A STOCHASTIC APPROACH FOR THE ECONOMIC ANALYSIS OF ASPHALTIC CONCRETE PRODUCTION

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PREFACE

The hot-mix paving contractor has a substantial investment in special purpose equipment per dollar revenue. With the average profit margin of the industry being roughly two percent of the total contract volume, the proper selection of equipment fleet composition and its subsequent efficient utilization is essential for a profitable operation. In order to estimate the most efficient and economical approach to a project, contractors rely mostly on experience and an estimating technique involving mean cycle times, which is not always reliable.

In recent years, simulation models have been developed which can closely approximate the actual performance of a real system. It was the purpose of this thesis to develop a simulation model which can be used to better estimate the production of hot-mix asphaltic concrete under various physical parameters and managerial policies. The model was then used to investigate the effects of various equipment combinations and management policies on the costs of production.

With the data obtained from the various experiments, correlation factors were developed which can be used to adjust conventional estimates to more realistic values. Certain conclusions were drawn concerning the most efficient and economical uses of various capacity equipment. The simulation model and instructions for modifying the program are provided in the appendices of this thesis in the hope that they will prove beneficial to anyone who desires to use them--whether the motive be profit or educational.

I have attempted to recognize and give credit to all sources from which I obtained data and ideas. Any omissions of recognition are unintentional.

I am greatly indebted to the following members of my graduate committee for their criticism, suggestions, and encouragement in the preparation of this study: Professor R. L. Janes, Civil Engineering faculty; Professor P. G. Manke, Civil Engineering faculty; Professor D. S. Ellifritt, Civil Engineering faculty; and Professor T. B. Auer, Industrial Engineering faculty.

Additionally, I am indebted to Professor F. M. Black, Management Sciences faculty who, in addition to serving as a member of my graduate committee, provided invaluable assistance in the actual GPSS programming which saved countless hours of frustration.

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Finally, I must acknowledge the sacrifice and moral support of my wife, Glenna, and my children, Bobby, Kathi, and Tonya. Without their understanding and encouragement, the effort represented on the following pages would not have been possible.

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CHAPTER I

INTRODUCTION

Simulation models allow a physical system to be represented in a logical form so that the performance of the system can be predicted without its actual existence. This study involves the development of a computer simulation model for a hot-mix asphaltic concrete production system and subsequent experiments on the model to determine performance of the system under specified parameters, and the effects of these parameters on the cost of production.

Though simulation models have demonstrated their ability to predict accurately actual production performance of construction systems, the majority of contractors still use "rules-of-thumb" or the conventional technique for estimating. As this study will illustrate, production estimates obtained by the conventional approach[1] are frequently too high and often lead to excessively low estimates of the cost of production.

The Conventional Approach to Estimation

The conventional approach to estimating the production output of a piece of construction equipment as expounded by Puerifoy (1) involves the summation of the mean times of each component of the cycle

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[1] Often referred to in the literature as the "deterministic" approach.

performed by a piece of equipment in order to establish a representative mean cycle time to accomplish a given task. The cycle time for producing a batch of hot-mix, for example, consists of a summation of the times required to weigh the hot aggregate, dump this material into the pugmill, dry mix the aggregate, weigh the asphalt cement, dump the asphalt into the pugmill, wet mix the combined materials, and dump the finished hot-mix from the pugmill into a truck or other carrier. The production of a system is then determined by combining the cycle times of the separate system components (subsystems) into a cycle time for the system.

A hot-mix paving system consists of three subsystems: production of the hot-mix, hauling, and laydown. Determination of the capacity of a hot-mix paving operation by the conventional approach would be accomplished in the following manner:

Example:

Plant capacity: 180 tph (5000-lb. pugmill, 50-sec. batch, 80 percent efficiency)
Paver capacity: 250 tph (2½-in. surface mix, 12-ft. lane)
Truck capacity: 15 tons

Cycle time:	load	5.00 min.	(pugmill cycle time x no. batches)
	haul	11.66 min.	(average haul for the day)
	maneuver	0.54 min.	
	dump	4.35 min.	(lay-down time)
	return	9.55 min.	(average return for the day)
Mean cycle time:		31.10 min.	

Number of trips/truck/hour: 50[2]/31.10 = 1.61
Production/truck/hour: 1.61 x 15 = 24.15 tons
Number of trucks for max. output: 180[3]/24.15 = 7.45

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[2] In the conventional approach, contractors estimate time lost to external delays (delays not due to the system) by using a 50-min. hour, 45-min. hour, etc., as productive work time, i.e., efficiency = 83.3%, 75.0%, etc.

[3] The plant capacity limits the production in this case.

The results of the above production estimate are shown graphically in Figure 1. Since the maximum output is achieved with 7.45 trucks, this is known as the balance point or the point where the production of all subsystems is equal. From Figure 1 it is obvious that the production "potential" is not balanced since the production capacity of the paver is not realized. The balance point thus implies only that the production potential of that subsystem with the lowest capacity is achieved.

From the calculations above, the contractor would employ seven or eight trucks on the project to achieve maximum system production. The effects on unit cost of selecting short or in excess of the balance point will be examined in Chapter IV.

Analysis of the conventional method for estimation of production or for determination of equipment fleet composition reveals several fallacies which cause the figures obtained by this method to be high[4] when compared to results actually achieved in the field. First, the method assumes that the system is in a steady state condition when actually such a condition will not be attained until some period of time after work begins. The length of time required for a hot-mix production system to achieve a steady state condition is a function of the capacities of the subsystems and the haul distance and could range from a few minutes to several hours. Thus, the production of the system until the steady state is achieved is overestimated. Also, delays at the plant or paver can interrupt the system causing the trucks to bunch up which would again reduce production until the steady state is re-attained.

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[4] It is possible, though unusual, for the conventional estimate to be low. This is discussed more fully in Chapter IV.

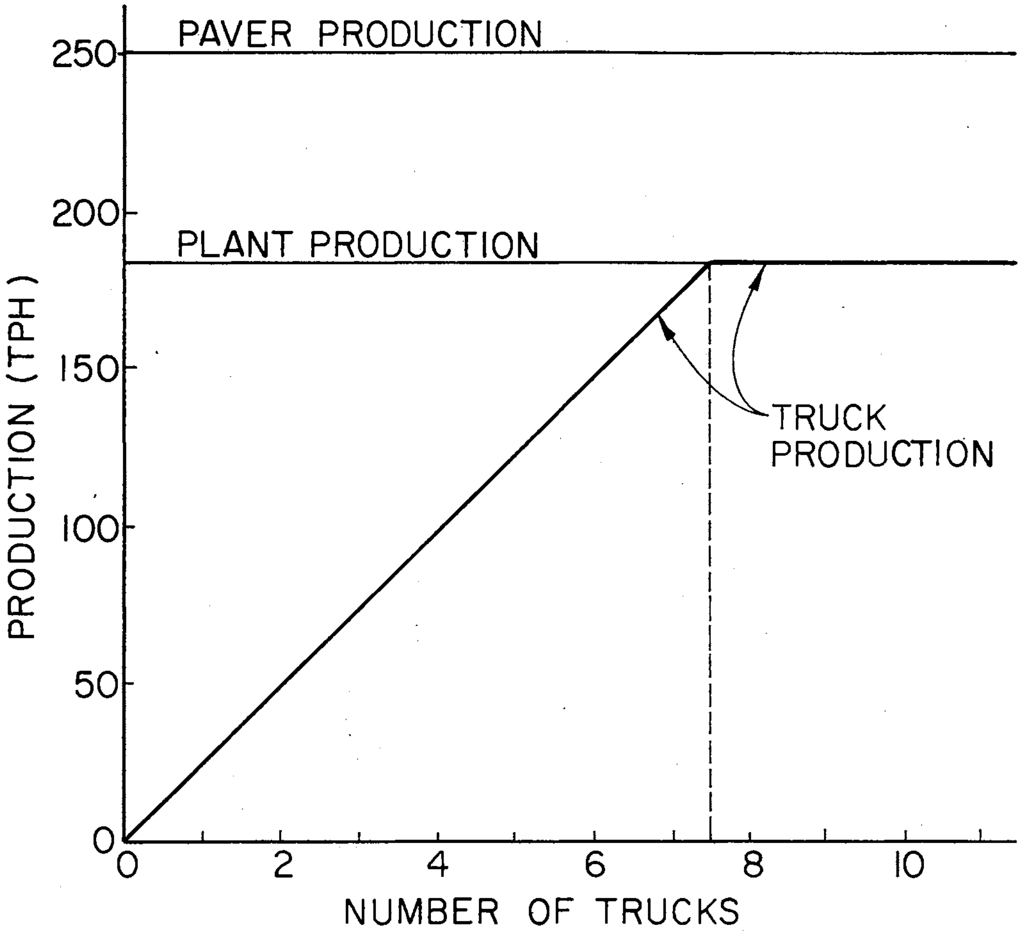

Figure 1. Production Estimate Using the Conventional Approach

Next, the summation of the component cycle times implies that these times are constant, when in reality they are not. Some of the component times will fall on one side of the mean and the balance on the other side so it appears that a statistical average will be obtained. If all of the subsystems of the paving operation, i.e., the plant, the paver, and the haul units, were entirely independent from each other, this would be true, but this is not the case. If the paver or the plant component times is greater than the mean, the production rate of the entire system is reduced. However, when one of the component times is less than the mean time, this could cause the haul units to bunch up at the other subsystem, and production would not necessarily be increased. Because of the dependence among the subsystems in the paving operation, fluctuations about the mean do not balance themselves out but tend to reduce the production of the system as an entity. This stochastic variation in component times and the degree of dependency inherent in a hot-mix paving system have a substantial effect on production. The extent of this effect will be investigated in Chapter VI.

Finally, in the example, assume that instead of 15-ton capacity trucks, 7½-ton capacity trucks are used. By the conventional approach the number of trucks required to obtain maximum production is 13.6 trucks, or almost twice the number of 15-ton trucks that are required. But by doubling the number of trucks, the probability of breakdowns is increased and the opportunities for one unit to interfere with another in a manner affecting production are also increased and production could be expected to decline.

The combined effect of these various influences on a system's production can be readily seen when the actual production curve is superimposed on the estimated production curve for the example. From Figure 2 it becomes obvious that the conventional method overestimates the production and that the introduction of additional trucks does not increase the system's production at a constant rate.

Prior Investigation

A number of persons have conducted studies to determine the extent of the effect of stochastic variations on production estimates, but to date no universal correlation factor has been developed. It appears that each kind of construction equipment has its own unique features. Schaffer (2) showed that the use of the conventional technique to estimate production yielded production rates which were on the average 12.5 percent greater than those actually achieved on site for a drag line-truck project. Likewise, Douglas (3) had similar results in his work with a truck-shovel combination as did Maliza (4) in his examination of pusher-scraper fleets.

Gaarslev (5) extended the studies of Douglas and Teicholz (6) and showed by stochastic models that the increase in production from adding an additional unit decreases considerably with the number of units already in the system. He also showed that replacing a large unit with smaller ones will decrease production when the units are dependent. All of the above named individuals proved what is obvious by logic--the conventional method of estimating presently employed by a majority of contractors tends to overestimate production. The significance of their work, however, is that they demonstrated that simulation models can be developed which accurately reflect the production actually obtained in the field.

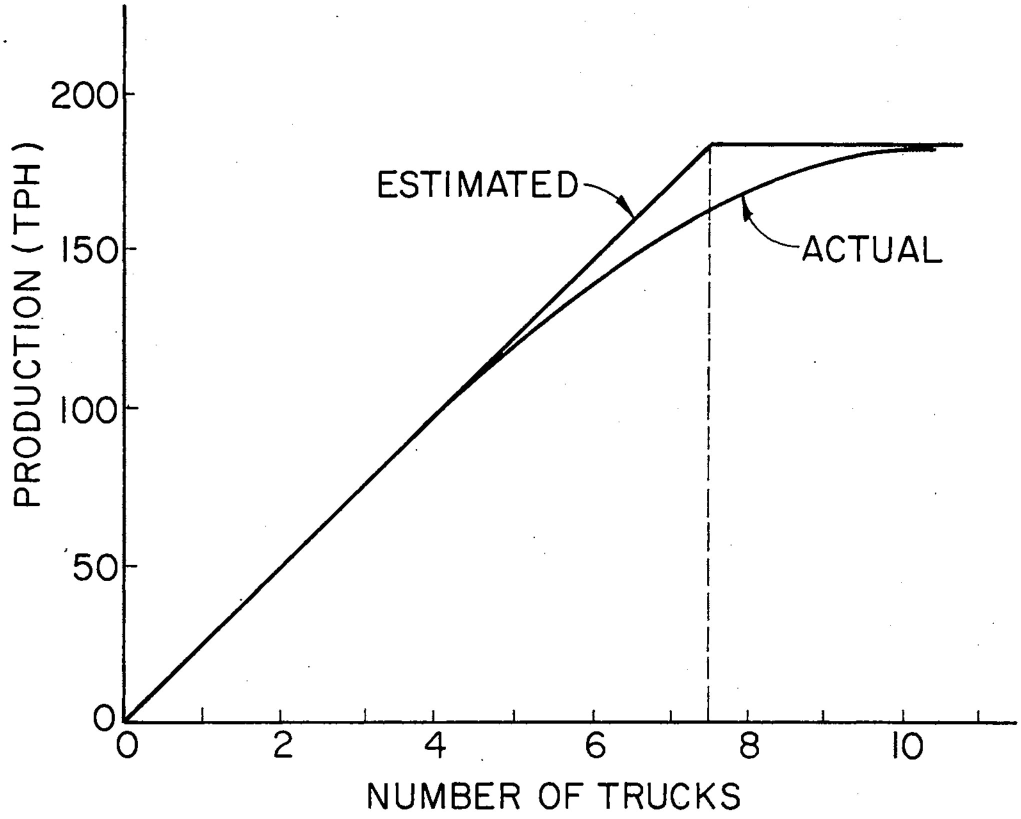

Figure 2. Actual Production Compared to Conventionally Estimated Production

In late 1972, the National Asphalt Paving Association published a study conducted by Texas A & M (7) which employed the techniques of simulation to determine the effects of various types of haul units on production in the construction of asphaltic cement pavements. This was the first and only attempt to date to employ simulation models to investigate asphaltic concrete mix production. No attempt was made by the study to develop a program which could be used by a contractor to estimate his production under given job parameters, nor was a detailed study conducted to determine the effect of variation in the job parameters on the unit cost of in-place hot-mix.

The Problem

It is not the intent of this study to supplement existing data on the advantages of stochastic models over the conventional model in estimating hot-mix production, though such data will accumulate as a by product. The primary objectives of the study are: (1) to develop a simulation model which can be used by hot-mix paving contractors to estimate production and determine the effect of various equipment combinations on unit price, (2) to examine the effects of management decisions such as composition of the equipment fleet and construction techniques on the unit cost of in-place hot-mix, and (3) to develop factors and/or guidelines which will assist the contractor in making policy decisions.

The first step in the study will be to develop a simulation model which will accurately depict the hot-mix paving operation. The development of the model and the decisions concerning the selection of available alternatives are contained in Chapter II. Conclusions based upon unreliable figures cannot be more reliable than the data themselves. Since there is no evidence of any studies of the statistical characteristics of the subsystems of an asphalt paving operation, extensive research will be conducted in an effort to develop probability distributions for each subsystem for incorporation into the model. Techniques employed in data collection and the subsequent development of the data are presented in Chapter III. Once the simulation model is developed, it will be used as the conveyance for analysis of the areas of interest of this study.

Specifically, the areas of interest include the effect on unit cost of in-place hot-mix by various equipment combinations, correlation of the conventional estimate to the simulated estimate, and the effects on unit cost of the introduction of surge loading into the system. The results of the analyses of these areas of interest are presented in Chapter IV and Chapter V.

Because of resource limitations, it is necessary to establish confines on the scope of the study. Thus, the investigation is limited to an analysis of those types and capacities of equipment within a feasible economic range of the smaller paving contractor. To this extent, plant capacities to be considered are 2,000-lb. to 6,000-lb. pugmill capacity[5], while the haul units to be considered are 7.5-ton, 15-ton, and 22-ton capacity. The Barber-Greene SA-41 paving machine will be used in all instances. Additionally, the type of hot-mix being produced and the thickness and width of the paving lane affect the capacities of the equipment. As will be noted in Chapter II, the mean

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[5] 53.6% of the hot-mix plants in use in 1970 fell into this range of pugmill capacity (8).

cycle time to produce a batch of hot-mix varied from 41 seconds to 64 seconds, depending upon the type of mix. As illustrated in Figure 3, the batch cycle time has a substantial effect upon the production capacity of the plant. For purposes of this study, all calculations will be based on a surface course mix with a batch cycle time of 43 seconds. The paving lane width will be 12 ft., and the depth of the surface course will be 2½ in. in all analyses.

The unit costs employed in the analsyses will have a significant impact on the results of this study. The sources of the cost data and the mathematical computations of the unit cost figures are presented in Appendix A.

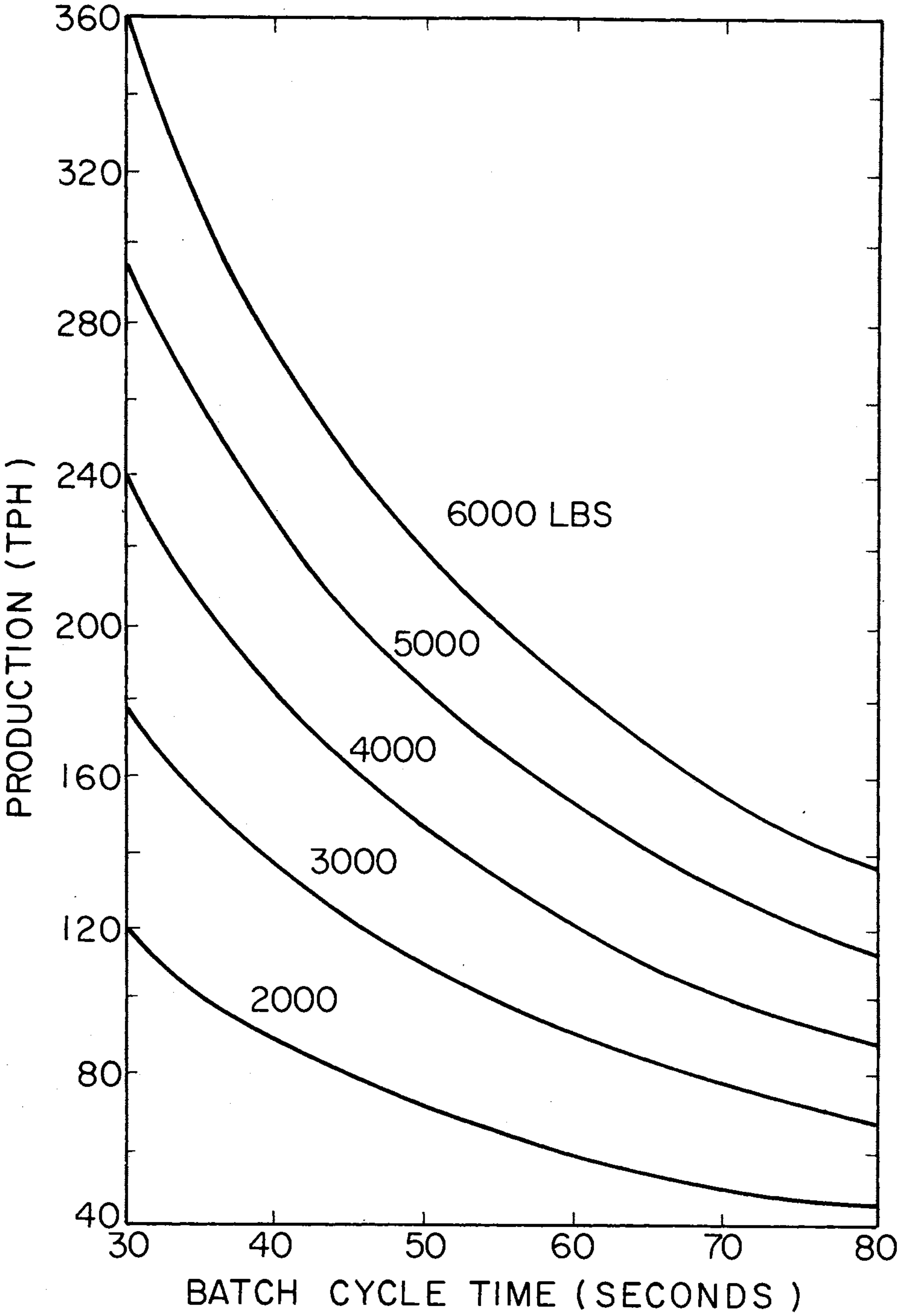

Figure 3. Plant Production Resulting From Variable Mean Batch Times

CHAPTER II

THE MODEL

As previously mentioned, the cycle times of the subsystems in a hot-mix paving operation are stochastic in nature; that is, they fluctuate randomly around a central value with no particular pattern to the occurrence of these times. It is this stochastic nature, or randomness, and the resulting interactions on the system's components which cause variation in the production of hot-mix over any specified period of time. As was demonstrated previously, it is the inability of the conventional model to reflect the effects of these variations that results in overly optimistic estimates. Thus, any model developed to represent the system must have some technique available which incorporates the stochastic variations into the performance of the model. Simulation models employing Monte Carlo techniques of random variable sampling possess this capability.

Monte Carlo techniques involve the experimental sampling of mathematically defined random variables. This sampling is accomplished by selecting a series of random numbers, each of which is associated with a particular random variable. The value of the random number is then related to the random variable by a table of relationships which matches the probability of occurrence of the random variable. The General Purpose Simulation System (GPSS) language offers a convenient computer method for accomplishing this random sampling. For this and other reasons which will be expounded later, a GPSS simulation model was adopted as the conveyance to achieve the objectives of this study.

The Language

A GPSS program operates by moving units upon which the system operates (called "transactions") from block to block of the simulation model in a manner similar to the way in which the units of traffic they represent progress in the real system. Each block describes some step in the action of the system. In the model for this study, the transactions represent trucks which move through a series of blocks, each of which affects the action of the truck in some way. For example, at one block the truck is loaded with hot-mix, at another block the truck "travels" to the paver, etc. Each of these movements within a block is an event that is due to occur at some point in time. This point in time may be specified by the programmer or it may be determined probabilistically based upon a specified distribution. The program maintains a record of the times at which these events are due to occur and executes them in their proper time sequence provided some situation does not prohibit the event from occurring. If such a situation is encountered, the program executes the event as soon as the prohibiting or blocking condition(s) change. In the study model, two trucks cannot dump at the paver simultaneously. Thus, if the haul time of one truck is completed before the preceding truck's time for dumping has expired, the second truck must wait until the point in time at which the first has completed its operation. When such waiting time occurs in a queue, as at the plant or paver, statistics are collected by the program.

In order to maintain the events in the correct time sequence, the GPSS program simulates a clock that is recording the instant of time that has been reached in the model of the real system. The program does not simulate the system at each successive interval of time, but updates the clock to the time at which the next most imminent event is to occur. Thus, the computer time used by the model is not a function of the length of time being simulated, but a function of the number of events which must be simulated within the time frame.

The language considers all times in the simulation model as integral numbers. The unit of time chosen must represent the smallest time unit desired, and all other times used in the model must be expressed in this same time unit. As will be noted in the study model, all times are expressed in seconds.

GPSS is a problem-oriented language in that data describing the operation to be simulated are contained within the program statements. This can be a disadvantage in circumstances where frequent changes in system parameters are desired because such changes involve modification of the program itself. To reduce the amount of modification required, a technique was employed in the study model which uses a standard numerical attribute (SNA) known as Savevalue (X) for introducing variable data into the program. When this technique is used, only the Savevalues must be changed to reflect new job parameters.

Another disadvantage of the GPSS language is that output format and contents are standardized and can be manipulated only to a minor degree.[1] Some output manipulation was accomplished in the model by

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[1] The Output Editor allows the standard output to be modified and permits selected statistics to be placed in a format more appropriate for a given application.

using Savevalues which are automatically printed as part of the standard output to compute the total production, the average hourly production, and the unit cost of the in-place hot-mix.

The disadvantages of the language are more than compensated for by the ease with which very complex actions can be incorporated into the program. The actual GPSS program for the simulation model required only three pages of program statements, whereas a Fortran program which would produce similar output would require many times this amount of space. For example, six lines or fewer were required to establish the probability distributions of the cycle times for each of the subsystems where a special subroutine would be required for each subsystem distribution in the Fortran or PL1 languages. This process is simplified in the GPSS language because of the availability of eight pseudorandom number generators which provide the capability of producing eight unique sequences of random numbers. The simplicity and flexibility of GPSS become even more apparent in the discussion of the program which follows.

The Program

The program consists of two models, each representing a different combination of conditions to be investigated. Model No. 1 is the basic program, while Model No. 2 is similar to Model No. 1 but has incorporated into it a surge loading system.

Succinctly, the logic of the program involves separating the hot-mix paving cycle into five elements: production of the hot-mix (loading), haul, maneuver, dump, and return. The time required for a truck to perform each of these five elements is obtained by a random sampling from a specific probability distribution which was constructed from data obtained through actual observation of paving projects. It is this random sampling of the distribution of the element times that permits the model to reflect the stochastic nature of the system. Chapter III describes the development of these distributions. Each computer run simulates an 8-hour shift. This time period was selected arbitrarily, and may be extended or reduced to reflect the duration desired.[2]

When the simulation begins, a specified number of trucks are at the plant. By random sampling, the time required to load the first truck is determined. In Model No. 1, this is accomplished by computing the time required to produce a single batch, and this operation is repeated by the number of batches required to load the selected size of truck. This approach to loading was adopted as opposed to selecting the total time required for loading a truck for one important reason. The mean, and probably the standard deviation, of the time required to load different capacity trucks will vary. With the selected approach, any capacity truck may be loaded and still reflect the proper distribution merely by adding or deleting cards designated "ADVANCE V2" in the program. Once the loading time required for the first truck is selected, the clock is advanced by this amount in time. At this specified point in the simulation, the time required to haul from the plant to the paver is randomly determined while at the same instant in the simulation the second truck begins its loading operation. This procedure is repeated for each truck and each element of the cycle for the duration of the simulation. Model No. 1 is written so that trucks load and dump

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[2] The procedures to manipulate and/or modify the model are provided in Appendix B.

on a first-in, first-out basis and, naturally, two trucks cannot perform either of these operations simultaneously. The model does allow faster trucks to pass slower trucks during the haul and return phases.

In addition to allowing the stochastic nature of the paving operation to be reflected in the simulation, the probability distributions also reflect the probability and the duration of delays to individual pieces of equipment resulting from minor breakdowns. For this study, a minor breakdown was considered to be a delay of 30 minutes or less. Major breakdowns were not considered for two reasons. First, such occurrences are a function of many variables such as age of the equipment, maintenance, operator skills, environment, etc. To develop accurately the probability of such an event would be impossible. Second, the inclusion of major breakdowns would detract from the purpose of this study in that the model would then represent a specific system instead of the general system.

To model actual conditions realistically, a technique is used to reflect the approach of the end of the shift. Rather than let the program run for a simulated eight hours and then terminate with trucks still in the system, a management decision is incorporated into the model. If a truck in the queue at the plant does not have time to complete a full cycle before the end of the shift, it is removed from the system. By changing the value of a Savevalue (X11), different management policies can be incorporated into the model. For example, if the value of the mean loading time of a truck is used in X11, the model would function on the basis that so long as sufficient time remained in the shift to load a truck, the truck would be loaded and allowed to complete the cycle before termination of the program. However, to investigate the unit cost of such policies where "overtime" is permitted, several blocks would have to be added to the program to incorporate the higher overtime rate for wages and the added equipment costs. Model No. 1, Appendix B, is used exclusively in the investigations discussed in Chapter IV.

Model No. 2, which is contained in Appendix C, differs from Model No. 1 in only one aspect. Hot-mix is produced and placed in a surge hopper from which trucks are loaded as opposed to loading directly from the pugmill into the haul units. One of the primary advantages of the surge hopper is to allow a supply of hot-mix to be stored prior to the beginning of the shift. This allows work to begin immediately upon commencement of the shift and reduces the amount of time required for the system to reach a steady state. With surge storage, the surge hopper could be filled the preceding evening, but with the unheated surge hopper, hot-mix can be held only an average of about ten hours without the onset of oxidation of the material. For purposes of this study, it is assumed that the plant will begin operation one hour prior to the beginning of the shift. Based upon observation of actual plants, this one-hour period would allow production of approximately 65 tons of hot-mix for a 2,000-lb. plant. Of course, this amount varies with the batch capacity of the plant and was changed as various capacity plants were simulated. A series of experiments was also conducted where no pre-loading was used to determine the effects of pre-loading on production and cost.

As stated above, the surge hopper cannot store material overnight without unacceptable deterioration. A feature was incorporated into the model which determines the time of day that the plant should be shut down to prohibit material remaining in the hopper at the end of the day. Since the unit prices derived from the simulation are based on the amount of hot mix actually placed during the shift, this feature of the model is not necessary for purposes of the study, but it was included for the convenience of future users of the model. The analysis discussed in Chapter V is based upon data obtained through simulation with Model No. 2.

The two models are identical in one respect; the output for each model is given in the standard GPSS format. A sample experiment with three 14-ton trucks and three 12-ton trucks hauling from a 4,000-lb. batch plant was simulated. The output from this simulation is included in Appendix C. On the first page of the output, pages 143-151, the total time of the simulation is given as ABSOLUTE CLOCK 29205 (29205 seconds = 8 hours, 6 minutes, and 45 seconds). Also given on this page is the total number of transactions which passed through each block[3] during the course of the simulation (TOTAL BLOCK COUNT) and the number of transactions in each block at the time of termination of the simulation (CURRENT BLOCK COUNT). When the program is functioning correctly, the CURRENT COUNT should be zero for all blocks except Blocks 4 and 6. Block 64 is the total number of large truck loads of hot-mix placed during the shift, and Block 74 contains a similar count for small trucks.

The next page of output contains data relating to the User Chain. This concerns the mechanics of the language and is not relevant to the experimental statistics.

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[3] The block number is the number in the left margin of the basic program. The number in the right margin is the card location in the program deck.

The following page provides statistics on the utilization of the surge hopper (Facility 1), the paver (Facility 2), and the batch plant (Facility 3). For the sample problem, the surge hopper was in the actual act of loading a truck 5.7 percent of the time. A total of 80 trucks was loaded with the average time to load each truck requiring 20.899 seconds. The paver was working 49.1 percent of the day. A total of 80 truckloads of hot-mix was placed with the average time to place each load requiring 179.27 seconds. The batch plant (Facility 3) statistics involve the production and storage of hot-mix in the surge hopper and are not as significant in Model No. 2 as in Model No. 1 where direct loading is used.

Page 154 provides data on the surge hopper. The capacity of the hopper is given as 100 tons. The hopper contained 26 tons at the end of the day and obtained the maximum amount of 100 tons at least once during the shift.

Page 155 lists the value of each Savevalue at the end of the simulation, and this is the production and cost data which is desired. Savevalue 13 contains the day's total production in tons, 1042 tons, while Savevalue 101 gives the average unit cost of the in-place hot-mix, $2.90. Savevalue 102 gives the average hourly production for the shift, 130 tph.

The following page provides the queue statistics. At the plant (QUEUE 1) the maximum number of trucks in the queue during the day was five. Of the 80 trucks loaded during the day, 70 did not have to wait to be loaded. Of the 10 which had to wait for loading, the average waiting time was 32 seconds. Similar statistics are provided for the paver (QUEUE 2).

Tables 1, 2 (Appendix C, pp 157, 158) provide identical statistics for the queues at the plant and paver, respectively. The purpose of these tables is to provide statistics on variations in the length of the queue. In Table 2 , for example, the statistics show that 80 trucks arrived at the paver during the shift. Of these 80 trucks, 76 did not have to wait in the queue. On three occasions there was one truck in the queue, and on one occasion there were two trucks in the queue.

Table 3 provides a data array for the interarrival times of trucks at the paver, while Table 4 provides similar statistics for the interarrival times of the trucks at the plant. These tables were included in the models to determine under what conditions the interarrival times of haul trucks conform to the exponential distribution. These tables may be omitted from the model, since they have no purpose other than that described above.

Simulation

Production of a hot-mix plant varies from day to day even though the same people use the same equipment for the same period of operation. Just as in the actual case, each replication of a simulation run will have varied results. Thus, the larger the number of replications, the more accurate the average production figure. However, some consideration must be given the economics of time and cost. For purposes of this study, five replications of each simulation were made, and the average production and unit cost figures from these replications were used in calculations and comparisons. In those instances where the results of a simulation appeared out of proportion to the other four runs, the production total of this replication was compared to the mean of the four. If there was greater than five percent deviation from the mean, the replication was discarded and another replication was run.

The development of the probability distributions for the model is discussed in the following chapter along with the procedures employed to verify the accuracy of the models described above.

CHAPTER III

RESEARCH

Objective

The objective of the research was to obtain data relating to each of the component sub-systems (load, haul, maneuver, dump, return) of a hot-mix paving operation in order to establish representative mean times and to develop probability distributions for each subsystem which, when incorporated into the simulation model, would accurately predict the system's production under various physical parameters. The essential elements of the research were (1) data collection, (2) data processing, (3) data manipulation, and (4) data analysis.

Data Collection

Data collection was accomplished by observing and photographing hot-mix operations in progress during the period November 1972 to May 1973. Data were collected at projects under construction and asphalt plants operated by the firms listed in Table I.

Two techniques were employed in recording data--timelapse photography and detailed stop-watch observations. Timelapse photography was used to record operations at the plant and vehicle arrival times at the laydown site. This photography was accomplished using a Nizo S 80 motion picture camera which exposed a frame at a rate varying from one-half second to 60 seconds between exposures. By trial and error it was found that plant operations could be accurately measured using an exposure rate of one frame every four seconds, while it was necessary to increase the exposure rate to one frame every two seconds for recording vehicle arrival times. In establishing these exposure rates, stop-watch observations were taken simultaneously with the photography, and the results of the two techniques compared. At the two- and four-second exposure rates outlined above, the maximum deviation of the results of the photography from the stop-watch observations was five percent. This deviation was deemed acceptable since it falls within the established confidence interval which is explained below.

TABLE I

SOURCES OF DATA COLLECTION

Firm	Location	Batch Capacity	Surge Capacity
Sam Finley Co.	Augusta, Ga.	5000 lbs.	100 tons
Evans and Throop	Stillwater, Okla.	4000 lbs.	none
Evans and Throop	Ponca City, Okla.	6000 lbs.	none
Haskell Lemon	Oklahoma City, Okla.	6000 lbs.*	300 tons
Kerns-Miller	Perkins, Okla.	2000 lbs.	none

*Modified to 5000 lbs. capacity

Because a frame counter was not available, a 12-inch diameter clock with a large visible sweep hand was positioned in such a manner that the time of occurrence to the nearest second of any event was recorded in each frame. To insure accurate identification of the hauling units in the photography, 12-inch numerals were placed in the lower right windshield and on the lefthand door of each unit. Essential identification features for each haul unit were recorded on pre-prepared forms, a sample of which is contained in Appendix D.

In addition to supplementing the timelapse photography, stop-watch observations were used exclusively to record surge loading at the plant and maneuver and dump times at the laydown site. Additionally, stop-watch observations were used to record down times of the plant and paver as well as time lost due to repositioning of the paver. Two stop-watches were employed to insure accuracy in all instances where one event ended and another began simultaneously.

When observations were made by stop-watch, data were recorded directly on forms designed for that purpose (the description of collection techniques is contained in Appendix D). When timelapse photography was used to record a specified segment of the operation, the form could not be completed nor could a complete examination of the data be made until the film was processed. This required from seven to ten days. This delay caused a loss of effort in some instances where the sample size proved too small to provide the specified degree of accuracy. By the time the data processing could be completed, the project had advanced to another phase or the physical and/or environmental conditions had changed sufficiently to bias additional observations. Because of this, the original sample had to be discarded.

Data Processing

Data processing consisted of performing the necessary mathematical computations to determine the mean, standard deviation, and probability distribution of the sample. Data processing was accomplished using a very simple program written in the GPSS language. The program and an example of processed data are contained in Appendix E. A Fortran program could have been written to perform the same function as the GPSS program and would have resulted in slightly lower computer costs but, for reasons which will become obvious when data manipulation is discussed, the GPSS language proved to be more desirable. Additionally, the time required to develop the GPSS program was infinitesimal when compared to the time required to develop a Fortran program which would provide similar output.

Each sample of observations was analyzed by the computer program. As indicated in Appendix E, page 172, the following information was obtained in the form of a frequency distribution table:

Column 1 - the upper limit of the class interval
Column 2 - the number of observed occurrences in that interval
Column 3 - the percentage of the total occurrences (the frequency with which an observation fell within the particular interval, $\left[f(x)\right]$)
Column 4 - the cumulative frequency distribution or the successive partial sums of frequencies up to each interval division point, $\left[F(x)\right]$
Column 5 - the cumulative remaining percentage of total observations $1 - F(x)$
Column 6 - the upper limit of the frequency interval expressed in the standard form $(\mu - x)/\sigma$.

Additionally, the mean of the sample, the total number of observations within the sample, and the standard deviation of the sample are included in the table. The program also provides a histogram of the frequency of occurrences which was beneficial in obtaining at a glance the spread and shape of the data.

Since the reliability of the arithmetic mean of a sample varies with the square root of the number of observations in the sample, the larger the number of observations, the greater the reliability of the sample as a whole. Because of changing physical phenomena such as weather and job site conditions or changing mixes at the plant, the number of observations within a sample was often limited. Even when the number of observations was not affected by outside influences, the limitations of time and finances on the observations forced some decision to be made as to how many observations were required to make a sample acceptable and how many samples were required to depict accurately the subsystem being observed. Since there are no real guidelines for the degree of accuracy required, the accuracy was arbitrarily based on commonly accepted levels of confidence.

