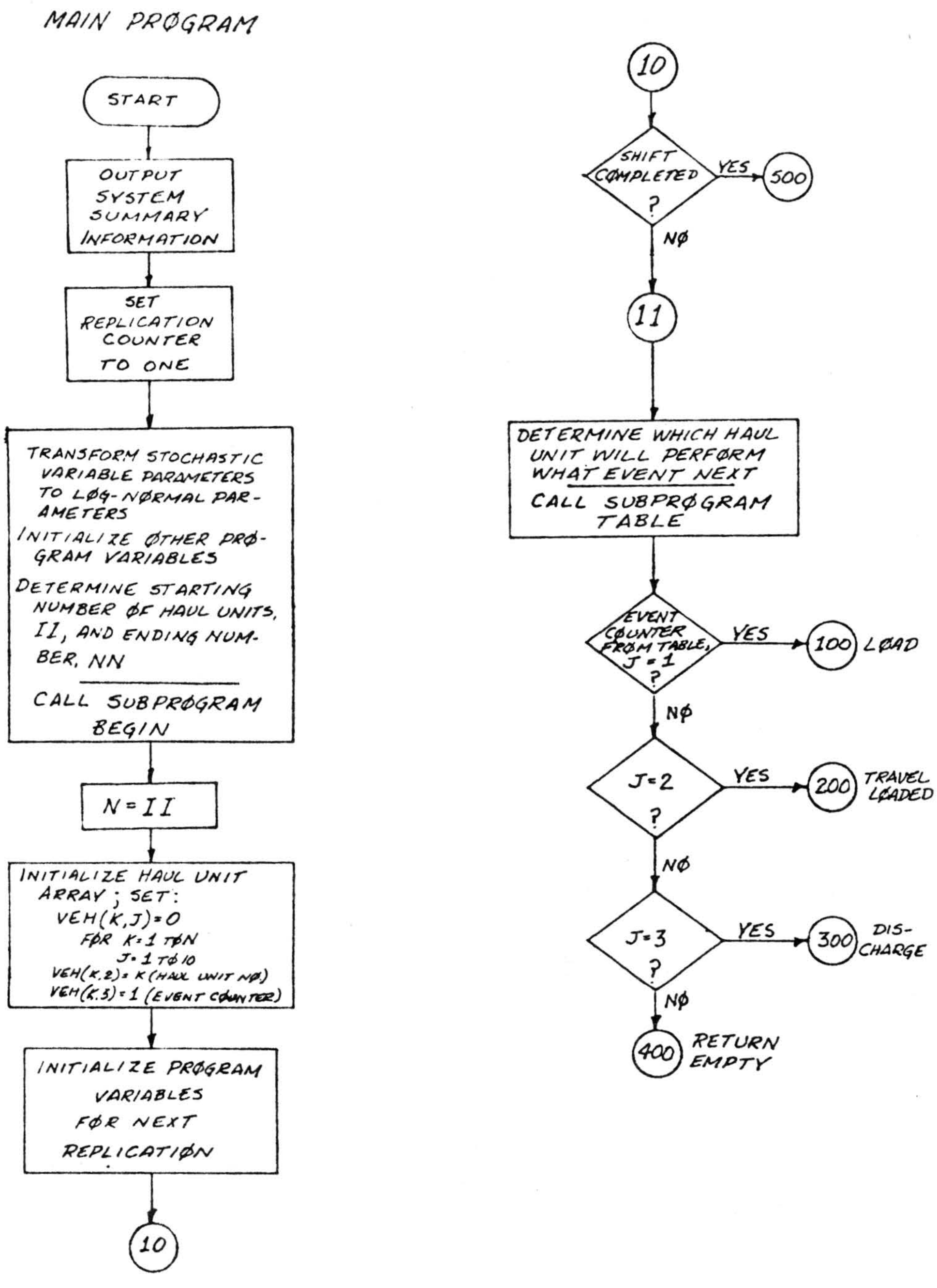

FIGURE I-1.- FLOW DIAGRAM: MAIN PROGRAM

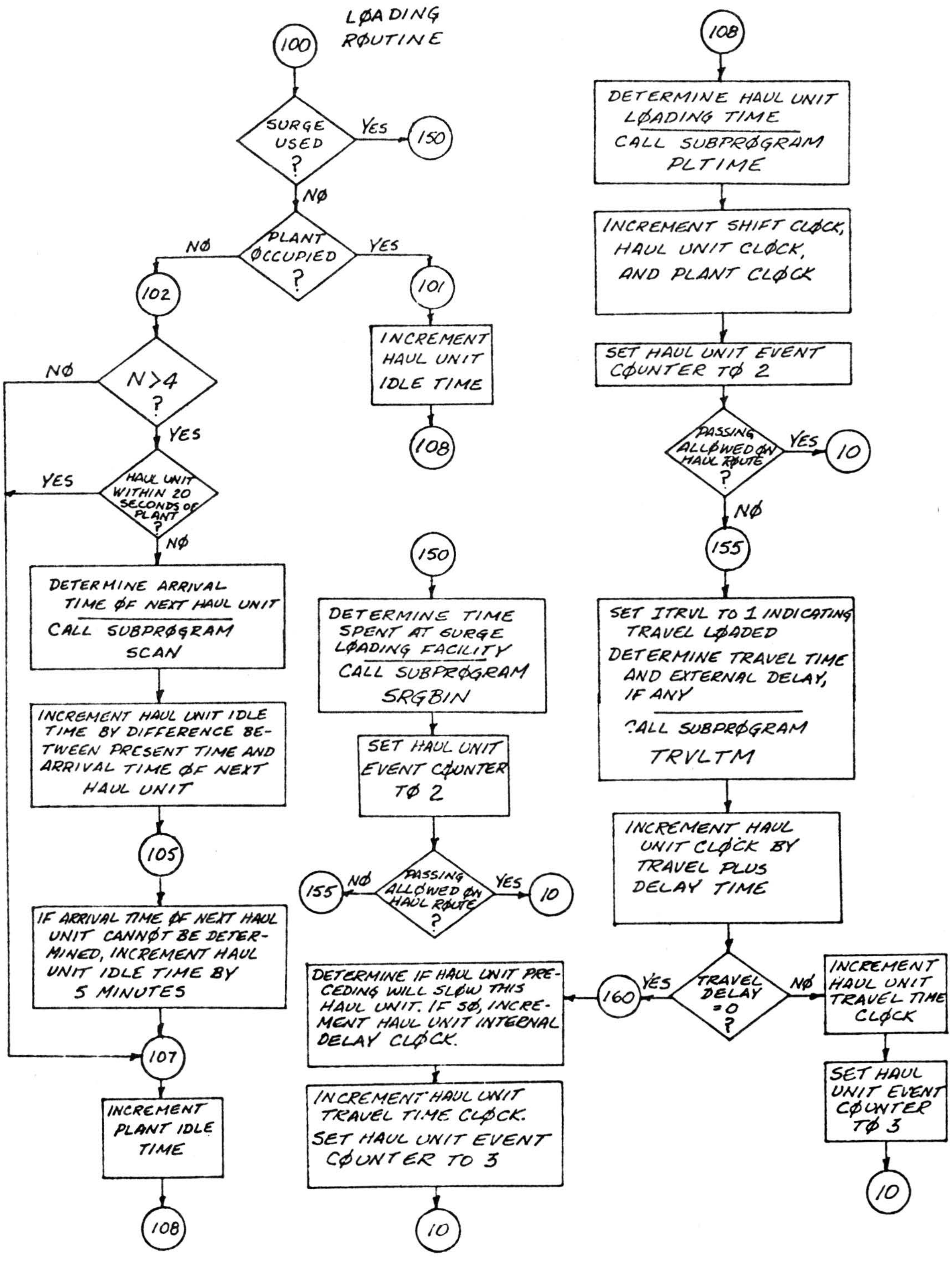

FIGURE I-1.- CONTINUED

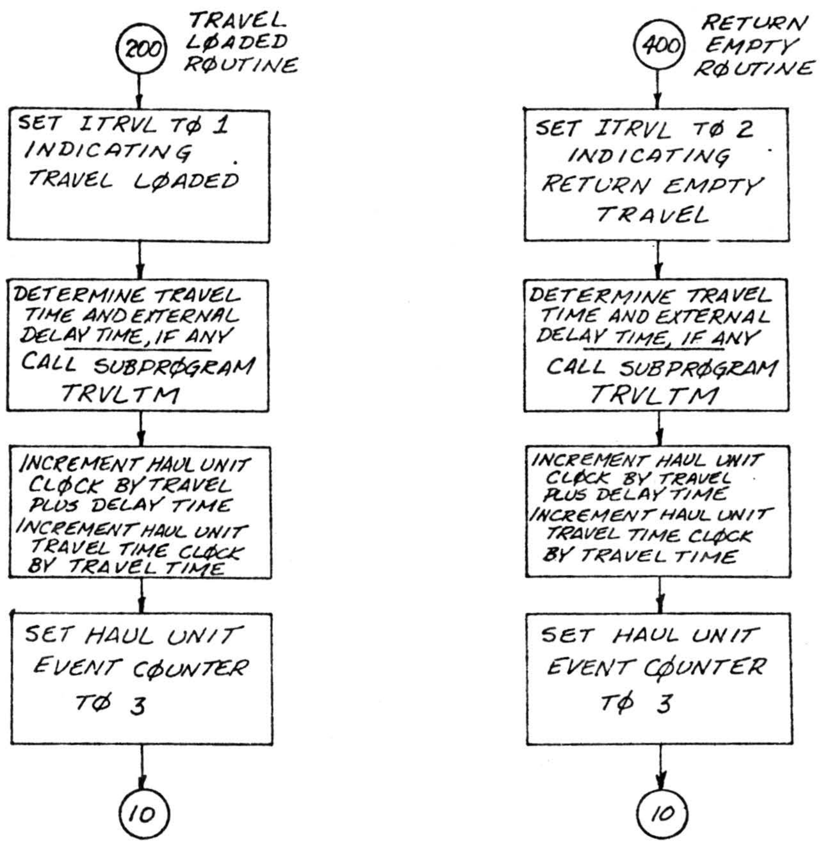

FIGURE I-1.- CONTINUED

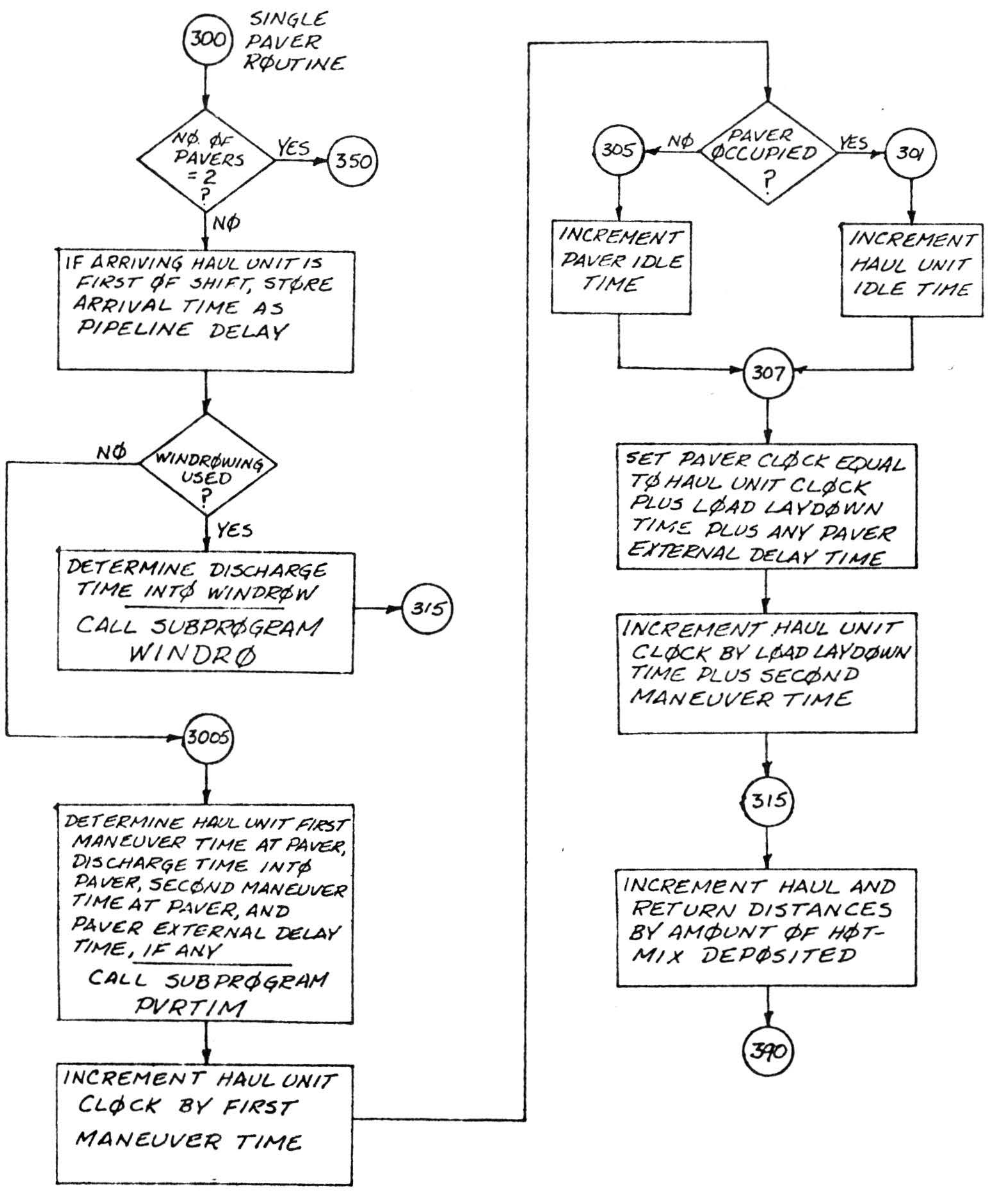

FIGURE I-1.- CONTINUED

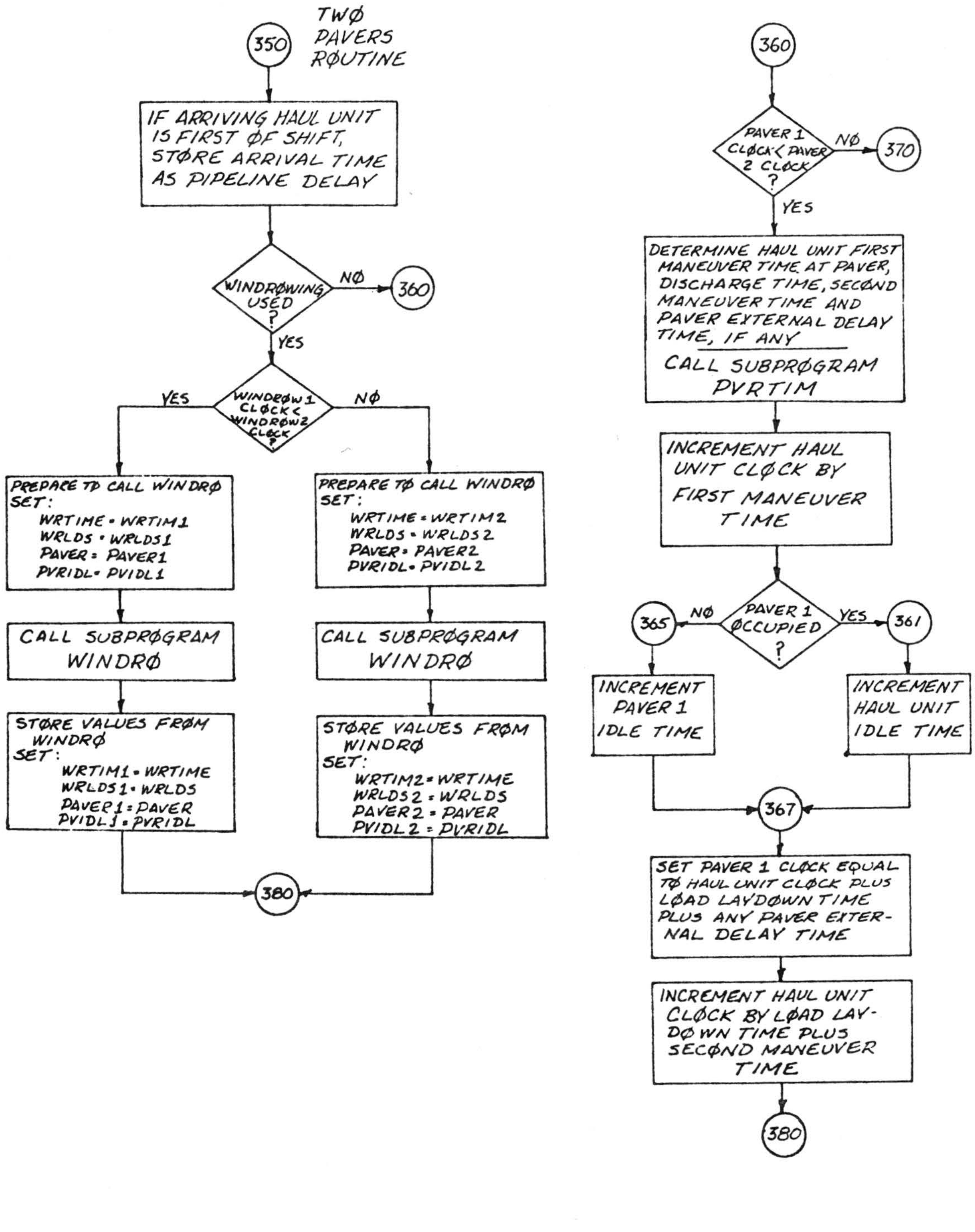

FIGURE I-1. - CONTINUED

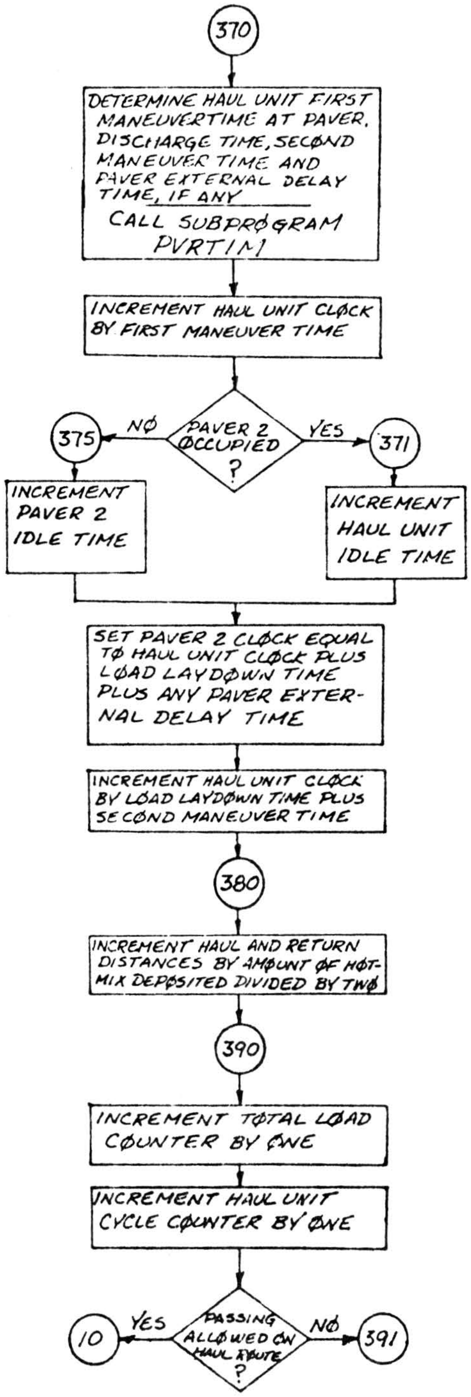

FIGURE I-1.- CONTINUED

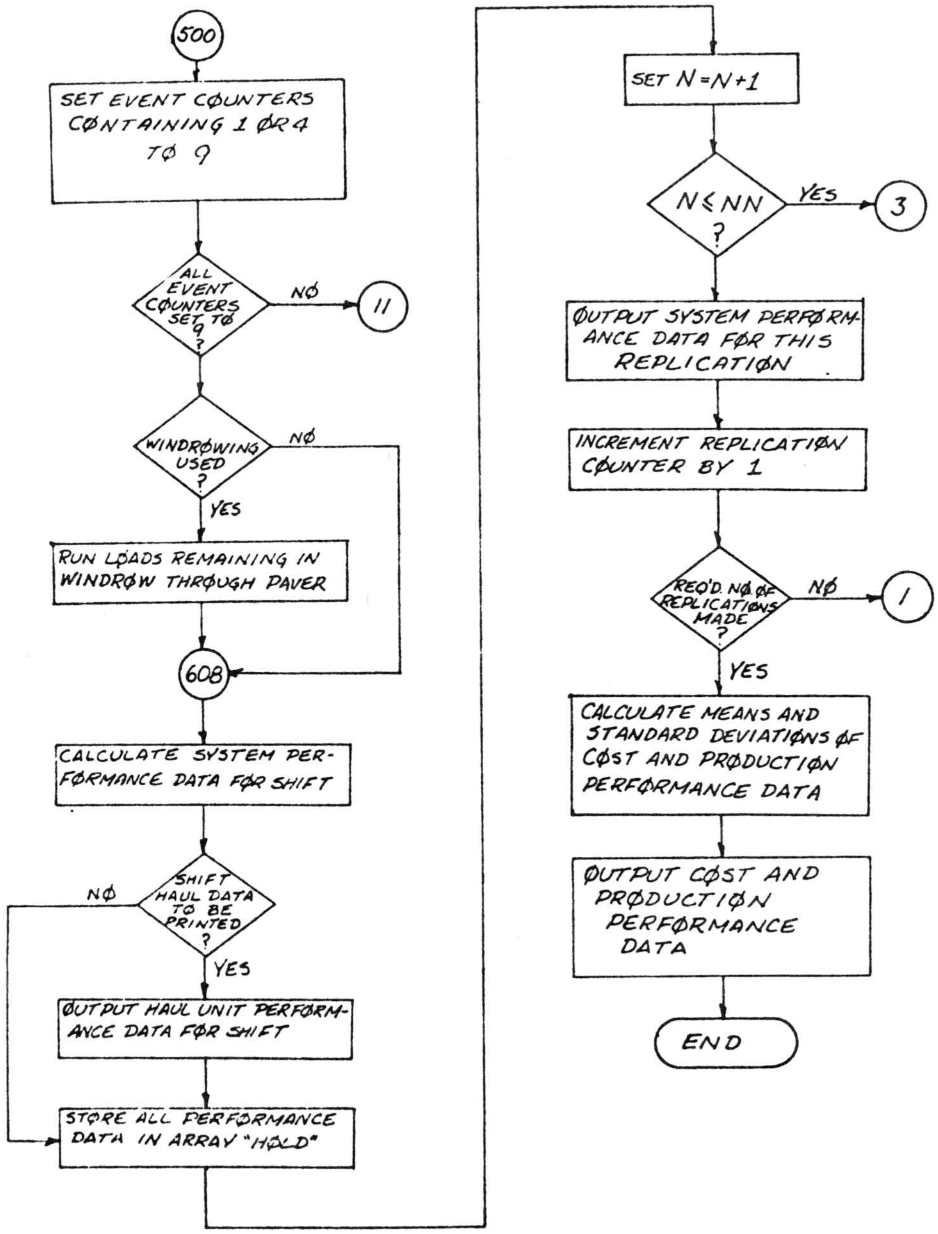

FIGURE I-1.- CONTINUED

BLOCK DATA Subprogram

All input to the computer program is entered by means of the BLOCK DATA subprogram. Through the use of COMMON storage locations, this data is available to the main program and all subprograms. Figure I-2 presents an example of the entries in a BLOCK DATA subprogram; the following explanation of entries is keyed to the numbered lines of Figure I-2.

Line 1. The values entered for IX and IY are seeds for the generation of the first random number by subroutine RANDU. The values entered must be odd numbered integers (no decimal points) of nine digits or less.

Line 2. The entry for HLDATA must be either a zero or one. If one is entered, individual haul unit performance data for each replication of each shift are printed out by the computer (see Figure 5, page 32). If zero is entered this data is not printed.

Line 3. The number of replications of the simulation to be performed is entered as an integer number in NRITER.

Line 4. The entry in IDEN provides a means of identifying the particular simulation run and is printed out as the Job No. with the system summarization output (see Figure 6, page 33). Entries to IDEN must be made in 5A4 format, i.e., in groups of 4 characters, each separated by apostrophes and commas up to a maximum of 5 groups.

Line 5. Entries in NMBR1 and NMBR2 set the number of haul units to be simulated in a computer run. If the program user desires to perform simulations for a specific range of haul unit fleet sizes,

```
DATA IX/493332765/,IY/495702389/
DATA HLDATA/  0/
DATA NRITER/  1/
DATA IDEN/'FLBY','/400','/7.5','TRV ','SRG '/
DATA NMBR1/ 3/,NMBR2/ 3/
DATA IURBAN/   0/
DATA SPDLMT/  60./
DATA PASCHK/  1/
DATA ISURGE/  1/
DATA NRPVR/   1/
DATA NRBTCH/  1/,BTCHWT/ 12000./,XLDWGT/ 45800./
DATA PVWDTH/  12./,PVDPTH/   4./,PVDNSY/  105./,PVCOMP/  144./
DATA PLTCST/ 423.90/,PVRCST/ 187.19/,VEHCST/ 22.85/
DATA SRGCAP/ 200./,SRGAVL/ 0./,SRGXCH/ 0.2/
DATA CSTMTL/  3.80/,SHIFT/  10./
DATA WNDROW/  0/,SPREDR/  0/,MXWRLD/  0/,HOOKUP/ 0.0/,UNHOOK/ 0.0/
DATA PVRATE/23.0/,BCHTIM/0.75/,HAUL1/7.5/,HAUL2/7.5/,IDOP/+1/
DATA XMAN1/ 0.7/,SDMAN1/ 0.4/,A1/ 0.3/
DATA XMAN2/ 1.406/,SDMAN2/ 0.627/,A2/ 0.75/
DATA SPRDMN/ 1.20/,SPRDSD/ 0.2/,ASPRD/ 0.9/
DATA PVDLMN/1.208/,PVDLSD/ 0.864/,APVDLY/0.500/,DLYPCT/ 83.3/
DATA PLTMN/ 0.917/,PLTSD/ 0.229/
DATA TRDLMN/  5.0/,TRDLSD/  10.0/,PTRDLY/  50.0/
DATA ITVLSC/ 1/,MXSGLD/ 4/
DATA VEHWGT/ 26100./,VEHHP/ 221./
END
```

FIGURE I-2. - BLOCK DATA ENTRIES

the lowest and highest fleet size values are entered; e.g., if simulations are desired for fleet sizes ranging from 4 to 8 haul units, then 4 is entered for NMBR1 and 8 for NMBR2. If it is desired to perform simulations for just one fleet size, then that number is entered for both NMBR1 and NMBR2. If the user desires to have data for a cost curve developed from which the optimum fleet size can be determined, zeroes are entered for both NMBR1 and NMBR2 (the starting and ending number of haul units in the fleet is then calculated by subroutine BEGIN). Entries must be integer numbers.

Line 6. Either an integer zero or one is entered for IURBAN. One indicates urban conditions prevail for the simulation; otherwise, a zero must be entered.

Line 7. The maximum speed limit for either rural or urban situations is entered in SPDLMT as a real number (i.e., with a decimal point included).

Line 8. Either an integer zero or one is entered for PASCHK. If passing along the haul route is not possible or allowed, a zero is entered; one is entered if passing is permitted.

Line 9. Either an integer zero or one is entered for ISURGE. If surge storage and loading is to be used at the plant, one is entered; if not, zero is entered.

Line 10. An integer one or two is entered for NRPVR to indicate whether the system being simulated employs one or two pavers. If traveling surge at the paver is being simulated, only one paver may be specified.

Line 11. The number of batches carried by a haul unit is entered as an integer number in NRBTCH. If surge loading is used an integer one must be entered. The weight in pounds of the batches being mixed is entered as a real number in BTCHWT. The total weight in pounds of the load of hot-mix carried by a haul unit is entered as a real number in XLDWGT.

Line 12. All entries are real numbers. The width in feet of the strip being laid by the paver is entered in PVWDTH. The depth in inches of the strip is entered in PVDPTH. Loose weight in pounds per cubic foot of hot-mix at the plant is entered in PVDNSY; final compacted weight in p.c.f. of hot-mix in place is entered in PVCOMP.

Line 13. All entries are real numbers. The total owning and operating cost in dollars per hour of the plant spread (including labor, supporting equipment and surge storage, if used) is entered in PLTCST. The total owning and operating cost in dollars per hour of the paver spread is entered in PVRCST. The owning and operating cost (including operator) in dollars per hour of one haul unit is entered in VEHCST.

Line 14. All entries are real numbers. If surge storage is used, the capacity in tons is entered in SRGCAP. The tons of hot-mix in storage at the beginning of a shift simulation is entered in SRGAVL. The time in minutes for a haul unit waiting in line to pull into position for surge loading is entered in SRGXCH (this entry will normally be a fraction of a minute). If surge loading is not simulated, all items are entered as zero.

Line 15. Entries are real numbers. The total cost of hot mix ingredients in dollars per ton at the plant is entered in CSTMTL. The shift duration to be simulated is entered in hours in SHIFT.

Line 16. If windrowing is to be simulated an integer one is entered in WNDROW; otherwise, a zero is entered. If windrowing is to be simulated and a windrow spreader box is to be used, an integer one is entered in SPREDR; otherwise, a zero is entered. If windrowing is to be simulated, the maximum number of haul unit loads that may be windrowed ahead of the paver is entered in MXWRLD as an integer number; if windrowing is not used, a zero is entered. If a one is entered in SPREDR, the time in minutes required to attach the spreader box to a haul unit is entered as a real number in HOOKUP and the time to disengage the spreader box in UNHOOK; otherwise, these items are entered as zeroes.