Once the data were processed and the mean and standard deviation for the day's observations were known, a check was made using Student's t-distribution in a technique recommended by Puerifoy (9) to determine if the number of observations was sufficient to insure the specified accuracy. Of course, Student's t-distribution is based upon the assumption that sample means will form a normal curve around the mean of the population, but if the population shows marked skewness or kurtosis (which proved to be the case in all cycle elements except haul and return times), then the distribution of means of small samples will show the same characteristic as the population, though to a lesser degree.

However, as the size of the sample from such a population increases, the distribution of the means becomes more nearly normal.[1] Thus, Student's t-distribution provides an acceptable, though perhaps not precise, indication of the accuracy of the data and the adequacy of the sample size.

The selected level of significance (P) for all sample sizes of the components of the cycle time was 0.1--that is to say, there is a 90 percent probability that the results of the data collected in a sample conform with the desired accuracy. The confidence interval (I) is a time interval which specifies the accuracy desired. The check for sample size adequacy was performed in the following manner: Calculate the confidence interval I_a provided by the sample of M observations with a standard deviation S_a, using the formula:

$$I_a = 2t_{0.90}\left(\frac{S_a}{\sqrt{M}}\right)$$

where t is a value of Student's t-distribution for M-1 degrees of freedom. If I_a as determined by the formula is equal to or less than the specified value of I, the number of observations is sufficient. If I_a is greater than the specified I, additional observations are required. The number of observations required can be determined by the formula

$$N = \frac{4(t)^2\ S_a{}^2}{I^2}$$

where I is the specified accuracy.

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[1] Based on the Central Limit Theorem.

The specified limits for the various subsystems were:

batch cycle time ± 2.5 sec.
maneuver time ± 2.0 sec.
dump time ± 10.0 sec.

When a day's observations for the batch cycle time did not meet the above criteria, the observations were rejected from further consideration. This was necessitated by the fact that the variance from day to day in temperature, aggregate moisture content, the number and size of haul units, and gas pressure on the dryer were reflected in the sample mean and standard deviation. Thus, it was not possible to increase the number of observations until the desired accuracy was obtained. With the other cycle elements, this was not the case. When a sample did not meet the specified accuracy, the number of observations necessary to obtain the desired accuracy was determined and the additional observations were obtained in a succeeding day. Again, the sample was tested to insure that it met the required accuracy since the additional data would cause some change in the sample standard deviation.

The number of samples necessary to reflect the system was obtained using a technique similar to the one used for determining sample size. Each time a sample was accepted, it was incorporated into an aggregate sample. When the point was reached where the addition of five additional samples caused less than a 0.5 percent deviation in the mean time, the data were accepted as representing accurately the system component's behavior. The above approach was used in evaluating the mean times and probability distributions of the batch, maneuver, and dump cycle times. Travel time probability distributions were treated differently.

Teicholz (6) and Gaarslev (5)[2] have shown that an exponential interarrival time distribution is generally a good approximation for trucks or haul units involved in various construction projects. Therefore, the number of samples taken of observations of haul and return times was limited to that necessary to verify that the exponential interarrival time distribution is applicable to trucks hauling hot-mix. Additionally, it was necessary to establish a relationship between the mean haul (and return) times and the standard deviation of the observations as opposed to determining the mean value of the samples. This was accomplished with a total of 30 samples having a combined total of 840 observations. A point that should be made regarding data collections relating to paving operations is that with each truck load of hot-mix laid, the haul and return distances increase slightly. To overcome this, the camera was placed in a convenient position and not moved during the day even though the paver may have progressed a mile or more. In this way the sample data involved a constant distance.

Sufficient data collection was achieved by mid-May 1973. The next step was to manipulate or arrange the data into some form where it could be analyzed and incorporated into the simulation model.

Data Manipulation

As explained previously, the computer program for data analysis

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[2] Gaarslev stipulated that the exponential distribution is valid only if the number of trucks is not too small and there is a degree of dependency among the trucks. His proof was based on results of a simulation model as opposed to actual observation.

reduces the data to a histogram which, unlike the array of raw data, gives an immediate impression of the range of data, the frequency of the occurrence of each value, and the extent to which it is scattered about the central or typical value. In the data processing phase, the purpose of subjecting the data to the computer analysis was to obtain the mean and standard deviation of the sample in order to test the adequacy of the sample size for the specified degree of accuracy. Thus, the intervals of the histogram were of little importance, but in order to analyze the data, the interval selection becomes extremely important.

A choice must be made as to the width and number of intervals to be used. Factors influencing this choice are primarily the number, n, and the range, R, of the observations, and the tendency to concentrate around particular values. Snedecor (10) recommends that the class interval should be no more than one-fourth of the standard deviation (s/4), which implies that the total number of class intervals should be no less than $\left(4 \frac{R}{s}\right)$ where R is the range of the observations.[3] Because the times of minor breakdowns of the plant, paver, and haul units were included in the sample, the range was often extreme. Thus, the above procedure proved inadequate because it ignores the relative frequency of the bulk of the data. Sturges (11) suggests that a rough estimate of the number of intervals, K, for a sample with n observations should be about $K = 1 + 3.3 \log_{10} n$. This technique also proved ineffective with data from the production of hot-mix since so many observations tended to concentrate around a central value. The selection technique

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[3] R equals the value of the maximum observation minus the value of the minimum observation.

finally adopted was to examine visually each sample. If the data tended to concentrate around a central value, small interval widths were chosen regardless of the range of the data. Conversely, if the data tended to be dispersed, larger interval widths were employed. Additionally, interval widths were manipulated to coincide with gaps or points of concentration which occurred in the data. In not all cases were equal class intervals used. Where the range of data was great due to an unusual event occurring, intervals were consolidated.

Emphasis is placed on selection of the class interval because it was found that the number and width of the intervals can alter one's impression of the data a great deal, particularly when the number of observations is small. When this is the case, the choice of the precise points at which interval divisions are to occur tend to alter significantly the appearance of the histogram. As an example, consider the histograms in Figure 4. These four histograms are for the same sample of data observed for the batch cycle time for a hot sand asphalt mix. The raw data were relatively dispersed. When small intervals were established (Figures 4a and 4b), there was no discernible pattern to the probability distribution, but as the class interval width was increased (Figures 4c and 4d), a distribution pattern approaching that of a normal distribution could be perceived. Conversely, the data in Figure 5 represents the batch cycle time for a surface course mix. The raw data showed a tendency to concentrate around a central value. When large class interval widths were assumed (Figures 5a and 5b), few conclusions could be drawn from the distribution. But when very small interval widths were examined (Figures 5c and 5d), the distribution appeared to approach that of a shifted exponential distribution.

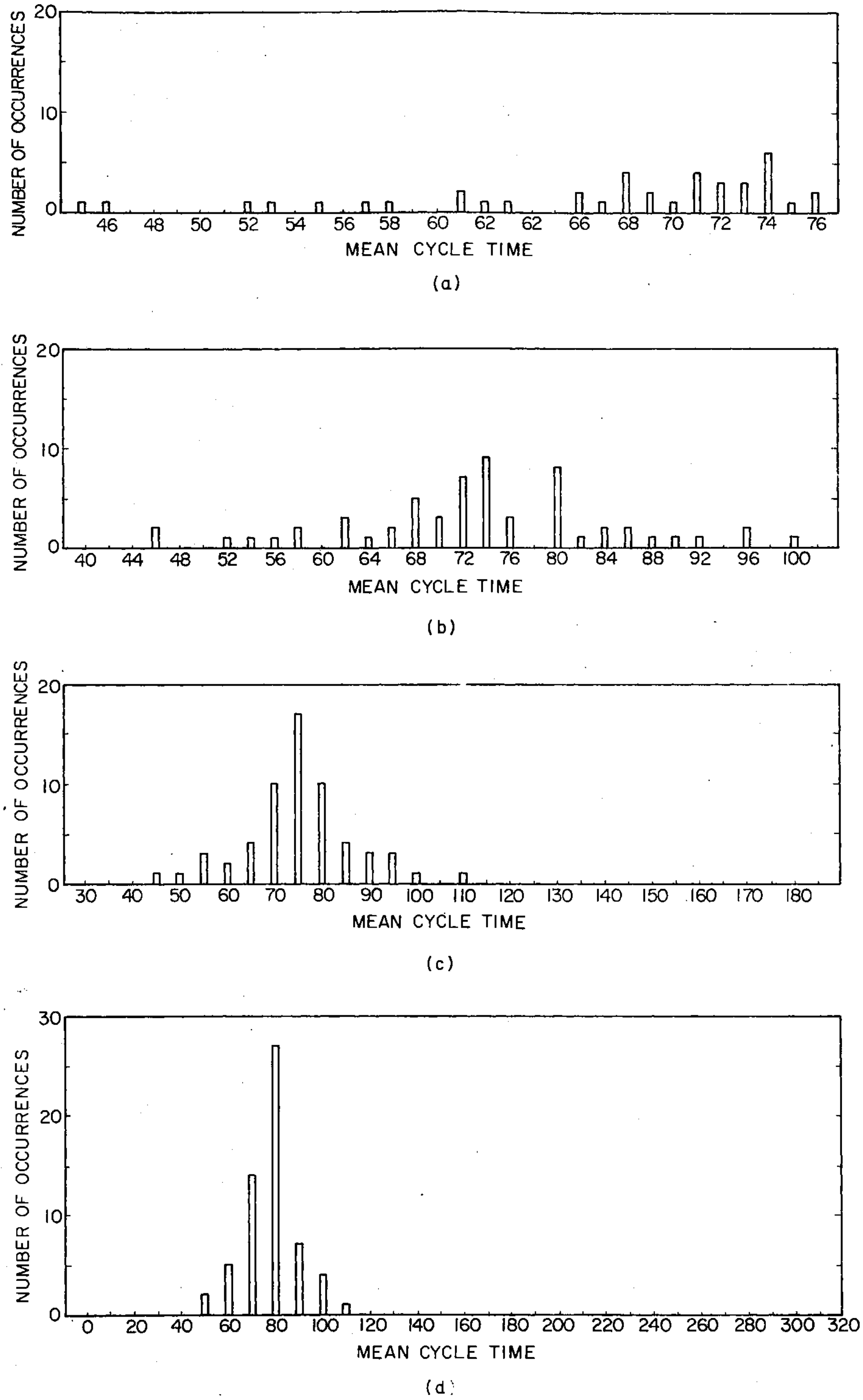

Figure 4. Class Intervals for the Batch Time of Hot Sand Asphaltic Concrete

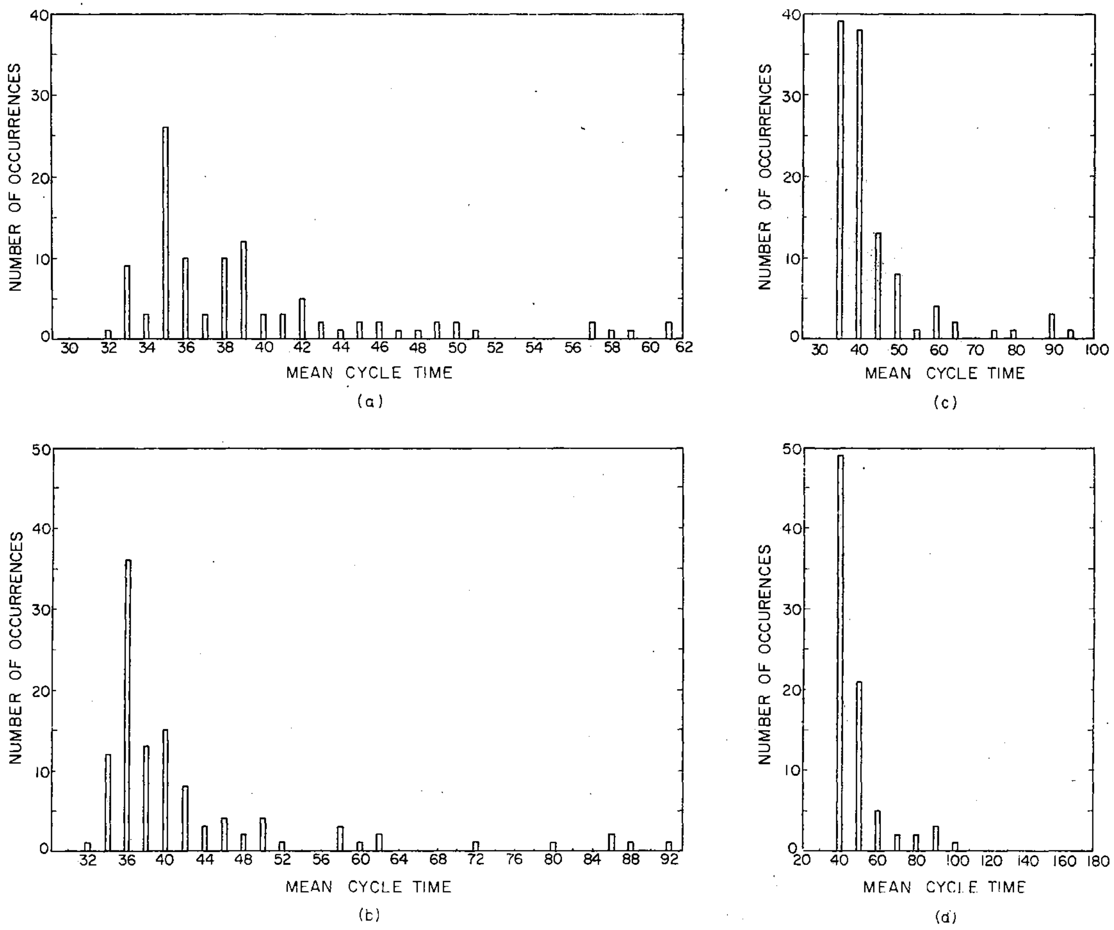

Figure 5. Class Intervals for the Batch Time of a Surface Course Mix

This failure of the data to display sharply defined features as the interval width is varied could be attributed to inadequate sample size or to the nature of the phenomenon being sampled. During the course of this research, sample sizes as small as 26 observations and as large as 740 observations were examined, and the majority displayed this tendency to fluctuate. Thus, the conclusion was reached that the nature of the subsystems of hot-mix production was primarily responsible for the variation in shape of the histogram.

As mentioned previously, the simplicity of the GPSS language facilitated greatly the manipulation of the data. By replacing one card, the interval width as well as the interval division points could be modified to reflect the desired changes in both the data and histograms.

Once the data were manipulated into decipherable form, the problem of analyzing the data for employment in the simulation model was undertaken.

Data Analysis

Several theories on the probability distributions of construction equipment cycle times have been expounded, most of which are based upon theoretical assumptions as opposed to actual detailed field observation and data analysis. As previously mentioned, Teicholz (6) and Gaarslev (5) analyzed the time study data provided by the Bureau of Public Roads and showed that an exponential interarrival time distribution was a good approximation for the distribution of arrival times for haul units. This is not surprising, since the same distribution has been widely accepted as a close approximation for the interarrival times of everything from telephone calls on a switchboard to cars at a traffic light.

This theory was not challenged by the research, though the data were examined to determine the validity of the theory when applied to hauling hot-mix. Data collected on the job site did tend to support the theory though it was found that the interarrival time of trucks hauling to the site more closely approximated the distribution than did those on the return trip. A possible explanation for this behavior could be that the drivers displayed less sense of urgency on the return trip than on the haul trip, i.e., there were more coke stops, relief stops, refuel stops, etc. Also, the difference in speed between the trucks was more pronounced on the return trip. As mentioned previously, the simulation model is written to provide a data histogram of the interarrival times of the haul units for simulated job conditions. A sample of the results of a typical simulation illustrating the similarity between the actual interarrival time distribution and the exponential distribution is contained in Appendix C.

For purposes of calculating the haul and return times for each haul unit in the simulation model, a truncated normal distribution was used to select the random variable. Gaarslev (5) used a normal distribution in his computer simulation model while the NAPA study (7) used a technique developed at Texas A & M which recognizes the significant characteristics of the haul units such as vehicle weight and horsepower as well as haul distance. The objective of the NAPA study centered on various means of transporting hot-mix and thus necessitated this more detailed treatment. The disadvantages of using such an approach are numerous. The technique does not provide for grade or road surface conditions, urban and rural conditions must be treated separately, various levels of maintenance between otherwise comparable trucks is not considered and, most importantly, there is no provision for considering the mixed haul fleets that most small contractors employ, i.e., different manufacturers, capacities, etc. For purposes of this dissertation, haul distances are expressed in time, and the truncated normal distribution considers the other variables. Thus, the nature of haul conditions is immaterial so long as the contractor knows the average time required to haul and return from the plant to the job site. Additionally, the model is capable of handling haul fleets of mixed capacity haul units.

Early simulation models employing the theory of queues were constructed by O'Shea (12) and Griffis (13), as well as several others. These models, which deal almost exclusively with predicting efficient equipment combinations for a loader-truck situation, employ the exponential distribution for not only the interarrival times but for service times as well. The reason for assuming service time distributions to be exponentially distributed is for convenience rather than for realism. In fact, if a distribution other than the exponential were used, the queueing theory approach to construction project simulation would be so mathematically complex as to make the solution impractical in simple simulations and impossible in more complex situations. Teicholz (5) studied the service time distributions of construction loading equipment and found them to fall between a skewed log-normal and a normal distribution. Gaarslev (5) used a family of Erlang[4] curves and found that the productivity of a system is affected very little by changes in K in the range between K = 5 (similar to a skewed log-normal) and

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[4] A gamma distribution where the parameter, K, is an integer value.

K = 20 (similar to a normal distribution). As a result of the above studies, persons wishing to simulate any construction operation, use a log-normal or normal distribution to represent the distribution of service times. No evidence could be found that any effort had been made physically to collect data to analyze the service time distributions for a hot-mix paving operation. For this reason, extensive research was conducted to obtain data which would accurately represent the batch cycle time, maneuver time, and dump time for an asphalt paving project.

The batch cycle times for the various types of hot-mix behaved in a predictable pattern; the smaller the maximum aggregate size of the mix, the greater the mean cycle time. Mean cycle times, including minor delays, ranged from 63.57 seconds for the hot sand mix to 41.66 seconds for a base mix. The unique characteristic of the batch cycle time proved to be its distribution. Hot sand mix displayed a distribution approaching that of a normal distribution, while base binder and surface mixes had distributions closely approximating that of a shifted exponential distribution.

The reasons for this variation in distributions between hot sand mix and the other types of asphalt mixes vary, but the primary reason was the inability of the dryer to maintain a level of hot aggregate sufficient to match the production capabilities of the other plant components when producing the hot sand mix. This problem most frequently occurred when the moisture content of the aggregate was in excess of six percent. The principal cause of the dryer inefficiency was low fuel pressure. Another factor which contributed to the spread of data for the hot sand mix was the number of trucks hauling. When the haul capability was small in comparison to the plant capacity, the level of aggregate in hot storage could be increased between haul units. When the plant was producing near maximum efficiency, this could not occur and longer batch times resulted. Conversely, when the number of haul units was small, the mean batch time was less, but the range of data and the standard deviation were high.

The Chi Square test[5] and the Kolmorgorov-Smirnov test[6] were used to test the "goodness-of-fit" for the various type mixes. The normal and the exponential distributions for batch cycle times were rejected for use in the simulation model, though the exponential distribution most nearly reflected the observed distributions for the base, binder, and surface mixes. Likewise, the normal distribution could have been used to reflect the hot sand asphalt mix cycle time distribution. However, the desire for accuracy in the simulation model prompted the author to develop an empirical distribution based upon actual observed performance.

As with the batch cycle times, the distributions of the maneuver and dump times were empirically developed as the result of the failure of the observed data to conform closely to one of the more familiar distributions. If it had been necessary to select one of the standard distributions for the maneuver and dump cycles in the simulation model, the truncated normal distribution or the log-normal distribution would have been selected since either of these distributions are close

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[5] The Chi Square test is based on a histogram's deviation from the predicted value.

[6] The Kolmorgorov-Smirnov test is based on the maximum deviation between the hypothesized and actual cumulative probability distribution.

approximations of the observed data. As previously mentioned, Gaarslev (5) proved that the results of a simulation vary little when the two distributions are interchanged.

A different approach was taken for determining the loading time of a truck by surge. This was necessitated because a sufficient number of observations for the loading time of any given capacity truck could not be obtained to establish an accurate empirical distribution of the times, nor was the amount of data adequate for comparison with a standard distribution. A total of 124 observations was made of the surge loading times of trucks ranging in capacity from two tons to 22 tons. These loading times were plotted with the amount of hot-mix loaded, and a linear regression was performed to determine a curve which best fit the data. A computer program was written using the Statistical Analysis System (SAS2) to perform the linear regression. The program and the results of the data analysis are contained in Appendix F. Two analyses were performed. In the first, the Y intercept was determined by the best fit of the curve. In the second, the Y intercept was specified at the origin. Based on the observations taken, the probability that the curve would pass though the origin was quite small, so the results of the first analysis were accepted. The formula for the curve of the loading times of the various capacity trucks is $Y = 2.489 + 1.56X$, where Y is the time (sec.) and X is load (tons). A plot of the loading times is shown in Figure 6.

The fact that the Y intercept does not pass through the origin is to be expected, since there is a brief delay from the time the discharge gates open until the material reaches the bed of the truck. The real hypothesis is that the relationship is linear. From the

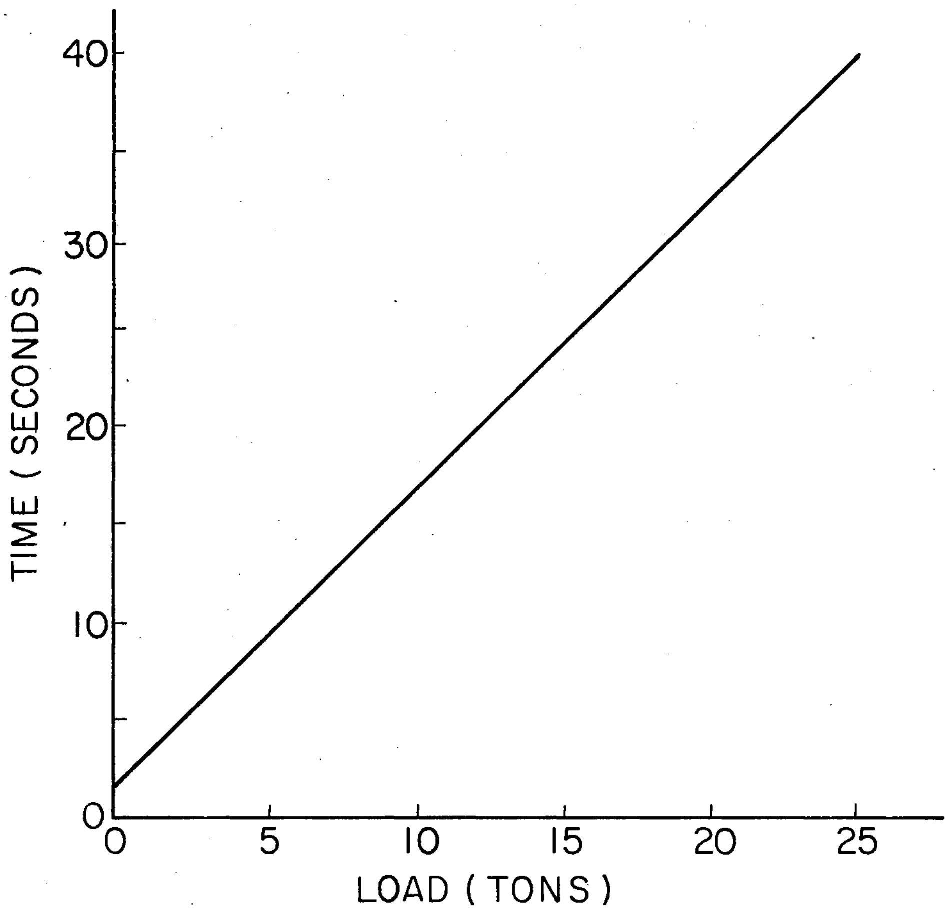

Figure 6. Surge Loading Times

observations made, this certainly seemed to be the case. One point should be made, and that is that the formula for surge loading was based on data obtained from loading base and surface mixes. The time to load the hot sand mix tends to exceed the formula figures by approximately 15 percent.

For lack of sufficient data to establish any other trend, the simulation model takes the mean time for a specific capacity truck from the formula and then treats the distribution about this mean as normal.

Model Verification

One of the major obstacles in the application of computer simulation models for solution of construction problems is that a single individual must have a thorough grasp of the computer language to be used and its capabilities, and be knowledgeable of the factors affecting the events to be simulated. Rarely can an accurate model be developed by a programmer from a description of the events to be simulated provided by a second person. A period of eight months was spent observing hot-mix paving operations and hot-mix production prior to developing the computer simulation model used in this study.

Once the model was developed, it was necessary to verify the accuracy and completeness of the model by comparing the results obtained through simulation with those achieved on an actual hot-mix paving operation. The project selected for this comparison involved a 4,000-lb. batch plant producing a surface course mix for highway improvement south of Stillwater, Oklahoma. A Barber-Greene SA-41 paver and a combination of 12- and 14-ton dump trucks were employed on the project. The average depth and width of the lift being applied were the same as those assumed for this study. Beginning haul times varied from 450 seconds to 1500 seconds.

The first approach used in the model verification was to obtain from the job superintendent the number and capacity of trucks to be used on the following day's operation, and to attempt to predict by simulation the total amount of in-place hot-mix for the first eight hours of the work day. This approach was not successful because of frequent fluctuations in haul capacity resulting from trucks being taken from the project for higher priority jobs or additional trucks being added to the project as they became available during the course of the work day. This approach to model verification was quickly abandoned in favor of a more certain, though less desirable, approach.

The approach adopted involved the observation of the project at the beginning of the day and the recording of the number and capacity of the trucks being used. The exact time of day that any change in haul capacity occurred was noted along with the amount of in-place hot-mix as of that time. The model was then modified to simulate a period of time corresponding with that observed, and the results obtained from the simulation compared with those recorded in the field: A total of five such procedures was accomplished. The simulated production ranged from two percent under to six percent over that actually obtained on the project. Because of the small number of comparisons and the randomness of the hot-mix system, the close correlation between the simulated and actual production figures confirms the assumption that the simulation model accurately represents the actual system.

CHAPTER IV

AN ANALYSIS OF THE CONVENTIONAL SYSTEM

For purposes of this report, a conventional hot-mix asphaltic concrete paving system is a hot-mix paving operation in which the haul units are loaded directly from the pugmill (no surge or storage silos) and discharged directly into the paver at the lay-down site (no hoppers, windrowing techniques, etc.). This chapter describes the results of a series of experiments with the simulation model wherein certain job parameters such as plant capacity, truck size and number, and haul distances are varied to determine the effects of such variations on total production and in-place unit cost of a conventional hot-mix system.

The Simulation Model

Model 1, as discussed in Chapter II, was used exclusively in each of the experiments described in this chapter. In addition to direct loading and direct discharge described above, the simulation model functions with the following conventional construction techniques: (1) loading and discharging of haul trucks are on a first-come basis, (2) passing of a slower truck by a faster truck on the haul road is permitted, (3) the paver operates in a direction which eliminates the necessity of trucks turning around while loaded, and (4) there are no scheduled lunch or rest breaks. In addition to these standard construction practices, Model No. 1 also incorporates the following managerial decisions into the experiments: (1) the period simulated for each work shift is eight hours, (2) the plant and paver are ready to begin production at the beginning of the first hour,[1] (3) if a truck does not have sufficient time to complete a cycle (based on mean cycle time) prior to the ending of the 8-hour shift, it is not loaded.

The results of each simulation are given in total tons of in-place hot-mix for the 8-hour period by the model. For convenience in comparing results obtained with the various job parameters, the total daily production was averaged for the 8-hour period.

Experimental Parameters

As previously mentioned, the availability of resources dictated the extent of each experiment and the number of repetitions each combination of parameters could receive. The experiments were conducted with various combinations of basic equipment and haul distances shown in Table II. A total of 549 combinations of equipment and haul distances were examined. Each experiment was repeated five times in order to obtain an average of the results and to determine the variability of the simulated production resulting from the random selection of subsystem cycle times. The total number of hours simulated was 21,960.

Certain impractical equipment combinations were ignored. For example, a 2000-second haul distance and a 6000-lb. batch plant would require 41.16 7½-ton trucks to theoretically balance the system. Such a combination is obviously impractical as well as uneconomical. With

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[1] This would necessitate work crews arriving at the plant and construction site some time prior to the beginning of the shift. This was the system employed on the majority of the projects observed during the data collection phase.

the maximum haul distance established at 2000 seconds (33.3 minutes) and the maximum plant size limited to a 6000-batch capacity, any combination of plant size and haul distance which would theoretically require in excess of 20 haul units to balance the system was ignored.

TABLE II

EXPERIMENTAL JOB PARAMETERS

Plant Capacity (pugmill size)	Truck Capacity (tons)	Haul Distance (seconds)
2000 lb.	7½	180
		300
4000 lb.	15	450
		600
6000 lb.	22	750
		900
		1050
		1500
		2000

In addition to the truck capacities listed in Table II, other loads were examined to determine the effect of partial loading versus full loading on unit cost. This was necessitated by the fact that, with the given batch size, certain trucks could not be filled to capacity by a given number of full batches. Thus, the question arises as to with alternative is the more economical: to place seven 3-ton batches in a 22-ton truck, or load eight partial batches to make a full load. This and other similar situations were examined and comparisons made between total production and in-place unit cost.

Conventional versus Simulated Estimates

The technique for arriving at the conventional estimate and a comparison between this production estimate and the production actually obtained in the field were discussed in Chapter I. As previously mentioned, Douglas (3), Teicholz (6), Gaarslev (5), and others have shown that in construction systems involving dependent subsystems such as shovel-truck or pusher-scraper production systems, the actual production achieved in the field is more closely approximated by simulation models than by conventional estimates. It has also been proven that the actual production is usually substantially less than the estimate obtained by conventional methods. The hot-mix asphaltic concrete production system proved to be no exception.

Figure 7 shows a comparison between the conventional estimate and the simulated estimate for a 4000-lb. batch plant loading a 22-ton capacity truck, and a 750-second haul distance. This is the typical relationship revealed in all 549 experiments, regardless of plant size, truck capacity, or haul distance. Of course, the simulated estimate is the result of a random process, so it was necessary to "fit" the curve to the data.

As shown in Figure 7, the simulated production estimate coincides with the conventional estimate in the lower ranges of production. The difference in the two estimates tends to increase until the balance point is reached. At this point, the simulated estimate again begins to approach that of the conventional estimate. The results of the experiments reveal that the marginal rate of production of each additional truck beyond the balance point decreases only slightly so that

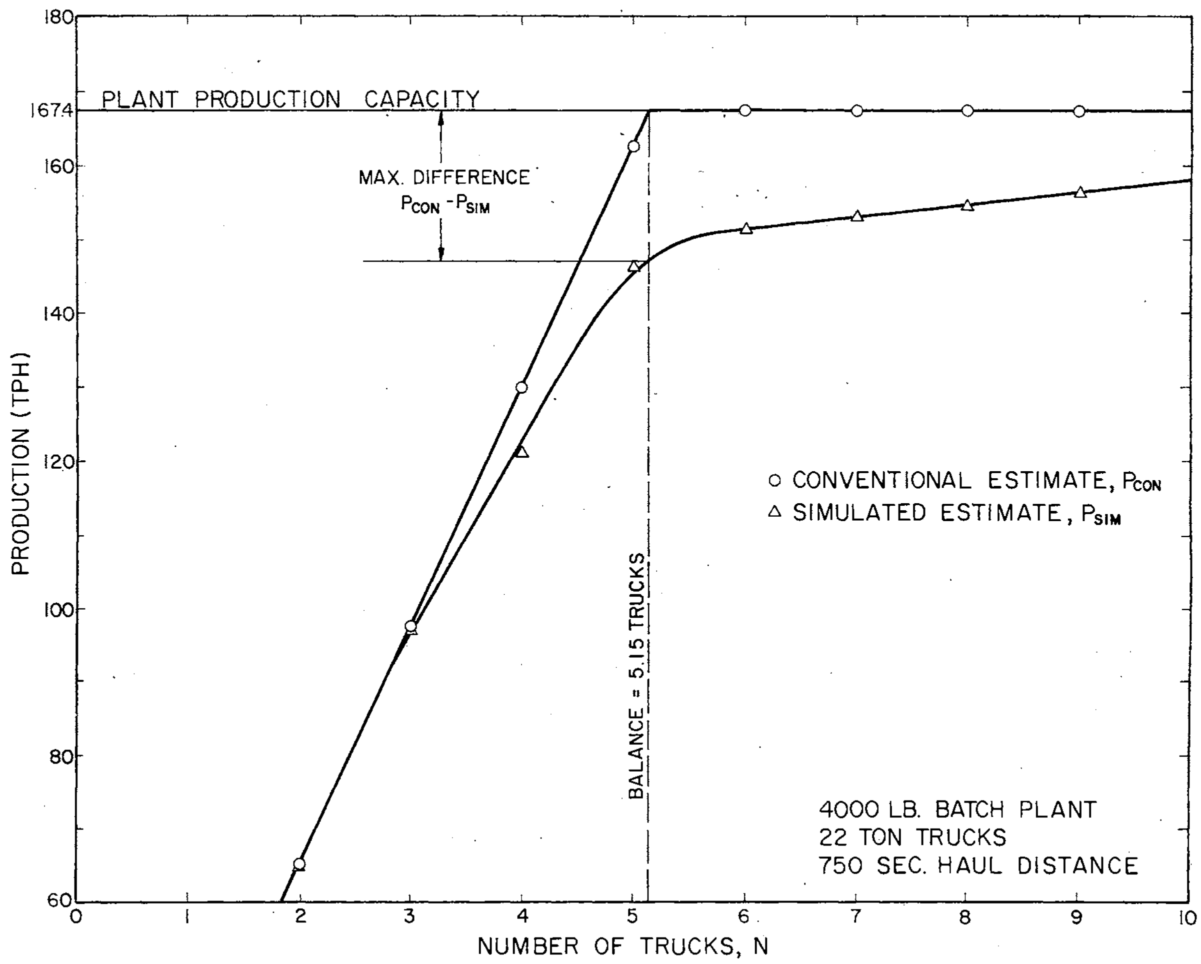

Figure 7. A Comparison of Conventional and Simulated Estimates

if enough trucks are added, the two estimates will again coincide. It is important to note that in every instance, the maximum difference between the conventional and simulated estimates occurred in close proximity to the balance point.

Contractors tend to select their equipment fleet composition as close to the theoretical balance point as is feasible and to base their bid on the corresponding production estimates. In this instance, if the contractor had elected to use six trucks, his estimated production would have been 167 tph with an estimated in-place unit cost of $2.33. As shown by the simulation, the production would be closer to 146.5 tph, resulting in an in-place unit cost of $2.65. If the contractor had selected any number of trucks other than at the balance point, the difference between his estimated unit cost and the actual unit cost would have been substantially less.

In Figure 7, the simulated estimate is shown to be always equal to or less than the conventional estimate. Of the 2745 individual simulations conducted in this study, this was the case in 96.6 percent of the experiments. In those instances where the simulated estimate exceeded the conventional estimate, the number of haul units was always substantially less than or greater than at the balance point. To assist the contractor in obtaining more realistic estimates of production, an attempt was made to derive correlation factors which could be used to convert the conventional estimate to the more realistic simulated estimate.

Correlation Between Conventional and Simulated Estimates

The variables which determine the balance point in the conventional estimate are considered when the mean cycle time for the system is determined; i.e., the batch cycle time, the size of the batch, the capacity of the haul unit, the haul and return distances, the maneuver time, and the dump time. As illustrated in Chapter I, this cycle time is then used to determine the number of trips per hour each individual truck can make (and thus the number of tons per hour it can haul). Since the capacity of the plant is constant, the conventional production estimate, P_{con}, is estimated by multiplying the number of tons per hour each truck can haul, P_H, by the number of trucks under consideration, N. Expressed mathematically:

$$P_{con} = P_H \times N$$

$$\therefore P_H \times N \leqq \text{plant capacity, } P_P$$

All of the above mentioned variables can be considered but placed in a more convenient form by establishing a ratio between plant capacity and haul capacity.

$$R = P_P \Big/ P_H \times N$$

When $N = 0$, R becomes ∞, and as N is increased, R approaches 0. Theoretically, a system would be in balance when $R = 1$. Using the data from the previous example (4000-lb. batch plant, 22-ton trucks, and a 750-second haul distance) and plotting the production in tons per hour with the ratio of plant capacity to haul capacity, R, the curves have identical values though the shapes of the curves may appear different if different scales are used (Figure 8).