Line 17. The non-delay mixing and drop time in minutes for one batch of hot-mix at the plant is entered as a real number in BCHTIM. The initial haul distance in miles from the plant to the paver is entered as a real number in HAUL1. The initial return distance in miles is entered as a real number in HAUL2. If the direction of hot-mix laydown is away from the plant (i.e., the haul distance is increasing) a positive integer one is entered in IDOP; if the direction is toward the plant, a negative one is entered in IDOP; if the haul distance is neither increasing nor decreasing (as in the case of paving a parking lot), a zero is entered in IDOP.

Line 18. All entries are real numbers. The mean value in minutes of the first maneuver of haul units at the paver is entered in XMAN1; the standard deviation is entered in SDMAN1; the minimum value is entered in A1.

Line 19. All entries are real numbers. The mean value in minutes of the second maneuver of haul units at the paver is entered in XMAN2; the standard deviation is entered in SDMAN2; the minimum value is entered in A2.

Line 20. All entries are real numbers. If windrowing is used, the mean value in minutes of the time required to windrow one load is entered in SPRDMN; the standard deviation is entered in SPRDSD; the minimum time is entered in ASPRD. If traveling surge at the paver is to be simulated, the mean, standard deviation and minimum times assumed for haul units to discharge to the traveling surge mechanism are entered in this line. If neither windrowing nor traveling surge are to be simulated, all items are entered as zero.

Line 21. All entries are real numbers. The mean time in minutes of external delays at the paver is entered in PVDLMN; the standard deviation is entered in PVDLSD; the minimum time is entered in APVDLY; and the probability in percent of an external delay occurring at the paver during the laydown of a load of hot-mix is entered in DLYPCT.

Line 22. Entries are real numbers. The mean time in minutes to load one haul unit with the required number of batches is entered in PLTMN; the standard deviation is entered in PLTSD. If surge loading is used, the mean and standard deviation of the time required to mix and drop one batch of hot-mix are entered.

Line 23. All entries are real numbers. The mean time in minutes of external delays experienced by haul units during a haul cycle is entered in TRDLMN; the standard deviation is entered in TRDLSD; the probability in percent of an external delay occurring during a haul unit cycle is entered in PTRDLY.

Line 24. If traveling surge is to be simulated an integer one is entered in ITVLSG; otherwise, a zero is entered. If traveling surge is simulated, the capacity of the traveling surge mechanism in haul unit loads is entered as an integer number in MXSGLD.

Line 25. Entries are real numbers. The empty weight in pounds of the type haul unit to be simulated is entered in VEHWGT. The rated horsepower of the haul unit is entered in VEHHP.

All items in every line of the BLOCK DATA subprogram require entries each time the program is run, even if values to be entered are zero. The items in lines 18, 19, 21, 22, and 23 must have values greater than zero entered in them. If it is desired to enter any of these items as zero, then a very small value such as 0.001 will achieve the same result and also meet the requirements of the program.

Subprogram BEGIN

Subprogram BEGIN is an initializing subprogram used only at the outset of a computer simulation run to calculate values for variables which will remain unchanged throughout all replications of the program, to determine starting and ending sizes of haul unit fleets for which simulations are to be performed (if these values are not provided as input data) and to calculate stochastic variate parameters for use by various other portions of the program during the simulation.

The starting haul unit fleet size for a simulation is determined based on input supplied to the program (if, again, the starting and ending fleet size values themselves are not provided). An average haul unit cycle time is calculated using the mean time values for loading, discharge and external delays input to the program and the appropriate mean values for haul and return travel speeds based on the distances involved (the average speed values used in the subprogram were calculated from the speed equations discussed in Chapter II). Having calculated an average cycle time (actually, a deterministic cycle time), the number of haul units required to service the hot-mix plant is determined (i.e., if the cycle time calculated is 30 minutes and the plant mean loading time is 5 minutes then 6 haul units are required). The number of haul units to service the paver is also determined. The lesser of the two values determined becomes the starting number of units in the haul unit fleet at the beginning of the simulation run. Shift simulations will be performed for all fleet sizes beginning with this value and running through this value plus six. Thus, performance data for seven fleet sizes will be simulated, from which the optimum system configuration can be determined.

The log-normal distribution is used throughout the program to provide values for stochastic operating variables (see the discussion on the log-normal distribution in Chapter II). The mean, standard deviation and minimum value for these variables ("$\bar{t}$", "S_t" and "a") must be transformed for use as parameters in equations for log-normally distributed random variables of the general form

$$t = a + \exp(\bar{x} + S_x \cdot V)$$

where V is a normally distributed random variable provided by subprogram NORMAL. The transformation is accomplished in subprogram BEGIN making use of statements executing the following relationships:

$$x = \ln(\bar{t}-a) - \frac{S_x^2}{2}$$

$$S_x = \{\ln[1 + (\frac{S_t}{\bar{t}-a})^2]\}^{\frac{1}{2}}$$

Parameter transformations are accomplished in the subprogram for the operating variables of loading at the plant, external delays at the paver, haul unit maneuver times at the paver, haul unit discharge times at the paver (if windrowing or traveling surge is used) and haul unit external delay times.

A flow diagram for subprogram BEGIN is shown in Figure I-3.

Subprogram TABLE

The function of subprogram TABLE is to examine the cumulative time clocks of the haul units comprising the haul fleet for a particular simulation and to find that haul unit with the lowest cumulative time and the event it is scheduled to perform next. The haul unit number and the number of its next event are returned to the main program. Subprogram TABLE is called upon the completion of any event in the program.

Figure I-4 presents a flow diagram for this subprogram.