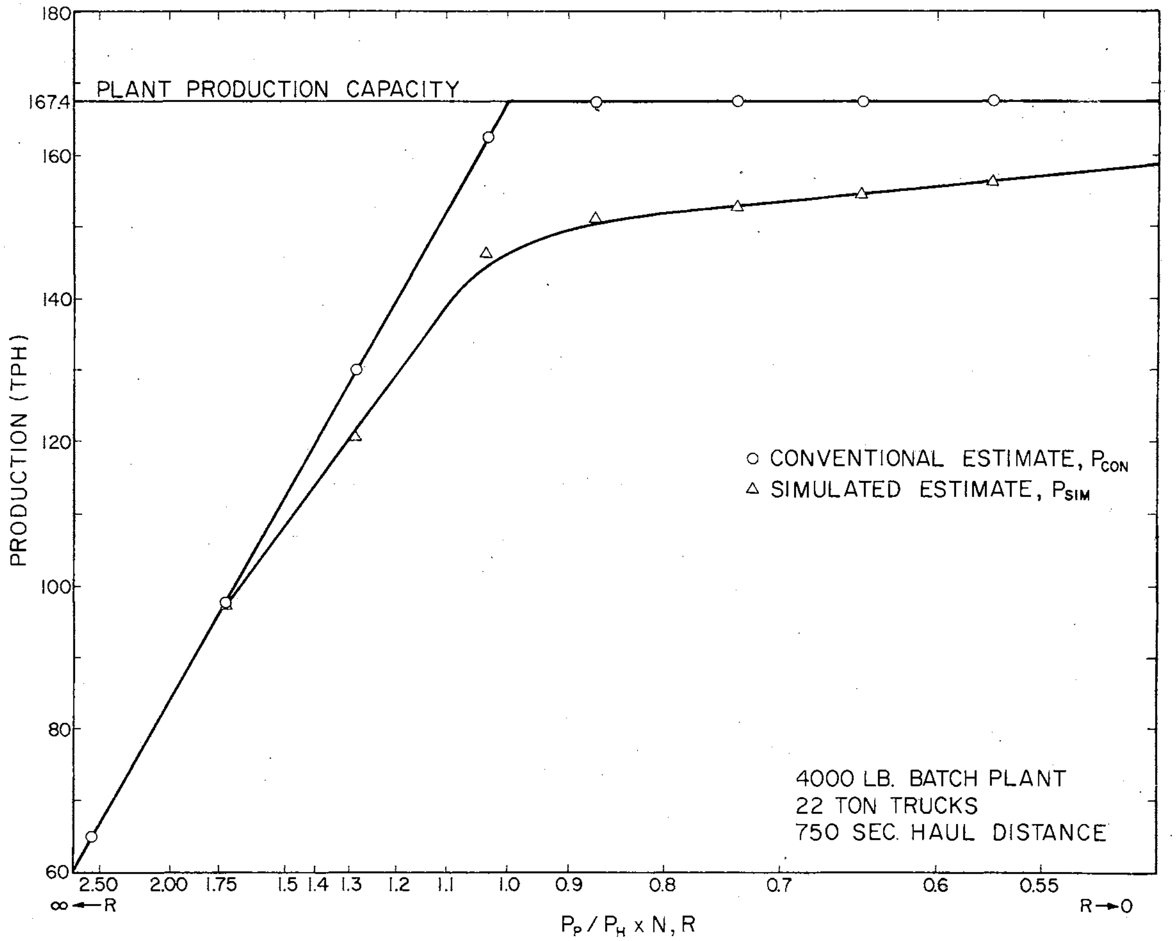

Figure 8. Production Related to R-Values

With a given capacity plant and a specified R, the estimated production is now constant regardless of truck capacity or haul distance. For example, with the 4000-lb. batch plant and R = 1, the estimated production will be 167.4 tph whether 7½-ton, 15-ton, or 22-ton trucks are used. Likewise, the haul distance may be 400 seconds, 740 seconds, etc., but as long as R = 1, the estimated production will continue to be 157.4 tph.

Similarly, the variation between the simulated estimate of production and the conventionally estimated production may be expressed as a ratio. For purposes of this report, this ratio is called the correlation factor, F. Thus,

$$F = P_{sim} / P_{con}$$

By using this approach, comparison of the various parameter combinations is facilitated.

As explained previously, for a given size plant the conventional estimate is the same for any combination of trucks and haul distances as long as the R-values are equal. It would seem to follow that the simulated estimate would deviate from the conventional estimate by approximately the same amount regardless of the size truck as long as the R-values were equal. It would also seem logical that if the plant capacity was increased, say from 2000-lb. to 4000-lb. batch, the deviation between the simulated and conventional estimates would remain in the same proportions for equal values of R since the conventional estimates increase proportionally. For example, with R = 1, the P_{con} for a 2000-lb. batch is 83.7 tph, while for a 4000-lb. batch, plant P_{con} is 167.4. If the R value is changed, say to R = 1.5, the P_{con} value increases by the same proportion from 55.8 tph to 111.6 tph.

If the system reacted as might be expected, it would be quite simple to correlate the deviation of the simulated estimate from the conventional estimate for various values of R and establish one table of universally applicable correlation factors.

Unfortunately, the system does not react as might be expected because of its stochastic nature. Results of the experiments revealed that as the number of vehicles (regardless of capacity) in the system increased, the difference between the simulated estimate and the conventional estimate also increased. A close examination of the computer results reveals two reasons for this reaction. First, as the number of haul units in the system increases, the probability of experiencing a delay or breakdown which interrupts the system also increases. Second, as the size of the plant is increased, the number of trucks required to maintain a specified value of R increases while the time required to load each truck decreases. Since the maneuver and dump times for a given load are relatively constant, this tends to cause bunching of the haul units at the paver. To illustrate the system's stochastic effect caused by increasing the number of haul units, either by decreasing the size truck or by increasing plant capacity, the results for a 750-second haul distance with R = 1 are shown in Table III. These data also show the effect which increasing the number of haul units has upon the difference between the simulated estimate and the conventional estimate (F value).

It was also noted in the analysis of the results of this series of experiments that as the number of haul units was increased to balance the system (haul distance increased but plant capacity held constant), the difference between the simulated and conventional estimates increased slightly. Thus, it was possible to develop a series of correlation factors for each truck capacity given a specific batch size.

TABLE III

EFFECTS OF INCREASING HAUL CAPACITY
Haul distance = 750 sec
R = 1

Plant Size (lbs)	Truck Cap. (tons)	No. Trucks	P_{con} (tph)	P_{sim} (tph)	F (%)	Ave Time in Plant Queue (sec)	Ave Time in Paver Queue (sec)
2000	7½	6	78.6	66.9	0.85	321	6.7
	15	4	83.7	71.7	0.858	422	0.63
	22	3	80.2	71.8	0.895	897	0.0
4000	7½	12	167.4	131.0	0.782	337	48.9
	15	7	167.4	140.6	0.839	351	23.6
	22	5	162.6	149.4	0.892	406	1.6
6000	7½	17	251	172.5	0.687	388	162
	15	9	238	190.6	0.800	224	189
	22	7	241.8	205.0	0.855	246	166

Figures 9, 10, and 11 give the correlation factors between the simulated and conventional estimates for loads of 7 to 22 tons for the 2000, 4000, and 6000-lb. batch plants, respectively. These graphs are used in the following manner: Given the R value (plant capacity/haul capacity) enter the graph and select the correlation factor, F. Multiply the conventional estimate for the R value of interest by the correlation factor to obtain the adjusted estimate of production. This

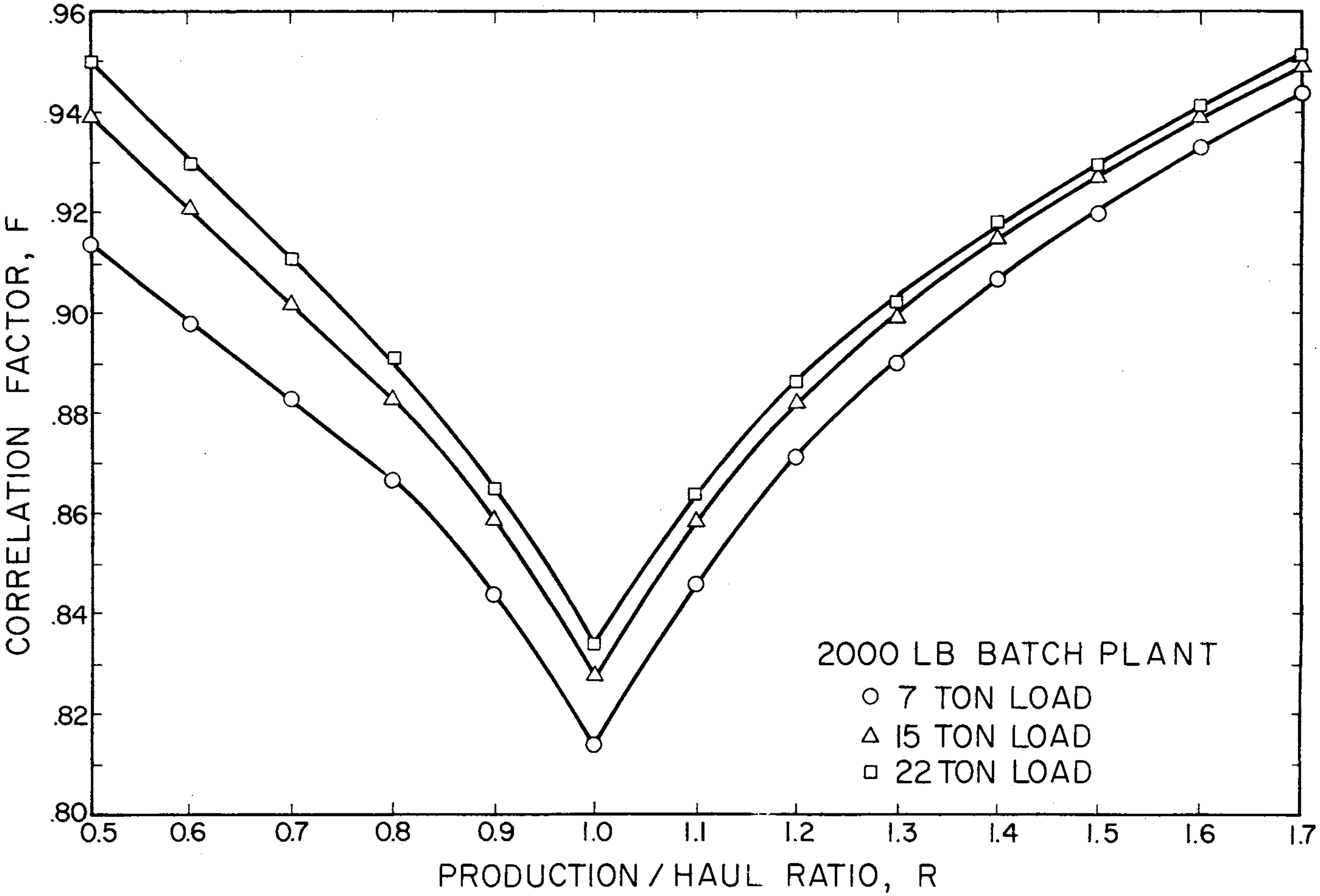

Figure 9. Correlation Factors for a 2000-lb. Capacity Batch Plant

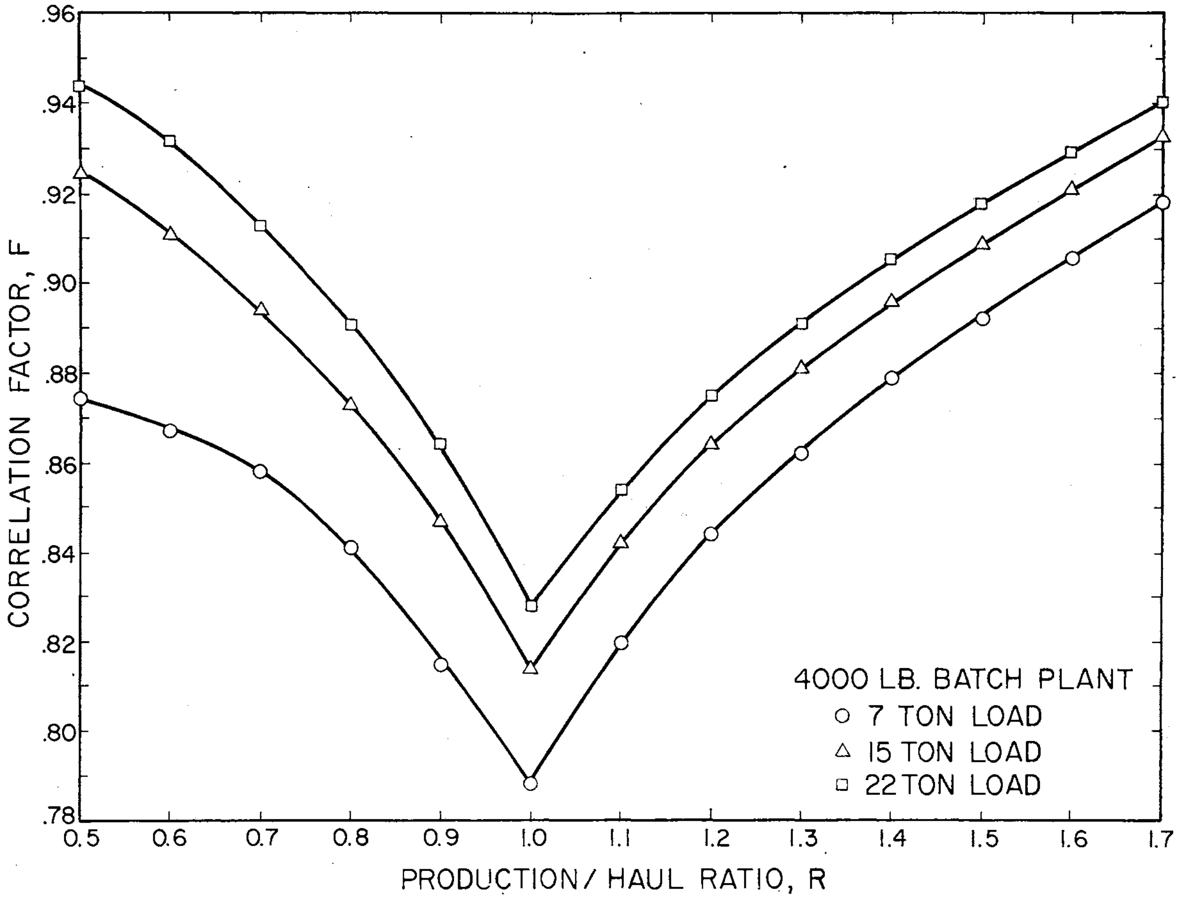

Figure 10. Correlation Factors for a 4000-lb. Capacity Batch Plant

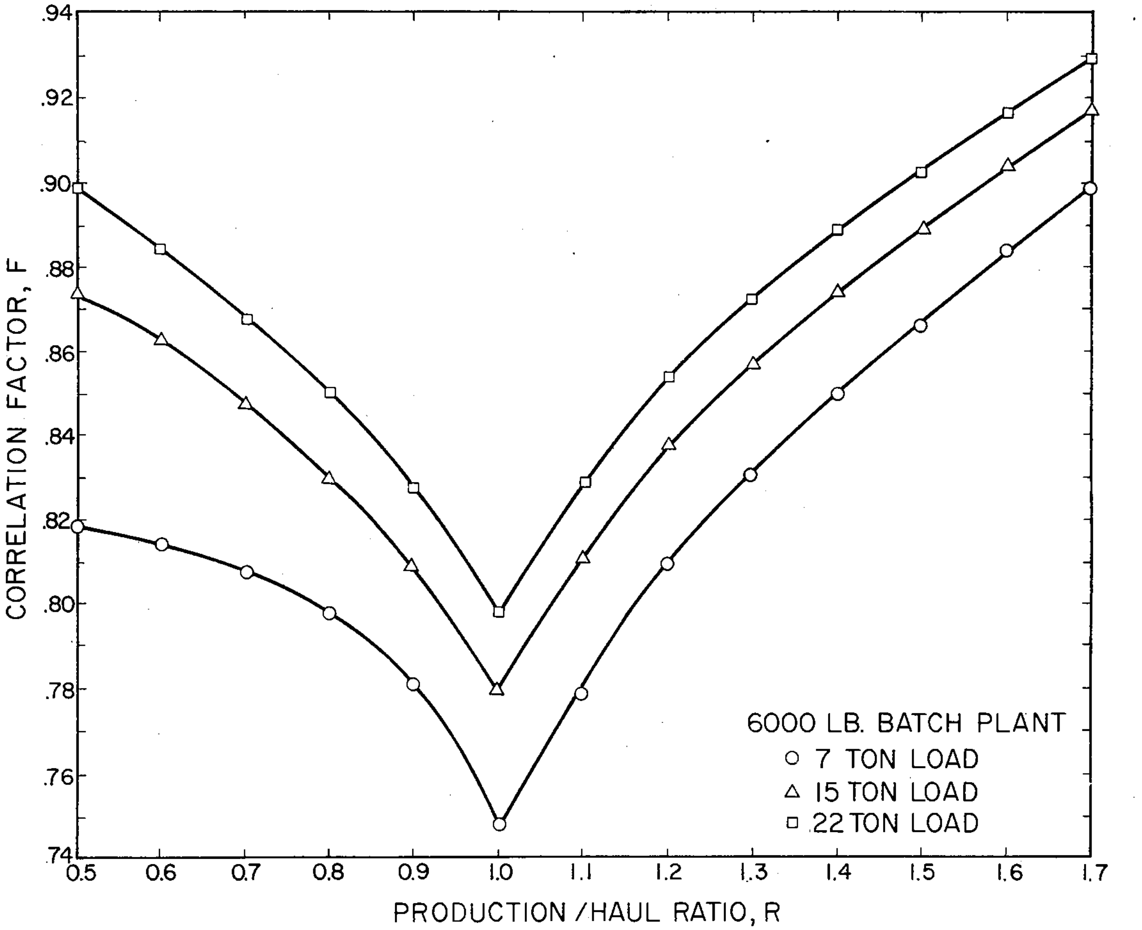

Figure 11. Correlation Factors for a 6000-lb. Capacity Batch Plant

adjusted estimate of production should then be used in determining bid costs and daily production estimates.

It is possible to use interpolation with the graphs to determine correlation factors for loads other than those specified. After the graphs were developed, loads of 7½, 12, 14, and 21 tons were simulated for the three batch plants and the results compared with the correlation factors determined from the graphs. The results were within one-half of one percent, which is as accurate as the graphs can be read.

By using these correlation factors, a contractor can predict more accurately his expected daily production without resorting to computer simulation. The simulation model used in this study could be used to develop correlation factors for plant sizes beyond the 6000-lb. batch capacity or for haul units outside the 7 to 22-ton range.

It should be emphasized that the correlation factors presented in this study were developed from data obtained solely from a hot-mix production system and, in all probability, are not applicable to other construction systems.

Thus far, the results of the experiments have concerned only production estimates. As will be discussed, maximum production does not always imply lowest unit cost. Since obtaining the lowest unit cost within given production ranges is the goal of every contractor, an economic analysis of the conventional hot-mix system was conducted.

Partial Batching for Maximum Loading

A problem common to every contractor visited during the course of the research for this study involved the decision as to whether or not to produce partial batches in order to fill a truck to its maximum capacity. The problem of partial batching arises from the fact that certain size trucks cannot be filled to rated capacity by a given number of full batches from specific plants. For example, a plant with a 4000-lb. batch capacity (2 tons) can put seven full batches on a 15-ton truck, or it can load seven full batches and one-half batch.

Of the contractors observed, some employed a policy of partial batching while others did not. One fact of interest which was observed is that that once a policy was established, it was not changed when plant-to-haul capacity ratios were altered by adding or deleting haul units.

To determine the effects, if any, of partial batching on total production and unit cost, the experiments conducted with the simulation model in the preceding analysis were repeated using partial batching in those situations where the batch capacity to truck capacity ratio necessitated partial batching to achieve maximum loading. The following comparisons were made for the specified batch plants as indicated:

Batch Capacity	Comparison
2000 lb.	7 ton vs. 7½ ton
4000 lb.	6 ton vs. 7½ ton
4000 lb.	14 ton vs. 15 ton
6000 lb.	6 ton vs. 7½ ton
6000 lb.	21 ton vs. 22 ton

The experiments were conducted at all haul distances previously specified. One additional assumption was made for these experiments, and that was that the time to produce a partial batch is the same as that required to produce a full one. Where partial batching was observed during the research, this was the case.

In comparing the 6-ton load versus a 7½-ton load, in every instance it was found that production was substantially greater when partial batching was used to load the truck to rated capacity. Not only was total production increased when partial batching was used, but also the unit cost of the in-place hot-mix was an average of 12.2 percent less. Under all conditions, the contractor is advised to use partial batching when faced with the choice of loading six tons or 7½ tons into a 7½-ton truck. This was not the case when the results of the other choices were analyzed.

Figures 12 through 17 illustrate the results obtained from the other comparisons. The dashed line indicates the theoretical balance point of the system as determined by the conventional estimate. In every instance it was found that the unit costs (and thus total production) for partial and maximum loading were equal at, or very near, the theoretical balance point. When haul capacity was less than that required to balance the system ($R > 1$) the lower unit cost was always obtained by maximum loading. Conversely, when haul capacity was greater than that required for theoretical balance ($R < 1$), the lowest unit cost was obtained by partial loading. It should be noted also that the greater the deviation of the haul capacity from the balance point, the greater the difference in the two unit costs. In other words, to the right of the balance point the marginal cost of production increases more rapidly for maximum loading, while to the left of the balance point the increase is less rapid for maximum loading. Thus, a contractor would obtain the lowest in-place unit cost by using a maximum loading policy (partial batching) when his theoretical haul capability is less than the theoretical plant capacity, and switching to a partial loading policy when the haul capacity exceeds plant capacity.