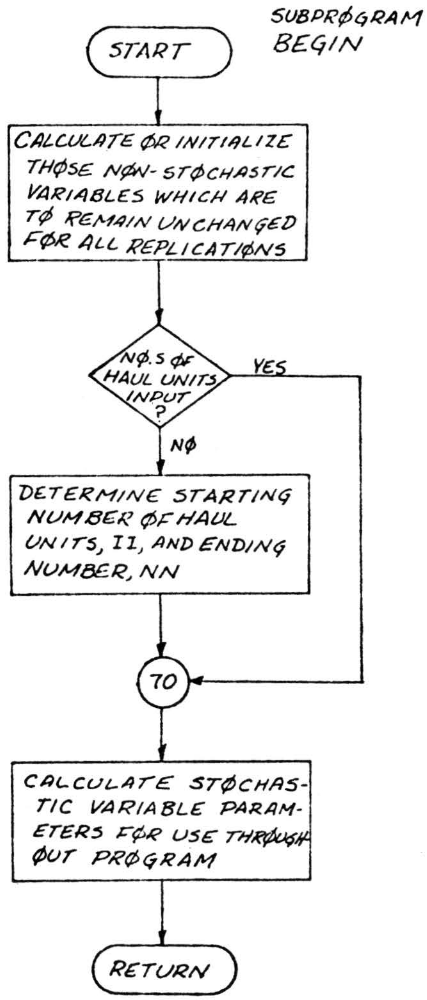

FIGURE I-3.- FLOW DIAGRAM: SUBPROGRAM BEGIN

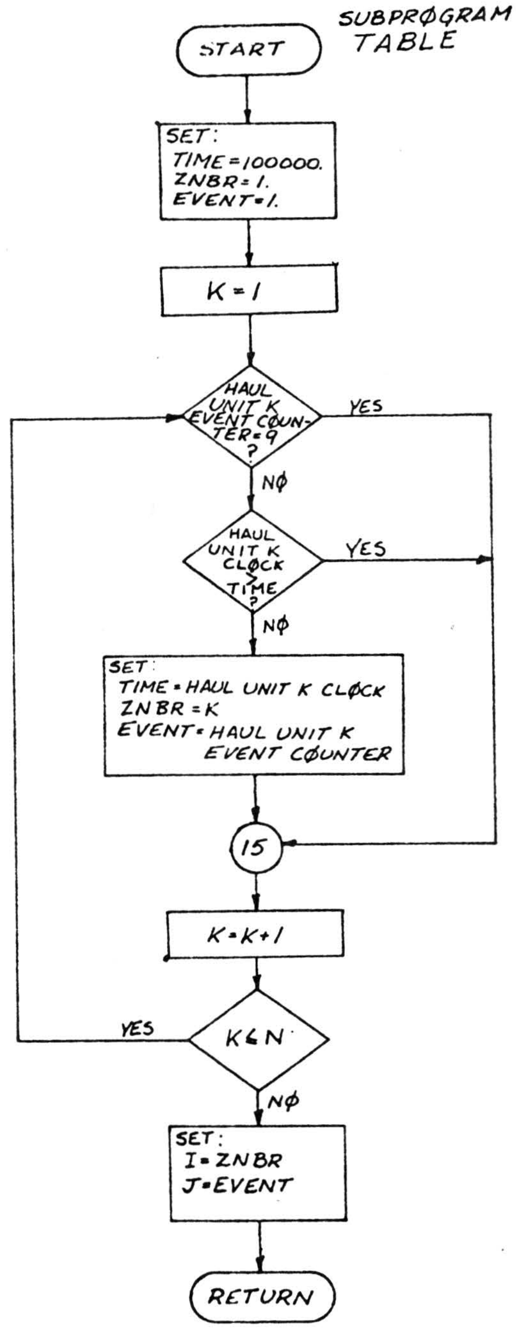

FIGURE I-4. - FLOW DIAGRAM: SUBPROGRAM TABLE

Subprogram SCAN

This subprogram is called by the main program to find the next haul unit scheduled to perform a particular event. The event number to be searched is passed to the subprogram which finds the haul unit with the least cumulative time scheduled to perform that event. The number of the haul unit and its cumulative time total are returned to the main program. SCAN is called from only one location in the main program, viz., the point at which it becomes necessary to determine the arrival time of the next haul unit for loading at the plant in the event the plant has been shut down for lack of hauling units.

Figure I-5 is a flow diagram for subprogram SCAN.

Subprogram PLTIME

Subprogram PLTIME calculates plant batching times and associated external delays. It is called from the main program if surge loading is not used and from subprogram SRGBIN when surge loading is used. In either event, the number of batches to be simulated by the plant, NRBTCH, is passed to the subprogram and a DO loop is established using 1 and NRBTCH as the indexing parameters. In each pass through the loop, a batch mixing time is randomly selected from the log-normal representation of batch mixing times. Any associated external delay time is determined by subtracting the non-delay batching time (an item of input data) from the generated batching time. Batching times and delay times are cumulatively totaled each pass through the loop. The loop is exited in one of two ways, viz., normally or, in

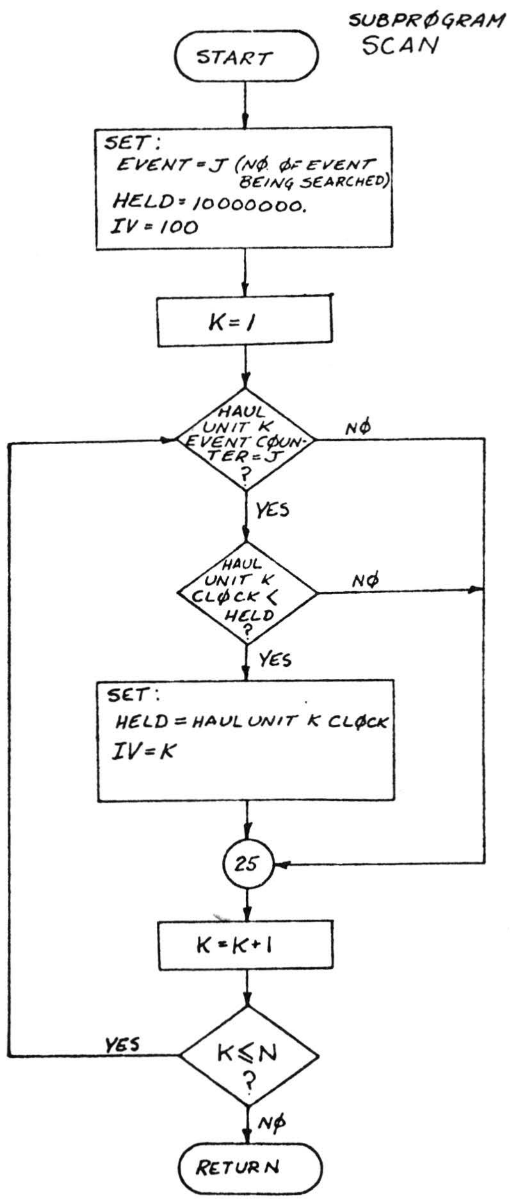

FIGURE I-5. - FLOW DIAGRAM: SUBPROGRAM SCAN the event surge loading is used, when the number of batches in surge storage becomes equal to the capacity of the surge storage. Two cumulative time clocks are maintained for the plant. One, PLANT, accumulates the total time that the plant is actually mixing batches (and therefore includes external delay time). The other, TOTPLT, accumulates total elapsed time during the shift and is used as the master clock for the program.

A flow diagram for the subprogram PLTIME appears in Figure I-6.

Subprogram SRGBIN

Subprobram SRGBIN incorporates the concept of surge bin storage and loading into the program. When a haul unit is to be loaded from surge, SRGBIN is called. If there is a waiting line for loading, the haul unit idle time clock is incremented by the haul unit waiting time. The amount of hot-mix available in storage is then checked. If a sufficient amount is available, the haul unit is loaded, the haul unit and surge clocks are incremented and the amount of surge in storage is reduced by one load. If sufficient hot-mix is not available, the plant master clock is checked. If it shows plant time to be less than the time on the haul unit clock, the plant is run for a period of time equal to the time difference and the amount of hot-mix in storage is again checked. If sufficient hot-mix is now available, the haul unit is loaded. If sufficient hot-mix is still not in storage and the plant master clock is at least equal to the haul unit clock, the haul unit stands idle while sufficient batches are mixed by the plant to complete a full load. The haul unit idle time clock is

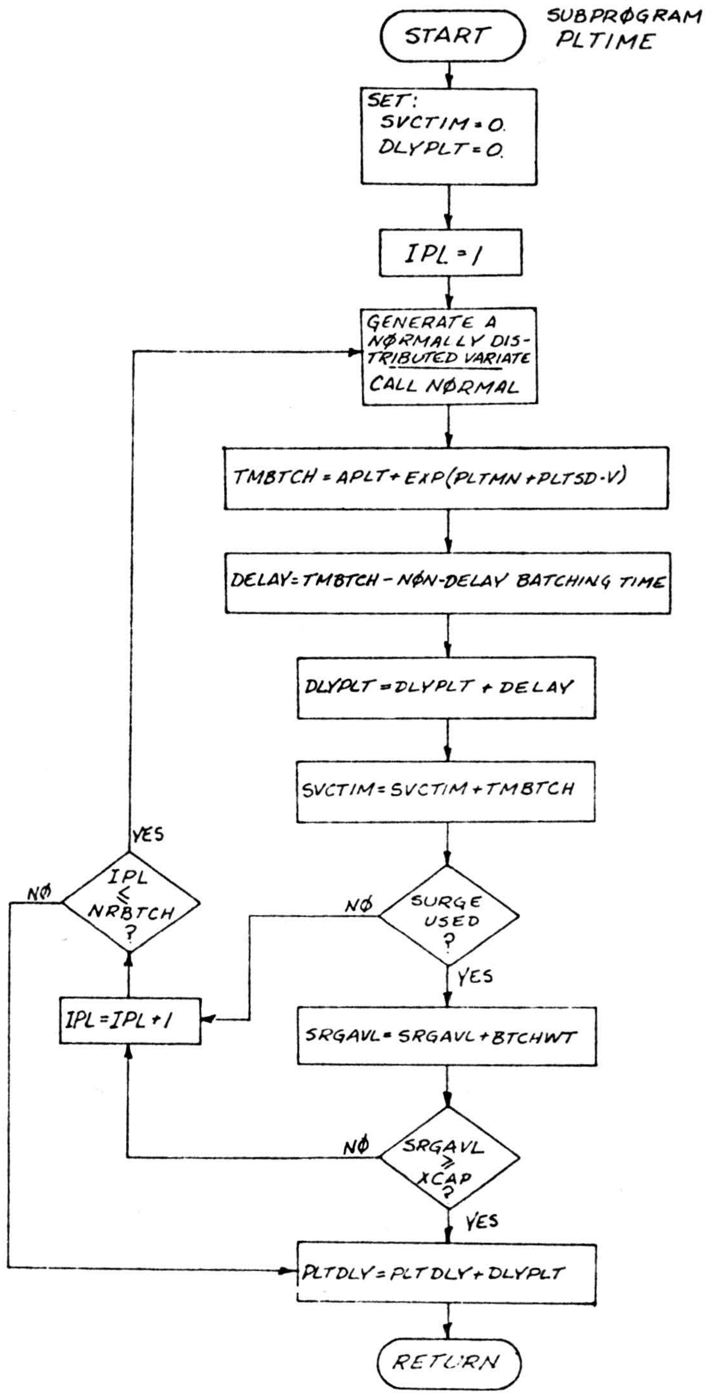

FIGURE I-6. -FLOW DIAGRAM: SUBPROGRAM PLTIME incremented by the amount of time the haul unit stands waiting and the haul unit, surge, plant, and master plant clocks are incremented by the plant service time. The haul unit then loads and the appropriate clocks are again incremented.

Figure I-7 is a flow diagram for subprogram SRGBIN.

Subprogram TRVLTM

Subprogram TRVLTM calculates haul unit travel times and any associated external delays. The subprogram checks to determine whether the haul unit is operating in a rural or urban haul situation, whether the travel to be performed is hauling to the paver or return, and the hauling distance involved. Depending on the outcome of these checks, the appropriate equation is selected to generate a travel speed. The speed generated is compared to the speed limit established for the haul situation, and if it exceeds that value, the speed is then set equal to the speed limit. Following this, a travel time is calculated based on the haul distance involved and the travel speed calculated. Next, a check is made (using a computer generated random number) to determine if an external delay will occur during that particular travel phase. If a delay is to occur, its value is calculated and added to an external delay cumulative clock for that haul unit. The total time spent in travel by the haul unit is determined by summing the travel time and delay time generated. This time is added to the haul unit cumulative time clock and the haul unit cumulative travel time clock.

External delay times are not generated for urban haul situations

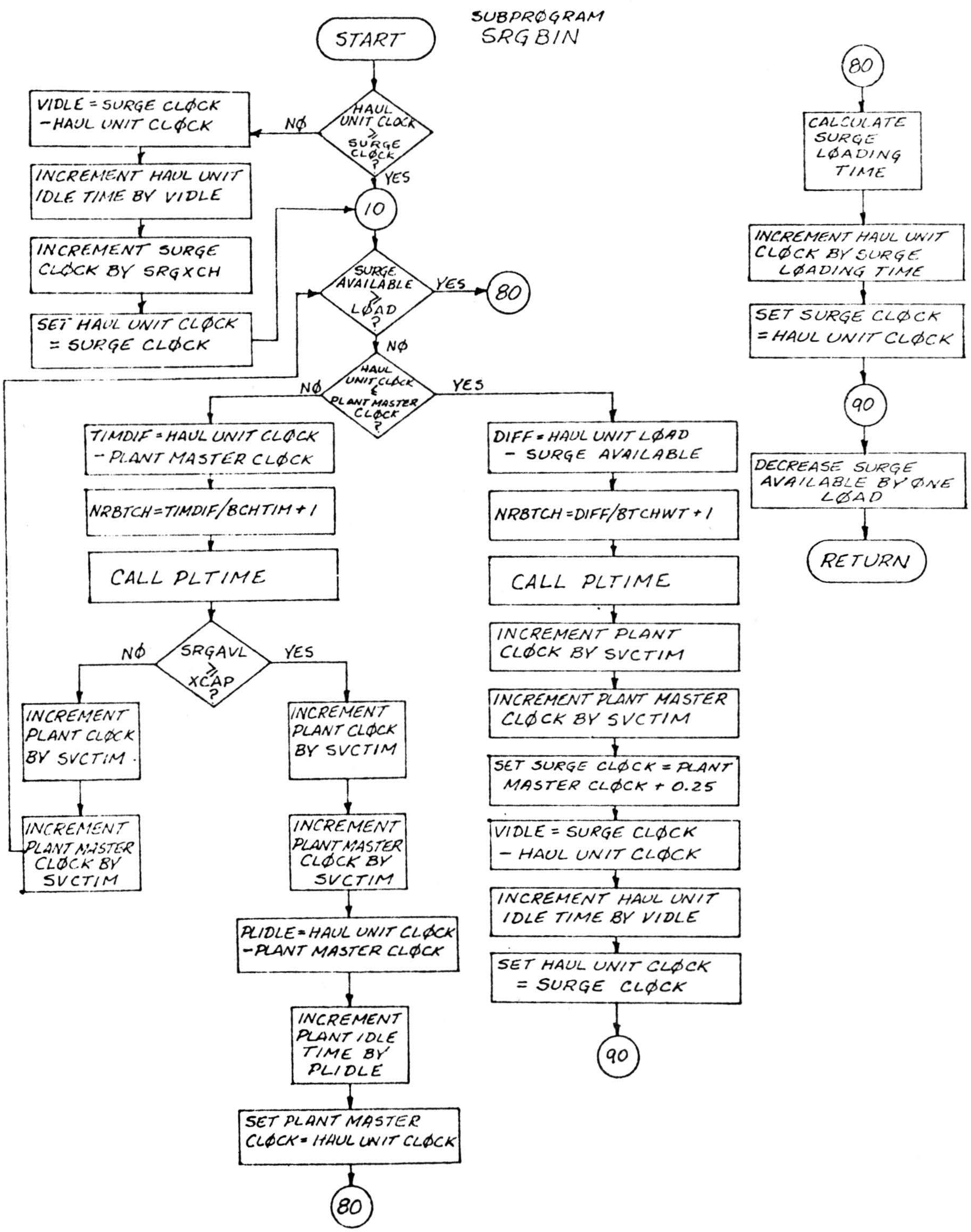

FIGURE I-7. - FLOW DIAGRAM: SUBPROGRAM SRGBIN since external delay times are already incorporated in the urban speed equations.

A flow diagram for subprogram TRVLTM is presented in Figure I-8.

Subprogram PVRTIM

Subprogram PVRTIM calculates external delay times associated with the laydown of a load of hot-mix at the paver and haul unit maneuver times into and out of the paver. It is called by the main program, by subprogram WINDRO if windrowing is simulated, or by subprogram TRVSRG if traveling surge is simulated. The non-delay laydown time for a load of hot-mix was calculated at the outset of the simulation run by subprogram BEGIN. A check is made (using a random number) to determine if an external delay time is to be associated with the particular load being laid by the paver. If a delay is to occur, its value is calculated and added to a cumulative delay time clock for the paver. The maneuver time of the haul unit subsequent to discharge (during which it maneuvers into position for the return trip to the plant) is then calculated.

The values calculated by subprogram PVRTIM are applied in various ways depending on whether PVRTIM is called by the main program, by subprogram WINDRO, or by subprogram TRVSRG.

Figure I-9 presents a flow diagram for subprogram PVRTIM.

Subprogram WINDRO

Subprogram WINDROW calculates discharge times and updates the appropriate cumulative time clocks if haul units are to simulate discharging into a windrow (as opposed to discharging into a paver).

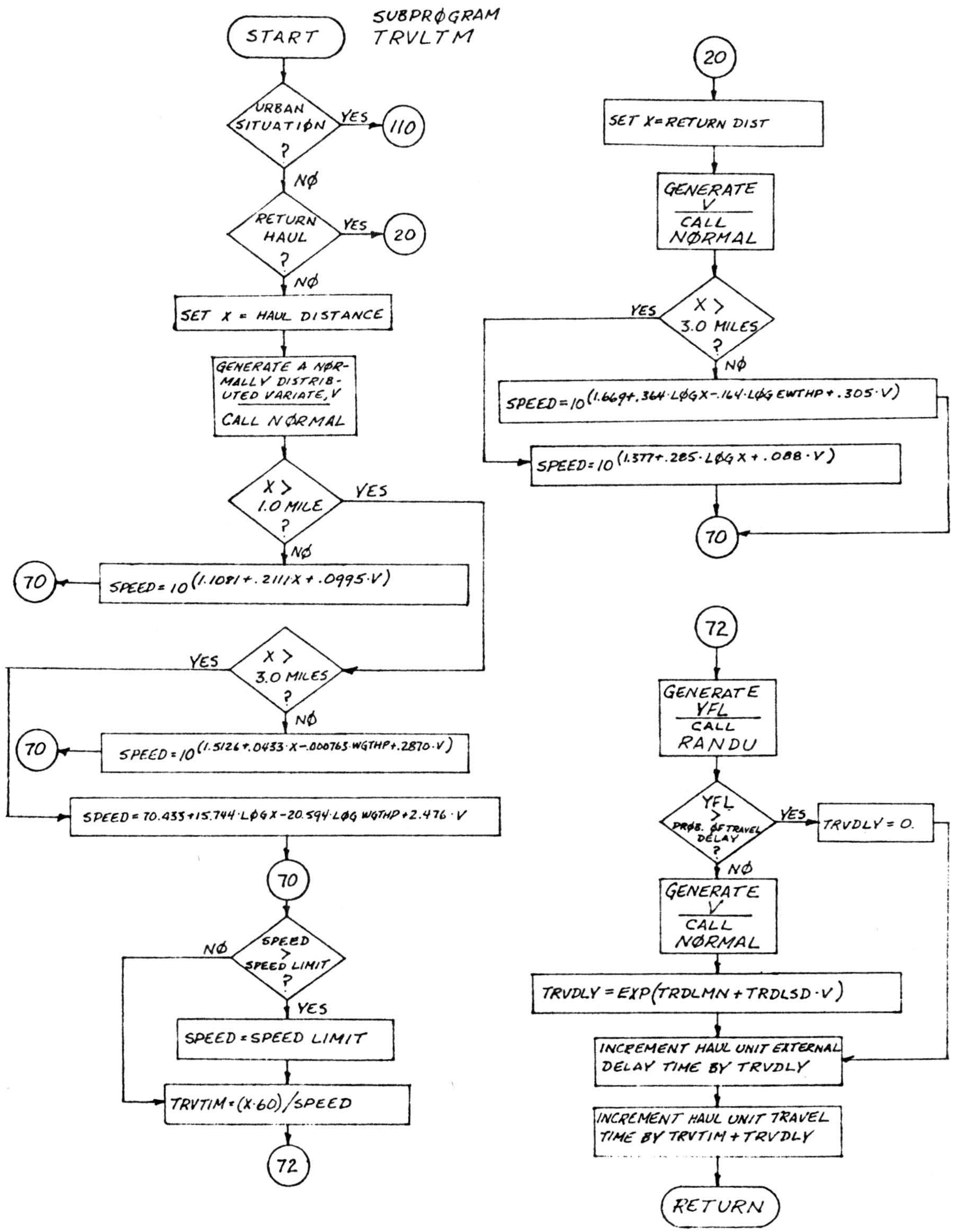

FIGURE I-8. - FLOW DIAGRAM: SUBPROGRAM TRVLTM

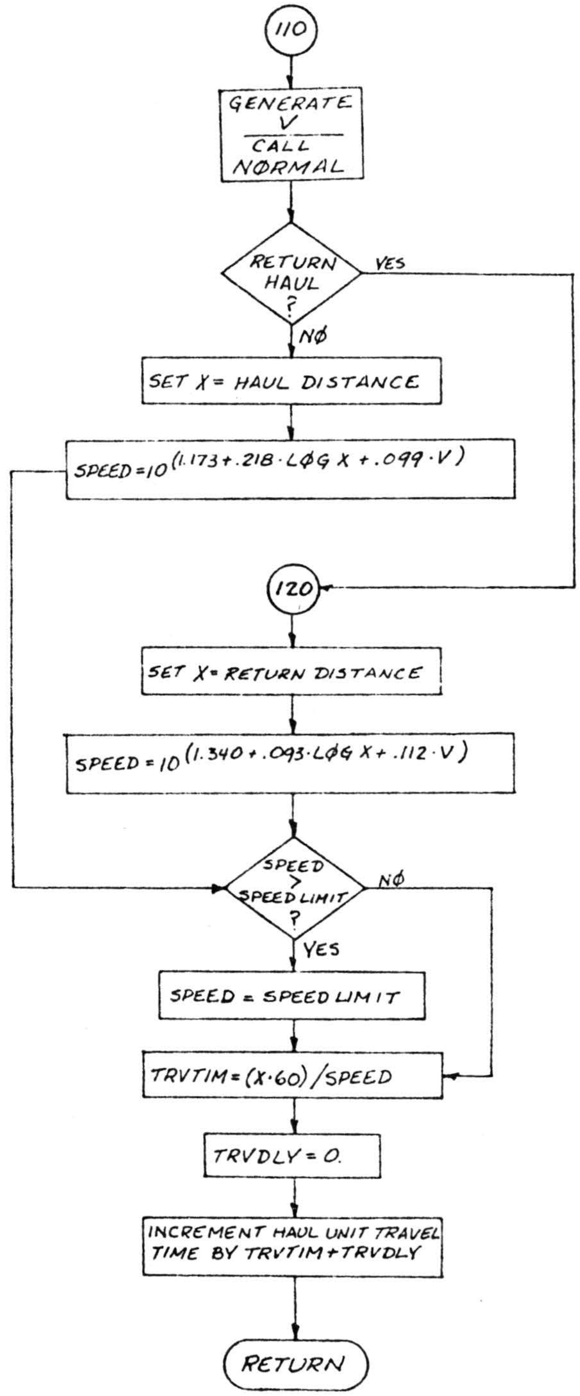

FIGURE I-8. - CONTINUED

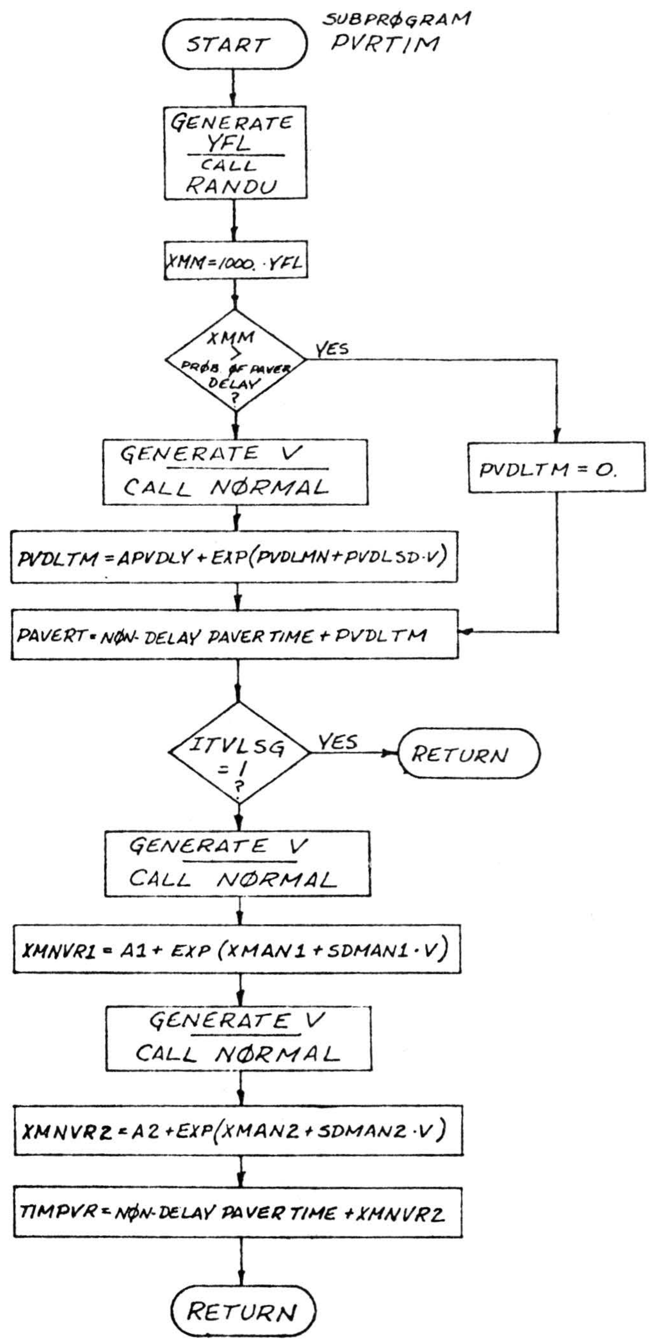

FIGURE I-9. - FLOW DIAGRAM: SUBPROGRAM PVRTIM

The subprogram is called only from the main program. WINDRO first checks to see if the windrow is clear for discharging; if it is not, the haul unit idle time cumulative clock is incremented by the amount of time the haul unit must wait. Next a check is made to determine if a spreader box is to be used to distribute the hot-mix into the windrow. If it is to be used, the haul unit clock is incremented by the hookup time (a non-stochastic input constant). Following this, a check is made to determine the number of loads already in the windrow ahead of the paver. If there are fewer loads than the maximum allowed (an input value), the load discharge time is calculated and added to the haul unit cumulative time clock. If there are no loads windrowed ahead of the paver, the amount of time the paver has been idle waiting for a haul unit to arrive is determined and the paver idle time clock incremented. If there are a maximum number of loads in the windrow, the amount of time the haul unit remains idle until it can discharge its load is calculated and added to the haul unit idle time clock. Finally, if a spreader box has been used, the haul unit clock is incremented by the amount of time required to unhook the box (also an input constant).

The flow diagram for subprogram WINDROW is shown in Figure I-10.

Subprogram TRVSRG

Subprogram TRVSRG simulates a traveling surge mechanism at the paver into which haul units discharge their loads of hot-mix. The subprogram is called only from the main program. TRVSRG has a fixed number of three points at which haul units may discharge their loads;

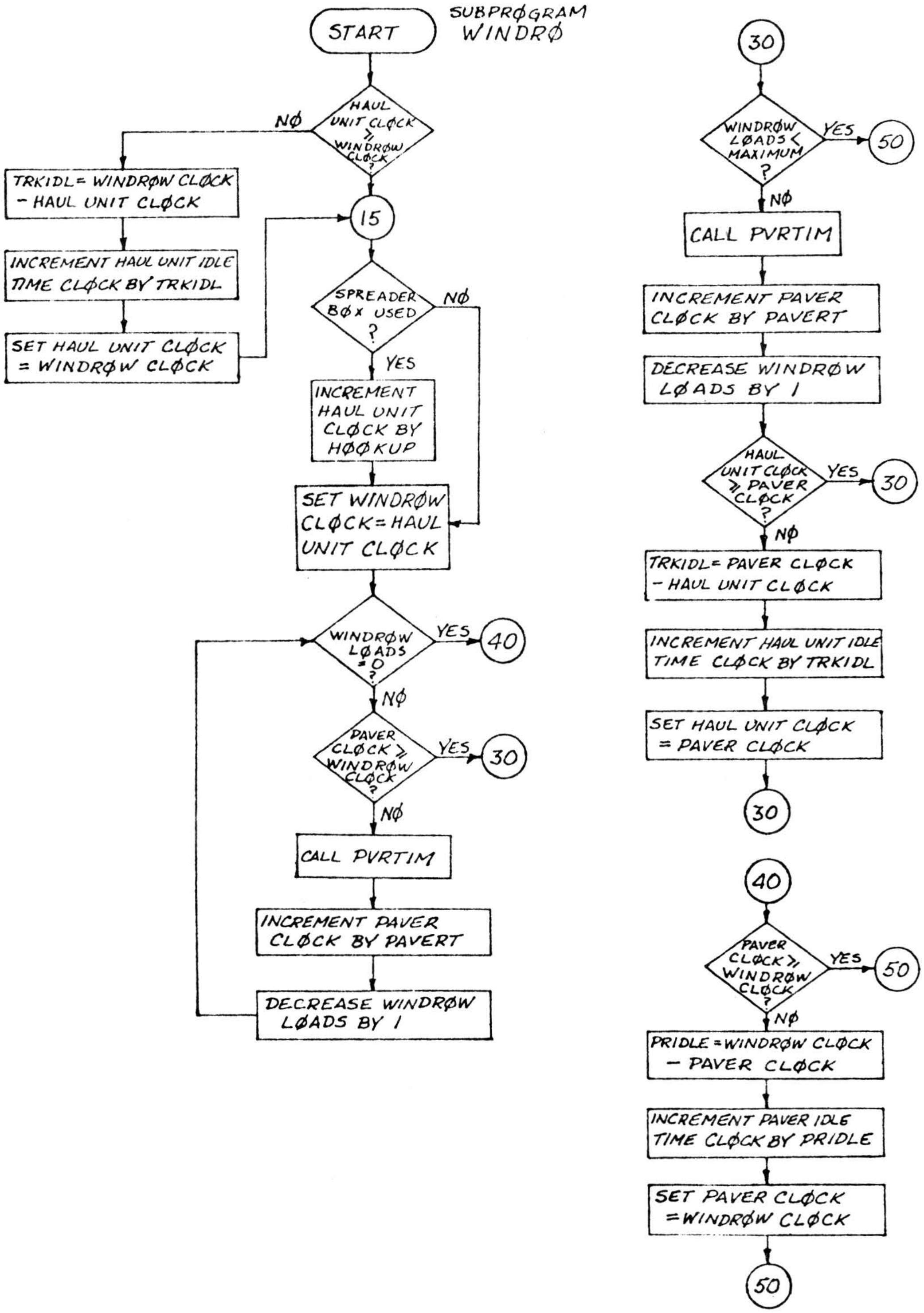

FIGURE I-10. -FLOW DIAGRAM: SUBPROGRAM WINDRO

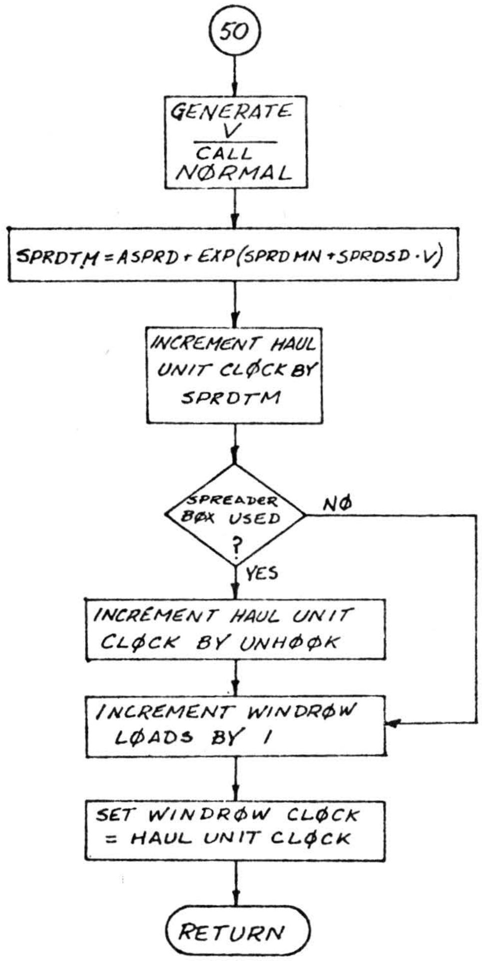

FIGURE I-10.- CONTINUED

the three points may be used simultaneously, allowing three haul units to be discharging at one time. Initially, a check is made to see which discharge point is free when a haul unit arrives at the traveling surge. The haul unit is assigned to the first free discharge point in numerical sequence. If no points are free, the haul unit is assigned to the first point becoming free, and its idle time clock is incremented by the amount of waiting time. Once a haul unit is assigned to a discharge point, its maneuver time into position is calculated. A check is then made to determine if the surge is filled to capacity. If it is, subprogram PVRTIM is called and the amount of surge is decreased by one load. If there is zero surge, the amount of time the paver has been idle is determined. When and if the surge mechanism is ready to receive a load, the haul unit discharge time is calculated and added to the haul unit cumulative clock. The discharge point clock is then set equal to the haul unit clock, the number of loads in surge is increased by one, and the haul unit second maneuver time is then calculated and added to the haul unit clock.

The flow diagram for subprogram TRVSRG appears in Figure I-11.