Two other factors of considerable interest to contractors are

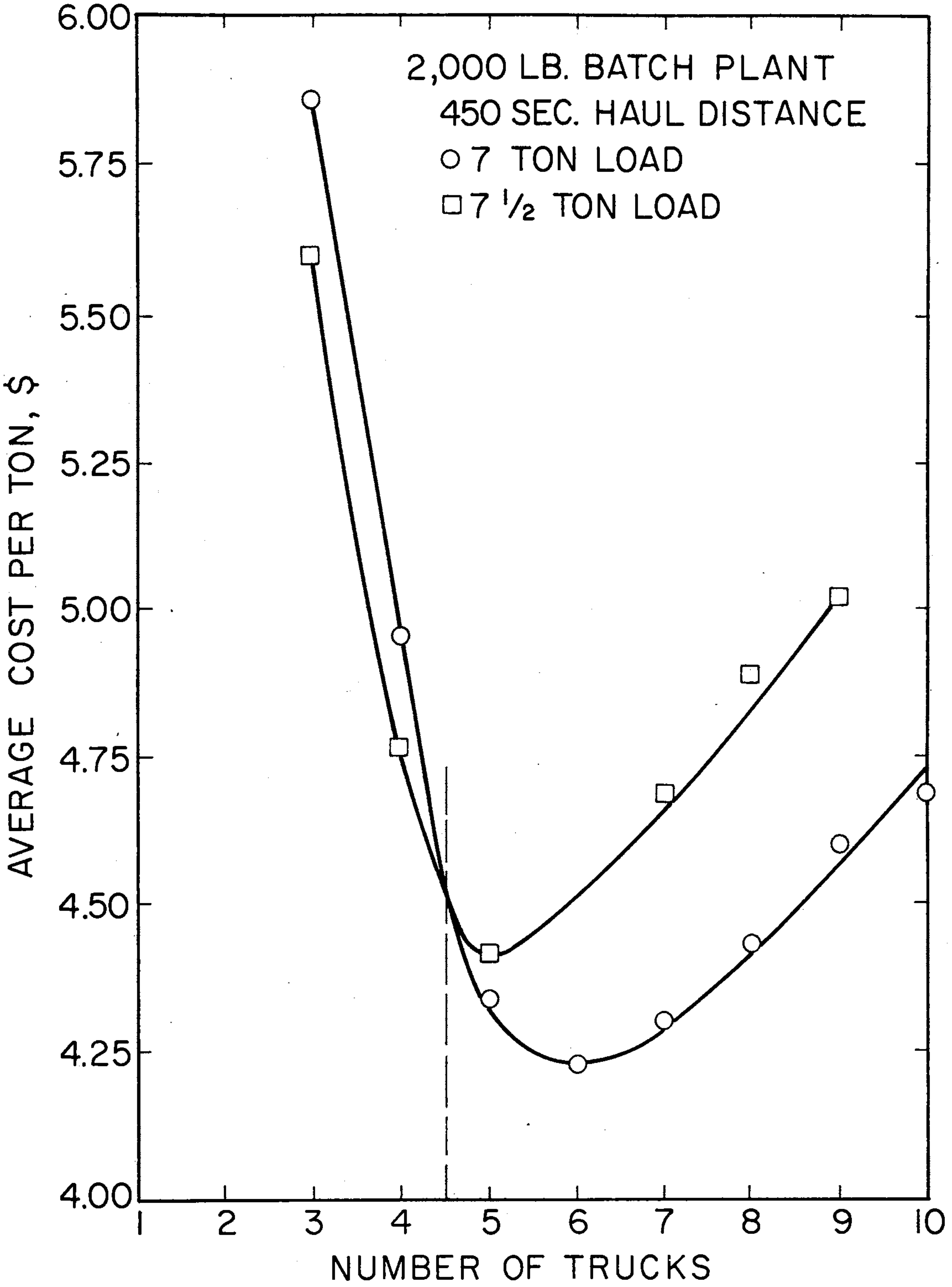

Figure 12. Partial Batching - 2000-lb. Plant and 450-Second Haul

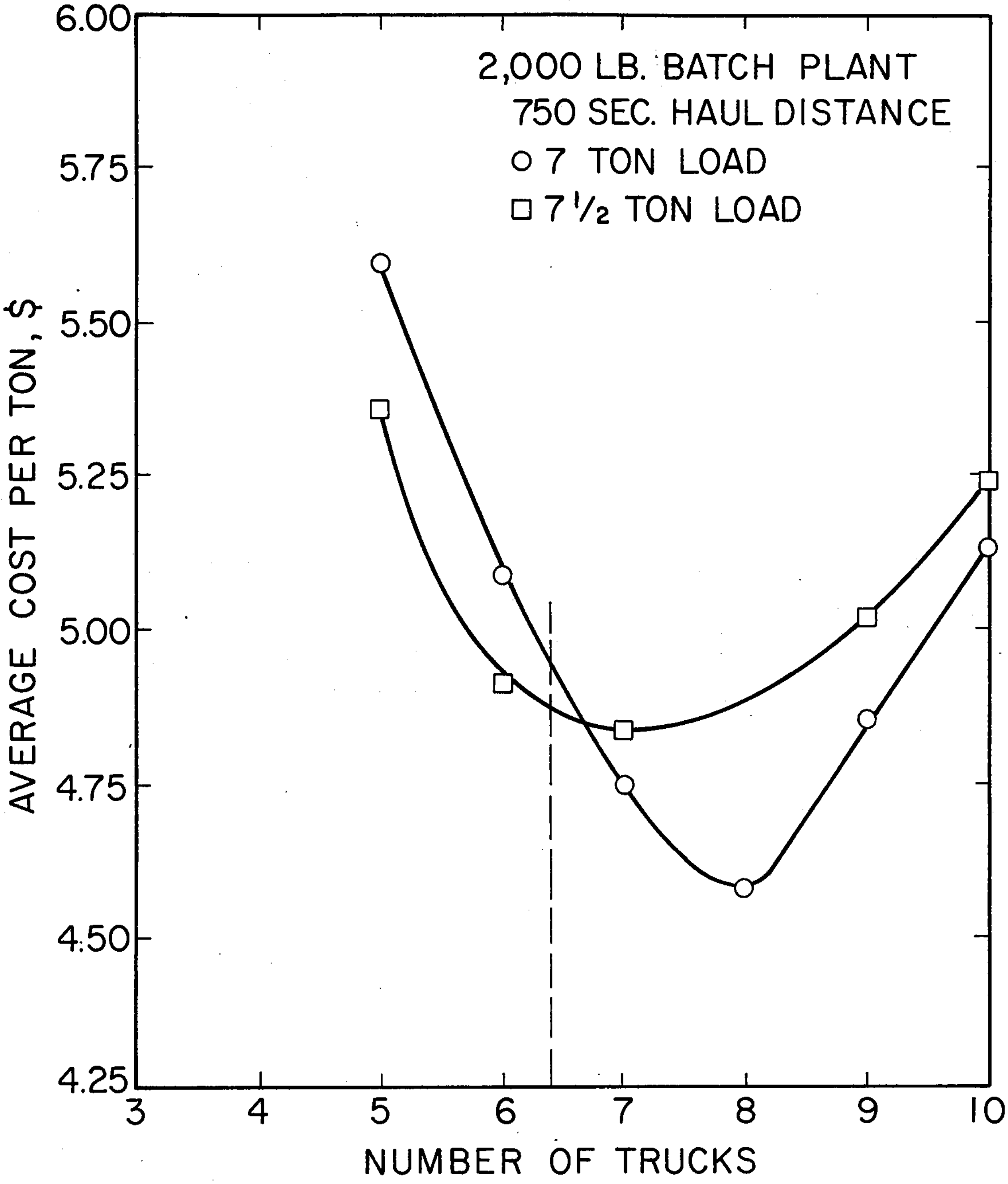

Figure 13. Partial Batching - 2000-lb. Plant and 750-Second Haul

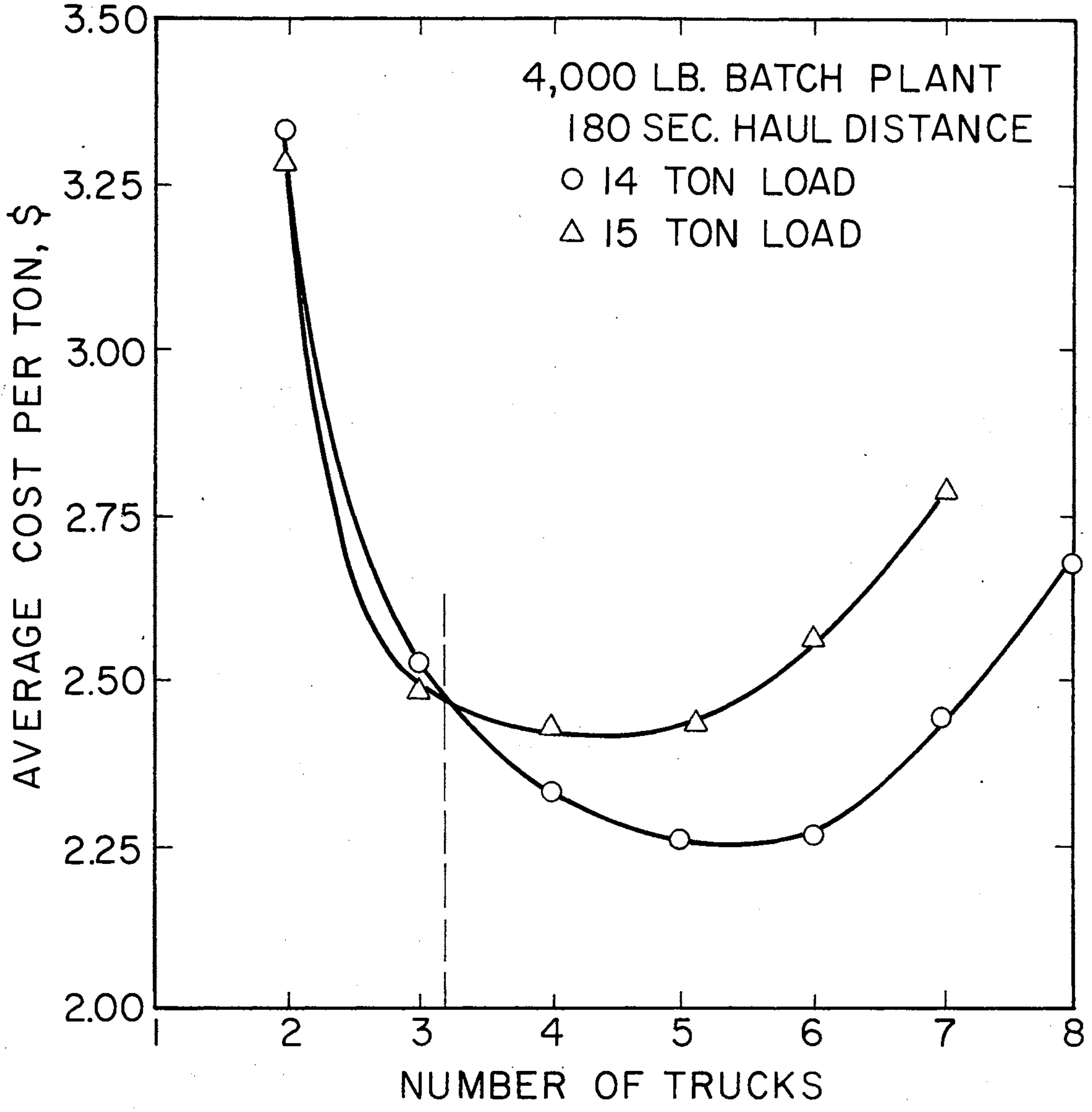

Figure 14. Partial Batching - 4000-lb. Plant and 180-Second Haul

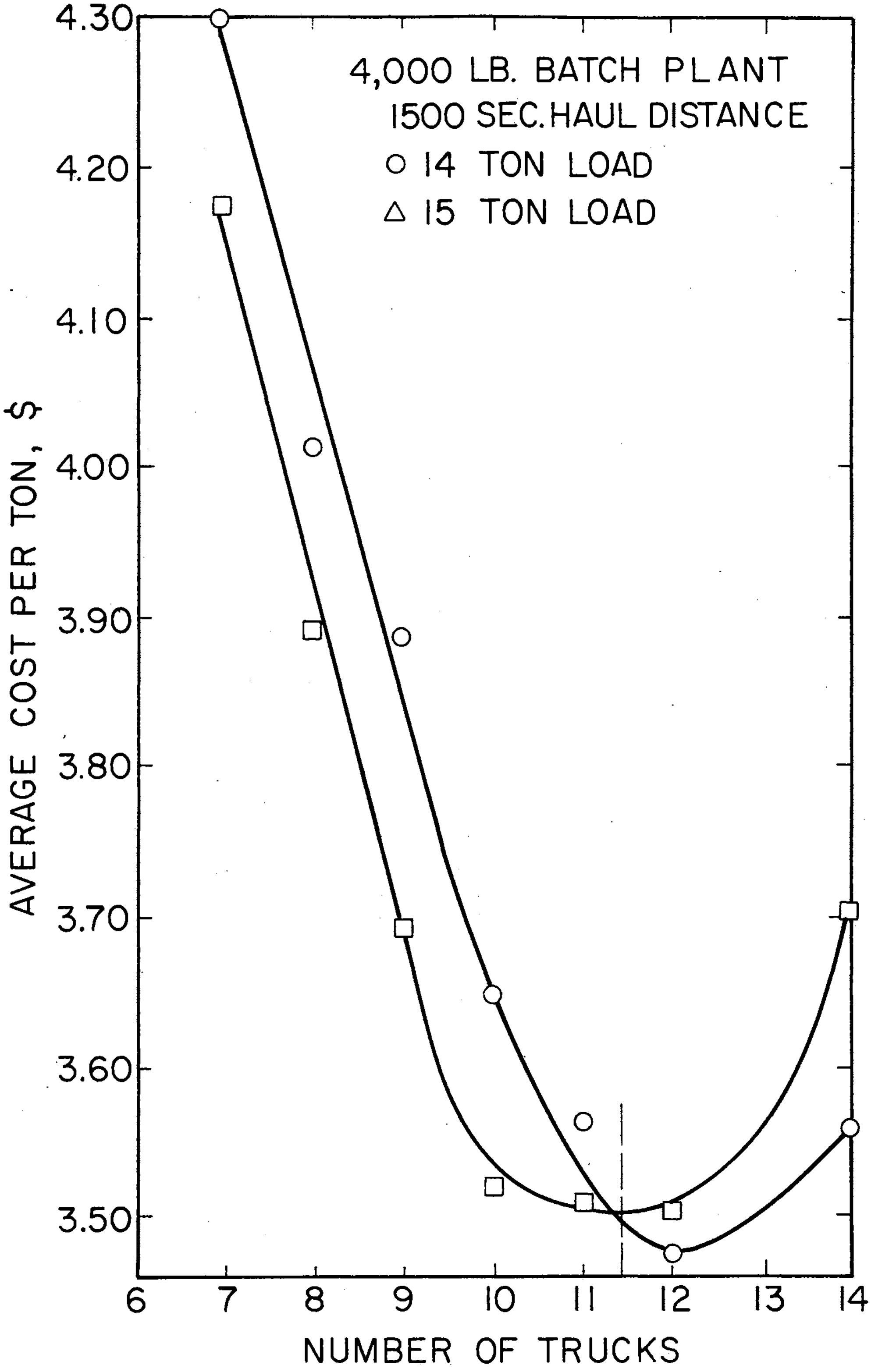

Figure 15. Partial Batching - 4000-lb. Plant and 1500-Second Haul

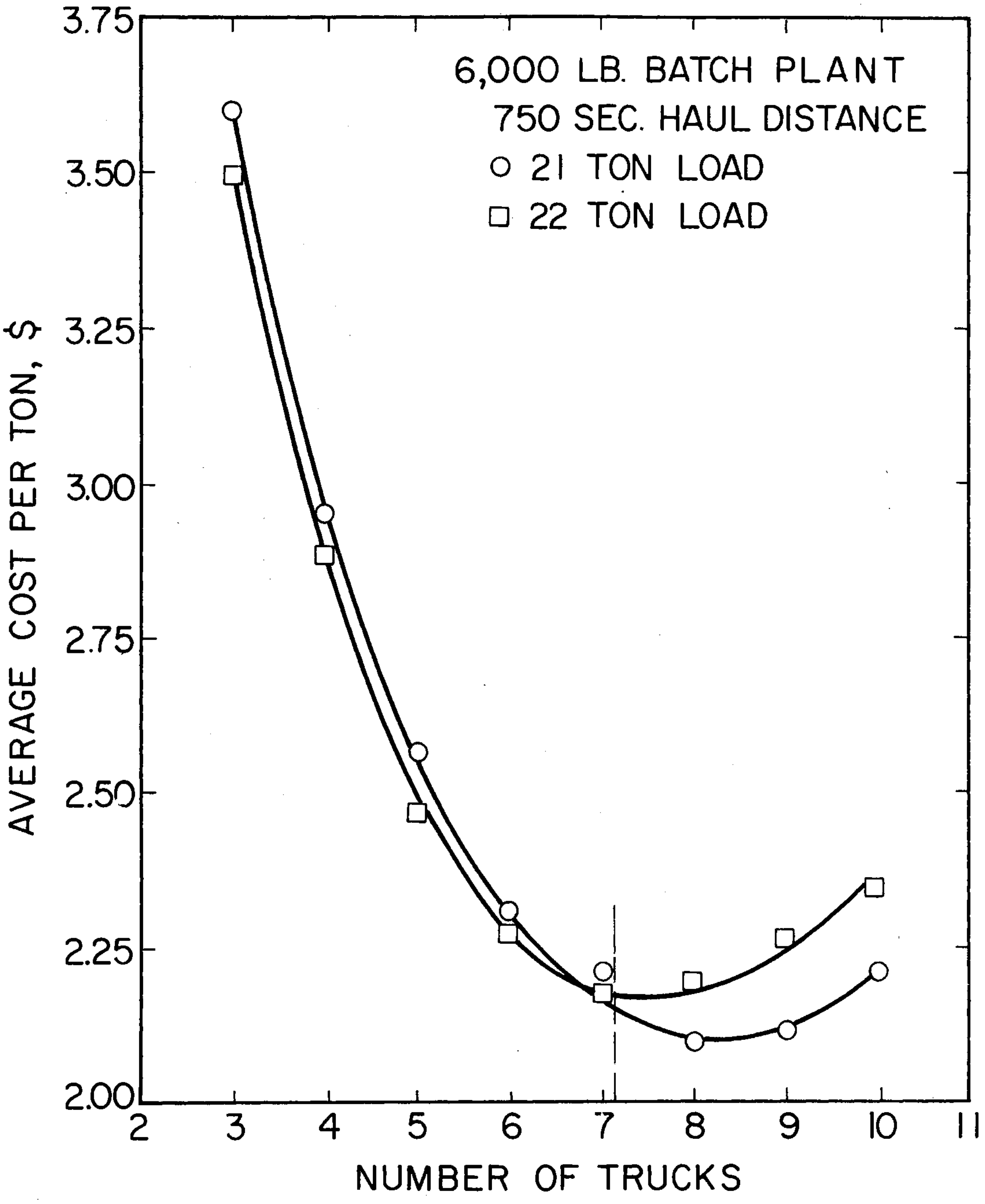

Figure 16. Partial Batching - 6000-lb. Plant and 750-Second Haul

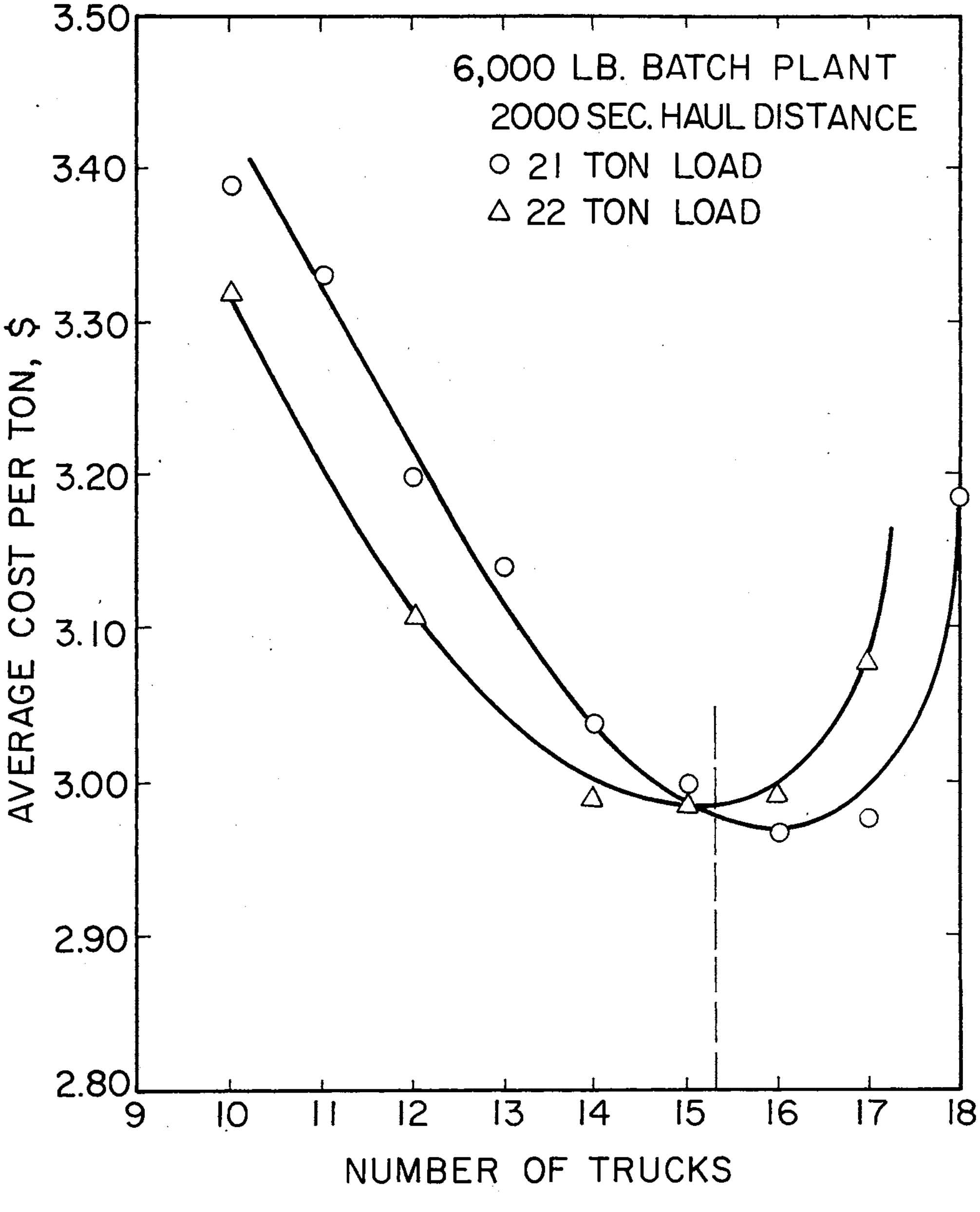

Figure 17. Partial Batching - 6000-lb. Plant and 2000-Second Haul

brought out in these experiments. When using the conventional estimating technique, it is quite rare for the balance point to fall at an even number of equipment items. It is normally 7.6 trucks, 8.1 scrapers, etc. Of course, it is impossible for the contractor to use 7.6 trucks, so he is faced with a decision of whether to base his estimates on seven or eight trucks. Most hot-mix contractors feel that since the cost of owning and operating the plant is so large in comparison with the owning and operating costs of a truck, it is better to use nine or ten trucks and always have a truck waiting at the plant than it is to have the plant standing idle. As is evidenced by the results presented in Figures 12 through 17, this is not the case. In every instance, the lowest unit cost is achieved by selecting the next higher number of trucks when the balance point is determined by maximum loading (which is the usual case). It should be kept in mind that the results plotted in these figures were determined by the simulation model which considers the probability of breakdowns, etc. As shown by the model, the next higher number of trucks beyond the balance point represents the point at which the marginal rate of production equals the marginal cost of production and is the point where the lowest unit cost is obtained. By adding additional trucks beyond this point, production is increased, but the increase in production is small when compared to the cost of the additional truck. It is this relationship which the contractor should consider as opposed to the ratio of plant cost to truck cost.

Perhaps more significant than the above fact is that the figures show the lowest possible unit cost can be obtained by adding one additional truck beyond the number which would normally be selected and operating under a partial load policy. This was found to be the case in each experiment conducted. An examination of the queue statistics and the efficiency of the plant and paver provided by the simulation model reveals a logical explanation for this phenomenon. When any number of trucks beyond the balance point is selected, there is usually a queue of trucks waiting at the plant. Thus, the plant is operating at or near maximum efficiency. However, the paver is not producing at maximum capacity and must occasionally wait on trucks to arrive. By reducing the amount of time required to load an individual truck (equal to one batch cycle), trucks arrive at the paver at a faster rate which increases the production rate of the paver. The addition of the extra truck allows the plant to continue operation at near maximum efficiency. The increase in the system's production is sufficient over the 8-hour period to more than offset the cost of the added truck and results in the lower unit cost. Any additional increase in haul capacity beyond the one extra truck does not, however, increase the system's production an adequate amount to offset the added cost of production.

This phenomenon of increasing haul capacity and producing with partial loads was most interesting since it had not been observed or mentioned during the course of the research. It also gave rise to an experiment which had not been anticipated. As observed during the research, there are often times when queues develop at the plant because of some equipment malfunction just as there are times when there are no trucks at the plant regardless of the plant-to-haul capacity ratio. Since the model proved that the unit cost can be reduced by partial loading when the system is theoretically balanced, it follows that production should be increased even more if a policy were adopted which allowed trucks to be filled to capacity when there are no trucks waiting at the plant and partial loading when there is a queue at the plant.

The simulation model was modified to test the results of this policy. A test step,

TEST E Q1, 0, BACK1

was inserted in front of the last ADVANCE block in the loading sequence. Thus, if one or more trucks were waiting at the plant, only partial loading was accomplished. The results of these experiments showed that such a policy had little or no effect on total production when the R value was greater than 1.2 and less than 0.83. Between these extremes there was an average increase in production of 5.1 percent. From the results of these experiments it is obvious that a flexible policy of loading and a certain amount of operator discretion would result in increased production and lower unit costs.

Economical Aspects of Equipment Selection

Most hot-mix paving contractors are rather limited in the alternatives available when selecting the fleet composition for a particular project. It was noted during the research phase, however, that several contractors had similar preferences when alternatives were available. For example, none used 7½-ton trucks when larger trucks were available even though haul distances were rather short. Some preferred 15-ton trucks over 22-ton trucks for short or moderate haul distances. There were other similar preferences which raised the question of what is the most economical combination of equipment to use for various haul distances.

A series of experiments was conducted using combinations of job and equipment parameters outlined previously. The first series of experiments involved a comparison of the unit costs associated with the various capacity trucks over a wide range of haul distances for a specified capacity plant. As shown in Figures 18 through 20, the lowest cost per ton was always obtained with the largest capacity truck. It should be noted also that as the haul distance increases, the more economical the larger trucks become. This is to be expected, since the greater the haul distance, the larger the ratio of small trucks to larger trucks required to produce the same output. Figures 21 and 22 show the production in tons per hour compared with the in-place cost per ton. They also serve to illustrate a point made previously. That is, once the lowest unit cost has been obtained, the cost to produce each additional ton rises sharply. As would be expected, the cost to produce each additional ton increases more rapidly for the larger trucks since the owning and operating costs are higher. This point is seen more clearly when the cost per ton is compared to the number of trucks required to sustain a given hourly production rate, as shown in Figures 23 through 25. Thus, a contractor should always use the largest haul unit available regardless of the haul distance involved. There are exceptions, of course. If physical limitations of the haul road, traffic conditions, job site turnaround, etc., substantially reduce the cycle time of the larger truck in comparison with a smaller one, then it is possible that the smaller ones would be the more economical.

Finally, a comparison was made of the unit costs resulting from the various capacity batch plants with a specified size truck. Naturally, the greater the capacity of a plant, the greater the hourly

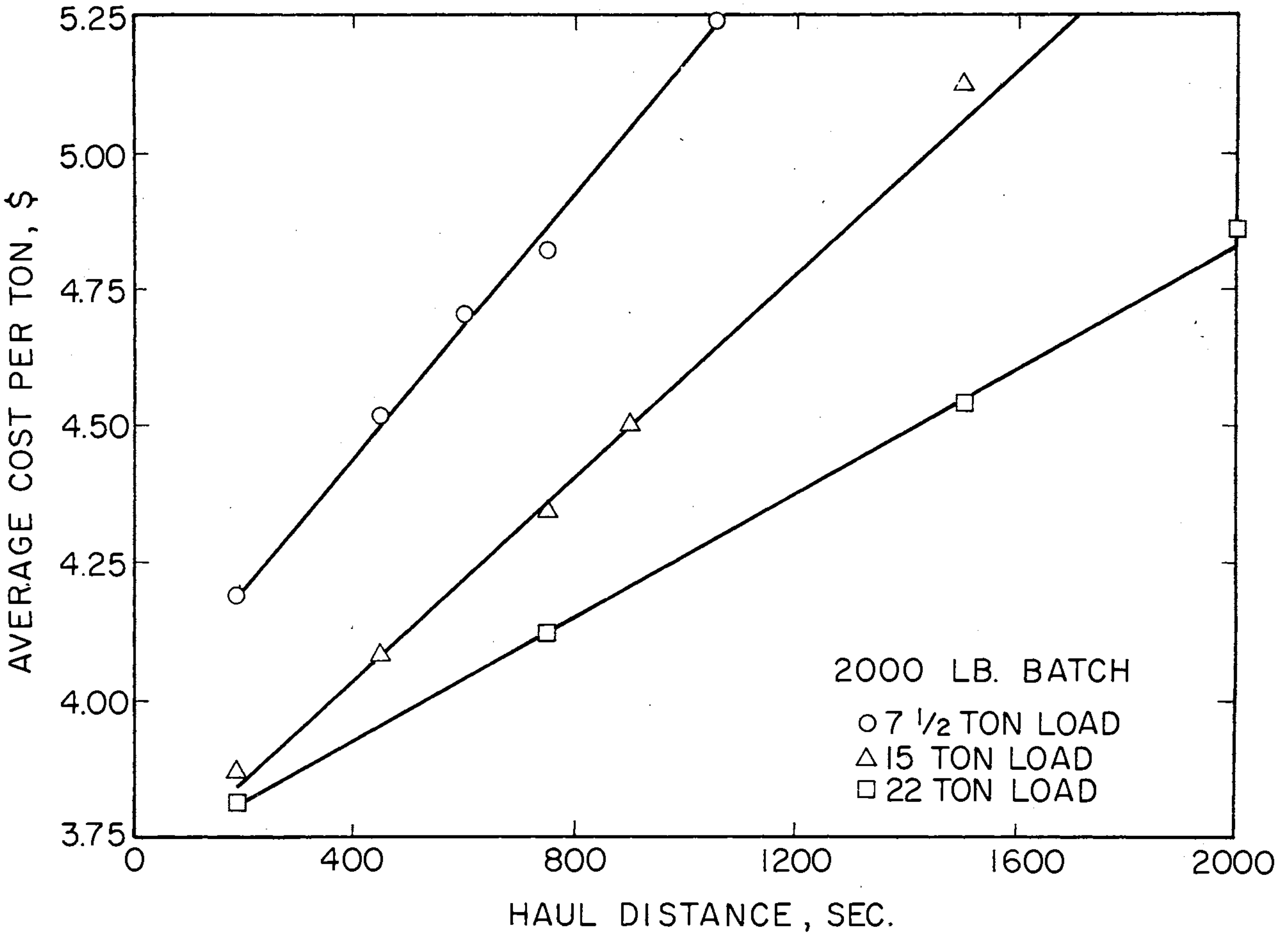

Figure 18. A Comparison of Unit Costs and Haul Distances for a 2000-lb. Batch Plant

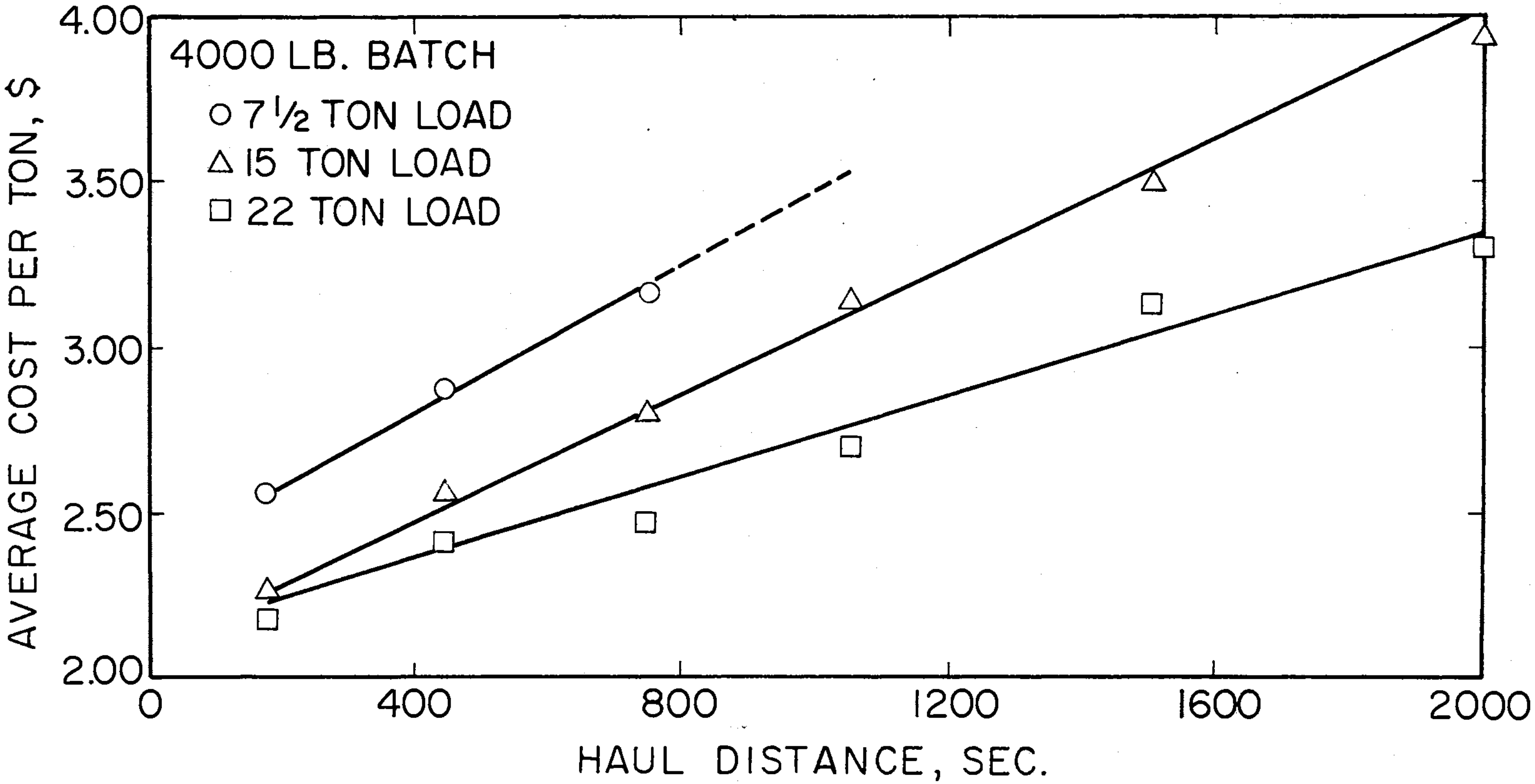

Figure 19. A Comparison of Unit Costs and Haul Distances for a 4000-lb. Batch Plant

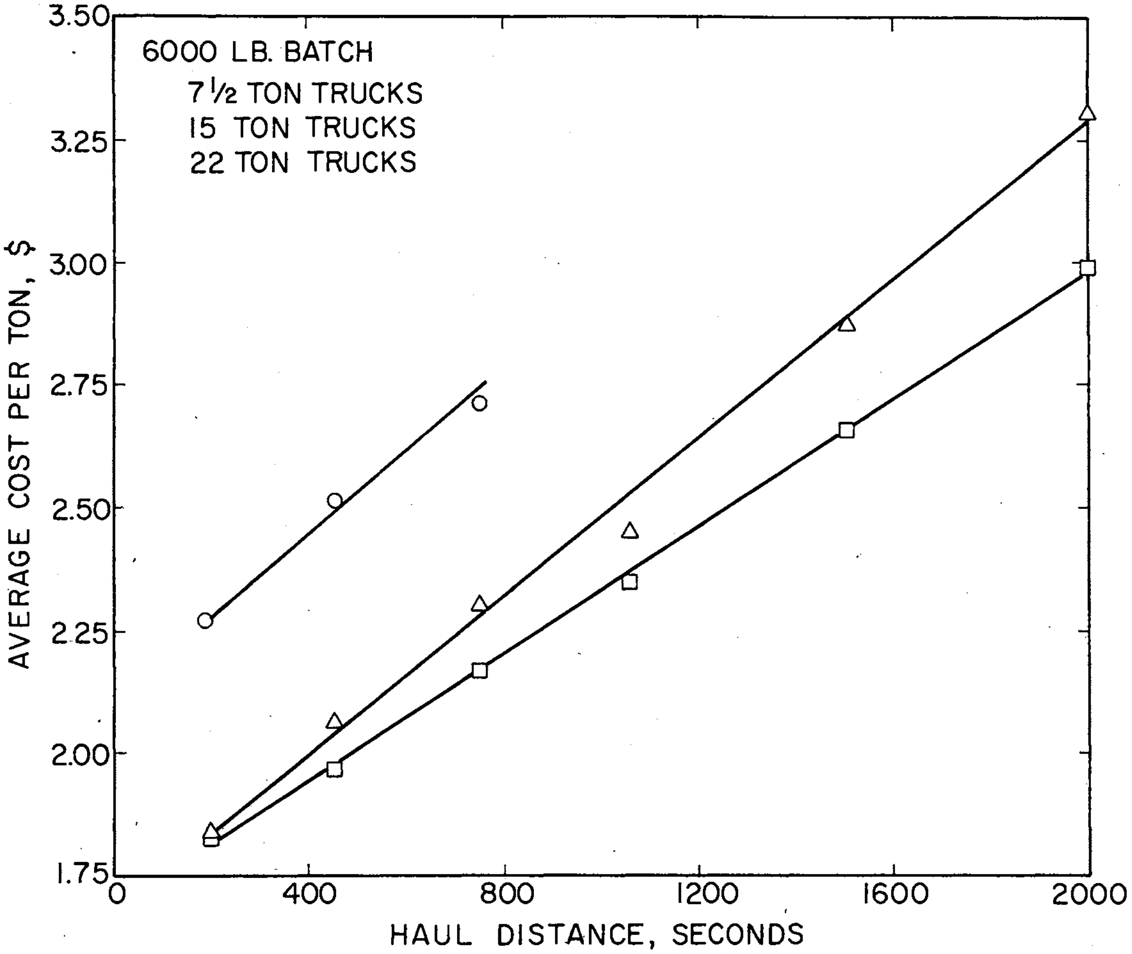

Figure 20. A Comparison of Unit Costs and Haul Distances for a 6000-lb. Batch Plant

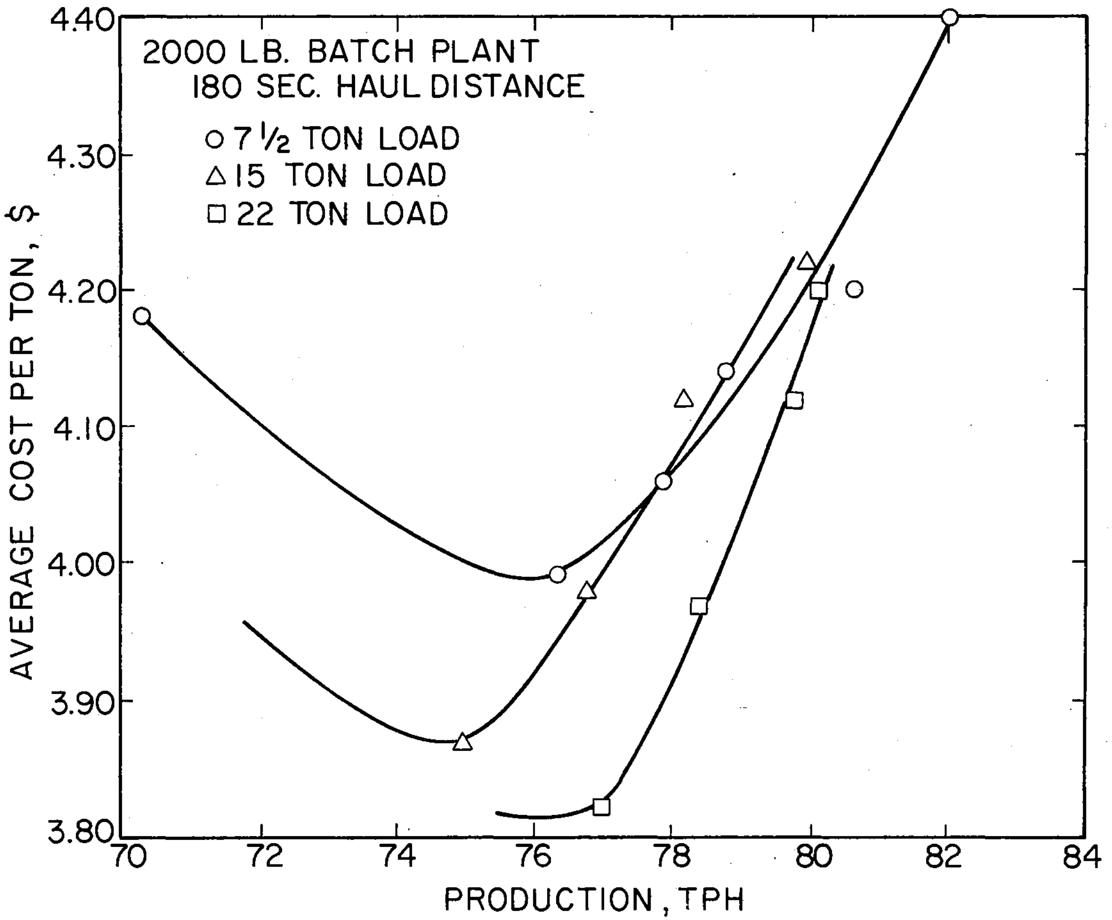

Figure 21. Production Costs for a 2000-lb. Batch Plant and 180-Second Haul

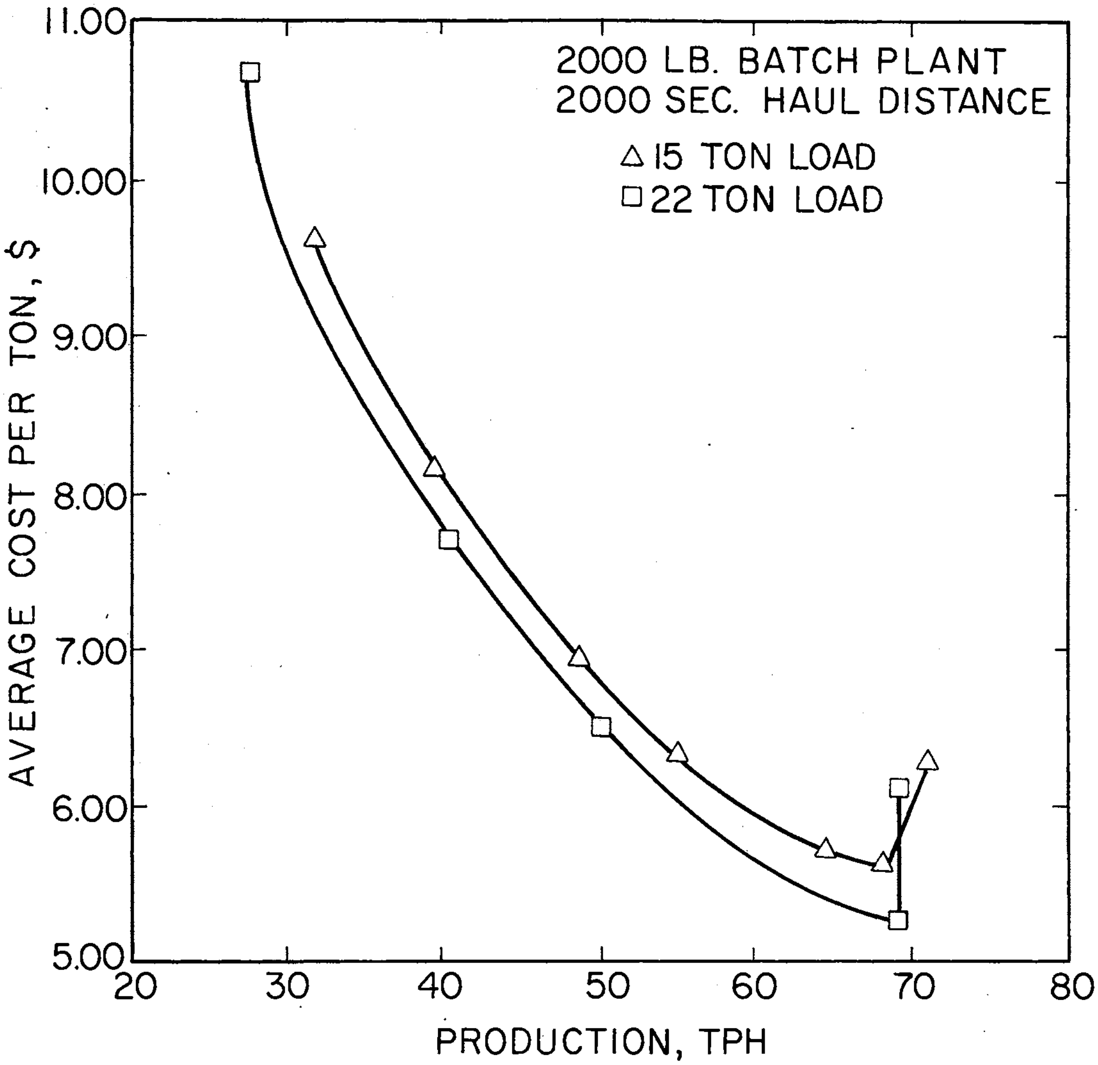

Figure 22. Production Costs for a 2000-lb. Batch Plant and 2000-Second Haul

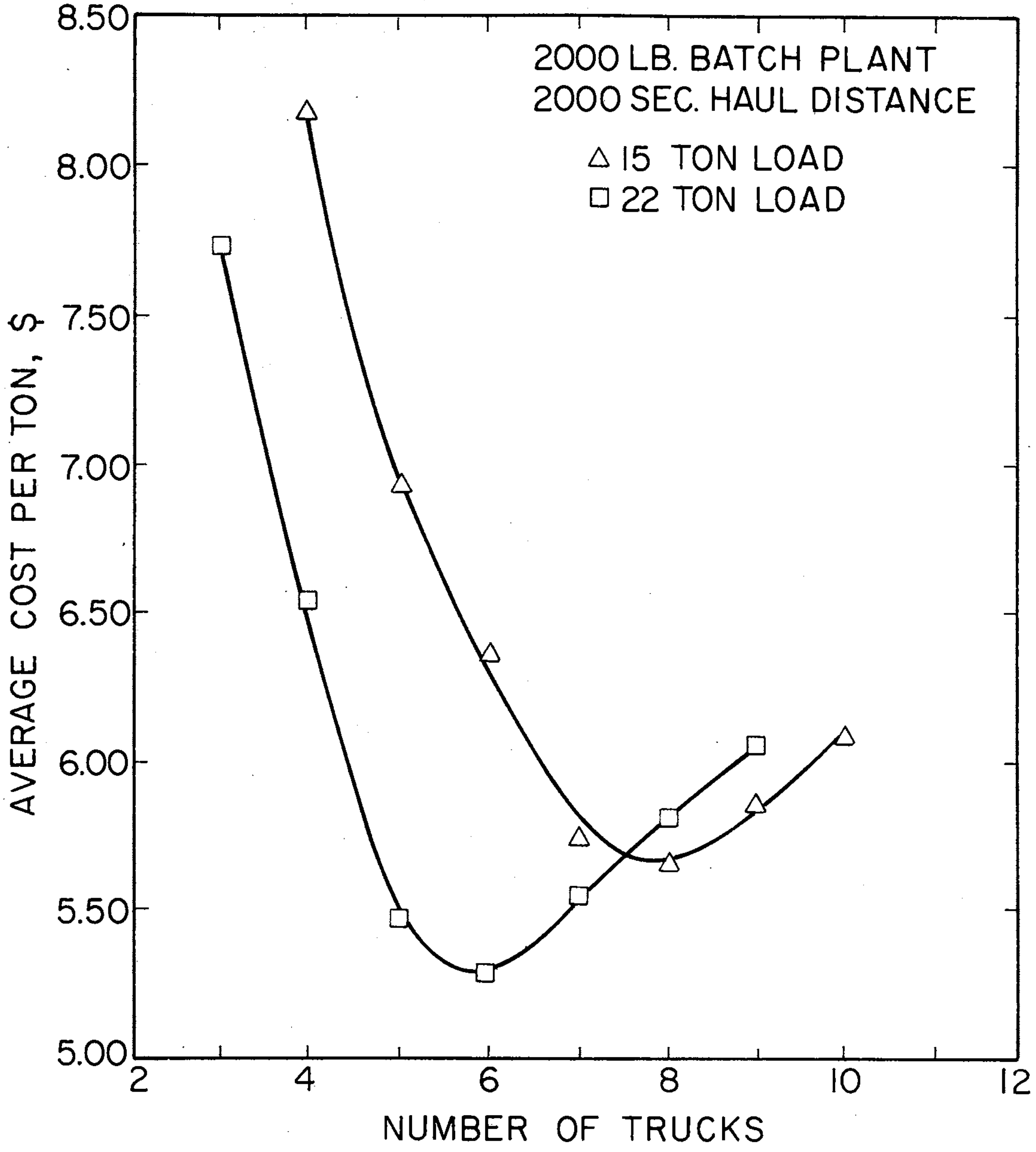

Figure 23. Haul Capacity and Unit Cost - 2000-lb. Batch Plant

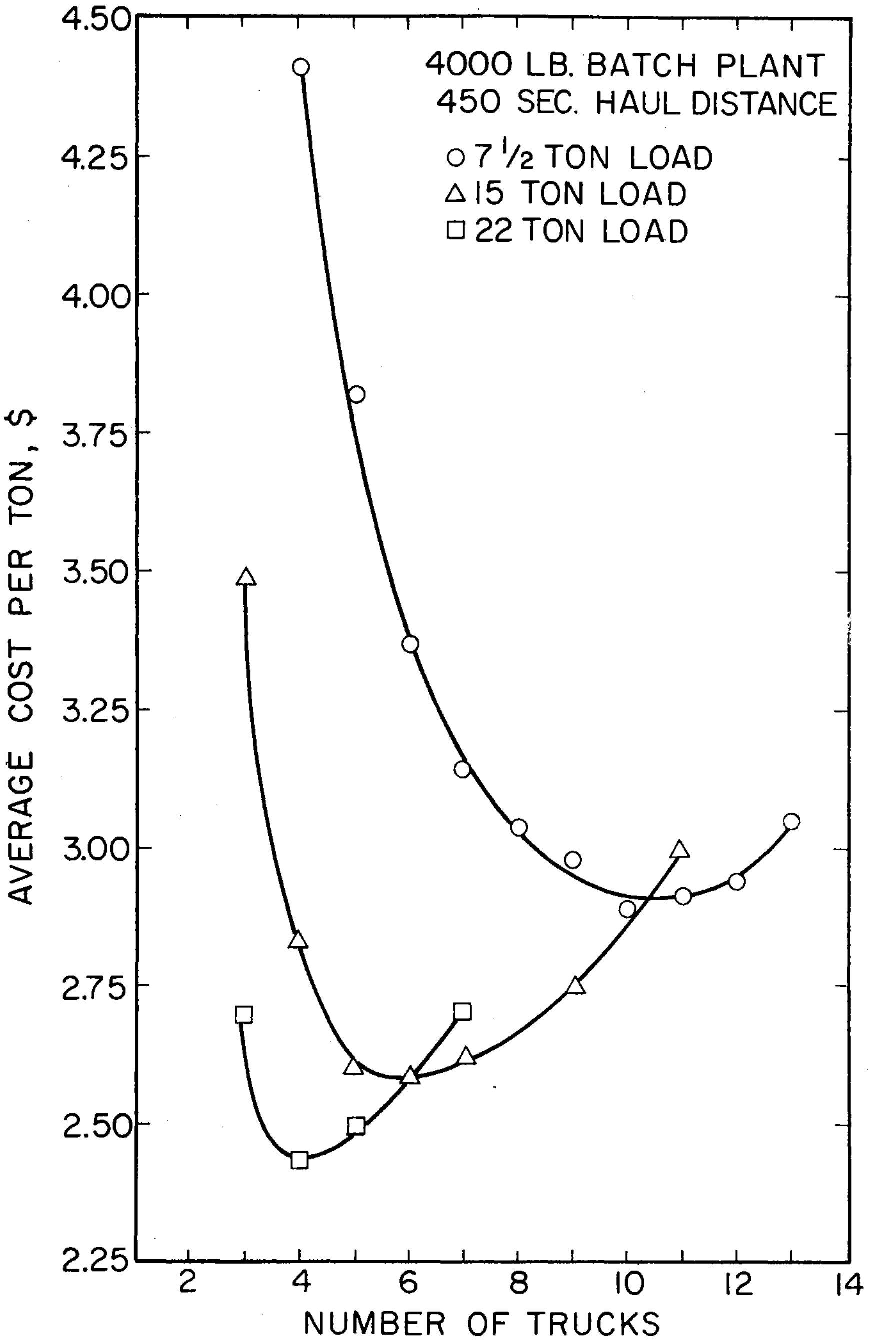

Figure 24. Haul Capacity and Unit Cost - 4000-lb. Batch Plant

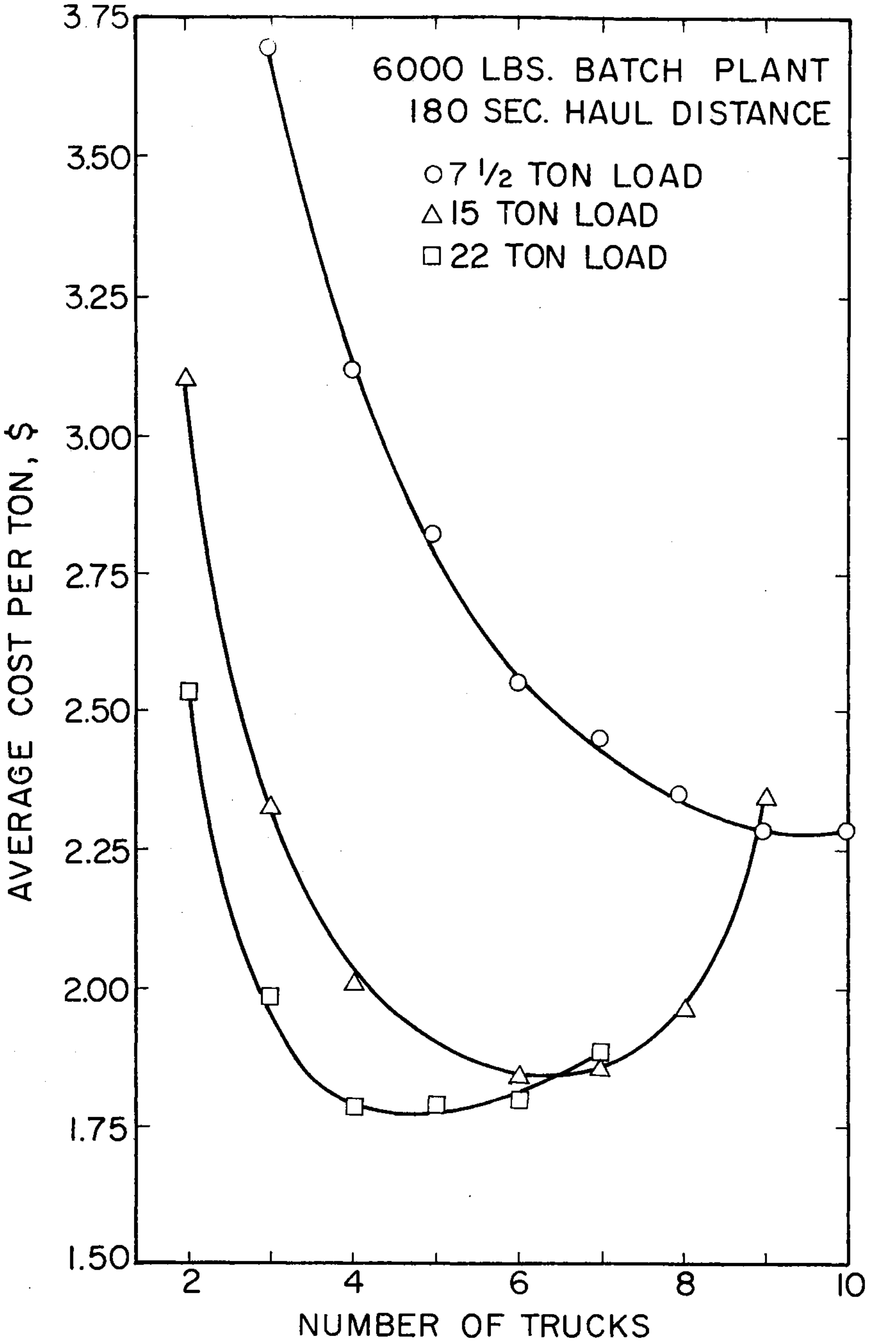

Figure 25. Haul Capacity and Unit Cost - 6000-lb. Batch Plant

production. However, there was some doubt as to the effect of hauling costs in relation to the plant costs on the unit cost of the in-place hot-mix. As shown earlier, the larger the number of haul units, the less the efficiency of the system because of the stochastic effects, but the results of the experiments indicate that the larger the plant capacity, the lower the unit cost which can be obtained.

Figure 26 shows the typical relationship between the production rates of the various batch plants regardless of truck size or haul distance. As expected, the larger the plant, the greater the hourly production. It is important to note that the difference in production rates is quite small and remains fairly constant when the haul capacity is small. It is not until the balance point of a system is approached that the greater capacity of a larger batch plant tends to manifest itself. Thus, the question arises: "Are the added owner and operating costs of the larger capacity plants offset by the increased production at the lower hourly production rates?" The answer proved to be "No."

Figures 27, 28, and 29 show the unit costs compared to the hourly production rates for the different batch plants. In each instance, the lowest unit cost is obtained with the largest batch plant, <u>provided</u> the average hourly production is maintained above a given level.

A compilation of all results from the simulation model reveals the following approximate breakeven points for the indicated batch plants with any combination of truck sizes and haul distances:

6000 lb. - 140 tph
4000 lb. - 80 tph

Thus, if a contractor estimates his sustained average hourly production at less than 80 tph, he would select the 2000-lb. batch plant, between 80 tph and 140 tph, the 4000-lb. batch plant, etc.

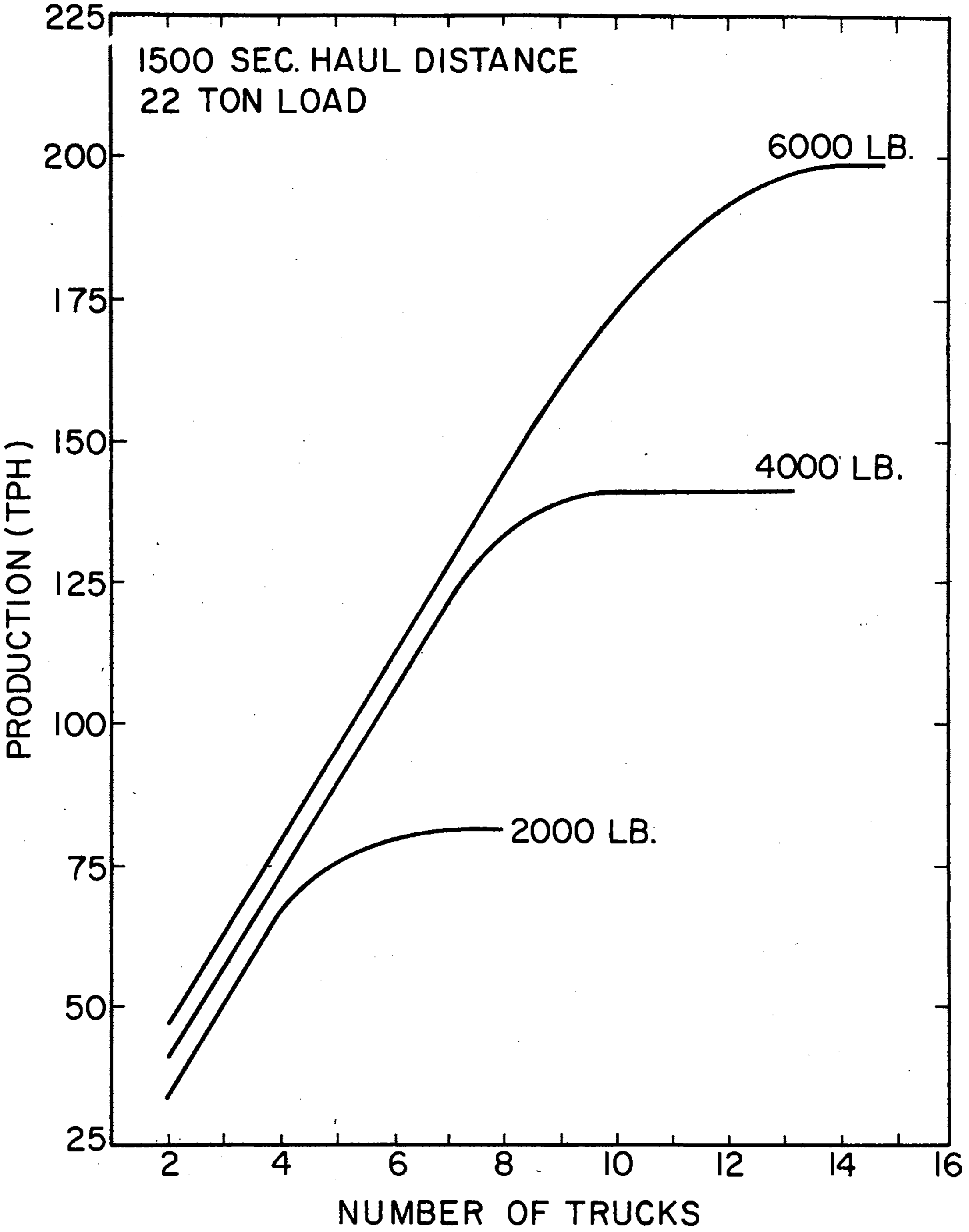

Figure 26. Production Rates and Haul Capacity

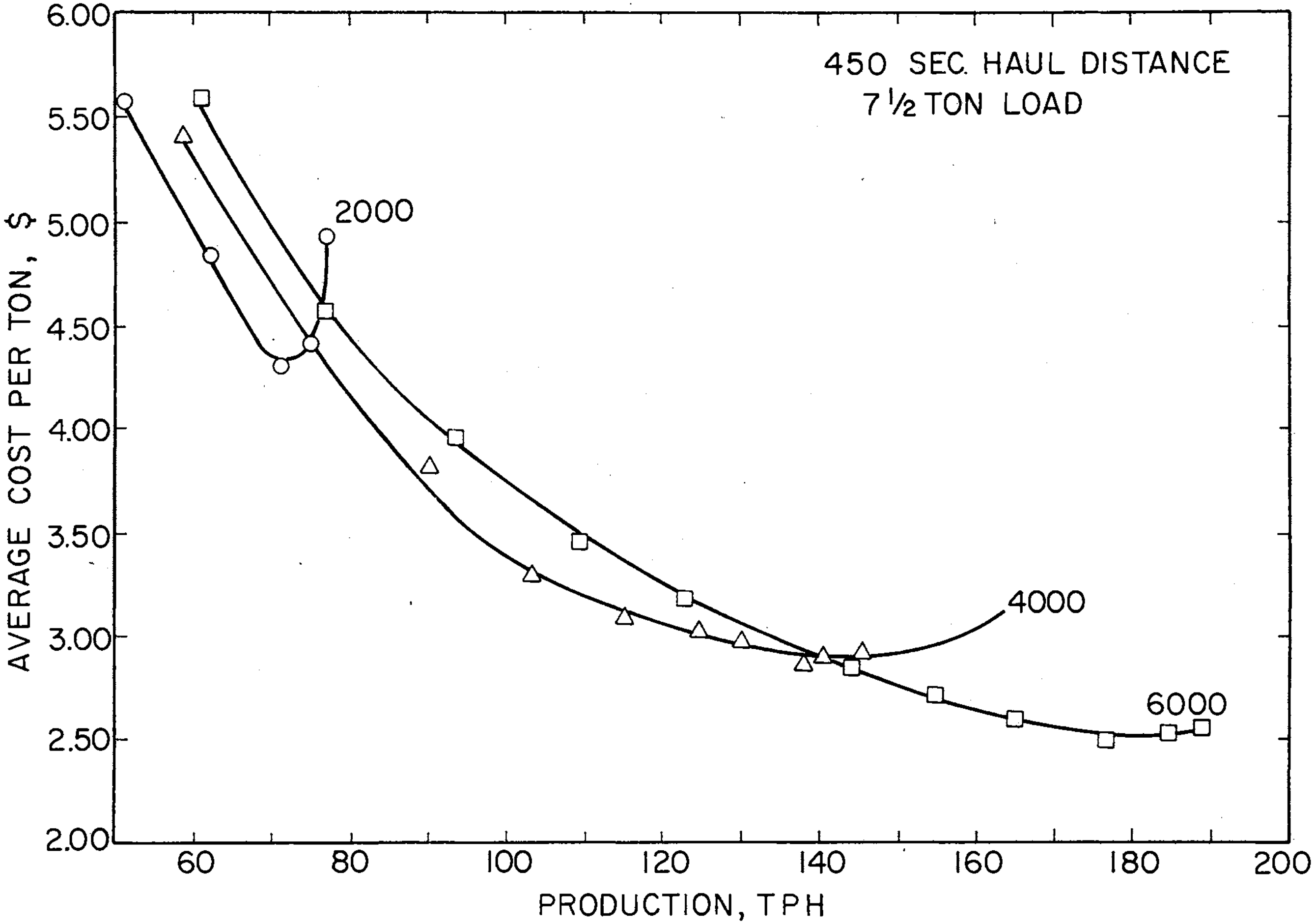

Figure 27. Unit Costs and Hourly Production - 7½-Ton Trucks

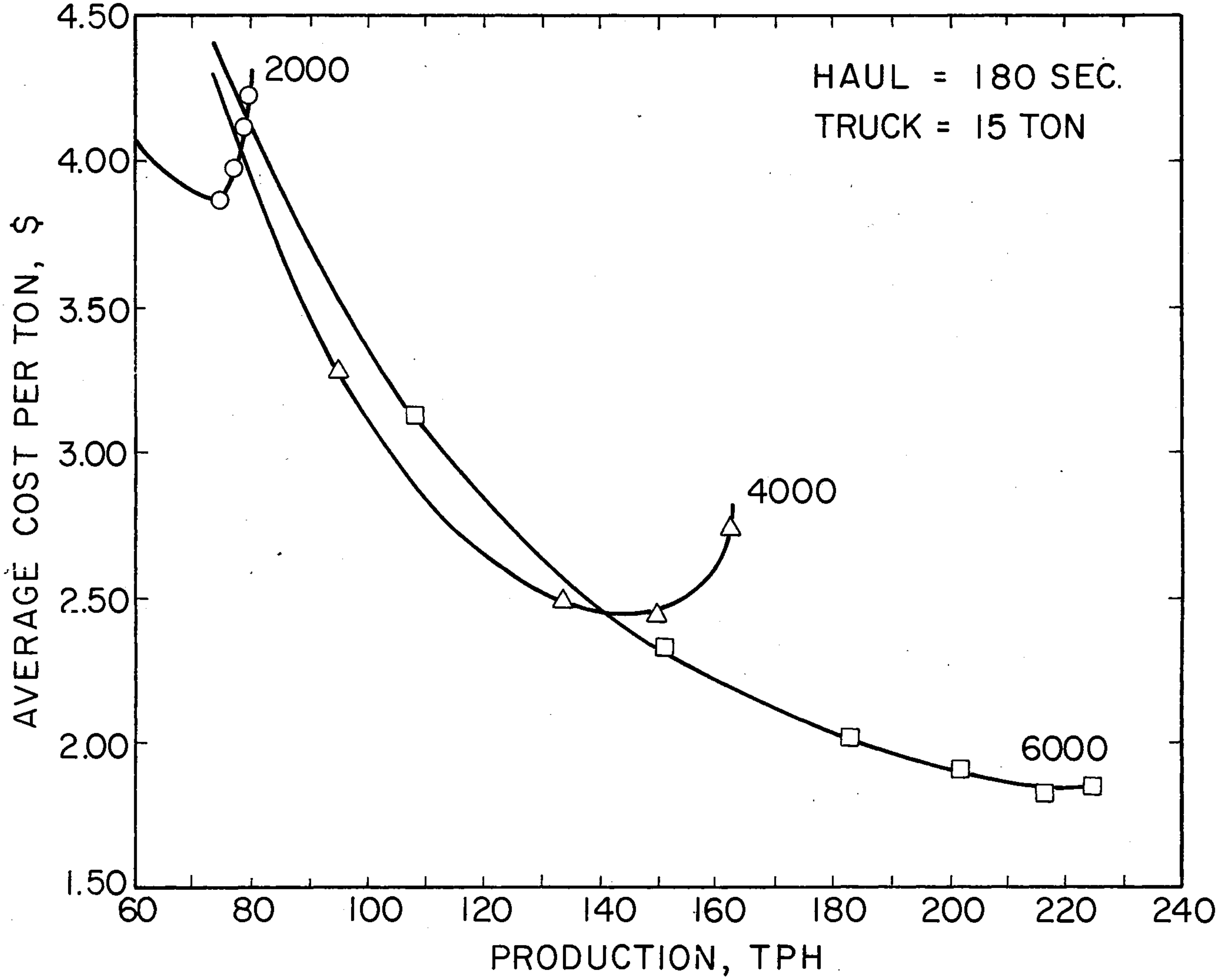

Figure 28. Unit Costs and Hourly Production - 15-Ton Trucks

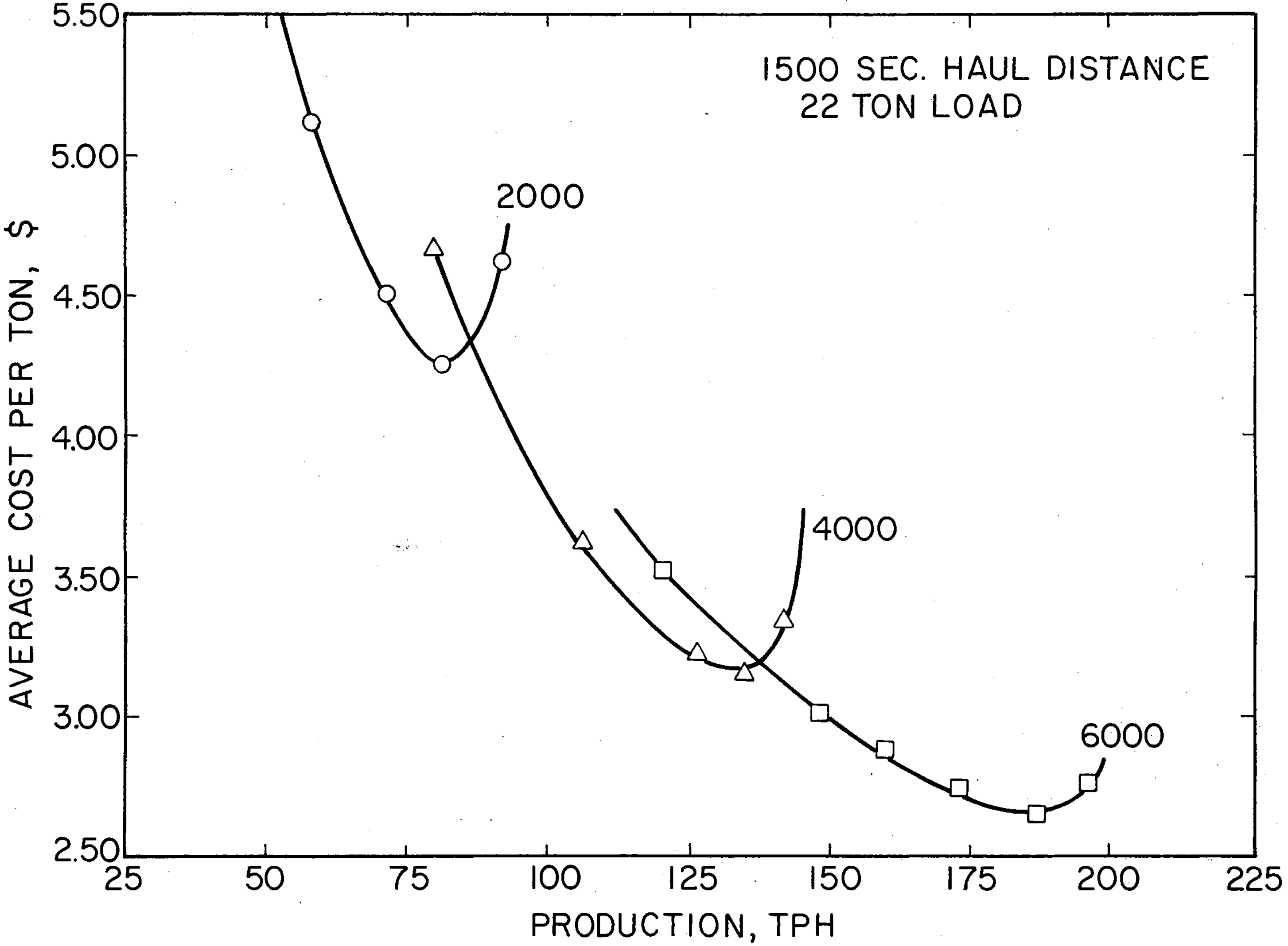

Figure 29. Unit Costs and Hourly Production - 22-Ton Trucks

These figures are not unexpected. They serve only to emphasize a point previously made; i.e., once the minimum unit cost is obtained, the cost of additional production increases rapidly. Also, if a plant is producing near its rated capacity, it is efficient from the economic viewpoint insofar as comparison with a larger plant is concerned.

The results of all experiments clearly indicate that the equipment with the largest capacities produce the lowest unit costs provided a given rate of production is maintained.

CHAPTER V

THE EFFECTS OF SURGE LOADING ON PRODUCTION

This chapter describes the results of a series of experiments with the simulation model to determine the effects of surge loading on the total production and in-place unit cost of a hot-mix asphaltic concrete system. The results of these experiments are compared with those obtained from experiments involving the conventional system (Chapter IV) to determine under what conditions, if any, the use of surge loading provides an economic advantage to the hot-mix paving contractor. Included in these experiments is an examination of the effects on total production of filling the surge hopper prior to the beginning of the work shift (pre-load) as opposed to starting the shift with the surge hopper empty (no-load).

Surge Loading

A surge hopper can store hot-mix for several hours without the onset of oxidation. This capability provides two distinct advantages over a conventional plant. First, it allows the plant to begin production prior to the beginning of the shift. This early start reduces the amount of non-productive time associated with plant startup in the conventional system and speeds the transition of the system to the steady state. Second, the holding capability of the surge hopper allows a plant to continue production during periods when the conventional plant would be forced to cease operation because of the non-availability of trucks. In addition to these two principal advantages, the time required to load a truck from the surge hopper is substantially less than that required by direct loading from the pugmill. This reduction in loading time decreases the system cycle time for each truck. Therefore, the number of trucks required for the system to produce a given amount of hot-mix is less than would be required to produce an equal amount with a conventional plant.

The increase in production and/or the reduction in required haul capacity resulting from the installation of a surge hopper into a hot-mix system must be sufficient to offset the owning and operating costs of the surge hopper. It is the purpose of the experiments described in this chapter to determine with what combinations of equipment and haul distances the installation of a surge hopper is justified. To accomplish these experiments, a surge hopper was introduced into the simulation model.

The Simulation Model

Model No. 2 (Appendix C) was used in each of the experiments described in this chapter. It functions in a manner identical to that described for Model No. 1 with the exception that a 100-ton surge hopper was inserted into the system at the plant. The model was constructed first to represent a system in which production begins one hour prior to the beginning of the work shift. This would be the most efficient use of the surge hopper. After the experiments with this system were complete, the early start option was removed and a series of experiments was conducted to determine what advantages accrued from the early start. The model also has the capability of switching from surge loading to direct loading any time the surge hopper does not contain sufficient hot-mix to load a truck. This is the procedure followed by those contractors who have surge loading because it saves energy costs and time.

The experimental job parameters investigated and discussed in this chapter are the same as those examined in Chapter IV. These parameters are given in Table II. The owning and operating costs for the surge hopper are developed in Appendix A.

The Effects of Truck and Plant Capacity on Production

The first series of experiments involved a comparison of the unit costs associated with the various capacity trucks over a wide range of haul distances for a specified plant capacity to determine if the use of a surge loading system would invalidate the results obtained for a conventional system in Chapter IV. The results of these experiments, like those for the conventional system, revealed that the lowest unit cost is always obtained with the largest capacity truck regardless of haul distance or batch capacity.

Figure 30 provides a comparison of the unit costs obtained with the various capacity trucks over the range of haul distances for a 6000-lb. batch plant. As with the conventional system, the greater the haul distance, the more pronounced the advantage of the larger capacity truck. At the shorter haul distances, the ratio of the number of small trucks to the number of large trucks required to achieve a balanced system is substantially less than at longer haul distances. It is

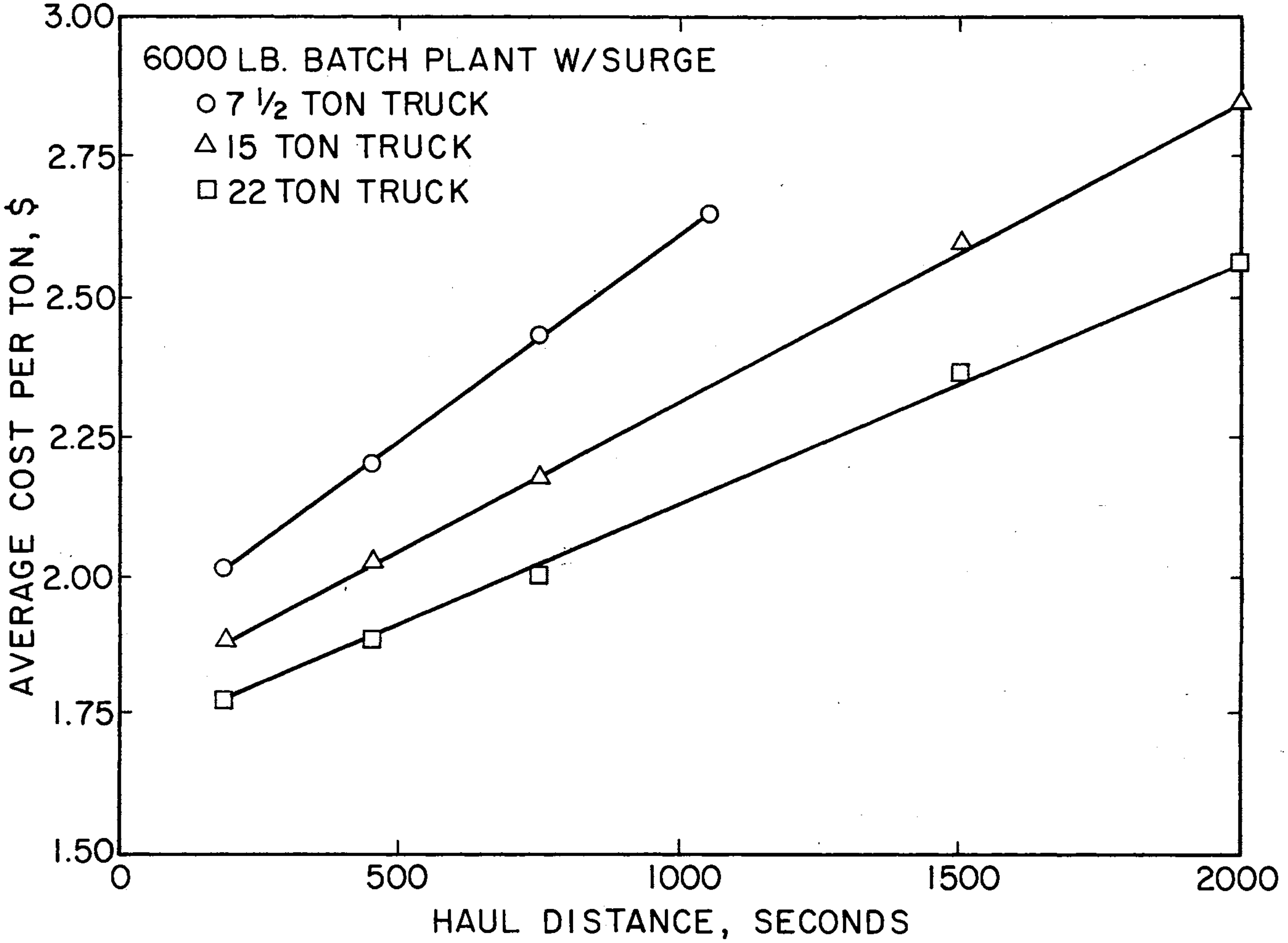

Figure 30. The Effects of Distance on Costs of Production

apparent that as the number of trucks in the system is increased, the increase in production resulting from each additional truck decreases. This is shown more clearly in Figure 31. The marginal rate of production for the fourth truck, X_4, is 24 tph (132 tph - 108 tph). As the number of trucks increases, the hourly production each contributes to the system decreases. The marginal rate of production for the eighth truck, for example, is 13 tph. Thus, the system with the smallest number of trucks for a specified haul capacity will result in the greatest production because of reduced stochastic effects on the system. Since the number of trucks required to produce a given quantity of hot-mix is less with a surge hopper than with direct loading, the reduction in production due to stochastic effects is also less.

A comparison between the unit costs obtained with the various capacity batch plants with surge loading and a specified truck size revealed results similar to those obtained for the conventional system. As shown in Figure 32, the lowest unit cost is obtained with the largest batch capacity, provided a given level of production is maintained. It was shown in Chapter IV that the levels of production which produced the lowest unit costs with the conventional system were approximately 72 tph, 145 tph, and 185 tph for the 2000, 4000, and 6000-lb. batch plants, respectively. Since a surge loading system increases production, the level of production at which the lowest unit cost can be obtained is also increased. Where the surge hopper is pre-loaded before the shift begins, the approximate levels of production at which the lowest unit costs can be obtained are approximately 83 tph, 162 tph, and 227 tph.

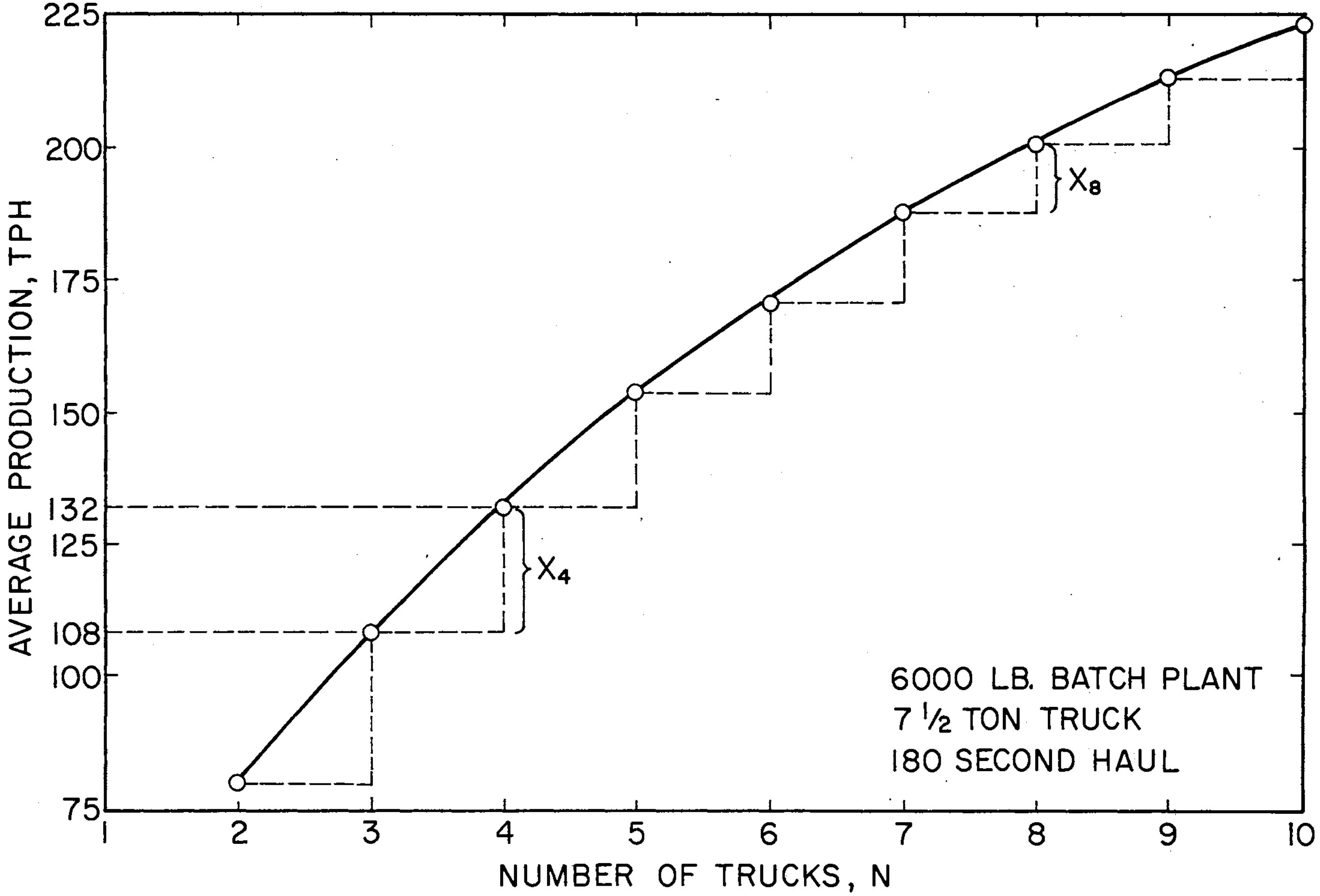

Figure 31. The Marginal Rate of Production - 6000-lb. Plant and 7½-ton Trucks

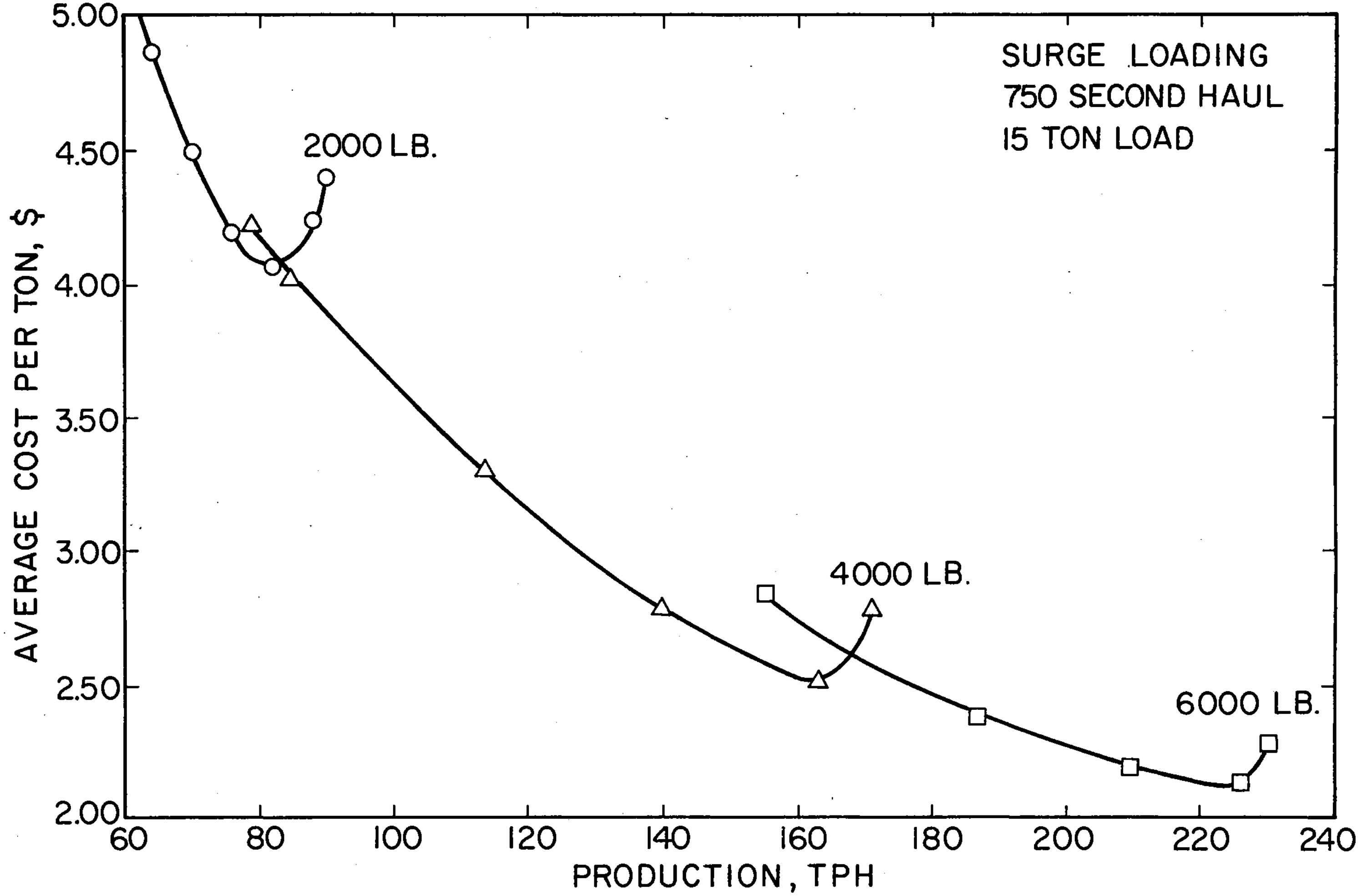

Figure 32. The Effects of Plant Capacity on Costs of Production

A Comparison of Conventional and Surge Systems

From the preceding comments and the discussion of the advantages of a surge hopper, it is obvious that the production of a system employing surge loading is expected to be higher than that for a conventional system where all other considerations are equal. This was the case in all 1296 simulations conducted for surge systems when the results were compared to the production rates of comparable conventional systems. This includes those experiments where the hopper was not pre-loaded.

Figure 33 shows the typical effects of surge loading on a hot-mix system. From Figure 33a it is obvious that, for a given haul capacity, the production rate of the surge system is substantially greater than that of the conventional system. This was true in every combination of parameters tested. Figure 33b shows the percentage of increase in production for each haul capacity when the surge hopper is used. As noted, the smaller the haul capacity, the greater the effect of surge loading. This fact should not be misconstrued to imply that the most efficient use of the surge hopper is with a large plant capacity/haul capacity ratio (R-Value). For example, from Figure 33b it is seen that the greatest percentage of increase in production occurs when two trucks are used for the system being examined. Figure 33a shows that the surge loading could be expected to increase production from 90 tph to 118 tph --an increase of 28 tph. This is a greater increase than can be obtained at any other haul capacity. However, it will be shown that when the owning and operating costs of the surge hopper are considered, there is a minimum level of production which must be maintained for the surge hopper to have an economic advantage over the conventional system.