Subroutine RANDU

Subroutine RANDU is a utility subprogram which generates uniformly distributed random numbers for use throughout the computer program. The method used in RANDU for random number generation was devised by Dr. Charles E. Gates of the Texas A&M Institute of Statistics. He describes it as being a "composite congruential random

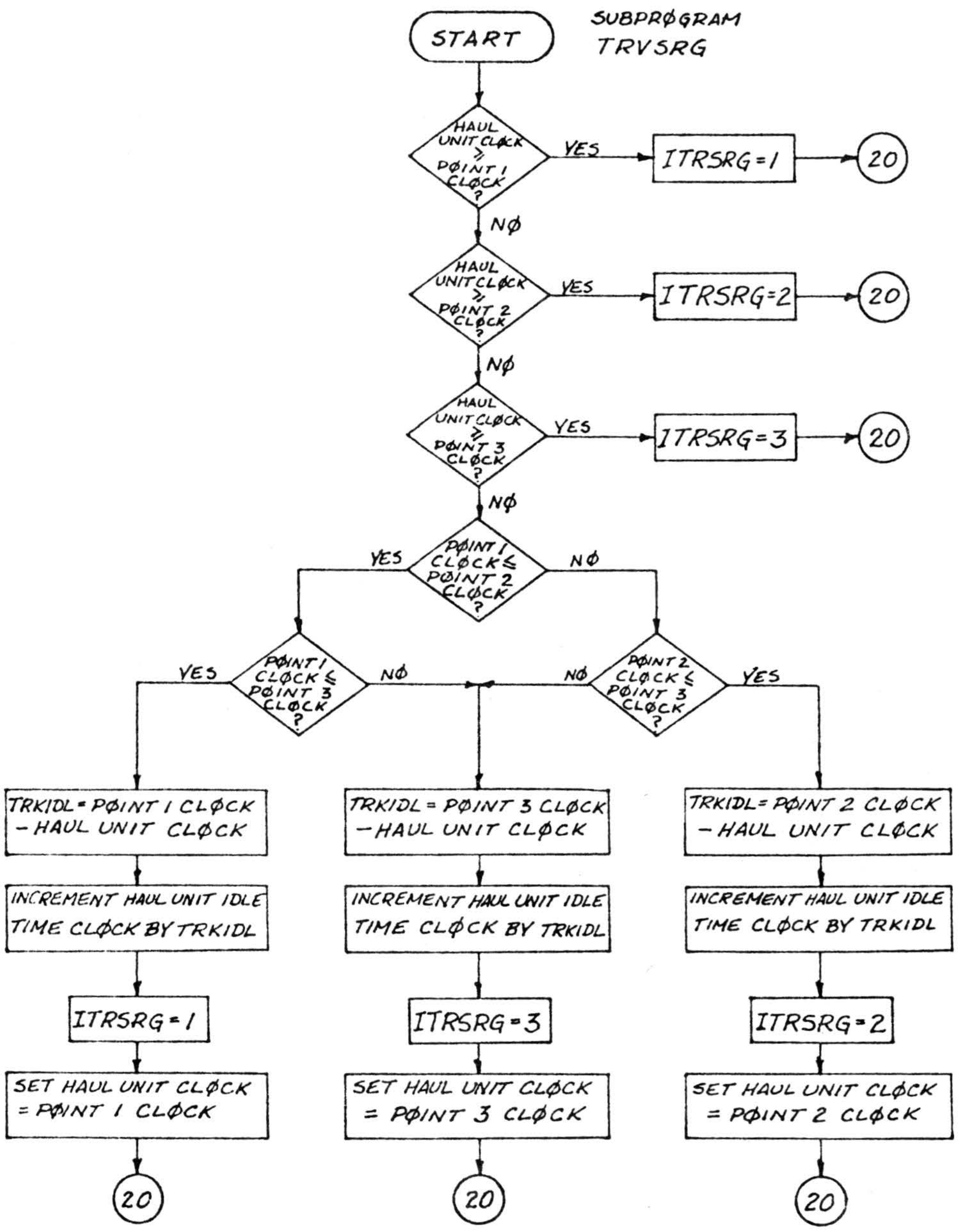

FIGURE I-11.- FLOW DIAGRAM: SUBPROGRAM TRVSRG.

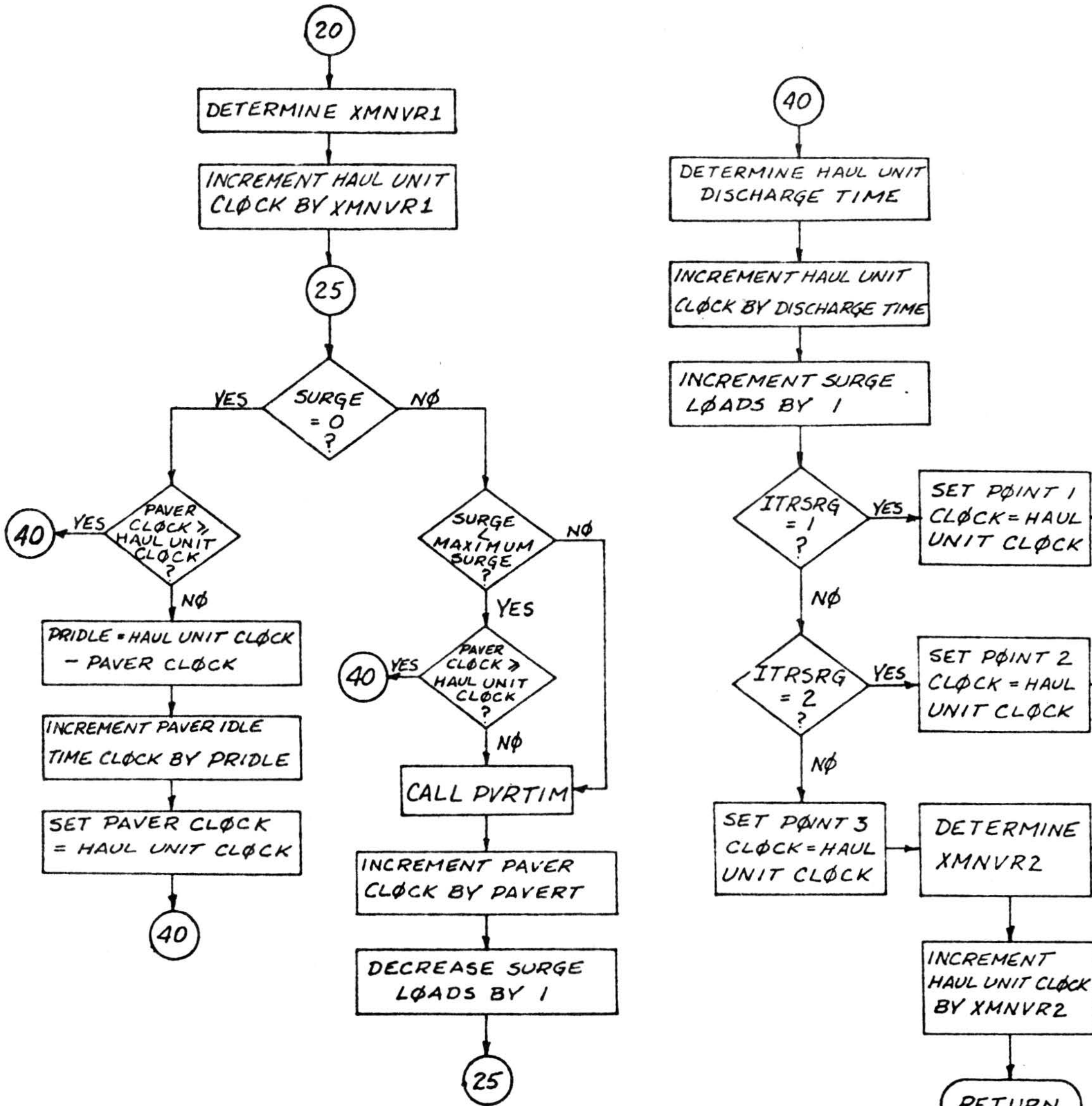

FIGURE I-11.-CONTINUED

uniform generator" (2). The generator initially requires two seed values (input data), consisting of any odd integer numbers of nine or less digits. From that point on, the generator is self-sustaining and reportedly can generate in excess of 10^5 random variables before the cycle begins to repeat itself.

The flow diagram for subprogram RANDU is shown in Figure I-12.

Subprogram NORMAL

Subprogram NORMAL is a utility subprogram which generates normally distributed random variables. It is called whenever a log-normally distributed operating variate is to be calculated in the computer program. The generator requires two different, uniformly distributed random variables (obtained from RANDU) to generate one normally distributed variable having a mean of zero and a standard deviation of one. A discussion of this method of normally distributed random number generation can be found in Reference 1.

A flow diagram for NORMAL is included in Figure I-12.

The Program Listing

On the following pages appears a program listing of the computer model discussed above. It should be noted that many of the numbered statements appearing in the listing are referenced by number in the diagrams presented in the preceding sections (numbers appear in connector circles).

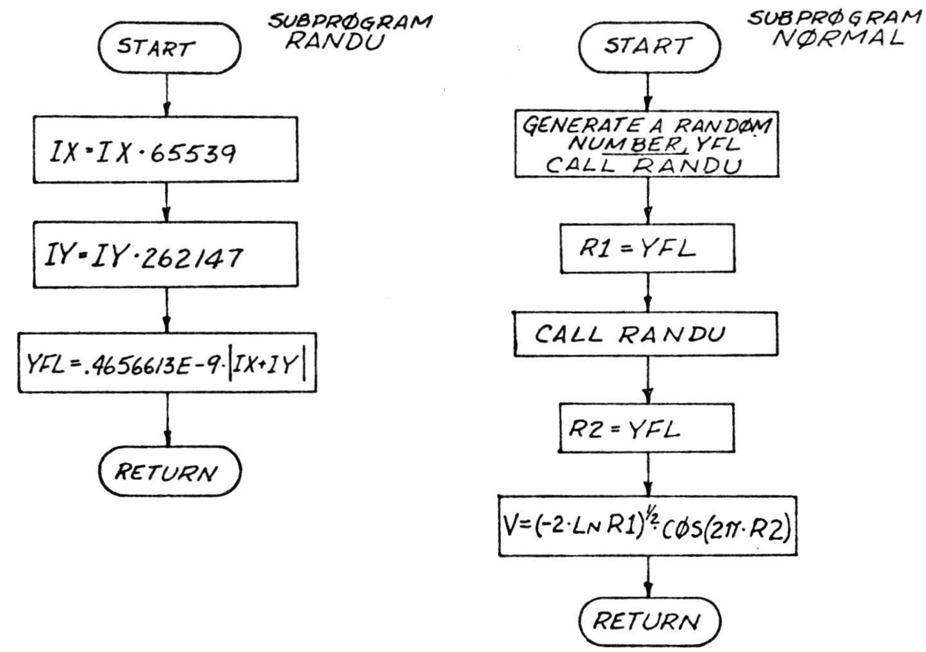

FIGURE I-12.- FLOW DIAGRAMS: SUBPROGRAMS RANDU AND NORMAL

References Cited in the Appendix

1. McMillan, Claude and Gonzalez, Richard F., Systems Analysis, Richard D. Irwin, Inc., Homewood, Illinois, 1968, pp. 259-260.