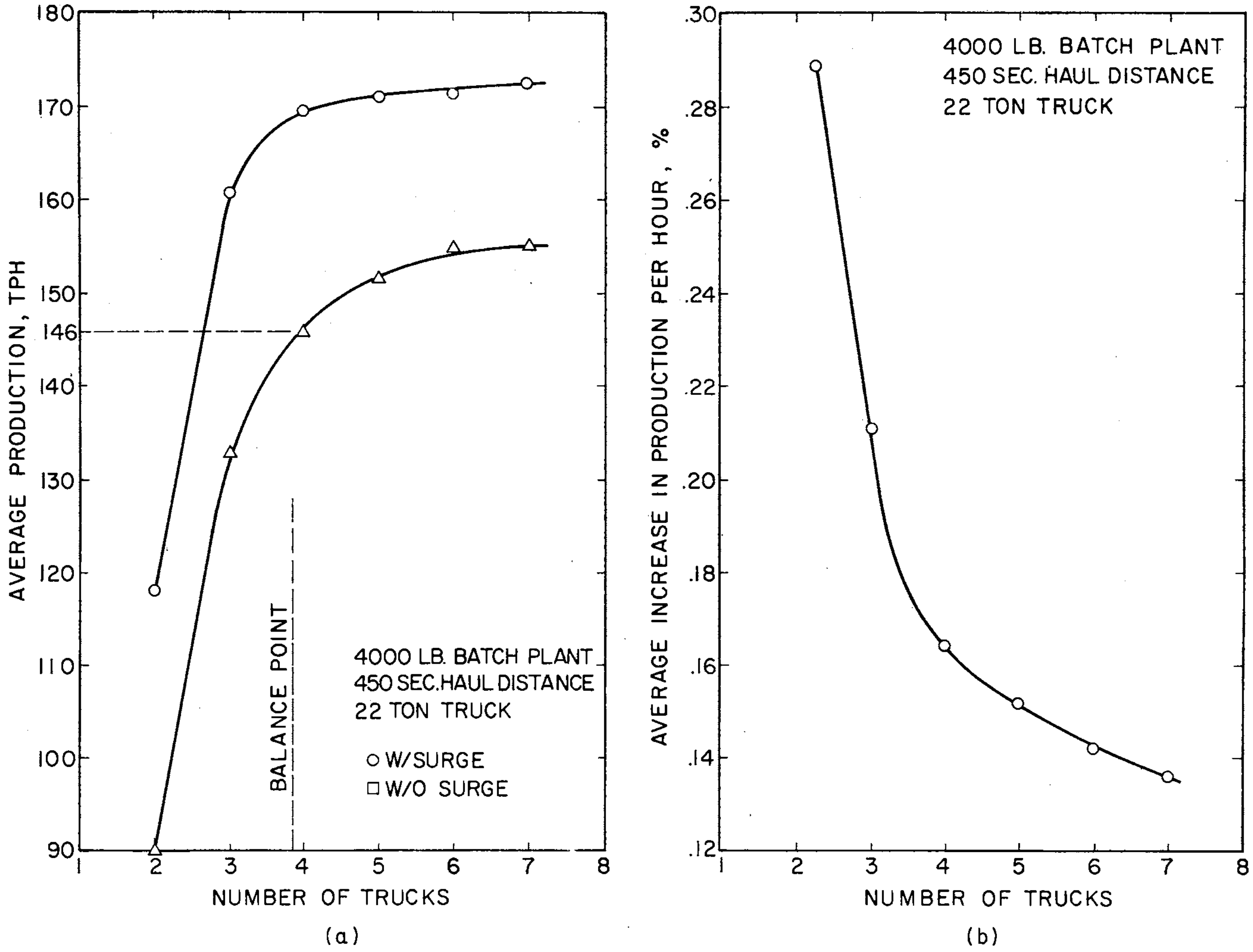

Figure 33. Production Rates of Hot-mix With and Without Surge

A comparison of the unit costs of production for each haul capacity for the conventional and surge systems is shown in Figure 34a. Notice that for a given haul capacity, the lowest in-place unit cost is obtained with the surge system. This indicates that the increase in production resulting from the surge hopper is sufficient to offset the owning and operating costs of the surge system with any haul capacity. This was the result in every combination of parameters except for 22-ton trucks hauling from a 2000-lb. batch plant. With this equipment combination, the surge hopper could not increase production a sufficient amount to offset the cost of the system.

If the cost per ton is compared to the rate of production as in Figure 34b, a most significant factor evolves. There is a rate of production below which the conventional system is more economical than the surge system. From Figure 33a, the balance point of the conventional system is 3.85 trucks. Based upon the investigations conducted in Chapter IV, four trucks would be selected for the system. From this same figure, the production rate for four trucks would be 146 tph. As shown in Figure 34b, the lowest unit cost is obtained with the production rate of 146 tph. It is approximately at this rate that the surge hopper becomes more economical than the conventional system. In every combination of equipment parameters[1] it was found that the breakeven point between the conventional and surge systems was at or very near the balance point.

Obviously, a paving contractor faced with the decision of whether or not to install surge loading should first examine his present operation and future expectations. If the conventional system normally

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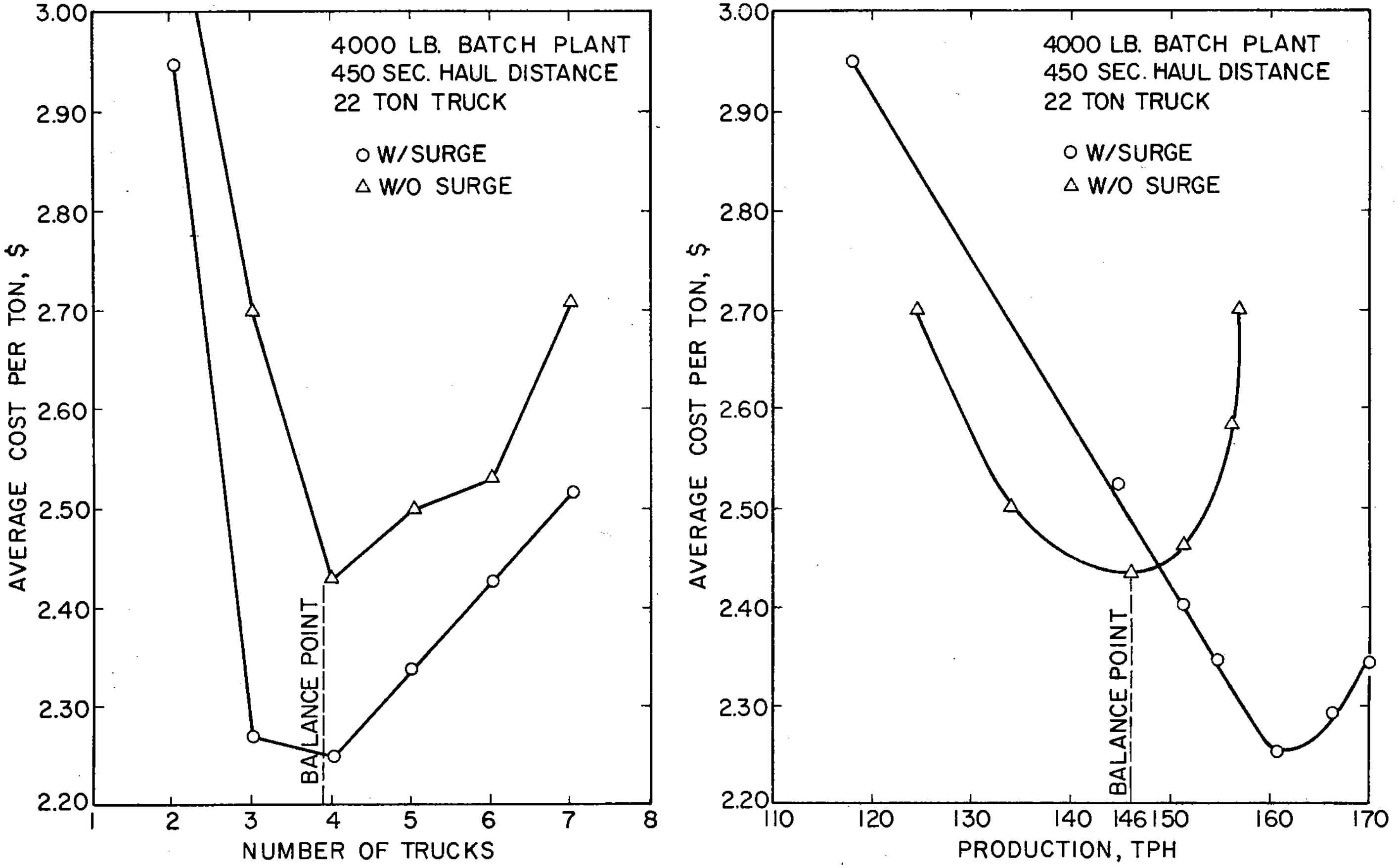
[1] Except for the 22-ton truck/2000-lb. batch plant combination.



(a) (b)

Figure 34. Costs of Production With and Without Surge

operates with the most efficient plant capacity/haul capacity ratio (R-Value) and if he can expect the average hourly production rate for the year[2] to equal or exceed the production rates given in Table IV, the installation of surge loading could be economically advantageous.

TABLE IV

OPTIMUM PLANT PRODUCTION RATES

Plant Capacity (batch size, lbs)	Optimum Production Range (tph)
2000	72
4000	145
6000	185

Further analyses of the results of the comparison of surge and conventional loading reveal another factor for consideration. If the increase in average hourly production is expected to exceed approximately 17 percent of the optimum production rate of the conventional plant, there are indications that it may be more economical to invest in a larger capacity conventional plant in lieu of installing surge loading. The experiments conducted for this study did not prove this theory conclusively. This is a subject which should be investigated in future analyses of the economics of hot-mix production.

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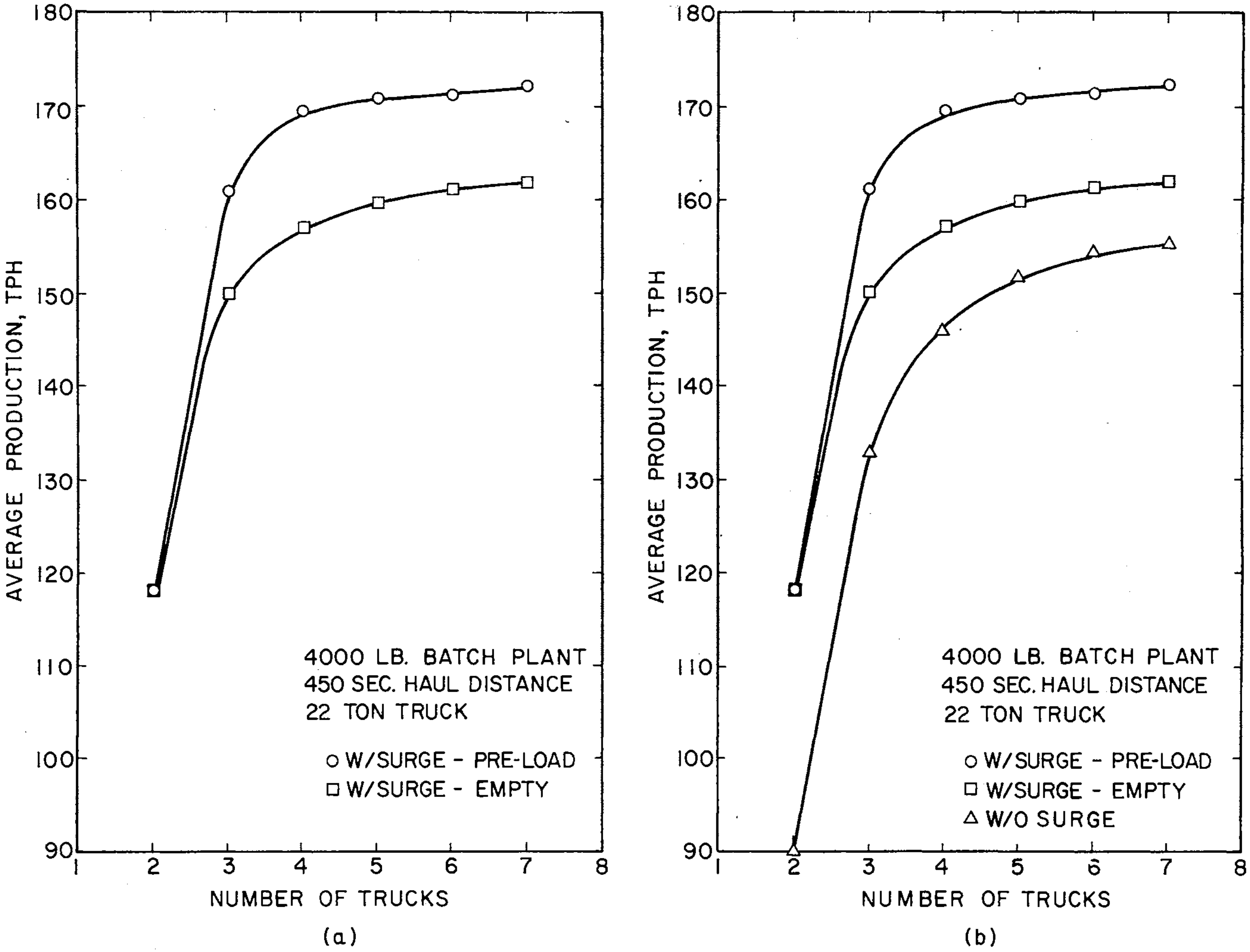
[2] Based upon 960 hours of operation per year (see Appendix A).

Pre-loading the Surge Hopper

As mentioned previously, one of the advantages of surge hoppers is the temporary storage capacity. By beginning the plant operation early, a supply of hot-mix can be on hand at the beginning of the shift. All of the prior experiments involved an early startup of one hour. The assumption was made that during this time period the 4000 and 6000-lb. batch plants would pre-store 100 tons of hot-mix, while the 2000-lb. plant would produce 65 tons. To determine the effects of the surge hopper on production when no early startup is used and when the plant is involved in continuous operation, each of the previous surge experiments was duplicated, but the surge hopper was empty at the beginning of the shift.

As noted in the preceding section, in every experiment the production rate with the surge hopper was greater than that of the conventional system when all parameters were equal. The reason for this is, that even in a balanced system there are periods when the plant is idle due to delays or breakdowns in the other subsystems. Of course, in systems where there is an insufficient number of haul units, the plant must frequently wait for trucks. With the surge hopper, the plant can continue to produce during this period. The question is, "Can the increase in production offset the costs of the surge system?"

Figure 35a shows a comparison of the production rates of a surge system when the hopper is pre-loaded and when the shift begins with the hopper empty. When the haul capacity is small in relation to plant capacity (high R-Value), the difference in production is quite small. The reason for this is, of course, with a small number of trucks the plant has sufficient time to build up the storage in the hopper between



(a) (b)

Figure 35. Production Rates With Pre-load and No-load Surge

truck arrivals. The difference in production rates reaches a maximum near the balance point of the system (R = 1) and remains relatively constant as haul capacity is increased beyond this point.

The production rates for a comparable conventional system are included in Figure 35b. For reasons previously mentioned, the conventional production rates are less than those obtained with the surge hopper. The maximum difference in production rates with and without surge also occurs near the balance point and remains relatively constant as haul capacity is increased beyond this point.

The production rates for a comparable conventional system are included in Figure 35b. For reasons previously mentioned, the conventional production rates are less than those obtained with the surge hopper. The maximum difference in production rates with and without surge also occurs near the balance point and remains relatively constant as haul capacity is increased beyond this point.

A comparison of unit costs for the system is shown in Figure 36. As would be expected, the difference in cost between the pre-load and no-load surge systems is quite small with the small haul capacity. Likewise, the cost difference reaches a maximum at the balance point and remains relatively constant.

As shown in Figure 36, the costs of production for the surge system with no-load and the conventional system become equal at the balance point and remain equal as haul capacity increases. Thus, with a no-load policy, the added production resulting from the surge hopper is adequate to offset the costs of the system but provides no economic advantage over a conventional system.

A contractor with a surge system can obtain the maximum efficiency

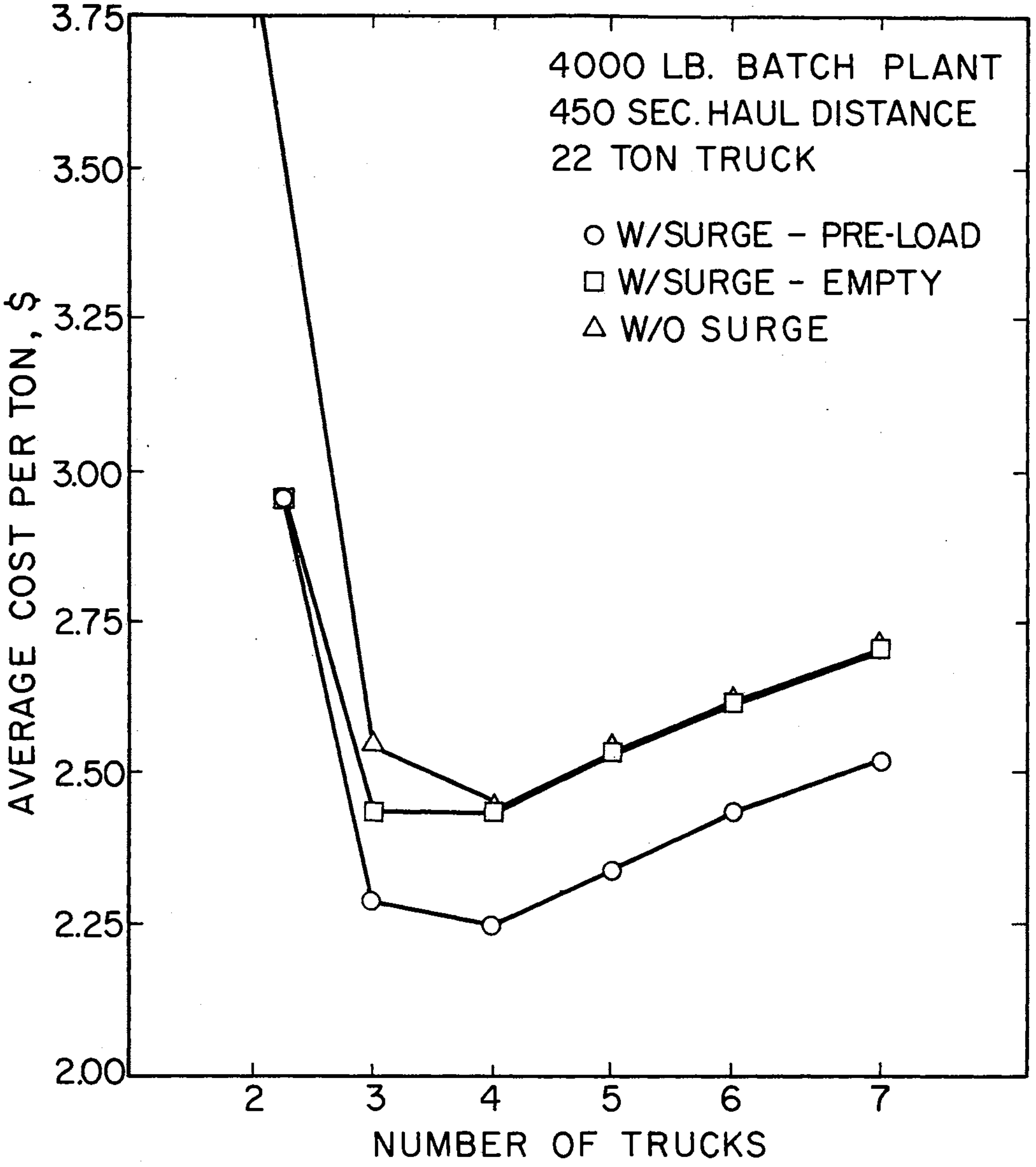


Figure 36. Costs of Production With Pre-load and No-load Surge

from his equipment by pre-loading the surge hopper--particularly when the plant capacity/haul capacity ratio approaches 1. With a surge system, a pre-load policy will increase daily production by approximately seven percent. When the plant capacity/haul capacity ratio is large, very little advantage accrues from an early start.

CHAPTER VI

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Simulation can be used to analyze construction projects whose complexity and dynamic nature are such that a mathematical solution is impossible. The construction engineer who has an understanding of simulation techniques and languages can describe the project as it is expected to function, define the physical parameters to be tested, and specify the form and the extent of the output. With sufficient time and access to a computer, any number of approaches to a particular project can be studied.

This study has demonstrated that a proposed construction project can be modeled accurately and analyzed thoroughly by means of simulation. A model to represent the production and placement of hot-mix asphaltic concrete was developed, tested for reliability and accuracy, and used for an analysis of the economic effects of various equipment combinations and physical parameters on hot-mix production.

As might be expected, extensive research was required prior to development of the model to determine the probability and the frequency of occurrence of specified events. The results of the research revealed that the most accurate representation of any system is obtained when the true probability distributions for that system are used in the model. Experimentation with the model indicated that when there is insufficient time or data to develop actual probability distributions, certain standard distributions may be substituted with an acceptable degree of accuracy. The truncated normal distribution is adequate for representation of the spread of haul and return times of trucks; the shifted exponential distribution reflects the distribution of batching times; and the log-normal distribution may be used for modeling paver lay-down times and truck maneuver times.

With the inclusion of probability distributions and a Monte Carlo technique of random sampling, the simulation model is capable of reproducing the stochastic effects caused by the dependence between associated segments of the system. When analysis of a project is based upon results obtained by such a model, the estimated system performance more closely approximates actual system performance than do estimates obtained by conventional means. The model used for this study and a commentary for modification of the model to represent various physical parameters have been provided for anyone desiring to use a stochastic approach for estimating production costs of hot-mix. For those without the accessibility to computer, a series of correlation factors was developed which will convert the conventional estimate to the simulated estimate.

Results of experiments with the model reveal that the lowest unit cost for production of hot-mix can be obtained with the largest size haul unit available for any plant capacity regardless of haul distance. Likewise, the lowest unit cost can be obtained with the largest capacity plant provided a given level of production is maintained.

In instances where partial batching is required to achieve maximum truck capacity, it is more economical to load the truck to maximum capacity if the system is underbalanced, but the lowest unit cost can be obtained by underloading the truck when the system is overbalanced. A slight increase in efficiency is possible by adopting a policy of underloading a truck when there is a queue of trucks at the plant and reverting to maximum loading when there is no queue.

Introduction of a surge hopper into the system will increase production in every instance. With all physical parameters equal, the increased production is adequate to offset the owning and operating costs of the surge hopper. However, the surge hopper will not lower the optimum minimum cost of production of a hot-mix system until the optimum production obtainable by the conventional system is exceeded.

During the research of available literature on the economic aspects of hot-mix production, it quickly became apparent that very little had been written on the effects of equipment selection or management policies on the costs of production. Manufacturers of specialized equipment make unsubstantiated claims of the advantages offered by their products, but very little is printed concerning total systems analysis. The scope of this study only begins to scratch the surface. The field is fertile for further development and research.

It is recommended that correlation factors for converting conventional estimates to closer approximations of expected production be developed for conventional plants above 6000-lb. batch capacity. Future studies should include factors influencing the decision to install surge loading or purchase a large capacity plant. Additionally, research involving optimum surge hopper capacity in relation to truck size and plant capacity would be most beneficial to larger contractors.

Contractors must be made more aware of the many advantages offered to the industry by simulation techniques. A valuable management tool is lying dormant. While the nation's largest industry readily accepts modern technological advances in equipment and other consumable products, decision-making processes are difficult to penetrate with new innovations. To date, little has been done in the application of simulation to concrete paving, high-rise building construction, or the many other facets of the construction industry. The field is wide open for simulation application to those who desire to make a contribution.

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APPENDIX A

OWNING AND OPERATING COSTS

Introduction

The owning and operating costs for the haul units, hot-mix plants, and the various equipment required for the laydown operation are developed in this Appendix. All mathematical computations are shown for the different size haul units and the paving equipment. Costs for the various capacity batch plants were all derived using the same techniques so only the computations for the costs of the 6000-lb. batch plant are presented. A summation of the remaining batch plant costs is included.

Materials

For purposes of this study, the cost of materials is ignored. Since this investigation is concerned primarily with the economics of equipment fleet composition and operation, and the cost of materials would affect each equipment combination equally, omitting these costs will not invalidate the results of the investigation. In fact, because of the wide variation in material costs with geographical area and physical location of the plant, the conclusions derived from the study will be more universally applicable.

Equipment

There are many options available in selecting construction equipment. An effort was made to select items of equipment for inclusion in this study which appear to be the most commonly employed equipment by paving contractors in the Oklahoma area. This was accomplished by interviews with Oklahoma contractors and by examination of the sales volume of comparable items of equipment as maintained by construction equipment retailers in Oklahoma City, and Dallas, Texas.

Retail costs for the items of equipment included in this study were obtained from manufacturers and dealers and are current as of January, 1973. Percentages for determining ownership expenses were obtained from The Associated General Contractors of America (30). Since these figures are based on a national average, some adjustments were necessary to better reflect the local and state conditions.

The costs of the hot-mix plants include a fabric filter-type dust collector. Even though this bag collector is approximately 20 percent more expensive than the wet wash system and is seldom, if ever, found on older plants, its inclusion in this study is justified by the fact that, eventually, all hot-mix plants will be required to convert to the bag collector by ecology legislation since bag filter particulate collection systems are the only systems capable of controlling both dust emission and water pollution from sludge.

The standard process for compacting asphaltic concrete is to use a three wheel steel roller for obtaining initial compaction, pneumatic tire rollers for intermediate rolling, and light tandem steel rollers for finish rolling. This process thus requires three pieces of equipment and three operators. However, Oklahoma and 24 other states have accepted an alternate compacting technique which employs only one vibratory roller for all three compaction stages. A Raygo Rustler 404 vibratory roller was observed during the data collection phase of this investigation. Data for the laydown operation were based on observation of the placement of more than 32,000 tons of base course and surface course mixes. Two density samples were tested daily by the State

Highway Department during the period of the observations, and not one failed to pass the minimum density requirements. Since the vibratory roller appears to be totally satisfactory for highway paving, and the economic benefits are obvious, the costs for compaction equipment are for one vibratory roller and operator.

The effects of introducting a 100-ton surge bin into the system is examined in this study. There is some confusion in the paving industry concerning surge/storage bins. Basically, a storage bin is designed to store asphaltic concrete for periods of up to 14 days, while a surge bin will hold a mix for a period of 8 to 12 hours without loss of temperature or penetration. The principal advantage of the surge bin is that it decreases plant loading time and increases plant efficiency when haul capacity is less than plant capacity. Surge bins are recommended for the plant which has continued production, while the storage bin is used where the demand for material is unpredictable. Only the effects of the surge bin are considered in this study.

Labor

Wage rates were obtained from <u>Engineering News Record</u> (19) and <u>Construction Review</u> (33) for the Oklahoma City area. The rates used in the cost estimate include the owner's contribution for Social Security tax, Workman's Compensation, and Employers' Liability Insurance. Crew size is based on observations of two local contractors.

Assumptions

In order to arrive at a unit cost for producing asphaltic concrete, it is necessary to make some assumptions concerning plant operation and life expectancy of the various equipment components of the system. The following assumptions are based on historical data maintained by the Association of General Contractors and on personal observations:

8-hour work shift
120 working days per year
10-year plant life (9600 hours)
5-year surge bin life
80% plant efficiency
75% dryer efficiency
asphaltic concrete: surface course mix
40% sand, 7% moisture, 5% stockpile loss
60% stone, 4% moisture, 5% stockpile loss

The above assumptions are used in all calculations contained in this study.

6000-lb. Batch Plant

Plant costs include a tower with 5' x 14' screen, 336 tph hot elevator, 9' x 30' dryer, Barber-Greene Model CE 12 bag house, 140' vertical conveyor, 3-bin cold feed, and 25,000-gallon asphalt cement storage and hot oil heater. Additionally, $6,000 is included to cover the costs of freight and erection.

1. Plant Costs

a. Plant. Initial cost of plant and related equipment including tax, freight, and installation $347,420

Average Annual Expense (% of Capital Investment)

Depreciation	10%
Repairs and maintenance	17%
Interest, taxes, insurance	11%
Total ownership expense	38%

$$\text{Ownership expense per day} = \frac{38\% \times \$347{,}420}{120 \text{ days}}$$

Ownership expense per day = $1,100.16/day

<u>b. Surge Bin</u>. Initial cost of surge bin and related equipment including tax, freight, and installation $65,575

Average Annual Expense (% of Capital Investment)

Depreciation	20%
Repairs and maintenance	5%
Interest, taxes, insurance	11%
Total ownership expense	36%

$$\text{Ownership expense per day} = \frac{36\% \times \$65{,}575}{120 \text{ days}}$$

Ownership expense per day = $196.73/day

<u>c. Energy</u>.

$$\begin{aligned}(1)\ \text{Dryer fuel (w/o surge)} &= \frac{\text{cost/gal} \times \text{tpd} \times \text{moisture content}}{0.07 \times \text{efficiency of dryer}} \\ &= \$0.12 \times 1536 \times \left[(0.07 \times 0.40) + (0.04 \times 0.60)\right] \\ &= \$182.55/\text{day}\end{aligned}$$

$$\begin{aligned}\text{Dryer fuel (w/surge)} &= \frac{\$0.12 \times 1920 \times \left[(0.07 \times 0.40) + (0.04 \times 0.60)\right]}{0.07 \times 0.75} \\ &= \$228.19/\text{day}\end{aligned}$$

(2) Electricity = cost x hp x .75 x hr/day

(w/o surge) = $0.015 x 320 x .75 x 8

= $28.80/day

(w/surge) = $0.015 x 370 x .75 x 8

= $33.30/day

(3) Asphalt heater fuel = 192 tph x $.06/hr x 8 hr

= $92.16/day

(4) Total Energy Costs

w/o surge	w/surge
$182.55	$228.19
28.80	33.30
92.16	92.16
$303.51	$353.65

d. Associated Equipment

(1) Truck, pickup, 1/2-ton

Initial cost of one truck	$2700.00
Depreciation	50%
Maintenance and repair	15%
Interest, taxes, insurance	11%

Total ownership expense = 76%

Ownership cost per day $= \frac{\$2700 \times 76\%}{120 \text{ days}}$

= $17.10/day

Fuel and other expenses = $ 1.10/hr x 9 hr

= $ 9.90/day

Total cost per day = $17.10 + $9.90 = $27.00/day

(2) Loader, front end, 3 to 5 c.y.

Initial cost	$12,200
Depreciation	20%
Maintenance and repairs	12%
Interest, taxes, insurance	11%
Total ownership expense	43%

Ownership expense per day $= \frac{\$12,200 \times 43\%}{120 \text{ days}}$

= $43.72/day

Fuel and other expenses = $ 1.93 x 8 hr

= $15.44/day

Total cost per day = $43.72 + $15.44 = $59.15/day

e. Labor

Foreman	8 hrs x $ 8.00/hr	= $ 64.00
	1 hr x $12.00/hr*	= $ 12.00
Mixer operator	8 hrs x $ 6.25/hr	= $ 50.00
Loader operator	8 hrs x $ 6.25/hr	= $ 50.00
Oiler	8 hrs x $ 4.50/hr	= $ 36.00
Laborers (3)	8 hrs x $ 4.25/hr	= $102.00
Total labor costs per day		= $314.00

*Overtime computed at 1½ times the hourly rate

f. Summary of Plant Costs per Day	w/o surge	w/surge
Plant	$1100.16	$1100.16
Surge bin	-	196.73
Energy	303.51	353.65
Equipment	86.15	86.15
Labor	314.00	314.00
Total	$1803.82	$2050.69

2. Paving Cost

a. Equipment

(1) Paver

Initial cost complete	\$32,000
Depreciation	25%
Maintenance and repair	15%
Interest, taxes, insurance	11%
Total ownership expense	51%
Ownership expense per day	$= \frac{\$32,000 \text{ x } 51\%}{120 \text{ days}}$
	= \$136.00

(2) Vibratory Roller

Initial cost complete	\$28,020
Depreciation	20%
Maintenance and repairs	18%
Interest, taxes, insurance	10%
Total ownership expense	49%
Ownership expense per day	$= \frac{\$28,020 \text{ x } 49\%}{120 \text{ days}}$
	= \$114.42

(3) Asphalt Distributor

Initial cost complete	\$9,950
Depreciation	20%
Maintenance and repairs	17%
Interest, taxes, insurance	11%
Total ownership expense	48%
Ownership expense per day	$= \frac{\$9,950 \text{ x } 48\%}{120 \text{ days}}$
	= \$39.80/day

(4) Fuel Truck

Initial cost complete	$7,500
Depreciation	20%
Maintenance and repairs	15%
Interest, taxes, insurance	11%
Total ownership expense	46%
Ownership expense per day	$= \frac{\$7,500 \times 46\%}{120 \text{ days}} \times 1/4 \text{ day}$
	= $7.19

(5) Broom, Rotary

Initial cost complete	$5,200
Depreciation	20%
Maintenance and repairs	15%
Interest, taxes, insurance	11%
Total ownership expense	46%
Ownership expense per day	$= \frac{\$5,200 \times 46\%}{120 \text{ days}}$
	= $19.93/day

(6) Fuel and Operating Costs (est.) $45.00/day

(7) Summary of Paving Equipment Costs

Paver	$136.00
Roller	$114.42
Asphalt distributor	$ 39.80
Fuel truck	$ 7.19
Broom	$ 19.93
Truck, pickup	$ 27.00
Fuel	$ 45.00

Total cost per day		$389.34

b. Labor

Foreman	8 hr x $8.00/hr =	$ 64.00
Paver operator	8 hr x $6.75/hr =	$ 54.00
Roller operator	8 hr x $4.00/hr =	$ 48.00
Laborer (3)	8 hr x $4.25/hr =	$102.00
Total labor costs per day	=	$268.00

c. Summary of Paving Costs per Day

Equipment	$389.34
Labor	$268.00
Total	$657.34

3. Hauling Costs	7.5-ton	15-ton	22-ton
Initial cost complete	$10,500	$17,500	$23,000
Depreciation	20%	20%	15%
Maintenance and repairs	15%	15%	15%
Interest, taxes, insurance	14%	14%	14%
Total ownership expense	49%	49%	44%
Ownership expense	$42.88	71.46	84.33
Operating expense	10.50	15.50	16.75
Labor expense	38.00	38.00	38.00
Total cost per truck	$91.38	$124.96	$139.08

Summary of Operating Costs

Plant Capacity	w/o surge	w/surge
6000-lb.	$1,803.82	$2,050.69
5000-lb.	$1,687.24	$1,923.97
4000-lb.	$1,621.40	$1,858.13
3000-lb.	$1,542.24	$1,778.97
2000-lb.	$1,420.15	$1,656.86

Paving costs per day: $657.34

Hauling costs per truck per day:

7.5-ton	$ 91.38
15-ton	$124.96
22-ton	$139.08

APPENDIX B

MODEL NO. 1

DIRECT LOADING

Appendix B contains Model No. 1, which is the simulation model for a conventional hot-mix operation. The results of a simulation for a sample experiment employing three 12-ton trucks and three 14-ton trucks hauling from a 4000-lb. batch plant are provided for illustrative purposes.

Figure 37 is a flow chart for Model No. 1. From the flow chart, the commentary provided within the model, and the comments which follow, modifications to the simulation model which will reflect the parameters desired by prospective users can be accomplished without difficulty.

The column of numbers on the right side of the sample computer print-out is the position of the card within the deck. This number is used as the reference for the explanation which follows. This card number should not be confused with the column of numbers appearing on the left side of the computer print-out which is the GPSS block number.

Card 1 - SIMULATE -

A GPSS command necessary for execution of the program. Omission of this command will result in a computer print-out of the program, but no simulation will occur.

Card 2 - RMULT - 543,37,31,5

This series of numbers sets the seed of random number generators. Any odd number may be used.

Cards 3-81

This is a commentary on the program description and designation of the Savevalues (Xn) which are used to establish the various parameters to be tested.

Cards 82-88 1 FUNCTION

This function describes the probability distribution for the batch

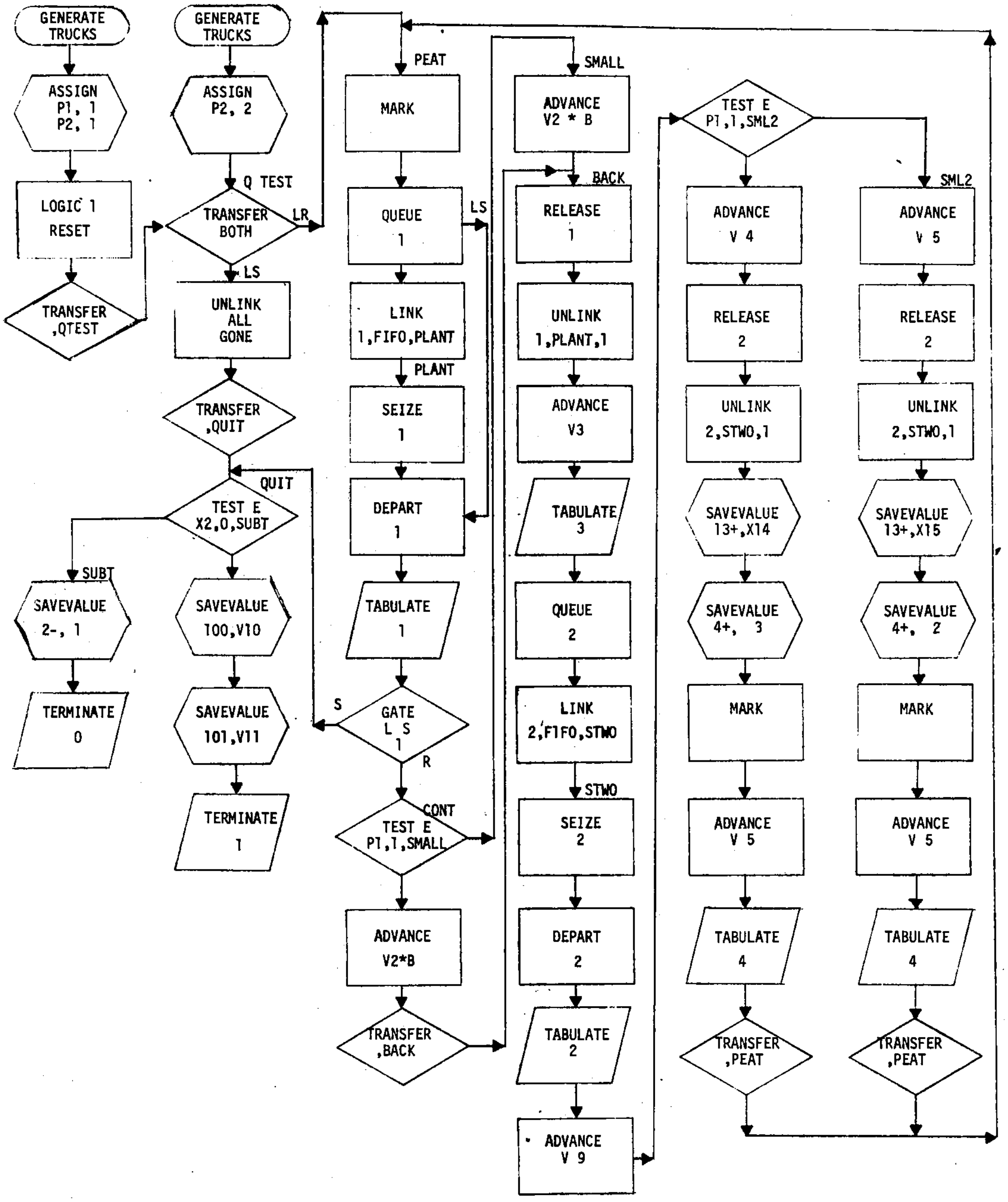

Figure 37. Flow Diagram for Model No. 1

time. For this program, the distribution is an empirical distribution.

Cards 89-93 2 FUNCTION

This function describes the probability distribution for haul time. This is a truncated normal distribution.

Cards 94-97 3 FUNCTION

The function for determining maneuver time. This is an empirical distribution.

Cards 99-101 4 FUNCTION

The empirical distribution for dump times.

Cards 102-106 5 FUNCTION

The truncated normal distribution for determining return time.

Cards 107-111 6 FUNCTION

The function used to determine the surge loading times of trucks. This is a normal distribution and is used only in Model No. 2 which models a surge loading system.

Cards 112-132

These cards establish the variables used in the program. A description of each variable is provided in the program comments. The only three changes which are possible are:

8 VARIABLE 28800 - XII

The value <u>28800</u> is the time to be simulated in seconds (in this case, eight hours). It should be changed to reflect the time in seconds of any other period of simulation.

10 FVARIABLE X18 + (X17*X7) + (X16*18) + 65734

The constant 65734 is the daily cost ($657.34) for the paving subsystem. All other costs are determined by the value of a Savevalue.

Cards 142-167 INITIAL

These cards establish the parameters such as plant size, number and size of trucks, cost data, etc., to be simulated. The description of each is provided in the sample program. X13, X100 - X102 should always be initialed to 0.

Cards 168-206

The purpose of each card is given in the program. These cards may not be modified.

Cards 207-212 ADVANCE V2

Each card represents the production of one batch of hot-mix. The number of ADVANCE V2 cards should equal the number of batches desired on each large truck. The batch capacity of the plant in the sample program is two tons. The large trucks are 14-ton capacity, thus seven batches (seven each ADVANCE V2 cards).

Cards 214-219 ADVANCE V2

These cards serve the same purpose for small trucks as those described above serve for large trucks. If only one truck size is being simulated, only card 214 must remain in the program. Cards 215-219 may be omitted.

Cards 220-252

The purpose of each card is described in the program. Except as noted below, these cards form a basic part of the program and may not be modified or omitted.

Cards 194, 224, 229, 240, 250 TABULATE 1,2,3,4

Each card causes the model to collect the statistics presented in Tables 1, 2, 3, 4, respectively. If any or all of these statistics are not desired, one or all of the cards may be omitted.

Cards 253-267

These cards function as the clock which signals the approach of the end of the shift or simulation. These cards may not be modified. Variations in the length of the period to be simulated are incorporated into the program by the Savevalues described above.

Cards 268-283

These cards are applicable to the surge system (Model No. 2) only and should be omitted when the conventional system is being modeled.

Cards 284-295

These cards serve as a safety to terminate the computer run in the event erroneous data or typographical errors have been introduced into the program. This feature may be omitted from the program, but experience has shown that errors which cause the expenditure of valuable computer time do occur.

Cards 296-304

These cards are necessary GPSS command cards and may not be modified or omitted.

The descriptions given above are for the conventional batch plant. Construction techniques and policies which are incorporated into the model are described in Chapter IV. The procedures to change these basic assumptions to reflect other policies are also discussed in Chapter IV.

The format for data output was discussed in Chapter II. Though it is possible to change the data format by use of the OUTPUT EDITOR, such changes are not recommended unless a person has experience with the GPSS language. The use of the OUTPUT EDITOR does increase the cost of a simulation slightly. Because of the very large number of simulations required for this thesis, the OUTPUT EDITOR was not used for economical reasons.

```
BLOCK                                                                                         CARD
NUMBER  *LOC    OPERATION  A,B,C,D,E,F,G             COMMENTS                                 NUMBER
                SIMULATE                                                                          1
                RMULT      543,37,31,5                                                            2
        *                                                                                         3
        *   SAMPLE PROBLEM FOR DISCUSSION PURPOSES.  4000 LB BATCH/14 & 12 TON.                   4
        *                                                                                         5
        *    THIS IS A PROGRAM MODEL TO SIMULATE THE PRODUCTION, HAULING, AND                     6
        * PLACING OF HOT-MIX ASPHALTIC CONCRETE.  THE PURPOSE OF THE SIMULATION                   7
        * IS TO DETERMINE THE EFFECT OF VARIOUS EQUIPMENT CAPACITY COMBINATIONS                   8
        * ON THE IN-PLACE UNIT COST OF THE HOT-MIX ASPHALTIC CONCRETE AND TO                      9
        * INVESTIGATE THE IMPACT OF VARIOUS MANAGEMENT DECISIONS ON PRODUCTION                   10
        * AND COSTS.                                                                             11
        *    THE PROGRAM IS COMPOSED OF FOUR MODELS, EACH OF WHICH REPRESENTS A                  12
        * DIFFERENT COMBINATION OF CONDITIONS TO BE INVESTIGATED.                                13
        *                                                                                        14
        * 1. MODEL 1                                                                             15
        *    THIS MODEL SIMULATES A BATCH PLANT LOADING DIRECTLY INTO THE HAUL                   16
        * UNITS.  THE MODEL HAS THE CAPABILITY OF SIMULATING HAUL UNITS OF                       17
        * DIFFERENT SIZES ON THE SAME PROJECT.  HAUL UNITS HAUL DIRECTLY TO THE                  18
        * PAVER.  ONE PAVER IS EMPLOYED WITH THIS MODEL.  TRUCKS ARE LOADED AND                  19
        * DUMPED ON A FIRST COME FIRST SERVED BASIS.  A FASTER HAUL UNIT MAY                     20
        * PASS A SLOWER ONE ON THE HAUL ROAD.                                                    21
        *                                                                                        22
        * 2. MODEL 2                                                                             23
        *    ALL EQUIPMENT PARAMETERS ARE THE SAME AS IN MODEL 1 EXCEPT THAT A                   24
        * 100 TON SURGE HOPPER IS INCORPORATED AT THE PLANT FOR LOADING.                         25
        *                                                                                        26
        * 3. MODEL 3                                                                             27
        *    THIS MODEL INCORPORATES INTO THE PROGRAM THE MANAGEMENT TECHNIQUE                   28
        * OF LOADING LARGER TRUCKS FIRST WHEN THERE IS A QUEUE AT THE PLANT.                     29
        * TRUCKS CONTINUE TO DUMP ON A FIRST COME FIRST SERVED BASIS.  BOTH                      30
        * SURGE AND DIRECT LOADING ARE CONSIDERED IN THIS MODEL.                                 31
        *                                                                                        32
        * 4. MODEL 4A                                                                            33
        *    THIS MODEL CREATES A DELAY FOR REPOSITIONING THE PAVER.  UPON                       34
        * COMPLETION OF ONE LANE THE PAVER IS REPOSITIONED AND STARTS THE                        35
        * ADJACENT LANE.  HAUL DISTANCES ARE ADJUSTED ACCORDINGLY.                               36
        *    MODEL 4B                                                                            37
        *    THIS MODEL ALLOWS PAVER TO TURN AROUND AND LAY THE PAVEMENT IN                      38
        * THE OPPOSITE DIRECTION.  MANEUVER TIMES AND HAUL DISTANCES ARE                         39
        * ADJUSTED ACCORDINGLY.                                                                  40
        *                                                                                        41
        *    ALL PRODUCTION AND LAYING TIMES ARE BASED ON CONSTRUCTION OF A 21/2                 42
        * INCH COMPACTED LIFT OF SURFACE COURSE MATERIAL.                                        43
        *    EACH SIMULATION IS FOR AN 8 HR SHIFT.  NO LUNCH BREAK IS CONSIDER-                  44
        * ED.  IF A TRUCK IN THE QUEUE AT THE PLANT DOES NOT HAVE TIME TO COM-                   45
        * PLETE A FULL CYCLE PRIOR TO THE END OF THE SHIFT, IT WILL NOT BE                       46
        * LOADED.                                                                                47
        *    ALL TIMES USED IN THE MODELS ARE IN SECONDS.                                        48
        *    ALL COSTS ARE IN CENTS. (X101/100 = DOLLAR COST.)                                   49
        *                                                                                        50
        *    THE FOLLOWING SAVEVALUES ARE COMMON TO ALL MODELS:                                  51
        *                                                                                        52
        *         X1  THE TOTAL NUMBER OF TRUCKS IN THE SYSTEM.                                  53
        *         X2  A VALUE USED TO DETERMINE WHEN ALL TRUCKS HAVE LEFT THE                    54
        *             SYSTEM AT THE END OF THE DAY.                                              55
```

```
*         X3  THE MEAN BATCH TIME.
*         X4  THE MEAN HAUL TIME.
*         X5  THE MEAN DUMP TIME FOR LARGE TRUCKS.
*         X6  THE MEAN RETURN TIME.
*         X7  THE NUMBER OF LARGE TRUCKS.
*         X8  THE NUMBER OF SMALL TRUCKS.
*         X10 THE MEAN DUMP TIME FOR SMALL TRUCKS.
*         X11 THE MEAN CYCLE TIME FOR THE SYSTEM.
*         X13 THE CUMULATIVE QUANTITY OF HOT-MIX PLACED.
*         X14 CAPACITY IN TONS OF LARGE TRUCKS.
*         X15 CAPACITY IN TONS OF SMALL TRUCKS.
*         X16 OPERATING COSTS OF SMALL TRUCKS.
*         X17 OPERATING COSTS OF LARGE TRUCKS.
*         X18 OPERATING COST OF PLANT.
*         X19 THE MEAN SURGE LOADING TIME FOR LARGE TRUCKS.
*         X20 THE MEAN SURGE LOADING TIME FOR SMALL TRUCKS.
*         X21 PLANT'S BATCH CAPACITY IN TONS.
*         X22 THE MEAN MANEUVER TIME.
*        X100 TOTAL COST OF DAY'S PRODUCTION.
*        X101 UNIT COST OF DAY'S PRODUCTION.
*        X102 AVERAGE HOURLY PRODUCTION.
*
*
*    THE FOLLOWING DISTRIBUTIONS, VARIABLES, AND TABLES ARE COMMON TO
* ALL OF THE MODELS:
*
 1 .    FUNCTION   RN3,C29      FUNCTION USED IN DETERMINING BATCH TIME.
0.0,.680/.004,.704/.034,.751/.183,.774/.288,.798/.407,.821/.495,.845
.563,.868/.595,.892/.632,.915/.680,.938/.702,.962/.714,.985/.731,1.009
.751,1.032/.776,1.058/.799,1.079/.812,1.103/.818,1.126/.834,1.150
.840,1.173/.854,1.291/.895,1.408/.934,1.525/.957,1.643/.967,1.760
.973,1.877/.983,2.323/1.000,11.737
*
 2      FUNCTION   RN2,C17      FUNCTION USED IN DETERMINING HAUL TIME.
0.0,.723/.048,.777/.125,.833/.203,.888/.266,.917/.338,.944/.418,.972
.500,1.00/.582,1.028/.662,1.056/.734,1.083/.797,1.111/.875,1.167
.944,1.222/.952,1.277/.981,1.333/1.000,1.400
*
 3      FUNCTION   RN4,C13      FUNCTION USED IN DETERMINING MANEUVER TIME
0.0,.409/.044,.546/.176,.684/.364,.821/.572,.958/.729,1.096/.830,1.233
.886,1.370/.924,1.645/.943,1.920/.955,2.195/.987,2.469/1.0,3.156
*
 4      FUNCTION   RN2,C8       FUCNTION USED IN DETERMINING DUMP TIMES.
0.0,.768/.125,.871/.406,.922/.531,1.025/.625,1.077/.812,1.180/.906,1.231
1.000,1.340
*
 5      FUNCTION   RN2,C18      FUNCTION USED IN DETERMINING RETURN TIME.
0.0,.663/.070,.667/.152,.767/.189,.800/.231,.833/.279,.867/.330,.900
.384,.933/.441,.966/.500,1.00/.559,1.033/.616,1.066/.670,1.100/.721,1.13
.811,1.20/.880,1.333/.980,1.467/1.00,1.64
*
 6      FUNCTION   RN3,C17      FUNCTION USED IN DETERMINING SURGE TIME.
0.0,.854/.001,.875/.006,.895/.023,.916/.067,.477/.097,.937/.159,.958
.308,.979/.401,.989/.500,1.00/.599,1.010/.692,1.020/.841,1.041
.933,1.062/.977,1.083/.994,1.104/1.00,1.125
*
 2      FVARIABLE  FN1*X3       COMPUTATIONS FOR LOADING TIME.
```

```
 3     FVARIABLE  FN2*X4      COMPUTATIONS FOR HAUL TIME TO PAVER.
 4     FVARIABLE  FN4*X5      COMPUTATIONS FOR DUMP TIME (LARGE)
 5     FVARIABLE  FN5*X6      COMPUTATIONS FOR RETURN TIME.
 6     FVARIABLE  FN1*X9      COMPUTATIONS FOR LOADING TIME (SMALL).
 7     FVARIABLE  FN4*X10     COMPUTATIONS FOR DUMP TIME (SMALL).
 8     VARIABLE   28800-X11   COMPUTATION FOR TIME CHECK.
 9     FVARIABLE  FN3*X22      COMPUTATIONS FOR MANEUVER TIME.
 10    FVARIABLE  X18+(X17*X7)+(X16*X8)+65734    TOTAL COST.
 11    FVARIABLE  V10/X13     UNIT COST COMPUTATION.
 13    FVARIABLE  X13/8        COMPUTATION OF AVERAGE HOURLY PRODUCTION.
 12    FVARIABLE  V8-(S1/X21)*X3  FACTORS TO DETERMINE WHEN PLANT SHOULD
 1     BVARIABLE  C1'GE'V12   BE SHUT DOWN TO PERMIT ALL MATERIAL IN
*                             SURGE TO BE CONSUMED BY THE END OF THE DAY
*
*
 1     TABLE      Q1,0,1,10   STATISTICS FOR QUEUE AT PLANT.
 2     TABLE      Q2,0,1,10   STATISTICS FOR QUEUE AT PAVER.
 3     TABLE      IA,0,60,30  TABLE FOR INTERARRIVAL TIMES AT PAVER.
 4     TABLE      IA,0,60,30  TABLE FOR INTERARRIVAL TIMES AT PLANT.
*
************************************************************************
************************************************************************
*                              MODEL 1                                 *
************************************************************************
************************************************************************
*
*
*
*    THE FOLLOWING INITIAL BLOCKS ESTABLISH THE SYSTEM PARAMETERS SUCH
* AS THE NUMBER OF TRUCKS, HAUL DISTANCES, PLANT CAPACITY, ETC.
*
       INITIAL    X1,6
       INITIAL    X2,5
       INITIAL    X3,43
       INITIAL    X4,950
       INITIAL    X5,186
       INITIAL    X6,780
       INITIAL    X7,3
       INITIAL    X8,3
       INITIAL    X10,160
       INITIAL    X11,2240
       INITIAL    X13,0
       INITIAL    X14,14
       INITIAL    X15,12
       INITIAL    X16,12496
       INITIAL    X17,12496
       INITIAL    X18,162140
       INITIAL    X19,0
       INITIAL    X20,0
       INITIAL    X21,2
       INITIAL    X22,36
       INITIAL    X100,0
       INITIAL    X101,0
       INITIAL    X102,0
*
*
************************************************************************
```

```
        **********************************************************************
        *    THE FOLLOWING PORTION OF THE PROGRAM SIMULATES THE LOADING,      *
        * HAULING, DUMPING AND RETURN TO THE PLANT.                           *
        **********************************************************************
        **********************************************************************
        *
        *
 1              GENERATE    0,0,,X7       GENERATE X7 LARGE TRUCKS.
 2              LOGIC R     1             INSURE TIME CHECK IS IN POSITION.
 3              LOGIC R     2             INSURE TIME CHECK 2 IS RESET.
 4              ASSIGN      1,1           THIS NUMBER IDENTIFIES LARGE TRUCKS.
 5        PEAT1 MARK        5             RECORD TIME THAT TRUCK ARRIVES AT PLANT.
 6              TRANSFER    ,QTEST        TRUCK GOES TO PLANT QUEUE.
 7              GENERATE    0,0,,X8       GENERATE X8 LARGE TRUCKS.
 8              LOGIC R     1             INSURE THAT TIME CHECK IS IN POSITION.
 9        PEAT2 MARK        4             RECORD TIME THAT TRUCK ARRIVES AT PLANT.
10        QTEST TRANSFER    BOTH,,WORK1   TEST SEQUENCE TO INSURE THAT TIME
11              GATE LS     1               REMAINS TO MAKE ANOTHER RUN.  IF SO,
12              UNLINK      1,GONE,ALL      TRUCKS LINE UP AT QUEUE.  IF NOT, THEY
13              TRANSFER    ,QUIT           GO TO BLOCK QUIT WHERE THEY LEAVE SYSTEM
14        WORK1 QUEUE       1             LINE UP FOR LOADING.
15              LINK        1,FIFO,PLANT  TRUCKS LINE UP ON FIRST COME BASIS.
16        PLANT SEIZE       1             A TRUCK IS IN POSITION FOR LOADING.
17        GONE  DEPART      1             ALL WAITING TRUCKS MOVE UP ONE PLACE.
18              TABULATE    1             GATHERS STATISTICS ON TIME IN PLANT QUEUE.
19              TRANSFER    BOTH,,CONT    ANOTHER TEST SEQUENCE TO INSURE THERE IS
20              GATE LS     1               TIME TO MAKE A CYCLE BEFORE QUITTING.
21        QUIT  TEST E      X2,0,SUBT     TRUCKS DEPART SYSTEM AT QUITTING TIME
        *                                   THROUGH NEXT SIX BLOCKS.
22              SAVEVALUE   100,V10       COMPUTE TOTAL COST.
23              SAVEVALUE   101,V11       COMPUTE UNIT COST.
24              SAVEVALUE   102,V13       COMPUTE AVERAGE HOURLY PRODUCTION.
25              TERMINATE   1
26        SUBT  SAVEVALUE   2-,1
27              TERMINATE   0
28        CONT  TEST E      P1,1,SMALL    IS THIS A LARGE OR SMALL TRUCK?
29              ADVANCE     V2,           TRUCK LOADS IN V2 SECONDS X NO. BATCHES.
30              ADVANCE     V2
31              ADVANCE     V2
32              ADVANCE     V2
33              ADVANCE     V2
34              ADVANCE     V2
35              ADVANCE     V2
36              TRANSFER    ,BACK1        TRUCK PREPARES TO DEPART PLANT.
37        SMALL ADVANCE     V2            TRUCK LOADS IN V2 SECONDS X NO. BATCHES.
38              ADVANCE     V2
39              ADVANCE     V2
40              ADVANCE     V2
41              ADVANCE     V2
42              ADVANCE     V2
43        BACK1 RELEASE     1             TRUCK IS LOADED AND MOVES AWAY FROM PLANT.
44              UNLINK      1,PLANT,1     NEXT WAITING TRUCK CAN MOVE TO PLANT.
45              MARK                       RECORDS TIME TRUCK DEPARTS PLANT.
46              ADVANCE     V3            TRUCK HAULS FROM PLANT TO PAVER.
47              TABULATE    3             GATHERS STATISTICS FOR INTERARRIVAL TIMES.
48              QUEUE       2             TRUCK LINES UP AT PAVER.
49              LINK        2,FIFO,STWO   TRUCKS IN LINE ON FIRST COME BASIS.
```

```
50       STWO  SEIZE      2          IS PAVER FREE?
51             DEPART     2
52             TABULATE   2          GATHERS STATISTICS ON TIME IN PAVER QUEUE.
53             TEST E     P1,1,SML2  IS THIS A LARGE OR SMALL TRUCK?  IF LARGE,
54             ADVANCE    V4           THEN DUMP IN V4 SECONDS.  IF SMALL, THEN
        *                              GO TO SML2 AND DUMP IN V7 SECONDS.
55             RELEASE    2          TRUCK DEPARTS FINISHER.
56             UNLINK     2,STWO,1   NEXT TRUCK MOVES TO FINISHER.
57             SAVEVALUE  13+,X14    THE TOTAL PRODUCTION IS INCREASED BY X14.
58             SAVEVALUE  4+,3       THE HAUL DISTANCE INCREASES.
59             SAVEVALUE  6+,2       THE RETURN TIME INCREASES.
60             MARK                   RECORDS TIME TRUCK DEPARTS PAVER.
61             ADVANCE    V5         TRUCK RETURNS TO PLANT.
62             TABULATE   4          GATHERS STATISTICS FOR INTERARRIVAL TIMES.
63             TRANSFER   ,PEAT1
64       SML2  ADVANCE    V7         SMALL TRUCKS DUMP IN V7 SECONDS.
65             RELEASE    2          TRUCK DEPARTS FINISHER.
66             UNLINK     2,STWO,1   NEXT TRUCK MOVES TO FINISHER.
67             SAVEVALUE  13+,X15    THE TOTAL PRODUCTION IS INCREASED BY X15.
68             SAVEVALUE  4+,2       HAUL DISTANCE INCREASES.
69             SAVEVALUE  6+,1       THE RETURN TIME INCREASES.
70             MARK                   RECORDS TIME TRUCK DEPARTS PAVER.
71             ADVANCE    V5         TRUCK RETURNS TO PLANT.
72             TABULATE   4          GATHERS STATISTICS FOR INTERARRIVAL TIMES.
73             TRANSFER   ,PEAT2
        *
        *
        ***********************************************************************
        ***********************************************************************
        *    THE FOLLOWING SERIES OF BLOCKS DETERMINE THE POINT IN THE DAY    *
        * WHEN THERE IS INSUFFICIENT TIME TO MAKE ANOTHER CYCLE.  WHEN THIS   *
        * POINT IN TIME OCCURS, A SIGNAL IS SENT THROUGH THE SYSTEM           *
        ***********************************************************************
        ***********************************************************************
        *
        *
74             GENERATE   ,,V8,1
75             LOGIC S    1
76             TERMINATE  0
        *
        *
        ***********************************************************************
        ***********************************************************************
        *    THIS PORTION OF THE PROGRAM DETERMINES THE POINT IN THE DAY WHEN *
        * THERE IS AN ADEQUATE SUPPLY OF HOT-MIX IN THE SURGE HOPPER TO COM-  *
        * PLETE THE DAY SO THAT THE PLANT CAN BE SHUT DOWN.                   *
        ***********************************************************************
        ***********************************************************************
        *
        *
77             GENERATE   ,,25200,1
78             TEST E     BV1,1
79             LOGIC S    2
80             TERMINATE  0
        *
        *
        ***********************************************************************
```

```
        ************************************************************************
        * THE FOLLOWING BLOCKS SERVE AS A SAFETY TO TERMINATE THE SIMULATION   *
        * IN THE EVENT OF ERRONEOUS DATA.                                      *
        ************************************************************************
        ************************************************************************
        *
        *
81             GENERATE   ,,29800,1
82             TERMINATE  1
        *
        *
        ************************************************************************
        ************************************************************************
        *   THE FOLLOWING BLOCKS CHANGE THE NUMBER OF TRUCKS, THE HAUL DISTANCE
        * OR OTHER PROJECT PARAMETER TO BE TESTED.                             *
        ************************************************************************
        ************************************************************************
               START      1
        *
        *
               END
```

```
RELATIVE CLOCK          28798  ABSOLUTE CLOCK          28798
BLOCK COUNTS
BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL
    1       0          3        11       0          5        21       0          6        31       0         33        41       0         31
    2       0          3        12       0          5        22       0          1        32       0         33        42       0         31
    3       0          3        13       0          5        23       0          1        33       0         33        43       0         64
    4       0          3        14       0         65        24       0          1        34       0         33        44       0         64
    5       0         36        15       0         65        25       0          1        35       0         33        45       0         64
    6       0         36        16       0         65        26       0          5        36       0         33        46       0         64
    7       0          3        17       0         65        27       0          5        37       0         31        47       0         64
    8       0          3        18       0         65        28       0         64        38       0         31        48       0         64
    9       0         34        19       0         65        29       0         33        39       0         31        49       0         64
   10       0         70        20       0          1        30       0         33        40       0         31        50       0         64

BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL     BLOCK CURRENT      TOTAL
   51       0         64        61       0         33        71       0         31        81       0          0
   52       0         64        62       0         33        72       0         31        82       0          0
   53       0         64        63       0         33        73       0         31
   54       0         33        64       0         31        74       0          1
   55       0         33        65       0         31        75       0          1
   56       0         33        66       0         31        76       0          1
   57       0         33        67       0         31        77       0          1
   58       0         33        68       0         31        78       0          1
   59       0         33        69       0         31        79       0          1
   60       0         33        70       0         31        80       0          1
```

```
USER CHAIN      TOTAL       AVERAGE        CURRENT       AVERAGE      MAXIMUM
               ENTRIES    TIME/TRANS      CONTENTS      CONTENTS     CONTENTS
      1            38       377.500                         .498            5
      2            13       120.769                         .054            1
```

```
FACILITY        AVERAGE         NUMBER        AVERAGE          SEIZING    PREEMPTING
              UTILIZATION      ENTRIES       TIME/TRAN        TRANS. NO.  TRANS. NO.
       1          .763              65         338.430            9
       2          .386              64         173.859
```

```
CONTENTS OF FULLWORD SAVEVALUES (NON-ZERO)
SAVEVALUE  NR,         VALUE      NR,          VALUE       NR,          VALUE      NR,          VALUE       NR,          VALUE
             1             6       3             43         4            1111        5            186        6             877
             7             3       8              3        10             160       11           2240       13             834
            14            14      15             12        16           12496       17          12496       18          162140
            21             2      22             36       100          302850      101            363      102             104
```

```
QUEUE      MAXIMUM    AVERAGE     TOTAL      ZERO     PERCENT      AVERAGE      $AVERAGE      TABLE     CURRENT
          CONTENTS   CONTENTS    ENTRIES    ENTRIES    ZEROS     TIME/TRANS    TIME/TRANS    NUMBER    CONTENTS
    1           5       .498        65         27       41.5       220.692       377.500
    2           1       .054        64         51       79.6        24.531       120.769
 $AVERAGE TIME/TRANS = AVERAGE TIME/TRANS EXCLUDING ZERO ENTRIES
```

```
TABLE   1
ENTRIES IN TABLE          MEAN ARGUMENT          STANDARD DEVIATION           SUM OF ARGUMENTS
              65                   .307                        .727                     20.000        NON-WEIGHTED

          UPPER       OBSERVED      PER CENT      CUMULATIVE       CUMULATIVE      MULTIPLE      DEVIATION
          LIMIT      FREQUENCY      OF TOTAL      PERCENTAGE        REMAINDER       OF MEAN      FROM MEAN
              0             51         78.46            78.4             21.5         -.000          -.423
              1             11         16.92            95.3              4.6         3.250           .952
              2              1          1.53            96.9              3.0         6.500          2.327
              3              1          1.53            98.4              1.5         9.750          3.703
              4              1          1.53           100.0               .0        13.000          5.078
REMAINING FREQUENCIES ARE ALL ZERO
```

```
TABLE    2
ENTRIES IN TABLE          MEAN ARGUMENT           STANDARD DEVIATION          SUM OF ARGUMENTS
            64                     -.000                         .000                        .000          NON-WEIGHTED

           UPPER         OBSERVED        PER CENT         CUMULATIVE        CUMULATIVE        MULTIPLE         DEVIATION
           LIMIT         FREQUENCY       OF TOTAL         PERCENTAGE         REMAINDER         OF MEAN         FROM MEAN
               0                64         100.00              100.0                .0           -.000             -.000
REMAINING FREQUENCIES ARE ALL ZERO
```

```
TABLE    3
ENTRIES IN TABLE          MEAN ARGUMENT            STANDARD DEVIATION         SUM OF ARGUMENTS
              63                424.428                       264.000                26739.000          NON-WEIGHTED

          UPPER        OBSERVED         PER CENT        CUMULATIVE        CUMULATIVE        MULTIPLE        DEVIATION
          LIMIT       FREQUENCY         OF TOTAL        PERCENTAGE         REMAINDER         OF MEAN        FROM MEAN
              0               0              .00                .0             100.0           -.000           -1.607
             60               6             9.52               9.5              90.4            .141           -1.380
            120               5             7.93              17.4              82.5            .282           -1.153
            180               3             4.76              22.2              77.7            .424            -.925
            240               6             9.52              31.7              68.2            .565            -.698
            300               0              .00              31.7              68.2            .706            -.471
            360               5             7.93              39.6              60.3            .848            -.244
            420               5             7.93              47.6              52.3            .989            -.016
            480               6             9.52              57.1              42.8           1.130             .210
            540               7            11.11              68.2              31.7           1.272             .437
            600               2             3.17              71.4              28.5           1.413             .665
            660               4             6.34              77.7              22.2           1.555             .892
            720               4             6.34              84.1              15.8           1.696            1.119
            780               6             9.52              93.6               6.3           1.837            1.346
            840               1             1.58              95.2               4.7           1.979            1.574
            900               0              .00              95.2               4.7           2.120            1.801
            960               1             1.58              96.8               3.1           2.261            2.028
           1020               1             1.58              98.4               1.5           2.403            2.255
           1080               1             1.58             100.0                .0           2.544            2.483
REMAINING FREQUENCIES ARE ALL ZERO
```

```
TABLE    4
ENTRIES IN TABLE          MEAN ARGUMENT          STANDARD DEVIATION          SUM OF ARGUMENTS
              63                428.698                     292.000                 27008.000        NON-WEIGHTED

         UPPER       OBSERVED      PER CENT      CUMULATIVE      CUMULATIVE      MULTIPLE      DEVIATION
         LIMIT      FREQUENCY      OF TOTAL      PERCENTAGE       REMAINDER       OF MEAN      FROM MEAN
             0              0           .00              .0           100.0         -.008         -1.468
            60              8         12.69            12.6            87.3          .139         -1.262
           120              4          6.34            19.0            80.9          .279         -1.057
           180              7         11.11            30.1            69.8          .419          -.851
           240              1          1.58            31.7            68.2          .559          -.646
           300              1          1.58            33.3            66.6          .699          -.440
           360              7         11.11            44.4            55.5          .839          -.235
           420              3          4.76            49.2            50.7          .979          -.029
           480              5          7.93            57.1            42.8         1.119           .175
           540              5          7.93            65.0            34.9         1.259           .381
           600              4          6.34            71.4            28.5         1.399           .586
           660              4          6.34            77.7            22.2         1.539           .792
           720              3          4.76            82.5            17.4         1.679           .997
           780              2          3.17            85.7            14.2         1.819          1.203
           840              3          4.76            90.4             9.5         1.959          1.408
           900              2          3.17            93.6             6.3         2.099          1.614
           960              1          1.58            95.2             4.7         2.239          1.819
          1020              0           .00            95.2             4.7         2.379          2.025
          1080              3          4.76           100.0              .0         2.519          2.230
REMAINING FREQUENCIES ARE ALL ZERO
```

APPENDIX C

MODEL NO. 2

SURGE LOADING

Appendix C contains Model No. 2, which is the simulation model for a hot-mix paving operation with a surge loading system. The results of a simulation for a sample experiment employing three 12-ton trucks and three 14-ton trucks hauling from a 4000-lb. batch plant are provided for illustrative purposes.

The discussion for the conventional simulation model (Model No. 1) was presented in Appendix B. Except as noted below, Model No. 2 functions in a manner identical to that of Model No. 1. For this reason, only the differences in the two models will be discussed in this Appendix.

Cards 167-197 introduce a surge loading system into the model. These cards function in the following manner:

Card 176 1 STORAGE 100

This card establishes the capacity of the surge hopper in tons. The figure 100 represents 100 tons of storage. By changing this figure, any storage capacity may be established.

Cards 177-180

These cards allow the hopper to be filled with a specified amount of hot-mix prior to the beginning of the shift. The amount to be preloaded is determined by Card 178 ENTER 1,100. The figure 100 specifies that 100 tons of hot-mix are to be placed in the hopper before the shift begins. This figure may range in value from 0 to the capacity specified in Card 176 above.

Cards 181-189

These cards are necessary program cards and may not be altered. Their functions in the model are described in the sample program.

Card 190 ADVANCE 60,5

This card models the hot-mix being transported from the pubmill to the hopper by the elevator. The 60 represents the mean time in seconds for a batch to be transported while the 5 represents a possible five-second fluxuation. Thus, the range in time required for this operation is 55 to 65 seconds.

Cards 190-195

These cards are necessary program cards and may not be altered.