2. "Random Number Generators Revisited," DPC News, Texas A&M University Data Processing Center, Vol. 3, No. 3, November, 1970, p. 5.

```
      DIMENSION ZPROD(10,10),ZCST(10,10)
      REAL MNPROD,MNCST
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      WRITE(6,999)IDEN,BTCHWT,NRPVR,ISURGE,PVWDTH,SRGCAP,PVDPTH,SRGAVL,
     *WNDROW,BCHTIM,MXWRLD,PLTMN,NRBTCH,SPREDR,PLTSD,HOOKUP,PLTCST,
     *UNHOOK,PVDNSY,SPRDMN,CSTMTL,SPRDSD,ASPRD,PVRATE
  999 FORMAT('1'//////T60,'SYSTEM INFORMATION'//T56,'JOB NO',1X,5A4///
     *T10,'PLANT',T74,'PAVER'/T14,'BATCH SIZE -',F7.0,' POUNDS',
     *T77,'NUMBER OF PAVERS -'I2/T14,'SURGE LOADING USED -',I2,
     *T77,'PAVEMENT WIDTH -',F5.1,' FEET'/T14,'SURGE CAPACITY -'F5.0,
     *' TONS',T77,'PAVEMENT DEPTH -',F5.1,' INCHES'/T14,'SURGE AVAILABLE
     * AT START -',F5.0,' TONS',T77,'WINDROWING USED -',I2/
     *T14,'SPECIFICATION BATCH TIME -',F5.2,' MIN',T77,'MAX WINDROW LOAD
     *S AHEAD OF PAVER -',I3/T14,'MEAN BATCHING TIME -',F6.3,' MIN FOR',
     *I3,' BATCHES',T77,'SPREADER BOX USED -',I2/T14,'BATCH TIME STANDAR
     *D DEVIATION -',F6.2,T77,'SPREADER BOX HOOKUP TIME -',F5.2,' MIN'/
     *T14,'TOTAL PLANT SPREAD O&O COST -$',F7.2,' PER HOUR',
     *T77,'SPREADER BOX UNHOOK TIME -',F5.2,' MIN'/T14,'MIX DENSITY AT P
     *LANT -',F5.0,' PCF',T77,'MEAN WINDROW DISCHARGE TIME -',F6.2,' MIN
     *'/T14,'MIX MATERIALS COST -$',F5.2,T77,'WINDROW DISCHARGE STD DEV
     *-',F6.2,' MIN'/T77,'MINIMUM WINDROW DISCHARGE TIME -',F6.2,' MIN'/
     *T77,'NON-DELAY PAVER LAYDOWN RATE -',F4.1,' FPM')
      WRITE(6,998)DLYPCT,XLDWGT,PVDLMN,PVDLSD,VEHHP,APVDLY,VEHWGT,PVRCST
     *,PTRDLY,PVCOMP,TRDLMN,TRDLSD,XMAN1,SDMAN1,A1,XMAN2,SDMAN2,HAUL1,
     *A2,HAUL2,VEHCST,IDOP,PASCHK,SPDLMT,IURBAN,SHIFT,NRITER
  998 FORMAT(    T10,'HAUL UNITS',T77,'EXTERNAL DELAY PROBABILITY -',F5.1
     *,' PCT'/T14,'LOAD WEIGHT -',F8.0,' POUNDS',T77,'DELAY MEAN -',
     *F7.3,' MIN,STD DEV -',F7.3,' MIN'/T14,'HORSEPOWER -',F5.0,T77,
     *'MINIMUM DELAY TIME -',F7.3,' MIN'/T14,'VEHICLE WEIGHT -',F7.0,
     *' POUNDS',T77,'TOTAL PAVER SPREAD O&O COST -$',F7.2,' PER HOUR'/
     *T14,'EXTERNAL DELAY PROBABILITY -',F5.1,' PCT',T77,'MIX DENSITY IN
     * PLACE -',F5.0,' PCF'/T14,'DELAY MEAN -',F7.3,' MIN, STD DEV -',
     *F7.3,' MIN'/T14,'FIRST MANEUVER MEAN -',F6.3,' MIN, STD DEV -',
     *F6.3,' MIN'/T14,'FIRST MANEUVER MINIMUM TIME -',F6.3,' MIN',T74,
     *'HAUL ROUTE'/
     *   T14,'SECOND MANEUVER MEAN -',F6.3,' MIN, STD DEV -',F6.3,' MIN'
     *T77,'HAUL DISTANCE AT START -',F6.2,' MILES'/T14,'SECOND MANEUVER
     *MINIMUM TIME -',F6.3,' MIN',T77,'RETURN DISTANCE AT START -',F6.2,
     *' MILES'/T14,'HAUL UNIT O&O COST -$',F6.2,' PER HOUR',T77,
     *'LAYDOWN DIRECTION -',I3/T77,'PASSING PERMITTED -',I2,',SPEED LIMI
     *T -',F4.0,' MPH'/T77,'URBAN HAUL -',I2///T55,'PROGRAM INFORMATION'
     *//T48,'APPROXIMATE SIMULATED SHIFT DURATION -',F4.0,' HOURS'/
     *T48,'NUMBER OF REPLICATIONS -',I2)
      ITER=1
      CALL BEGIN
    1 N=II
      JRPT=0
      JXYZ=0
```

```
    3 DO 5K=1,N
      DO 4J=1,10
    4 VEH(K,J)=0.0
      VEH(K,2)=K
    5 VEH(K,3)=1.
      PLANT=0.0
      PLTIDL=0.0
      PLTDLY=0.0
      PAVER=0.0
      PVRIDL=0.0
      PVRDLY=0.0
      PAVER1=0.
      PAVER2=0.
      PVIDL1=0.
      PVIDL2=0.
      SURGE=0.0
      TOTPLT=0.0
      QUEU1=0.0
      QUEU2=0.0
      WRLGTH=0.
      WRTIME=0.
      WRLDS=0
      WRTIM1=0.
      WRTIM2=0.
      WRLDS1=0
      WRLDS2=0
      LDSRG=0
      TRSRG1=0.
      TRSRG2=0.
      TRSRG3=0.
      HAULX=HAUL1
      HAULY=HAUL2
      SRGAVL=AVLSRG
      JBATCH=0
      NLOADS=0
C CHECK TO SEE IF SHIFT IS COMPLETE. IF NOT, CALL TABLE SUBROUTINE TO
C DETERMINE WHICH HAUL UNIT WILL PERFORM WHAT EVENT NEXT.
   10 IF(TOTPLT .GE. SHIFT)GO TO 500
   11 CALL TABLE
      GO TO (100,200,300,400),J
C PLANT ROUTINE
C CHECK TO SEE IF SURGE BIN IS BEING USED.
  100 IF(ISURGE .EQ. 1)GO TO 150
C SURGE BIN NOT USED.
C CHECK TO SEE IF PLANT IS OCCUPIED.
      IF(VEH(I,1)-TOTPLT)101,108,102
C PLANT IS OCCUPIED - INCREMENT HAUL UNIT PLANT IDLE TIME
  101 VIDLE=TOTPLT-VEH(I,1)
      VEH(I,4)=VEH(I,4)+VIDLE
      VEH(I,1)=TOTPLT
      GO TO 108
C PLANT IS UNOCCUPIED - IF HAUL UNIT IS NOT WITHIN 20 SECONDS OF PLANT,
C PLANT SHUTS DOWN AND DOES NOT START UP AGAIN UNTIL TWO HAUL UNITS ARE
C WAITING TO BE LOADED. IN EITHER CASE, INCREMENT PLANT IDLE TIME.
  102 IF(N .LE. 4)GO TO 107
      CHECK=TOTPLT+0.33
      IF(VEH(I,1) .LE. CHECK)GO TO 107
      VEH(I,3)=2
      J=1
      CALL SCAN
      IF(IV .EQ. 100)GO TO 105
```

```
      XVIDLE=VEH(IV,1)-VEH(I,1)
      VEH(I,4)=VEH(I,4)+XVIDLE
      VEH(I,1)=VEH(IV,1)
      GO TO 107
  105 VEH(I,1)=VEH(I,1)+5.0
      VEH(I,4)=VEH(I,4)+5.0
  107 PLIDLE=VEH(I,1)-TOTPLT
      PLTIDL=PLTIDL+PLIDLE
      TOTPLT=VEH(I,1)
  108 CALL PLTIME
      VEH(I,1)=VEH(I,1)+SVCTIM
      TOTPLT=VEH(I,1)
      PLANT=PLANT+SVCTIM
      VEH(I,3)=2
C IF PASSING IS ALLOWED, CALL TABLE. IF NOT, CARRY HAUL UNIT THROUGH
C TRAVEL EVENT
      IF(PASCHK .EQ. 1)GO TO 10
      GO TO 155
C SURGE BIN LOADING USED.
  150 CALL SRGBIN
      VEH(I,3)=2
      IF(PASCHK .EQ. 1)GO TO 10
C NO PASSING ON HAUL ROUTE.
  155 ITRVL=1
      CALL TRVLTM
      VEH(I,1)=VEH(I,1)+TRAVEL
C  IF THE HAUL UNIT EXPERIENCES AN EXTERNAL DELAY, IT CAN BE PASSED.
C  OTHERWISE, UNDER CONDITION OF NO PASSING, UNIT MAYCAUSE FOLLOWING
C  UNITS TO BE SLOWED, AND IT IN TURN  MAY BE SLOWED BY A PRECEDING
C  UNIT
      IF(TRVDLY .EQ. 0.)GO TO 160
      VEH(I,3)=3
      VEH(I,9)=VEH(I,9)+TRVTIM
      GO TO 10
C CHECK TO SEE IF HAUL UNIT AHEAD OF HAUL UNIT(I) WILL SLOW UNIT(I).
C IF SO, INCREMENT INTERNAL TRAVEL DELAY TIME FOR UNIT.
  160 IF(QUEU1 .LT. VEH(I,1))GO TO 175
      HOLDUP=QUEU1-VEH(I,1)
      VEH(I,7)=VEH(I,7)+HOLDUP
      VEH(I,9)=VEH(I,9)+TRAVEL+HOLDUP
      VEH(I,1)=QUEU1
      GO TO 180
  175 QUEU1=VEH(I,1)
      VEH(I,9)=VEH(I,9)+TRAVEL
  180 VEH(I,3)=3
      GO TO 10
C PASSING IS ALLOWED. COMPUTE TRAVEL TIME.
  200 ITRVL=1
      CALL TRVLTM
      VEH(I,1)=VEH(I,1)+TRAVEL
      VEH(I,3)=3
      VEH(I,9)=VEH(I,9)+TRVTIM
      GO TO 10
C PAVER ROUTINE
C  CHECK TO SEE IF ONE OR TWO PAVERS USED
  300 IF(NRPVR .EQ. 2)GO TO 350
C  ONE PAVER USED
C STORE PIPELINE DELAY.
      IF(PAVER .EQ. 0.)PIPLIN=VEH(I,1)
C  CHECK TO SEE IF WINDROWING IS USED
      IF(WNDROW .EQ. 0)GO TO 3005
```

```
      CALL WINDRO
      GO TO 315
C  CHECK TO SEE IF TRAVELING SURGE IS TO BE USED
 3005 IF(ITVLSG .EQ. 0) GO TO 3010
      CALL TRVSRG
      GO TO 315
 3010 CALL PVRTIM
      VEH(I,1)=VEH(I,1)+XMNVR1
C  CHECK TO SEE IF PAVER IS OCCUPIED
      IF(VEH(I,1)-PAVER)301,307,305
C PAVER IS OCCUPIED. INCREMENT HAUL UNIT PAVER IDLE TIME.
  301 TRKIDL=PAVER-VEH(I,1)
      VEH(I,5)=VEH(I,5)+TRKIDL
      VEH(I,1)=PAVER
      GO TO 307
C PAVER IS UNOCCUPIED. INCREMENT PAVER IDLE TIME.
  305 PRIDLE=VEH(I,1)-PAVER
      PVRIDL=PVRIDL+PRIDLE
      PAVER=VEH(I,1)
C DETERMINE TIME AT PAVER INCLUDING EXTERNAL DELAYS AND MANEUVER TIMES.
  307 PAVER=VEH(I,1)+PAVERT
      VEH(I,1)=VEH(I,1)+TIMPVR
C INCREMENT HAUL AND RETURN DISTANCES BY AMOUNT LAID.
  315 HAULX=HAULX+XLNGTH
      HAULY=HAULY+XLNGTH
      GO TO 390
C  TWO PAVERS USED
C  STORE PIPELINE DELAY
  350 IF(PAVER1 .EQ. 0. .AND. PAVER2 .EQ. 0.)PIPLIN=VEH(I,1)
C  CHECK TO SEE IF WINDROWING IS USED
      IF(WNDROW .EQ. 0)GO TO 360
C  WINDROWING USED. DIRECT HAUL UNIT TO PAVER WITH LEAST WINDROW TIME.
      IF(WRTIM1 .GT. WRTIM2)GO TO 355
      WRTIME=WRTIM1
      WRLDS=WRLDS1
      PAVER=PAVER1
      PVRIDL=PVIDL1
      CALL WINDRO
      WRTIM1=WRTIME
      WRLDS1=WRLDS
      PAVER1=PAVER
      PVIDL1=PVRIDL
      GO TO 380
  355 WRTIME=WRTIM2
      WRLDS=WRLDS2
      PAVER=PAVER2
      PVRIDL=PVIDL2
      CALL WINDRO
      WRTIM2=WRTIME
      WRLDS2=WRLDS
      PAVER2=PAVER
      PVIDL2=PVRIDL
      GO TO 380
C  HAUL UNITS DISCHARGING INTO PAVERS
C  DIRECT HAUL UNIT TO PAVER WITH SHORTEST QUEUE
  360 IF(PAVER2 .LE. PAVER1)GO TO 370
C  HAUL UNIT DIRECTED TO PAVER 1
      CALL PVRTIM
      VEH(I,1)=VEH(I,1)+XMNVR1
      IF(VEH(I,1)-PAVER1)361,367,365
C  PAVER IS OCCUPIED - INCREMENT HAUL UNIT PAVER IDLE TIME
```

```
  361 TRKIDL=PAVER1-VEH(I,1)
      VEH(I,5)=VEH(I,5)+TRKIDL
      VEH(I,1)=PAVER1
      GO TO 367
C  PAVER IS UNOCCUPIED - INCREMENT PAVER IDLE TIME
  365 PRIDLE=VEH(I,1)-PAVER1
      PVIDL1=PVIDL1+PRIDLE
      PAVER1=VEH(I,1)
C  DETERMINE TIME AT PAVER
  367 PAVER1=VEH(I,1)+PAVERT
      VEH(I,1)=VEH(I,1)+TIMPVR
      GO TO 380
C  HAUL UNIT DIRECTED TO PAVER 2
  370 CALL PVRTIM
      VEH(I,1)=VEH(I,1)+XMNVR1
      IF(VEH(I,1)-PAVER2)371,377,375
C  PAVER IS OCCUPIED - INCREMENT HAUL UNIT PAVER IDLE TIME
  371 TRKIDL=PAVER2-VEH(I,1)
      VEH(I,5)=VEH(I,5)+TRKIDL
      VEH(I,1)=PAVER2
      GO TO 377
C  PAVER IS UNOCCUPIED - INCREMENT PAVER IDLE TIME
  375 PRIDLE=VEH(I,1)-PAVER2
      PVIDL2=PVIDL2+PRIDLE
      PAVER2=VEH(I,1)
C  DETERMINE TIME AT PAVER
  377 PAVER2=VEH(I,1)+PAVERT
      VEH(I,1)=VEH(I,1)+TIMPVR
C  INCREMENT HAUL AND RETURN DISTANCES BY AMOUNT LAID
  380 HAULX=HAULX+XLNGTH/2.
      HAULY=HAULY+XLNGTH/2.
C  INCREMENT NUMBER OF LOADS HAULED
  390 NLOADS=NLOADS+1
C  INCREMENT HAUL UNIT CYCLES
      VEH(I,8)=VEH(I,8)+1.
      VEH(I,3)=4
C IF PASSING IS ALLOWED, CALL TABLE. IF NOT, CARRY HAUL UNIT THROUGH
C RETURN TRAVEL EVENT.
      IF(PASCHK .EQ. 1)GO TO 10
C NO PASSING ON HAUL ROUTE.
      ITRVL=2
      CALL TRVLTM
      VEH(I,1)=VEH(I,1)+TRAVEL
C  IF THE HAUL UNIT EXPERIENCES AN EXTERNAL DELAY, IT CAN BE PASSED.
C  OTHERWISE, UNDER CONDITION OF NO PASSING, UNIT MAYCAUSE FOLLOWING
C  UNITS TO BE SLOWED, AND IT IN TURN  MAY BE SLOWED BY A PRECEDING
C  UNIT
      IF(TRVDLY .EQ. 0.)GO TO 392
      VEH(I,3)=1
      VEH(I,9)=VEH(I,9)+TRVTIM
      GO TO 10
C CHECK TO SEE IF HAUL UNIT AHEAD OF HAUL UNIT(I) WILL SLOW UNIT(I). IF
C SO, INCREMENT INTERNAL TRAVEL DELAY TIME FOR UNIT.
  392 IF(QUEU2 .LT.  VEH(I,1))GO TO 394
      HOLDUP=QUEU2-VEH(I,1)
      VEH(I,7)=VEH(I,7)+HOLDUP
      VEH(I,9)=VEH(I,9)+TRAVEL+HOLDUP
      VEH(I,1)=QUEU2
      GO TO 396
  394 QUEU2=VEH(I,1)
      VEH(I,9)=VEH(I,9)+TRAVEL
```

```
  396 VEH(I,3)=1
      GO TO 10
C PASSING IS ALLOWED.
C RETURN TRAVEL TIME
  400 ITRVL=2
      CALL TRVLTM
      VEH(I,1)=VEH(I,1)+TRAVEL
      VEH(I,3)=1
      VEH(I,9)=VEH(I,9)+TRVTIM
      GO TO 10
C ROUTINE TO HANDLE HAUL UNITS IN SYSTEM AT END OF SHIFT.
  500 NVC=0
      DO 510 IC=1,N
      IF(VEH(IC,3) .EQ. 2. .OR. VEH(IC,3) .EQ. 3.) GO TO 510
      VEH(IC,3)=9.
      NVC=NVC+1
      IF(NVC .EQ. N)GO TO 600
  510 CONTINUE
      GO TO 11
  600 IF(WNDROW .EQ. 0)GO TO 608
C  ROUTINE FOR RUNNING LOADS REMAINING IN WINDROW THROUGH PAVER
  601 IF(WRLDS .EQ. 0)GO TO 608
      I=51
      VEH(I,1)=1000.
      CALL WINDRO
      GO TO 601
C SHIFT IS COMPLETED. CALCULATE OUTPUT DATA.
C PLANT EFFICIENCY
  608 PLTPCT=(PLANT-PLTDLY)*100./TOTPLT
      PLTIDL=(TOTPLT-PLANT)*100./TOTPLT
      PLTDLY=PLTDLY*100./TOTPLT
C PAVER EFFICIENCY
      IF(NRPVR .EQ.1)GO TO 610
      PAVER=PAVER1+PAVER2
      PVRIDL=PVIDL1+PVIDL2
      PIPLIN=PIPLIN*2.
  610 PVRPCT=(PAVER-PVRDLY-PVRIDL)*100./(PAVER-PIPLIN)
      PVRIDL=(PVRIDL-PIPLIN)*100./(PAVER-PIPLIN)
      PVRDLY=PVRDLY*100./(PAVER-PIPLIN)
C  DETERMINE HAUL UNIT PERFORMANCE
      SUM=0.
      SUM1=0.
      SUM2=0.
      SUM3=0.
      SUM4=0.
      SUM5=0.
      SUM6=0.
      DO 615K=1,N
      SUM=SUM+VEH(K,1)
      SUM1=SUM1+VEH(K,6)
      SUM2=SUM2+VEH(K,4)
      SUM3=SUM3+VEH(K,5)
      SUM4=SUM4+VEH(K,9)
      SUM5=SUM5+VEH(K,7)
  615 SUM6=SUM6+VEH(K,8)
      XN=N
      VEHPCT=(SUM-(SUM1+SUM2+SUM3+SUM5))*100./SUM
      VEHDLY=SUM1*100./SUM
      VEHPLT=SUM2*100./SUM
      VEHPVR=SUM3*100./SUM
      VINDLY=SUM5*100./SUM
```

```
      VTRVTM=SUM4*100./SUM
C EXPRESS TIMES IN HOURS.
      IF(NRPVR .EQ.1)GO TO 620
      TOTHRS=PAVER/120.
      PLNTHR=PLANT/60.
      PVRHRS=(PAVER-PIPLIN)/120.
      GO TO 625
  620 TOTHRS=PAVER/60.
      PLNTHR=PLANT/60.
      PVRHRS=(PAVER-PIPLIN)/60.
C DETERMINE PRODUCTION
C MILES AND TONS LAID
  625 XLDS=NLOADS
      XMILES=ABS(HAUL1-HAULX)
      IF(IDOP .EQ.0)XMILES=FTPRLD/5280.*XLDS
      TONS=XLDS*XLDWGT/2000.
C DETERMINE TONS LAID PER HOUR
      TNSPHR=TONS/TOTHRS
C DETERMINE TOTAL COSTS
      CSTPLT=PLNTHR*PLTCST
      IF(NRPVR .EQ. 1)CSTPVR=PVRHRS*PVRCST
      IF(NRPVR .EQ. 2)CSTPVR=PVRHRS*PVRCST*2.
      CSTVEH=0.0
      DO 645K=1,N
  645 CSTVEH=CSTVEH+VEHCST*VEH(K,1)/60.
C DETERMINE UNIT COSTS PER TON
      CSTTOT=CSTPLT+CSTPVR+CSTVEH+TONS*CSTMTL
      CSTPTN=CSTTOT/TONS
      IF(HLDATA .EQ. 0)GO TO 766
      IF(JXYZ .NE. 0)GO TO 703
      WRITE(6,995)ITER
  995 FORMAT('1'//////T59,'REPLICATION',I3///
     *                    T43,'HAUL UNIT PERFORMANCES - TIMES ARE IN MINUT
     *ES'///              T29,'HAUL        TOTAL       DELAY       DELAY       TOT
     *AL       TOTAL       TIME      NUMBER'/T29,'UNIT      OPERATING  TIME AT
     * TIME AT  EXTERNAL  INTERNAL   SPENT IN     OF'/T30,'NO          TIME
     *      PLANT       PAVER     DELAYS     DELAYS      TRAVEL    CYCLES'//)
      JXYZ=1
  703 WRITE(6,713)N
  713 FORMAT(' ',T25,I2,' HAUL UNITS OPERATING')
      DO 707I=1,N
      NCYCLS=VEH(I,8)
  707 WRITE(6,747)I,VEH(I,1),(VEH(I,J),J=4,7),VEH(I,9),NCYCLS
  747 FORMAT(' ',T30,I2,F13.2,F9.2,3F10.2,F11.2,I7)
  766 CONTINUE
      WRITE(6,705)
  705 FORMAT(' '//)
      JRPT=JRPT+1
      L=JRPT
      RN=N
      HOLD(L,1)=RN
      HOLD(L,2)=VEHPCT
      HOLD(L,3)=VEHDLY
      HOLD(L,4)=VINDLY
      HOLD(L,5)=VEHPLT
      HOLD(L,6)=VEHPVR
      HOLD(L,7)=VTRVTM
      HOLD(L,8)=PLTPCT
      HOLD(L,9)=PLTDLY
      HOLD(L,10)=PLTIDL
      HOLD(L,11)=PVRPCT
```

```
      HOLD(L,12)=PVRDLY
      HOLD(L,13)=PVRIDL
      HOLD(L,14)=SUM6
      HOLD(L,15)=XMILES
      HOLD(L,16)=TONS
      HOLD(L,17)=TNSPHR
      HOLD(L,18)=CSTPTN
      ZPROD(ITER,L)=HOLD(L,17)
      ZCST(ITER,L)=HOLD(L,18)
      N=N+1
      IF(N .LE. NN)GO TO 3
      WRITE(6,990)ITER
  990 FORMAT('1'///T59,'REPLICATION',I3///
     *                  T44,'SYSTEM PERFORMANCE - TIMES ARE PERCENTS OF T
     *OTAL TIMES'///T33,'AVG     AVG     AVG'/T19,'AVG      AVG      UNIT    UN
     *IT   UNIT'/T5,'NO OF    AVG    UNIT    UNIT    IDLE    IDLE    TIME',
     *T67,'PLANT',T88,'PAVER',T117,'TONS  COST'/T6,'HAUL  UNIT   EXT
     *INT    TIME    TIME     IN    PLANT  PLANT    IDLE  PAVER  PAVER   IDL
     *E  TOTAL  MILES    TONS    PER    PER'/T5,'UNITS    EFF  DELAY  DELAY
     *  PLANT  PAVER  TRAVEL  EFF    DELAY    TIME    EFF    DELAY    TIME  L
     *OADS    LAID     LAID   HOUR    TON')
      DO 777I=1,JRPT
      N=HOLD(I,1)
      NRLDS=HOLD(I,14)
  777 WRITE(6,989)N,(HOLD(I,L),L=2,13),NRLDS,(HOLD(I,L),L=15,18)
  989 FORMAT('0',T6,I3,12(F7.2),I6,F8.2,F8.1,F6.1,F6.2)
      ITER=ITER+1
      IF(ITER .LE. NRITER)GO TO 1
      WRITE(6,825)NRITER
  825 FORMAT('1',14(/),T50,'MEAN COST AND PRODUCTION'//T54,I2,' REPLICAT
     *IONS'//T52,'PRODUCTION            UNIT COST'/T40,'NUMBER OF     TONS
     */HOUR              DOLLARS/TON'/T39,'HAUL UNITS  MEAN  STD DEV   MEAN
     * STD DEV  PCT DEV')
      X=NRITER
      DO 888J=1,JRPT
      SUM1=0.
      SUM2=0.
      DO 885I=1,NRITER
      SUM1=SUM1+ZPROD(I,J)
  885 SUM2=SUM2+ZCST(I,J)
      MNPROD=SUM1/X
      MNCST=SUM2/X
      SUM1=0.
      SUM2=0.
      DO 886I=1,NRITER
      SUM1=SUM1+(ZPROD(I,J)-MNPROD)**2
  886 SUM2=SUM2+(ZCST(I,J)-MNCST)**2
      PRODSD=(SUM1/X)**0.5
      CSTSD=(SUM2/X)**0.5
      CSTPCT=(CSTSD*100.)/MNCST
      N=HOLD(J,1)
  888 WRITE(6,830)N,MNPROD,PRODSD,MNCST,CSTSD,CSTPCT
  830 FORMAT('0',T43,I2,T50,F5.1,T58,F5.2,T66,F5.2,T74,F5.3,T83,F5.2)
      WRITE(6,919)
  919 FORMAT('1')
      STOP
      END
C*********************************************************************
C*********************************************************************
C***************** BLOCK DATA ****************************************
      BLOCK DATA
```

PROGRAM LISTING - CONTINUED

```
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      DATA IX/493332765/,IY/495702389/
      DATA HLDATA/  0/
      DATA NRITER/  1/
      DATA IDEN/'FLBY','/400','/7.5','TRV ','SRG '/
      DATA NMBR1/ 3/,NMBR2/ 3/
      DATA IURBAN/    0/
      DATA SPDLMT/  60./
      DATA PASCHK/  1/
      DATA ISURGE/  1/
      DATA NRPVR/   1/
      DATA NRBTCH/  1/,BTCHWT/ 12000./,XLDWGT/ 45800./
      DATA PVWDTH/  12./,PVDPTH/   4./,PVDNSY/  105./,PVCOMP/  144./
      DATA PLTCST/ 423.90/,PVRCST/ 187.19/,VEHCST/ 22.85/
      DATA SRGCAP/ 200./,SRGAVL/ 0./,SRGXCH/ 0.2/
      DATA CSTMTL/  3.80/,SHIFT/  10./
      DATA WNDROW/  0/,SPREDR/  0/,MXWRLD/  0/,HOOKUP/ 0.0/,UNHOOK/ 0.0/
      DATA PVRATE/23.0/,BCHTIM/0.75/,HAUL1/7.5/,HAUL2/7.5/,IDOP/+1/
      DATA XMAN1/ 0.7/,SDMAN1/ 0.4/,A1/ 0.3/
      DATA XMAN2/ 1.406/,SDMAN2/ 0.627/,A2/ 0.75/
      DATA SPRDMN/ 1.20/,SPRDSD/ 0.2/,ASPRD/ 0.9/
      DATA PVDLMN/1.208/,PVDLSD/ 0.864/,APVDLY/0.500/,DLYPCT/ 83.3/
      DATA PLTMN/ 0.917/,PLTSD/ 0.229/
      DATA TRDLMN/  5.0/,TRDLSD/  10.0/,PTRDLY/  50.0/
      DATA ITVLSG/ 1/,MXSGLD/ 4/
      DATA VEHWGT/ 26100./,VEHHP/ 221./
      END
C**********************************************************************
C**********************************************************************
C****************** SUBROUTINE TABLE ***********************************
C
      SUBROUTINE TABLE
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      TIME=100000
      ZNBR=1.
```

```
      EVENT=1.
      DO 15K=1,N
      IF(VEH(K,3) .EQ. 9.)GO TO 15
      IF(TIME .LE. VEH(K,1))GO TO 15
      TIME=VEH(K,1)
      ZNBR=VEH(K,2)
      EVENT=VEH(K,3)
   15 CONTINUE
      I=ZNBR
      J=EVENT
      RETURN
      END
C*************************************************************************
C*************************************************************************
C***************** SUBROUTINE SCAN ***************************************
C
      SUBROUTINE SCAN
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      EVENT=J
      HELD=10000000.
      IV=100
      DO 25K=1,N
      IF(VEH(K,3) .NE. EVENT)GO TO 25
      IF(VEH(K,1) .GE. HELD)GO TO 25
      HELD=VEH(K,1)
      IV=K
   25 CONTINUE
      RETURN
      END
C ************************************************************************
C ************************************************************************
C ****************** SUBROUTINE BEGIN ************************************
C
      SUBROUTINE BEGIN
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
```

```
C  CALCULATE OR INITIALIZE PARAMETERS
      SRGCAP=SRGCAP*2000.
      XCAP=SRGCAP-BTCHWT
      AVLSRG=SRGAVL*2000.
      SHIFT=SHIFT*60.
      YNB=NRBTCH
      WGTHP=(VEHWGT+XLDWGT)/VEHHP
      EWGTHP=VEHWGT/VEHHP
      DOP=IDOP
C DETERMINE LINEAL FEET OF PAVEMENT PER LOAD
      PDSPFT=PVWDTH*PVDPTH/12.*PVCOMP
      FTPRLD=XLDWGT/PDSPFT
      XLNGTH=FTPRLD/5280.*DOP
      PDSMIN=PVRATE*PDSPFT
      PAVRTM=XLDWGT/PDSMIN
C DETERMINE STARTING NUMBER OF VEHICLES
      DISCHG=PAVRTM+PVDLMN
      XNRPVR=NRPVR
      IF(NRPVR .GT. 1)DISCHG=DISCHG/XNRPVR
      IF(IURBAN .EQ. 1)GO TO 5
      IF(HAUL1 .LE. 1.0)XMVTIM=(HAUL1+HAUL2)/16.75*60.
      IF(HAUL1 .GT. 1. .AND. HAUL1 .LE. 3.)XMVTIM=(HAUL1+HAUL2)/28.5*60.
      IF(HAUL1 .GT. 3. .AND. HAUL1 .LE. 10.)XMVTIM=(HAUL1+HAUL2)/39.2*60
     *.
      IF(HAUL1 .GT. 10. .AND. HAUL1 .LE. 20.)XMVTIM=(HAUL1+HAUL2)/46.3*
     *60.
      IF(HAUL1 .GT. 20.)XMVTIM=(HAUL1+HAUL2)/51.9*60.
      GO TO 9
    5 XMVTIM=(HAUL1+HAUL2)/23.9*60.
    9 CYCLTM=XMVTIM+PLTMN+DISCHG
      IF(NMBR1 .GT. 0)GO TO 68
      XNR1=CYCLTM/PLTMN
      XNR2=CYCLTM/DISCHG
      IF(XNR1 .LE. XNR2)GO TO 10
      NRVEH=XNR2
      GO TO 20
   10 NRVEH=XNR1
   20 IF(ISURGE .EQ. 1)GO TO 50
      NMBR=NRVEH
      IF(NMBR .LE. 0)GO TO 30
      II=NMBR
      GO TO 40
   30 II=1
   40 NN=II+6
      GO TO 70
   50 NMBR=NRVEH
      IF(NMBR .LE. 0)GO TO 60
      II=NMBR
      GO TO 65
   60 II=1
   65 NN=II+6
      GO TO 70
   68 II=NMBR1
      NN=NMBR2
   70 CONTINUE
C  CALCULATE PARAMETERS FOR PLANT AND PAVER
      ZZ=NRBTCH
      PLTMN=PLTMN/ZZ
      PLTSD=(PLTSD**2/ZZ**2)**0.5
      APLT=BCHTIM
      SIGX2=(PLTSD/(PLTMN-APLT))**2+1.
```

PROGRAM LISTING - CONTINUED

```
      SIGXSQ=ALOG(SIGX2)
      PLTSD=SIGXSQ**0.5
      PLTMN=ALOG(PLTMN-APLT)-SIGXSQ/2.
      SIGX2=(PVDLSD/(PVDLMN-APVDLY))**2+1.
      SIGXSQ=ALOG(SIGX2)
      PVDLSD=SIGXSQ**0.5
      PVDLMN=ALOG(PVDLMN-APVDLY)-SIGXSQ/2.
      DLYPCT=DLYPCT*10.
C  CALCULATE PARAMETERS FOR HAUL UNIT MANEUVERS AT PAVER
      SIGX2=(SDMAN1/(XMAN1-A1))**2+1.
      SIGXSQ=ALOG(SIGX2)
      SDMAN1=SIGXSQ**0.5
      XMAN1=ALOG(XMAN1-A1)-SIGXSQ/2.
      SIGX2=(SDMAN2/(XMAN2-A2))**2+1.
      SIGXSQ=ALOG(SIGX2)
      SDMAN2=SIGXSQ**0.5
      XMAN2=ALOG(XMAN2-A2)-SIGXSQ/2.
      IF(WNDROW .EQ. 0 .AND. ITVLSG .EQ. 0) GO TO 100
      SIGX2=(SPRDSD/(SPRDMN-ASPRD))**2+1.
      SIGXSQ=ALOG(SIGX2)
      SPRDSD=SIGXSQ**0.5
      SPRDMN=ALOG(SPRDMN-ASPRD)-SIGXSQ/2.
C  CALCULATE PARAMETERS FOR HAUL UNIT EXTERNAL DELAYS
  100 SIGX2=(TRDLSD/TRDLMN)**2+1.
      SIGXSQ=ALOG(SIGX2)
      TRDLSD=SIGXSQ**0.5
      TRDLMN=ALOG(TRDLMN)-SIGXSQ/2.
      PTRDLY=PTRDLY*.005
      RETURN
      END
C***************************************************************************
C***************************************************************************
C****************** SUBROUTINE PLTIME *************************************
C
      SUBROUTINE PLTIME
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      SVCTIM=0.0
      DLYPLT=0.0
      KBATCH=0
      DO 50IPL=1,NRBTCH
      JBATCH=JBATCH+1
      KBATCH=KBATCH+1
      CALL NORMAL
      TMBTCH=APLT+EXP(PLTMN+PLTSD*V)
      DELAY=TMBTCH-BCHTIM
      DLYPLT=DLYPLT+DELAY
      SVCTIM=SVCTIM+TMBTCH
      IF(ISURGE .EQ. 0)GO TO 50
```

```
      SRGAVL=SRGAVL+BTCHWT
      IF(SRGAVL .GE. XCAP)GO TO 55
   50 CONTINUE
   55 PLTDLY=PLTDLY+DLYPLT
   80 RETURN
      END
C*********************************************************************
C*********************************************************************
C***************** SUBROUTINE SRGBIN *********************************
C
      SUBROUTINE SRGBIN
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      TIME=(XLDWGT/1000.)/60.
      IF(VEH(I,1) .GE. SURGE)GO TO 10
      VIDLE=SURGE-VEH(I,1)
      VEH(I,4)=VEH(I,4)+VIDLE
      SURGE=SURGE+SRGXCH
      VEH(I,1)=SURGE
   10 IF(SRGAVL .GE. XLDWGT)GO TO 80
      IF(VEH(I,1) .LE. TOTPLT)GO TO 50
      TIMDIF=VEH(I,1)-TOTPLT
      NRBTCH=TIMDIF/BCHTIM+1.
      CALL PLTIME
      PLANT=PLANT+SVCTIM
      IF(SRGAVL .GE. XCAP)GO TO 30
      TOTPLT=TOTPLT+SVCTIM
      GO TO 10
   30 TOTPLT=VEH(I,1)
      IF(TOTPLT .GE. PLANT)GO TO 80
      TOTPLT=PLANT
      GO TO 80
   50 DIFF=XLDWGT-SRGAVL
      NRBTCH=DIFF/BTCHWT+1.
      CALL PLTIME
      PLANT=PLANT+SVCTIM
      TOTPLT=TOTPLT+SVCTIM
      SURGE=TOTPLT+0.25
      VIDLE=SURGE-(VEH(I,1)+TIME)
      VEH(I,4)=VEH(I,4)+VIDLE
      VEH(I,1)=SURGE
      GO TO 90
   80 VEH(I,1)=VEH(I,1)+TIME
      SURGE=VEH(I,1)
   90 SRGAVL=SRGAVL-XLDWGT
      RETURN
      END
C*********************************************************************
C*********************************************************************
```

```
C****************** SUBROUTINE TRVLTM ***********************************
C
      SUBROUTINE TRVLTM
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      IF(IURBAN .EQ. 1)GO TO 110
      IF(ITRVL .EQ. 2)GO TO 20
      X=HAULX
      CALL NORMAL
      IF(X .GT. 1.0)GO TO 10
      Z=2.3*(1.1081+.2111*X+.0995*V)
      SPEED=EXP(Z)
      GO TO 70
   10 IF(X .GT. 3.0)GO TO 15
      Z=2.3*(1.5126+.0433*X-.000763*WGTHP+.2870*V)
      SPEED=EXP(Z)
      GO TO 70
   15 SPEED=70.433+15.7435*ALOG10(X)-20.5937*ALOG10(WGTHP)+2.4763*V
      GO TO 70
   20 X=HAULY
      CALL NORMAL
      IF(X .GT. 3.0)GO TO 30
      Z=2.3*(1.6688+.3639*ALOG10(X)-.164*ALOG10(EWGTHP)+.3046*V)
      SPEED=EXP(Z)
      GO TO 70
   30 Z=2.3*(1.3767+.2847*ALOG10(X)+.0883*V)
      SPEED=EXP(Z)
   70 IF(SPEED .GT. SPDLMT)SPEED=SPDLMT
      TRVTIM=(X*60.)/SPEED
C   DETERMINE IF DELAY IS TO BE GENERATED
      CALL RANDU
      IF(YFL .GT. PTRDLY)GO TO 75
      CALL NORMAL
      TRVDLY=EXP(TRDLMN+TRDLSD*V)
      GO TO 80
   75 TRVDLY=0.
   80 VEH(I,6)=VEH(I,6)+TRVDLY
      TRAVEL=TRVTIM+TRVDLY
      RETURN
  110 CALL NORMAL
      IF(ITRVL .EQ. 2)GO TO 120
      X=HAULX
      Z=2.3*(1.17333+.21751*ALOG10(X)+.09860*V)
      SPEED=EXP(Z)
      GO TO 130
  120 X=HAULY
      Z=2.3*(1.34004+.09312*ALOG10(X)+.11170*V)
      SPEED=EXP(Z)
  130 IF(SPEED .GT. SPDLMT)SPEED=SPDLMT
```

```
      TRVTIM=(X*60.)/SPEED
      TRVDLY=0.
      TRAVEL=TRVTIM+TRVDLY
      RETURN
      END
C**********************************************************************
C**********************************************************************
C****************** SUBROUTINE PVRTIM **********************************
C
      SUBROUTINE PVRTIM
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
C  DETERMINE PAVER TIME
      CALL RANDU
      XMM=1000.*YFL
      IF(XMM .GE. DLYPCT)GO TO 25
      CALL NORMAL
      PVDLTM=APVDLY+EXP(PVDLMN+PVDLSD*V)
      GO TO 30
   25 PVDLTM=0.0
   30 CONTINUE
      PAVERT=PAVRTM+PVDLTM
      PVRDLY=PVRDLY+PVDLTM
      IF(ITVLSG .EQ. 1) GO TO 75
C  DETERMINE HAUL UNIT MANEUVER TIMES AT PAVER
      CALL NORMAL
      XMNVR1=A1+EXP(XMAN1+SDMAN1*V)
      CALL NORMAL
      XMNVR2=A2+EXP(XMAN2+SDMAN2*V)
   70 TIMPVR=PAVRTM+XMNVR2
   75 RETURN
      END
C**********************************************************************
C**********************************************************************
C****************  SUBROUTINE WINDRO ***********************************
      SUBROUTINE WINDRO
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
```

```
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      IF(VEH(I,1)-WRTIME)10,15,15
   10 TRKIDL=WRTIME-VEH(I,1)
      VEH(I,5)=VEH(I,5)+TRKIDL
      VEH(I,1)=WRTIME
   15 IF(SPREDR .EQ. 0)GO TO 20
      VEH(I,1)=VEH(I,1)+HOOKUP
   20 WRTIME=VEH(I,1)
   25 IF(WRLDS .EQ. 0)GO TO 40
      IF(PAVER .GE. WRTIME)GO TO 30
      CALL PVRTIM
      PAVER=PAVER+PAVERT
      WRLDS=WRLDS-1
      GO TO 25
   30 IF(WRLDS .LT. MXWRLD)GO TO 50
      CALL PVRTIM
      PAVER=PAVER+PAVERT
      WRLDS=WRLDS-1
      IF(VEH(I,1) .GE. PAVER)GO TO 30
      TRKIDL=PAVER-VEH(I,1)
      VEH(I,5)=VEH(I,5)+TRKIDL
      VEH(I,1)=PAVER
      GO TO 30
   40 IF(I .EQ. 51)GO TO 70
      IF(PAVER .GE. WRTIME)GO TO 50
      PRIDLE=WRTIME-PAVER
      PVRIDL=PVRIDL+PRIDLE
      PAVER=WRTIME
   50 CALL NORMAL
      SPRDTM=ASPRD+EXP(SPRDMN+SPRDSD*V)
      VEH(I,1)=VEH(I,1)+SPRDTM
      IF(SPREDR .EQ. 0)GO TO 60
      VEH(I,1)=VEH(I,1)+UNHOOK
   60 WRLDS=WRLDS+1
      WRTIME=VEH(I,1)
   70 RETURN
      END
C ***************************************************************************
C ***************************************************************************
C ******************SUBROUTINE TRVSRG ****************************************
      SUBROUTINE TRVSRG
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      IF(VEH(I,1) .GE. TRSRG1)GO TO 5
      IF(VEH(I,1) .GE. TRSRG2)GO TO 6
      IF(VEH(I,1) .GE. TRSRG3)GO TO 7
      IF(TRSRG1 .LE. TRSRG2)GO TO 1
      IF(TRSRG2 .GT. TRSRG3)GO TO 3
      TRKIDL=TRSRG2-VEH(I,1)
```

```
      VEH(I,1)=TRSRG2
      VEH(I,5)=VEH(I,5)+TRKIDL
    6 ITRSRG=2
      GO TO 20
    1 IF(TRSRG1 .GT. TRSRG3)GO TO 3
      TRKIDL=TRSRG1-VEH(I,1)
      VEH(I,1)=TRSRG1
      VEH(I,5)=VEH(I,5)+TRKIDL
    5 ITRSRG=1
      GO TO 20
    3 TRKIDL=TRSRG3-VEH(I,1)
      VEH(I,1)=TRSRG3
      VEH(I,5)=VEH(I,5)+TRKIDL
    7 ITRSRG=3
   20 CALL NORMAL
      XMNVR1=A1+EXP(XMAN1+SDMAN1*V)
      VEH(I,1)=VEH(I,1)+XMNVR1
   25 IF(LDSRG .EQ. 0)GO TO 30
      IF(LDSRG .LT. MXSGLD .AND. PAVER .GE. VEH(I,1))GO TO 40
      CALL PVRTIM
      PAVER=PAVER+PAVERT
      LDSRG=LDSRG-1
      GO TO 25
   30 IF(PAVER .GE. VEH(I,1))GO TO 40
      PRIDLE=VEH(I,1)-PAVER
      PVRIDL=PVRIDL+PRIDLE
      PAVER=VEH(I,1)
   40 CALL NORMAL
      SPRDTM=ASPRD+EXP(SPRDMN+SPRDSD*V)
      VEH(I,1)=VEH(I,1)+SPRDTM
      LDSRG=LDSRG+1
      IF(ITRSRG .EQ. 1)TRSRG1=VEH(I,1)
      IF(ITRSRG .EQ. 2)TRSRG2=VEH(I,1)
      IF(ITRSRG .EQ. 3)TRSRG3=VEH(I,1)
      CALL NORMAL
      XMNVR2=A2+EXP(XMAN2+SDMAN2*V)
      VEH(I,1)=VEH(I,1)+XMNVR2
      RETURN
      END
C***********************************************************************
C***********************************************************************
C****************** SUBROUTINE RANDU ***********************************
      SUBROUTINE RANDU
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      COMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      COMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      COMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      IX=IX*65539
      IY=IY*262147
      YFL= .4656613E-9*FLOAT(IABS(IX+IY))
      RETURN
```

```
      END
C ***********************************************************************
C ***********************************************************************
C *****************SUBROUTINE NORMAL **************************************
      SUBROUTINE NORMAL
      INTEGER PASCHK,WNDROW,SPREDR,WRLDS,WRLDS1,WRLDS2,HLDATA
      CCMMON AVLSRG,SPRDMN,SPRDSD,ASPRD,IDEN(5),HLDATA,IURBAN,VEHWGT,
     *VEHHP,WGTHP,EWGTHP,TOTPLT,PAVR,HOLD(10,18),TRDLMN,TRDLSD,IDOP,
     *DLYPCT,PVDLTM,XMNVR1,WRTIM1,WRTIM2,WRLDS1,WRLDS2,PVDLMN,PVDLSD,
     *APVDLY,PTRDLY,ITER,NRITER,PVRMN,PVRSD,APVR,PLTMN,PLTSD,APLT,
     *NMBR1,NMBR2,WNDROW,SPREDR,XMAN1,XMAN2,SDMAN1,SDMAN2,A1,A2,WRLGTH,
     *WRTIME,MXWRLD,PVRIDL,WRLDS,SPRDTM,HOOKUP,UNHOOK,V,VEH(51,10),IV
      CCMMON XDLY1,XDLY2,CYCLTM,PAVER,WRMAX,SPDLMT,NRBTCH,BTCHWT,BCHTIM,
     *SVCTIM,PLTDLY,PAVRTM,TIMPVR,PVRDLY,PVRATE,PVWDTH,PVDPTH,PVDNSY,
     *PAVERT,XLNGTH,FTPRLD,HAULX,HAULY,II,NN,IX,IY,YFL,SHIFT,PASCHK,
     *TRAVEL,HAUL1,HAUL2,PLTCST,SRGCST,ITRVL,PVRCST,VEHCST,XLDWGT,SURGE,
     *SRGCAP,SRGAVL,ISURGE,JBATCH,XSRG,PLTIDL,SRGXCH,PVCOMP,CSTMTL,I,J,
     *PLANT,XCAP,N,PAVER1,PAVER2,NRPVR,PVIDL1,PVIDL2,TRVDLY,TRVTIM
      CCMMON MXSGLD,LDSRG,TRSRG1,TRSRG2,TRSRG3,ITVLSG
      CALL RANDU
      R1=YFL
      CALL RANDU
      R2=YFL
      V=(-2.0*ALOG(R1))**0.5*COS(6.283*R2)
      RETURN
      END
```

APPENDIX II

COMPILATION OF OWNING AND OPERATING COSTS

FOR BASIC SYSTEMS PLANT AND PAVER SPREADS

Plant Size: 200 TPH

6,000 Pounds Maximum Batch Size

Assumptions:

10 hour shift
100 working days per year
10 year plant life
5 year surge bin life
No salvage value
Investment cost 16% of average value
Plant 80% efficient without surge
Plant 100% efficient with surge

I. MATERIALS COST

Mix Design: 37.6% Sand
56.4% Stone
6.0% Asphalt

Sand:

40% sand, 10% moisture, and 5% stockpile loss
Delivered cost = $2.10/ton

37.6% x $2.10 =	$0.79	
Loss = 15% x $0.79 =	0.12	
	$0.91	$0.91

Stone:

60% stone, 6% moisture, and 5% stockpile loss
Delivered cost = $2.50/ton

56.4% x $2.50 =	$1.41	
Loss = 11% x $1.41 =	0.16	
	$1.57	$1.57

Asphalt:

6% of 85-100 pen AC
Delivered cost = $22.00/ton

6% x $22.00 =	$1.32
TOTAL COST	$3.80/ton

II. PLANT COST

Basic Plant

Purchase price (includes all accessories), F.O.B.	$330,000
Freight	3,040
Tax	13,322
	$346,362

Surge Bin (100 Ton)

Purchase price, F.O.B.	$70,000
Freight	1,088
Tax	2,844
	$73,932

Owning and Operating Costs

Plant:

$$\text{Depreciation} = \frac{\$346,362}{10,000 \text{ hours}} = \$34.64/\text{hour}$$

Maintenance and repair - assume 80% of depreciation
$34.64 x 0.80 = $27.72/hour

Investment costs - average value of plant with 10-year life is 55% of total cost F.O.B. the job

$$\frac{0.55 \times \$346,362 \times 0.16}{1,000} = \$30.45/\text{hour}$$

Sum of owning and operating costs less energy cost =
$34.64 x $27.72 x $30.45 = $92.81/hour

Surge Bin:

$$\text{Depreciation} = \frac{\$73,932}{5,000 \text{ hours}} = \$14.78/\text{hour}$$

Maintenance and repair - assume 100% of depreciation =
$14.78/hour

Investment costs - average value of surge bin with 5-year life is 60% of total cost F.O.B. the job

$$\frac{0.60 \times \$73,932 \times 0.16}{1,000} = \$7.10/\text{hour}$$

Sum of owning and operating costs less energy cost =
$14.78 + $14.78 + $7.10 = $36.66/hour

Other Equipment:

Front loader -	1 at	$21.59/hour
Pick-up trucks -	1½* at	$7.48/hour
		$29.07

*1 pick-up floating between plant and road

Energy:

Dryer fuel = cost x production x efficiency

$0.175 x 200 TPH x 0.80 : w/o storage	$28.00/hour
$0.175 x 200 TPH x 1.0 : w/storage	$35.00/hour

Electricity = cost x HP x 0.75

$0.015 x 329.5 x 0.75 : w/o storage	$3.71/hour
$0.015 x 379.5 x 0.75 : w/storage	$3.98/hour

Asphalt heater fuel

200 TPH x $0.055/hour	$11.00/hour

Recapitulation

w/o storage	w/storage
$28.00	$35.00
3.71	3.98
11.00	11.00
$42.71/hour	$49.98/hour

Labor:

Includes overtime, social security, and workman's compensation

Plant operator (also superintendent) - 1 at	$8.00/hour
Laborer - 1 at	$5.00/hour
Front loader operator - 1 at	$6.50/hour
	$19.50

Move-in Cost:

Pro-rated over 1 year on an hourly basis

w/o storage - $4,800/1,000 =	$4.80 hour
w/storage - $5,000/1,000 =	$5.00/hour

Plant Summary

	w/o storage	w/storage
Owning Cost	$92.81	$129.47
Other Equipment	29.07	29.07
Energy	42.71	49.98
Labor	19.50	21.41
Move-in	4.80	5.00
	$188.89/hour	$234.93/hour

III. PAVER COST

Equipment (hourly owning and operating costs):

1 Paver	$22.21
3 Rollers (1 breakdown & 2 pneumatic)	33.64
1 Asphalt distributor	8.95
1 Lube truck	7.83
1½ Pick-ups	7.48
1 Broom	6.88
	$86.99

Labor (hourly):

1 Foreman	$8.00
1 Paver operator	6.50
3½ Drivers	17.50
1 Broom operator	5.00
3 Roller operators	16.50
	$53.50

Total Cost w/o Windrow	$140.49/hour
Windrow Equipment (hourly cost):	
1 Ko-Cal feeder	$2.27
1 Spreader box	$0.45
Total Cost w/Windrow	$143.21/hour

Plant Size: 400 TPH

12,000 lbs. Maximum Batch Size

Plant Cost:

Cost/Hour

	Without Storage	With Storage
Ownership	$215.25	$252.25
Labor	37.50	37.50
Energy	48.21	56.75
Equipment	51.22	51.22
Move-in	8.15	8.65
Total	$360.33	$406.37

Paver Cost:

Cost/Hour

	Without Windrow	With Windrow
Paving train	$101.19	$103.91
Labor	51.00	51.00
Total	$152.19	$154.91

Plant Size: 600 TPH

15,000 lbs. Maximum Batch Size

Plant Cost:

Cost/Hour

	Without Storage	With Storage
Ownership	$264.74	$300.45
Labor	51.00	51.00
Energy	53.66	63.49
Equipment	134.99	134.99
Move-in	9.20	9.70
Total	$513.59	$559.63

Paver Cost:

Cost/Hour

	Without Windrow	With Windrow
Paving train	$101.24	$103.96
Labor	61.00	61.00
Total	$162.24	$164.96

Plant Size: 1000 TPH

Plant Cost:

Cost/Hour

	Without Storage	With Storage
Ownership	$304.19	$339.90
Labor	67.00	67.00
Energy	70.00	79.83
Equipment	151.70	151.70
Move-in	12.55	13.05
Total	$605.44	$651.48

Paver Cost:

Cost/Hour

	Without Windrow	With Windrow
Paving train	$103.94	$106.66
Labor	52.00	52.00
Total	$155.94*	$158.66*

*Per each paver used

Plant Size: 1000 TPH (Screenless, Continuous-Mix)

30,000 lbs. Maximum Batch Size

Plant Cost:

Cost/Hour

	Without Storage	With Storage
Ownership	$172.75	$208.46
Labor	67.00	67.00
Energy	70.00	79.83
Equipment	151.70	151.70
Move-in	12.55	13.05
Total	$474.00	$520.04

Paver Cost: Same as for conventional 1000 TPH Plant

APPENDIX III

FORMS FOR RECORDING PLANT AND PAVER OBSERVATIONS

Page _____ of _____

PLANT DATA

JOB:

PLANT: OWNER ______________________ MANUFACTURER _____________ RATED CAPACITY _________

DATE:

HAUL DISTANCE: START _____________________ FINISH __________________________

NO. VEHICLES HAULING ____________________

SHIFT DURATION ____________________________ FILM: SECONDS/FRAME _______________

TRUCK #	ARRIVE IN QUEUE (1)	BEGIN LOADING (2)	COMPLETE LOADING (3)	TIME IN QUEUE (4)	LOADING TIME (5)	TIME BETWEEN ARRIVALS (6)	RUN TIME (7)			

FORM FOR PLANT DATA

INSTRUCTIONS FOR COMPLETING PLANT FORM

Entries (1), (2) and (3) completed in field or from film.

(1) Vehicle arrives in queue when it has come to a standstill.

(2) Vehicle begins loading sequence when front bumper passes beneath discharge chute; if there is no queue, (1) and (2) will be identical.

(3) Vehicle completes loading when rear bumper clears discharge chute.

(4) Time in queue = (2) - (1).

(5) Loading time = (3) - (2).

(6) Time between arrivals = (1)j - (1)i (i-preceding; j-succeeding).

(7) Run time = (1)j - (3)i for the same vehicle.

Page ________ of ________

PAVER DATA

JOB:

DATE:

PAVER OWNER ____________________ MAKE & MODEL ____________________ RATED CAPACITY ____________

LAYDOWN DIMENSIONS: WIDTH ____________________ DEPTH ______________________________

STATION NUMBER: START ______________________ FINISH ______________________________

FILM: SECONDS/FRAME ______________

TRUCK #	ARRIVE AT QUEUE (1)	BEGIN MANEUVER INTO PAVER (2)	BEGIN DISCHARGE TO PAVER (3)	COMPLETE DISCHARGE (4)	DEPART PAVER (5)	TIME IN QUEUE (6)	FIRST MANEUVER TIME (7)	DISCHARGE TIME (8)	SECOND MANEUVER TIME (9)	TIME BETWEEN ARRIVAL (10)

FORM FOR PAVER DATA

INSTRUCTIONS FOR COMPLETING PAVER FORM

Entries (1), (2), (3), (4), and (5) completed in field or from film.

(1) Vehicle arrives in queue when its forward motion stops and it is either in line or ready to back into paver or into windrowing position.

(2) Maneuver into paver begins when vehicle begins movement into paver; if there is no waiting line, (2) = (1). If hot-mix is being windrowed, enter time that maneuver into windrowing position begins.

(3) Discharge to paver or windrow begins when truck bed begins to rise or when hot-mix begins to flow.

(4) Discharge is completed when vehicle pulls away from paver or from windrow.

(5) Vehicle departs paver when it passes the midpoint of the paver on its return to the plant.

(6) Time in queue = (2) - (1).

(7) First maneuver time = (3) - (2).

(8) Discharge time = (4) - (3).

(9) Second maneuver time = (5) - (4).

(10) Time between arrivals = (1)j - (1)i; (i-preceding; j-succeeding).

(11) Run time = (1)j - (5)i for the same vehicle.

APPENDIX IV

CONTRACTORS VISITED

THE CONTRACTORS LISTED BELOW WERE VISITED DURING THE COURSE OF THIS PROJECT

BOTH NAPA AND TEXAS A&M UNIVERSITY WISH TO EXPRESS APPRECIATION FOR THEIR COOPERATION

CONTRACTOR	DATE	JOB
Allan Construction Company, Inc. 6959 San Pedro Avenue San Antonio, Texas 78216	October 8, 1971 December 21, 1971	State Highway 6 By-Pass, Bryan, Texas State Highway 6 By-Pass, Bryan, Texas
Arkansas Rock and Gravel Company P. O. Box I Murfreesboro, Arkansas 71958	August 23, 1971 March 16, 1972	U.S. Highway 71, vicinity Mena, Arkansas U.S. Highway 70, vicinity Glenwood, Ark.
Austin Paving Company P. O. Box 1590 Dallas, Texas 75221	April 6, 1972	Urban projects, Dallas, Texas
B & E Construction Company Route 2, Box 201 Corpus Christi, Texas 78409	December 16, 1971	South By-Pass, El Campo, Texas
Dahlstrom Corporation P. O. Box 21007 Dallas, Texas	November 12, 1971	I.H.-10, Gonzalez County, Texas
Heldenfels Brothers P. O. Box 1917 Corpus Christi, Texas 78403	December 17, 1971	Padre Island Drive, Corpus Christi, Texas
Hood & Sons Construction Co., Inc. 3487 Mission Road San Antonio, Texas 78214	June 9, 1971 June 16, 1971	I.H.-10, vicinity Luling, Texas I.H.-10, vicinity Luling, Texas
Jones G. Finke, Inc. P. O. Box 698 Sealy, Texas 77474	November 16, 1972	State Highway 71, vicinity Ellinger, Texas

CONTRACTOR	DATE	JOB
L. H. Bossier, Inc. Alexandria, Louisiana	March 22, 1972	U.S. Highway 171, vicinity Leesville, La.
Mid-State Paving Company P. O. Box 5498 Meridian, Mississippi 39301	August 2, 1971 August 4, 1971 January 13, 1972 March 24, 1972	I.H.-55, vicinity Pickens, Mississippi I.H.-55, vicinity Pickens, Mississippi I.H.-55, vicinity Pickens, Mississippi I.H.-55, vicinity Durant, Mississippi
Motheral Contractors, Inc. P. O. Box 476 Weslaco, Texas 78596	June 9, 1971	I.H.-10, vicinity Luling, Texas
Rio Paving Company P. O. Box 1207 Harlingen, Texas 78550	June 16, 1972	I.H.-10, vicinity Luling, Texas
Texas Bitulithic Company 2121 Irving Boulevard Dallas, Texas 75207	April 7, 1972	Urban projects, Dallas, Texas
T. L. James & Company, Inc. P. O. Box 8 Kenner, Louisiana 70062	January 5, 1972 January 5, 1972 January 7, 1972 January 12, 1972 March 25, 1972 April 18, 1972	I.H.-10 Harrison County, Mississippi I.H.-10, Jackson County, Mississippi I.H.-10, vicinity Lafayette, Louisiana U.S. Highway 61, vicinity Natchez, Miss. U.S. Highway 84, vicinity Washington, Miss. I.H.-55, vicinity Durant, Mississippi
Warren Brothers Company Gulf District P. O. Box 2572 Houston, Texas 77001	July 22, 1971	I.H.-45, Houston, Texas

CONTRACTOR	DATE	JOB
Warren Brothers Company Mississippi District P. O. Box 917 Jackson, Mississippi	August 3, 1971	I.H.-10, vicinity Jackson, Mississippi
Wilson & Sons, Incorporated P. O. Box 13398 New Orleans, Louisiana	January 6, 1972	G.S.A. Parking Lot, New Orleans, Louisiana