The remaining cards are necessary for the proper functioning of the model and may not be modified or omitted except as noted in Appendix B.

```
BLOCK                                                                                  CARD
NUMBER  *LOC   OPERATION  A,B,C,D,E,F,G            COMMENTS                            NUMBER
               SIMULATE                                                                   1
               RMULT      543,37,31,5                                                     2
        *                                                                                 3
        *   SAMPLE PROBLEM FOR DISCUSSION PURPOSES.  4000 LB BATCH/14 & 12 TON.           4
        *                                                                                 5
        *     THIS IS A PROGRAM MODEL TO SIMULATE THE PRODUCTION, HAULING, AND            6
        * PLACING OF HOT-MIX ASPHALTIC CONCRETE.  THE PURPOSE OF THE SIMJLATION           7
        * IS TO DETERMINE THE EFFECT OF VARIOUS EQUIPMENT CAPACITY COMBINATIONS           8
        * ON THE IN-PLACE UNIT COST OF THE HOT-MIX ASPHALTIC CONCRETE AND TO              9
        * INVESTIGATE THE IMPACT OF VARIOUS MANAGEMENT DECISIONS ON PRODUCTION           10
        * ANC COSTS.                                                                     11
        *     THE PROGRAM IS COMPOSED OF FOUR MODELS, EACH OF WHICH REPRESENTS A         12
        * DIFFERENT COMBINATION OF CONDITIONS TO BE INVESTIGATED.                        13
        *                                                                                14
        * 1. MODEL 1                                                                     15
        *     THIS MODEL SIMULATES A BATCH PLANT LOADING DIRECTLY INTO THE HAUL          16
        * UNITS.  THE MODEL HAS THE CAPABILITY OF SIMULATING HAUL UNITS OF               17
        * DIFFERENT SIZES ON THE SAME PROJECT.  HAUL UNITS HAUL DIRECTLY TO THE          18
        * PAVER.  ONE PAVER IS EMPLOYED WITH THIS MODEL.  TRUCKS ARE LOADED AND          19
        * DUMPED ON A FIRST COME FIRST SERVED BASIS.  A FASTER HAUL UNIT MAY             20
        * PASS A SLOWER ONE ON THE HAUL ROAD.                                            21
        *                                                                                22
        * 2. MODEL 2                                                                     23
        *     ALL EQUIPMENT PARAMETERS ARE THE SAME AS IN MODEL 1 EXCEPT THAT A          24
        * 100 TON SURGE HOPPER IS INCORPORATED AT THE PLANT FOR LOADING.                 25
        *                                                                                26
        * 3. MODEL 3                                                                     27
        *     THIS MODEL INCORPORATES INTO THE PROGRAM THE MANAGEMENT TECHNIQUE          28
        * OF LOADING LARGER TRUCKS FIRST WHEN THERE IS A QUEUE AT THE PLANT.             29
        * TRUCKS CONTINUE TO DUMP ON A FIRST COME FIRST SERVED BASIS.  BOTH              30
        * SURGE AND DIRECT LOADING ARE CONSIDERED IN THIS MODEL.                         31
        *                                                                                32
        * 4. MODEL 4A                                                                    33
        *     THIS MODEL CREATES A DELAY FOR REPOSITIONING THE PAVER.  UPON              34
        * COMPLETION OF ONE LANE THE PAVER IS REPOSITIONED AND STARTS THE                35
        * ADJACENT LANE.  HAUL DISTANCES ARE ADJUSTED ACCORDINGLY.                       36
        *     MODEL 4B                                                                   37
        *     THIS MODEL ALLOWS PAVER TO TURN AROUND AND LAY THE PAVEMENT IN             38
        * THE OPPOSITE DIRECTION.  MANEUVER TIMES AND HAUL DISTANCES ARE                 39
        * ADJUSTED ACCORDINGLY.                                                          40
        *                                                                                41
        *     ALL PRODUCTION AND LAYING TIMES ARE BASED ON CONSTRUCTION OF A 21/2        42
        * INCH COMPACTED LIFT OF SURFACE COURSE MATERIAL.                                43
        *     EACH SIMULATION IS FOR AN 8 HR SHIFT.  NO LUNCH BREAK IS CONSIDER-         44
        * ED.  IF A TRUCK IN THE QUEUE AT THE PLANT DOES NOT HAVE TIME TO COM-           45
        * PLETE A FULL CYCLE PRIOR TO THE END OF THE SHIFT, IT WILL NOT BE               46
        * LOADED.                                                                        47
        *     ALL TIMES USED IN THE MODELS ARE IN SECONDS.                               48
        *     ALL COSTS ARE IN CENTS. (X101/100 = DOLLAR COST.)                          49
        *                                                                                50
        *     THE FOLLOWING SAVEVALUES ARE COMMON TO ALL MODELS:                          51
        *                                                                                52
        *         X1  THE TOTAL NUMBER OF TRUCKS IN THE SYSTEM.                          53
        *         X2  A VALUE USED TO DETERMINE WHEN ALL TRUCKS HAVE LEFT THE            54
        *             SYSTEM AT THE END OF THE DAY.                                      55
```

```
*         X3  THE MEAN BATCH TIME.
*         X4  THE MEAN HAUL TIME.
*         X5  THE MEAN DUMP TIME FOR LARGE TRUCKS.
*         X6  THE MEAN RETURN TIME.
*         X7  THE NUMBER OF LARGE TRUCKS.
*         X8  THE NUMBER OF SMALL TRUCKS.
*         X10 THE MEAN DUMP TIME FOR SMALL TRUCKS.
*         X11 THE MEAN CYCLE TIME FOR THE SYSTEM.
*         X13 THE CUMULATIVE QUANTITY OF HOT-MIX PLACED.
*         X14 CAPACITY IN TONS OF LARGE TRUCKS.
*         X15 CAPACITY IN TONS OF SMALL TRUCKS.
*         X16 OPERATING COSTS OF SMALL TRUCKS.
*         X17 OPERATING COSTS OF LARGE TRUCKS.
*         X18 OPERATING COST OF PLANT.
*         X19 THE MEAN SURGE LOADING TIME FOR LARGE TRUCKS.
*         X20 THE MEAN SURGE LOADING TIME FOR SMALL TRUCKS.
*         X21 PLANT'S BATCH CAPACITY IN TONS.
*         X22 THE MEAN MANEUVER TIME.
*        X100 TOTAL COST OF DAY'S PRODUCTION.
*        X101 UNIT COST OF DAY'S PRODUCTION.
*        X102 AVERAGE HOURLY PRODUCTION.
*
*
*    THE FOLLOWING DISTRIBUTIONS, VARIABLES, AND TABLES ARE COMMON TO
* ALL OF THE MODELS:
*
 1      FUNCTION   RN3,C29      FUNCTION USED IN DETERMINING BATCH TIME.
0.0,.680/.004,.704/.034,.751/.183,.774/.288,.798/.407,.821/.495,.845
.563,.868/.595,.892/.632,.915/.680,.938/.702,.962/.714,.985/.731,1.009
.751,1.032/.776,1.058/.799,1.079/.812,1.103/.818,1.126/.834,1.150
.840,1.173/.854,1.291/.895,1.408/.934,1.525/.957,1.643/.967,1.760
.973,1.877/.983,2.323/1.000,11.737
*
 2      FUNCTION   RN2,C17      FUNCTION USED IN DETERMINING HAUL TIME.
0.0,.723/.048,.777/.125,.833/.203,.888/.266,.917/.338,.944/.418,.972
.500,1.00/.582,1.028/.662,1.056/.734,1.083/.797,1.111/.875,1.167
.944,1.222/.952,1.277/.981,1.333/1.000,1.400
*
 3      FUNCTION   RN4,C13      FUNCTION USED IN DETERMINING MANEUVER TIME
0.0,.409/.044,.546/.176,.684/.364,.821/.572,.958/.729,1.096/.830,1.233
.886,1.370/.924,1.645/.943,1.920/.955,2.195/.987,2.469/1.0,3.156
*
 4      FUNCTION   RN2,C8       FUCNTION USED IN DETERMINING DUMP TIMES.
0.0,.768/.125,.871/.406,.922/.531,1.025/.625,1.077/.812,1.180/.906,1.231
1.000,1.340
*
 5      FUNCTION   RN2,C18      FUNCTION USED IN DETERMINING RETURN TIME.
0.0,.663/.070,.667/.152,.767/.189,.800/.231,.833/.279,.867/.330,.900
.384,.933/.441,.966/.500,1.00/.559,1.033/.616,1.066/.670,1.100/.721,1.13
.811,1.20/.880,1.333/.980,1.467/1.00,1.64
*
 6      FUNCTION   RN3,C17      FUNCTION USED IN DETERMINING SURGE TIME.
0.0,.854/.001,.875/.006,.895/.023,.916/.067,.477/.097,.937/.159,.958
.308,.979/.401,.989/.500,1.00/.599,1.010/.692,1.020/.841,1.041
.933,1.062/.977,1.083/.994,1.104/1.00,1.125
*
 2      FVARIABLE  FN1*X3       COMPUTATIONS FOR LOADING TIME.
```

```
 3     FVARIABLE  FN2*X4      COMPUTATICNS FOR HAUL TIME TO PAVER.
 4     FVARIABLE  FN4*X5      COMPUTATIONS FOR DUMP TIME (LARGE)
 5     FVARIABLE  FN5*X6      COMPUTATIONS FOR RETURN TIME.
 6     FVARIABLE  FN1*X9      COMPUTATIONS FOR LOADING TIME (SMALL).
 7     FVARIABLE  FN4*X10     COMPUTATIONS FOR DUMP TIME (SMALL).
 8     VARIABLE   28800-X11   COMPUTATION FOR TIME CHECK.
 9     FVARIABLE  FN3*X22      COMPUTATIONS FOR MANEUVER TIME.
 10    FVARIABLE  X18+(X17*X7)+(X16*X8)+65734    TOTAL COST.
 11    FVARIABLE  V10/X13     UNIT COST COMPUTATION.
 13    FVARIABLE  X13/8        COMPUTATION OF AVERAGE HOURLY PRODUCTION.
 12    FVARIABLE  V8-(S1/X21)*X3  FACTORS TO DETERMINE WHEN PLANT SHOULD
 1     BVARIABLE  C1'GE'V12   BE SHUT DOWN TO PERMIT ALL MATERIAL IN
*                             SURGE TO BE CONSUMED BY THE END OF THE DAY
*
*
 1     TABLE      Q1,0,1,10   STATISTICS FOR QUEUE AT PLANT.
 2     TABLE      Q2,0,1,10   STATISTICS FOR QUEUE AT PAVER.
 3     TABLE      IA,0,60,30  TABLE FOR INTERARRIVAL TIMES AT PAVER.
 4     TABLE      IA,0,60,30  TABLE FOR INTERARRIVAL TIMES AT PLANT.
*
************************************************************************
************************************************************************
*                              MODEL 2                                 *
************************************************************************
************************************************************************
*
*
*
*    THE FOLLOWING INITIAL BLOCKS ESTABLISH THE SYSTEM PARAMETERS SUCH
* AS THE NUMBER OF TRUCKS, HAUL DISTANCES, PLANT CAPACITY, ETC.
*
       INITIAL    X1,6
       INITIAL    X2,5
       INITIAL    X3,43
       INITIAL    X4,950
       INITIAL    X5,186
       INITIAL    X6,780
       INITIAL    X7,3
       INITIAL    X8,3
       INITIAL    X10,160
       INITIAL    X11,1975
       INITIAL    X13,0
       INITIAL    X14,14
       INITIAL    X15,12
       INITIAL    X16,12496
       INITIAL    X17,12496
       INITIAL    X18,162140
       INITIAL    X19,23
       INITIAL    X20,20
       INITIAL    X21,2
       INITIAL    X22,36
       INITIAL    X100,0
       INITIAL    X101,0
       INITIAL    X102,0
*
************************************************************************
************************************************************************
```

```
        *    THE FOLLOWING PORTION OF THE PROGRAM SIMULATES THE PRODUCTION OF  *
        * HOT-MIX AND ITS STORAGE IN THE HOPPER.
        ************************************************************************
        ************************************************************************
        *
        *
         1    STORAGE    100         ESTABLISHES SURGE HOPPER CAPACITY.
1             GENERATE   ,,,1,100    THE NEXT THREE BLOCKS FILL THE HOPPER WITH
2             ENTER      1,100        100 TONS OF HOT-MIX BEFORE THE SHIFT.
3             TERMINATE  0           THIS OPTION MAY BE OMITTED, OR THE AMOUNT
        *                            TO BE PRE-STORED MAY BE VARIED.
4             GENERATE                REGULAR PRODUCTION BEGINS.
5             GATE NU    3           MECHANICAL DEVICE FOR CONTROL OF XACTIONS.
6             SEIZE      3           MATERIALS LOADED INTO THE PUGMILL.
7             GATE LR    2           IS THERE ENOUGH HOT-MIX FOR THE DAY?
8             TEST GE    R1,X21      IS THERE ENOUGH SPACE IN HOPPER FOR MIX?
9             ADVANCE    X3,FN1      MATERIALS WEIGHED AND MIXED.
10            TEST GE    S1,X14,YYY  IF THERE IS NOT ENOUGH HOT-MIX IN SURGE TO
        *                             FILL THE TRUCK, THEN GO TO DIRECT LOAD.
11            RELEASE    3           HOT-MIX DUMPED INTO CHARGING CHUTE.
12            ADVANCE    60,5        HOT-MIX LIFTED BY HOT ELEVATOR TO SURGE.
13            ENTER      1,X21       HOT-MIX PLACED INTO SURGE HOPPER.
14       BYEE TERMINATE  0           EXCESS XACTIONS REMOVED FROM THE SYSTEM.
15       YYY  ENTER      1,X21       DIRECT LOADING WHEN HOPPER IS EMPTY.
16            RELEASE    3
17            TERMINATE  0
        *
        *
        ************************************************************************
        ************************************************************************
        *    THE FOLLOWING PORTION OF THE PROGRAM SIMULATES THE LOADING,       *
        * HAULING, DUMPING AND RETURN TO THE PLANT.                            *
        ************************************************************************
        ************************************************************************
        *
        *
18            GENERATE   0,0,,X7     GENERATE X7 LARGE TRUCKS.
19            LOGIC R    1           INSURE TIME CHECK IS IN POSITION.
20            LOGIC R    2           INSURE TIME CHECK 2 IS RESET.
21            ASSIGN     1,1         THIS NUMBER IDENTIFIES LARGE TRUCKS.
22       PEAT1 MARK      5           RECORD TIME THAT TRUCK ARRIVES AT PLANT.
23            TRANSFER   ,QTEST      TRUCK GOES TO PLANT QUEUE.
24            GENERATE   0,0,,X8     GENERATE X8 LARGE TRUCKS.
25            LOGIC R    1           INSURE THAT TIME CHECK IS IN POSITION.
26       PEAT2 MARK      4           RECORD TIME THAT TRUCK ARRIVFS AT PLANT.
27       QTEST TRANSFER  BOTH,,WORK1 TEST SEQUENCE TO INSURE THAT TIME
28            GATE LS    1             REMAINS TO MAKE ANOTHER RUN.  IF SO,
29            UNLINK     1,GONF,ALL    TRUCKS LINE UP AT QUEUE.  IF NOT, THEY
30            TRANSFER   ,QUIT         GO TO BLOCK QUIT WHERE THEY LEAVE SYSTEM
31       WORK1 QUEUE     1           LINE UP FOR LOADING.
32            LINK       1,FIFO,PLANT TRUCKS LINE UP ON FIRST COME BASIS.
33       PLANT SEIZE     1           A TRUCK IS IN POSITION FOR LOADING.
34       GONE DEPART     1           ALL WAITING TRUCKS MOVE UP ONE PLACE.
35            TABULATE   1           GATHERS STATISTICS ON TIME IN PLANT QUEUE.
36            TRANSFER   BOTH,,CONT  ANOTHER TEST SEQUENCE TO INSURE THERE IS
37            GATE LS    1             TIME TO MAKE A CYCLE BEFORE QUITTING.
38       QUIT TEST E     X2,0,SUBT   TRUCKS DEPART SYSTEM AT QUITTING TIME
```

```
       *                                     THROUGH NEXT SIX BLOCKS.
39                SAVEVALUE  100,V10       COMPUTE TOTAL COST.
40                SAVEVALUE  101,V11       COMPUTE UNIT COST.
41                SAVEVALUE  102,V13       COMPUTE AVERAGE HOURLY PRODUCTION.
42                TERMINATE  1
43          SUBT  SAVEVALUE  2-,1
44                TERMINATE  0
45          CONT  TEST E     P1,1,SMALL  IS THIS A LARGE OR SMALL TRUCK?
46                TEST GE    S1,X14        IS THERE ENOUGH HOT-MIX IN HOPPER TO LOAD?
47                ADVANCE    X19,FN6       LARGE TRUCKS LOAD.
48                LEAVE      1,X14         THE AMOUNT OF HOT-MIX IN HOPPER REDUCED.
49                TRANSFER   ,BACK1        TRUCK PREPARES TO DEPART PLANT.
50          SMALL TEST GE    S1,X15        IS THERE ENOUGH HOT-MIX IN HOPPER TO LOAD?
51                ADVANCE    X20,FN6       SMALL TRUCKS LOAD.
52                LEAVE      1,X15         THE AMOUNT OF HOT-MIX IN HOPPER REDUCED.
53          BACK1 RELEASE    1             TRUCK IS LOADED AND MOVES AWAY FROM PLANT.
54                UNLINK     1,PLANT,1     NEXT WAITING TRUCK CAN MOVE TO PLANT.
55                MARK                      RECORDS TIME TRUCK DEPARTS PLANT.
56                ADVANCE    V3            TRUCK HAULS FROM PLANT TO PAVER.
57                TABULATE   3             GATHERS STATISTICS FOR INTERARRIVAL TIMES.
58                QUEUE      2             TRUCK LINES UP AT PAVER.
59                LINK       2,FIFO,STWO   TRUCKS IN LINE ON FIRST COME BASIS.
60          STWO  SEIZE      2             IS PAVER FREE?
61                DEPART     2
62                TABULATE   2             GATHERS STATISTICS ON TIME IN PAVER QUEUE.
63                TEST E     P1,1,SML2     IS THIS A LARGE OR SMALL TRUCK?  IF LARGE,
64                ADVANCE    V4              THEN DUMP IN V4 SECONDS.  IF SMALL, THEN
       *                                     GO TO SML2 AND DUMP IN V7 SECONDS.
65                RELEASE    2             TRUCK DEPARTS FINISHER.
66                UNLINK     2,STWO,1      NEXT TRUCK MOVES TO FINISHER.
67                SAVEVALUE  13+,X14       THE TOTAL PRODUCTION IS INCREASED BY X14.
68                SAVEVALUE  4+,3          THE HAUL DISTANCE INCREASES.
69                SAVEVALUE  6+,2          THE RETURN TIME INCREASES.
70                MARK                      RECORDS TIME TRUCK DEPARTS PAVER.
71                ADVANCE    V5            TRUCK RETURNS TO PLANT.
72                TABULATE   4             GATHERS STATISTICS FOR INTERARRIVAL TIMES.
73                TRANSFER   ,PEAT1
74          SML2  ADVANCE    V7            SMALL TRUCKS DUMP IN V7 SECONDS.
75                RELEASE    2             TRUCK DEPARTS FINISHER.
76                UNLINK     2,STWO,1      NEXT TRUCK MOVES TO FINISHER.
77                SAVEVALUE  13+,X15       THE TOTAL PRODUCTION IS INCREASED BY X15.
78                SAVEVALUE  4+,2          HAUL DISTANCE INCREASES.
79                SAVEVALUE  6+,1          THE RETURN TIME INCREASES.
80                MARK                      RECORDS TIME TRUCK DEPARTS PAVER.
81                ADVANCE    V5            TRUCK RETURNS TO PLANT.
82                TABULATE   4             GATHERS STATISTICS FOR INTERARRIVAL TIMES.
83                TRANSFER   ,PEAT2
       *
       *
       ************************************************************************
       ************************************************************************
       *    THE FOLLOWING SERIES OF BLOCKS DETERMINE THE POINT IN THE DAY      *
       * WHEN THERE IS INSUFFICIENT TIME TO MAKE ANOTHER CYCLE.  WHEN THIS     *
       * POINT IN TIME OCCURS, A SIGNAL IS SENT THROUGH THE SYSTEM             *
       ************************************************************************
       ************************************************************************
       *
```

```
       *
84            GENERATE   ,,V8,1
85            LOGIC S    1
86            TERMINATE  0
       *
       *
       ***********************************************************************
       ***********************************************************************
       *    THIS PORTION OF THE PROGRAM DETERMINES THE POINT IN THE DAY WHEN  *
       * THERE IS AN ADEQUATE SUPPLY OF HOT-MIX IN THE SURGE HOPPER TO COM-   *
       * PLETE THE DAY SO THAT THE PLANT CAN BE SHUT DOWN.                    *
       ***********************************************************************
       ***********************************************************************
       *
       *
87            GENERATE   ,,25200,1
88            TEST E     BV1,1
89            LOGIC S    2
90            TERMINATE  0
       *
       *
       ***********************************************************************
       ***********************************************************************
       * THE FOLLOWING BLOCKS SERVE AS A SAFETY TO TERMINATE THE SIMULATION   *
       * IN THE EVENT OF ERRONEOUS DATA.                                      *
       ***********************************************************************
       ***********************************************************************
       *
       *
91            GENERATE   ,,29800,1
92            TERMINATE  1
       *
       *
       ***********************************************************************
       ***********************************************************************
       *    THE FOLLOWING BLOCKS CHANGE THE NUMBER OF TRUCKS, THE HAUL DISTANCE
       * OR OTHER PROJECT PARAMETER TO BE TESTED.                             *
       ***********************************************************************
       ***********************************************************************
              START      1
       *
       *
              END
```

```
RELATIVE CLOCK          29205  ABSOLUTE CLOCK          29205
BLOCK COUNTS
BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL
    1       0          1       11       0        484       21       0          3       31       0         80       41       0          1
    2       0          1       12       0        484       22       0         44       32       0         80       42       0          1
    3       0          1       13       0        484       23       0         44       33       0         80       43       0          5
    4       1        486       14       0        484       24       0          3       34       0         80       44       0          5
    5       0        485       15       0          0       25       0          3       35       0         80       45       0         80
    6       1        485       16       0          0       26       0         42       36       0         80       46       0         41
    7       0        484       17       0          0       27       0         86       37       0          0       47       0         41
    8       0        484       18       0          3       28       0          6       38       0          6       48       0         41
    9       0        484       19       0          3       29       0          6       39       0          1       49       0         41
   10       0        484       20       0          3       30       0          6       40       0          1       50       0         39

BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL    BLOCK CURRENT      TOTAL
   51       0         39       61       0         80       71       0         41       81       0         39       91       0          0
   52       0         39       62       0         80       72       0         41       82       0         39       92       0          0
   53       0         80       63       0         80       73       0         41       83       0         39
   54       0         80       64       0         41       74       0         39       84       0          1
   55       0         80       65       0         41       75       0         39       85       0          1
   56       0         80       66       0         41       76       0         39       86       0          1
   57       0         80       67       0         41       77       0         39       87       0          1
   58       0         80       68       0         41       78       0         39       88       0          1
   59       0         80       69       0         41       79       0         39       89       0          1
   60       0         80       70       0         41       80       0         39       90       0          1
```

```
USER CHAIN        TOTAL        AVERAGE        CURRENT        AVERAGE        MAXIMUM
                 ENTRIES      TIME/TRANS      CONTENTS       CONTENTS       CONTENTS
       1            10          32.000                          .010              5
       2            27         114.000                          .105              3
```

```
FACILITY          AVERAGE        NUMBER        AVERAGE          SEIZING   PREEMPTING
                UTILIZATION      ENTRIES      TIME/TRAN       TRANS. NO.  TRANS. NO.
       1           .057            80          20.899
       2           .491            80         179.274
       3           .999           485          60.214            12
```

```
STORAGE      CAPACITY     AVERAGE       AVERAGE         ENTRIES       AVERAGE       CURRENT      MAXIMUM
                         CONTENTS     UTILIZATION                   TIME/TRAN      CONTENTS     CONTENTS
      1           100     80.354          .803             1068     2197.336            26          100
```

```
CONTENTS OF FULLWORD SAVEVALUES (NON-ZERO)
SAVEVALUE  NR,        VALUE      NR,         VALUE       NR,         VALUE       NR,         VALUE       NR,        VALUE
             1            6       3             43        4           1151        5            186        6            901
             7            3       8              3       10            160       11           1975       13           1042
            14           14      15             12       16          12496       17          12496       18         162140
            19           23      20             20       21              2       22             36      100         302850
           101          290     102            130
```

```
QUEUE      MAXIMUM      AVERAGE      TOTAL       ZERO      PERCENT      AVERAGE        $AVERAGE       TABLE      CURRENT
           CONTENTS     CONTENTS    ENTRIES     ENTRIES     ZEROS     TIME/TRANS      TIME/TRANS     NUMBER     CONTENTS
    1           5         .010         80          70        87.5         4.000          32.000
    2           3         .105         80          54        67.4        38.474         118.384
 $AVERAGE TIME/TRANS = AVERAGE TIME/TRANS EXCLUDING ZERO ENTRIES
```

```
TABLE    1
ENTRIES IN TABLE            MEAN ARGUMENT           STANDARD DEVIATION            SUM OF ARGUMENTS
               80                    .125                          .603                      10.000        NON-WEIGHTED

           UPPER        OBSERVED       PER CENT       CUMULATIVE       CUMULATIVE       MULTIPLE      DEVIATION
           LIMIT       FREQUENCY       OF TOTAL       PERCENTAGE        REMAINDER        OF MEAN      FROM MEAN
               0              76          94.99             94.9              5.0          -.000          -.207
               1               1           1.24             96.2              3.7          8.000          1.451
               2               1           1.24             97.4              2.5         16.000          3.109
               3               1           1.24             98.7              1.2         24.000          4.767
               4               1           1.24            100.0               .0         32.000          6.425
REMAINING FREQUENCIES ARE ALL ZERO
```

```
TABLE    2
ENTRIES IN TABLE          MEAN ARGUMENT          STANDARD DEVIATION          SUM OF ARGUMENTS
              80                   .062                        .290                     5.000        NON-WEIGHTED

          UPPER       OBSERVED        PER CENT       CUMULATIVE       CUMULATIVE       MULTIPLE        DEVIATION
          LIMIT       FREQUENCY       OF TOTAL       PERCENTAGE        REMAINDER        OF MEAN        FROM MEAN
              0              76          94.99             94.9              5.0          -.000            -.214
              1               3           3.74             98.7              1.2         16.000            3.224
              2               1           1.24            100.0               .0         32.000            6.663
REMAINING FREQUENCIES ARE ALL ZERO
```

```
TABLE    3
ENTRIES IN TABLE          MEAN ARGUMENT          STANDARD DEVIATION          SUM OF ARGUMENTS
              79                344.594                     258.000                 27223.000          NON-WEIGHTED

         UPPER        OBSERVED        PER CENT        CUMULATIVE        CUMULATIVE        MULTIPLE        DEVIATION
         LIMIT       FREQUENCY        OF TOTAL        PERCENTAGE         REMAINDER         OF MEAN        FROM MEAN
             0               0             .00                .0             100.0           -.000           -1.335
            60               8           10.12              10.1              89.8            .174           -1.103
           120               5            6.32              16.4              83.5            .348            -.870
           180              10           12.65              29.1              70.8            .522            -.637
           240               8           10.12              39.2              60.7            .696            -.405
           300               5            6.32              45.5              54.4            .870            -.172
           360               8           10.12              55.6              44.3           1.044             .059
           420              13           16.45              72.1              27.8           1.218             .292
           480               5            6.32              78.4              21.5           1.392             .524
           540               4            5.06              83.5              16.4           1.567             .757
           600               2            2.53              86.0              13.9           1.741             .989
           660               4            5.06              91.1               8.8           1.915            1.222
           720               2            2.53              93.6               6.3           2.089            1.455
           780               1            1.26              94.9               5.0           2.263            1.687
           840               1            1.26              96.2               3.7           2.437            1.920
           900               1            1.26              97.4               2.5           2.611            2.152
           960               0             .00              97.4               2.5           2.785            2.385
          1020               0             .00              97.4               2.5           2.959            2.617
          1080               0             .00              97.4               2.5           3.134            2.850
          1140               1            1.26              98.7               1.2           3.308            3.082
          1200               0             .00              98.7               1.2           3.482            3.315
          1260               0             .00              98.7               1.2           3.656            3.548
          1320               0             .00              98.7               1.2           3.830            3.780
          1380               0             .00              98.7               1.2           4.004            4.013
          1440               0             .00              98.7               1.2           4.178            4.245
          1500               0             .00              98.7               1.2           4.352            4.478
          1560               1            1.26             100.0                .0           4.527            4.710
REMAINING FREQUENCIES ARE ALL ZERO
```

```
TABLE    4
ENTRIES IN TABLE         MEAN ARGUMENT          STANDARD DEVIATION          SUM OF ARGUMENTS
              79                348.139                    247.937                 27503.000          NON-WEIGHTED

          UPPER         OBSERVED         PER CENT       CUMULATIVE         CUMULATIVE      MULTIPLE          DEVIATION
          LIMIT        FREQUENCY         OF TOTAL       PERCENTAGE          REMAINDER       OF MEAN          FROM MEAN
              0                0              .00               .0              100.0         -.000             -1.404
             60               12            15.18             15.1               84.8          .172             -1.162
            120                8            10.12             25.3               74.6          .344              -.920
            180                6             7.59             32.9               67.0          .517              -.678
            240                5             6.32             39.2               60.7          .689              -.436
            300                4             5.06             44.3               55.6          .861              -.194
            360                4             5.06             49.3               50.6         1.034               .047
            420               10            12.65             62.0               37.9         1.206               .289
            480                8            10.12             72.1               27.8         1.378               .531
            540                7             8.86             81.0               18.9         1.551               .773
            600                3             3.79             84.8               15.1         1.723              1.015
            660                5             6.32             91.1                8.8         1.895              1.257
            720                0              .00             91.1                8.8         2.068              1.499
            780                2             2.53             93.6                6.3         2.240              1.741
            840                2             2.53             96.2                3.7         2.412              1.983
            900                1             1.26             97.4                2.5         2.585              2.225
            960                1             1.26             98.7                1.2         2.757              2.467
           1020                0              .00             98.7                1.2         2.929              2.709
           1080                1             1.26            100.0                 .0         3.102              2.951
REMAINING FREQUENCIES ARE ALL ZERO
```

APPENDIX D

FORMS AND INSTRUCTIONS FOR RECORDING FIELD DATA

Page____of____

PLANT DATA

Date______________________

Owner_____________________

Location__________________

Pugmill Cap.______________

Film____________ Sec/Frame

Time______________________

Weather___________________

Mix Type__________________

(1) Truck No.	(2) Arrive Queue	(3) Begin Load	(4) Depart	(5) Time in Queue	(6) Load Time	(7) Time Between Arrivals	(8) Return Time

INSTRUCTIONS FOR PLANT OBSERVATIONS

All times recorded to nearest second.

Columns (1), (2), (3), and (4) are completed in the field or from timelapse photography analysis.

a = preceding truck.

b = succeeding truck.

(1) Truck identification number.

(2) Truck arrives in queue when it comes to a halt in line.

(3) If there is no queue, truck begins loading when front end passes beneath pugmill. If there is a queue, truck begins loading time when preceding truck departs from beneath pugmill. If surge loading is used, loading begins at instant discharge chute opens.

(4) Truck departs plant when discharge chute of pugmill or surge hopper closes.

(5) Time in queue = (3) - (2).

(6) Load time = (4) - (3).

(7) Time between arrivals = (2)a - (2)b.

(8) Return time = (6)[1] - (2).

[1] Time from column (6) on paver data sheet for truck No. x.

PAVER DATA

Date____________________

Owner____________________

Location____________________

Paver Capacity____________________

Film______________Sec/frame

Pavement width______Thickness________

Mix type____________________

Repositioning time____________________

Distance____________________

(1) Truck No.	(2) Arrive Queue	(3) Depart Queue	(4) Time in Queue	(5) Begin Dump	(6) Maneuver Time	(7) Depart Site	(8) Dump Time	(9) Time Between Arrivals	(10) Travel Time

INSTRUCTIONS FOR PAVER OBSERVATIONS

All times recorded to nearest second.

Columns (1), (2), (3), (5), and (7) are completed in the field or from timelapse photography analysis.

a = preceding truck.

b = succeeding truck.

(1) Truck identification number.

(2) Truck arrives in queue when it passes midpoint of paver. If there is no queue, this time is recorded as beginning of maneuver time.

(3) Truck departs queue when it begins backward motion into dump position. This column is left blank if there is no queue.

(4) Time in queue = (2) - (3).

(5) Truck begins dumping when rear tires are engaged in the Layton hitch.

(6) Maneuver time = (5) - (2) if there is no queue.
(5) - (3) if there is a queue.

(7) Truck departs site when Layton hitch is released.

(8) Dump time = (7) - (5).

(9) Time between arrivals = (2)a - (2)b.

(10) Haul time = (4)*- (2).

*Time from column (4) on plant data sheet for truck No. x.

TRUCK DATA

Date____________________

Owner____________________

Location____________________

Truck No.	Firm No.	Color	Capacity	Comments

APPENDIX E

PROGRAM FOR DATA ANALYSIS

```
BLOCK                                                                                            CARD
NUMBER  *LOC   OPERATION  A,B,C,D,E,F,G              COMMENTS                                    NUMBER
               SIMULATE                                                                              3
        *                                                                                            4
        *                                                                                            5
        *    LOCATION  :  HASKELL LEMON CONSTRUCTION COMPANY                                         6
        *                 OKLAHOMA CITY, OKLAHOMA                                                    7
        *    DATE      :  5 FEB 1973                                                                 8
        *    WEATHER   :  CLOUDY, 48 F.                                                              9
        *    MIX       :  SURFACE MIX, TYPE C                                                       10
        *    PLANT     :  EAST PLANT, 5000 LB PUGMILL CAPACITY                                      11
        *                                                                                           12
        *                                                                                           13
        *********************************************************************                      14
        *                                                                   *                       15
        *                 THE FOLLOWING SEGMENT OF THE PROGRAM              *                       16
        *               PLACES THE VALUE OF EACH OBSERVATION OF             *                       17
        *                 THE SAMPLE INTO A SAVEVALUE LOCATION              *                       18
        *                                                                   *                       19
        *********************************************************************                      20
        *                                                                                           21
        *                                                                                           22
               INITIAL    X1,38/X2,38/X3,39/X4,34/X5,33/X6,33/X7,43/X8,33/X9,35                     23
               INITIAL    X10,34/X11,34/X12,34/X13,52/X14,35/X15,34/X16,35                          24
               INITIAL    X17,34/X18,35/X19,34/X20,34/X21,35/X22,35/X23,35                          25
               INITIAL    X24,35/X25,36/X26,35/X27,32/X28,35/X29,35/X30,39                          26
               INITIAL    X31,35/X32,46/X33,34/X34,34/X35,37/X36,35/X37,56                          27
               INITIAL    X39,53/X40,57/X41,55/X42,103/X43,106/X44,35                               28
               INITIAL    X38,59/X45,48/X46,49/X47,34/X48,35/X49,46/X50,63                          29
               INITIAL    X51,63/X52,51/X53,35/X54,45/X55,52/X56,43/X57,53                          30
               INITIAL    X58,49/X59,36/X60,35/X61,37/X62,40/X63,36                                 31
               INITIAL    X64,210/X65,27/X66,35/X67,32/X68,51/X69,41                                32
               INITIAL    X70,34/X71,35/X72,34/X73,35/X74,35/X75,37/X76,46                          33
               INITIAL    X77,45/X78,45/X79,46/X80,44/X81,44/X82,41/X83,40                          34
               INITIAL    X84,40/X85,40/X86,40/X87,40/X88,37/X89,34/X90,35                          35
               INITIAL    X91,34/X92,49/X93,46/X94,55/X95,34/X96,35/X97,35                          36
               INITIAL    X98,35/X99,42/X100,4C/X101,39/X102,40/X103,56                             37
               INITIAL    X104,45/X105,39/X106,35/X107,36/X108,35/X109,46                           38
               INITIAL    X110,39/X111,43/X112,57/X113,35/X114,48/X115,40                           39
               INITIAL    X116,40/X117,44/X118,41/X119,34/X120,34/X121,35                           40
               INITIAL    X122,35/X123,34/X124,36/X125,40/X126,38/X127,41                           41
               INITIAL    X128,38/X129,40/X130,44/X131,59/X132,40/X133,41                           42
               INITIAL    X134,39/X135,43/X136,40/X137,41/X138,40/X139,35                           43
               INITIAL    X140,35/X141,38/X142,40/X143,43/X144,64/X145,34                           44
               INITIAL    X146,35/X147,35/X148,35/X149,54/X150,35/X151,35                           45
               INITIAL    X152,39/X153,38/X154,38/X155,36/X156,35/X157,34                           46
               INITIAL    X158,35/X159,38/X160,37/X161,57/X162,35/X163,47                           47
               INITIAL    X164,61/X165,56/X166,51/X167,59/X168,37/X169,39                           48
               INITIAL    X170,41/X171,49/X172,44/X173,62/X174,36/X175,37                           49
               INITIAL    X176,34/X177,35/X178,47/X179,41/X180,37/X181,40                           50
               INITIAL    X182,38/X183,60/X184,35/X185,35/X186,40/X187,39                           51
               INITIAL    X188,38/X189,46/X190,42/X191,45/X192,43/X193,38                           52
               INITIAL    X194,35/X195,44/X196,44/X197,40/X198,38/X199,42                           53
               INITIAL    X200,41/X201,35/X202,39/X203,45/X204,34/X205,35                           54
               INITIAL    X206,38/X207,36/X208,35/X209,35/X210,54/X211,35                           55
               INITIAL    X212,35/X213,35/X214,35/X215,51/X216,40/X217,39                           56
               INITIAL    X218,39/X219,40/X220,38/X221,198/X222,40/X223,83                          57
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INITIAL     X224,94/X225,104/X226,39/X227,43/X228,35/X229,33                       58
INITIAL     X230,36/X231,35/X232,36/X233,36/X234,35/X235,36                        59
INITIAL     X236,36/X237,37/X238,36/X239,36/X240,36/X241,36                        60
INITIAL     X242,36/X243,36/X244,39/X245,35/X246,35/X247,35                        61
INITIAL     X248,35/X249,39/X250,61/X251,36/X252,36/X253,36                        62
INITIAL     X254,35/X255,37/X256,35/X257,45/X258,36/X259,38                        63
INITIAL     X260,42/X261,39/X262,37/X263,40/X264,35/X265,33                        64
INITIAL     X266,52/X267,40/X268,46/X269,49/X270,44/X271,31                        65
INITIAL     X272,37/X273,44/X274,50/X275,44/X276,44/X277,34                        66
INITIAL     X278,35/X279,35/X280,46/X281,45/X282,47/X283,48                        67
INITIAL     X284,36/X285,43/X286,45/X287,42/X288,50/X289,35                        68
INITIAL     X290,36/X291,34/X292,35/X293,48/X294,67/X295,35                        69
INITIAL     X296,36/X297,35/X298,457/X299,60/X300,47/X301,33                       70
INITIAL     X302,40/X303,42/X304,35/X305,35/X306,35/X307,39                        71
INITIAL     X308,35/X309,36/X310,35/X311,35/X312,36/X313,46                        72
INITIAL     X314,46                                                                73
INITIAL     X315,33/X316,33/X317,74/X318,31/X319,30/X320,32                        74
INITIAL     X321,33/X322,33/X323,31/X324,31/X325,33/X326,33                        75
INITIAL     X327,34/X328,33/X329,44/X330,33/X331,32/X332,31                        76
INITIAL     X333,34/X334,35/X335,34/X336,49/X337,33/X338,33                        77
INITIAL     X339,33/X340,34/X341,34/X342,39/X343,34/X344,35                        78
INITIAL     X345,34/X346,35/X347,34/X348,35/X349,34/X350,39                        79
INITIAL     X351,45/X352,31/X353,32/X354,52/X355,34/X356,34                        80
INITIAL     X357,61/X358,34/X359,33/X360,34/X361,34/X362,72                        81
INITIAL     X363,58/X364,63/X365,33/X366,35/X367,53/X368,33                        82
INITIAL     X369,35/X370,34/X371,41/X372,36/X373,41/X374,34                        83
INITIAL     X375,70/X376,40/X377,33/X378,33/X379,33/X380,40                        84
INITIAL     X381,58/X382,56/X383,39/X384,44/X385,33/X386,36                        85
INITIAL     X387,34/X388,40/X389,33/X390,33/X391,39/X392,34                        86
INITIAL     X393,33/X394,34/X395,37/X396,39/X397,55/X398,33                        87
INITIAL     X399,45/X400,43/X401,33/X402,33/X403,34/X404,33                        88
INITIAL     X405,34/X406,51/X407,33/X408,34/X409,33/X410,32                        89
INITIAL     X411,39/X412,33/X413,32/X414,33/X415,37/X416,39                        90
INITIAL     X417,56/X418,33/X419,37/X420,40/X421,34/X422,49                        91
INITIAL     X423,39/X424,40/X425,53/X426,33/X427,35/X428,40                        92
INITIAL     X429,39/X430,36/X431,77/X432,33/X433,33/X434,33                        93
INITIAL     X435,34/X436,33/X437,57/X438,33/X439,33/X440,34                        94
INITIAL     X441,32/X442,52/X443,33/X444,64/X445,34/X446,33                        95
INITIAL     X447,33/X448,33/X449,34/X450,34/X451,34/X452,33                        96
INITIAL     X453,33/X454,34/X455,33/X456,33/X457,46/X458,33                        97
INITIAL     X459,33/X460,33/X461,34/X462,33/X463,52/X464,33                        98
INITIAL     X465,33/X466,36/X467,41/X468,46/X469,59/X470,33                        99
INITIAL     X471,34/X472,40/X473,34/X474,49/X475,42/X476,33                       100
INITIAL     X477,38/X478,62/X479,32/X480,33/X481,33/X482,33                       101
INITIAL     X483,64/X484,33/X485,33/X486,33/X487,33/X488,47                       102
INITIAL     X489,55/X490,30/X491,32/X492,35/X493,68/X494,33                       103
INITIAL     X495,33/X496,33/X497,33/X498,34/X499,77/X500,33                       104
INITIAL     X501,34/X502,33/X503,33/X504,33/X505,34/X506,72                       105
INITIAL     X507,32/X508,34/X509,34/X510,33/X511,55/X512,34                       106
INITIAL     X513,33/X514,33/X515,33/X516,34/X517,85/X518,33                       107
INITIAL     X519,33/X520,33/X521,33/X522,33/X523,58/X524,33                       108
INITIAL     X525,231/X526,33/X527,33/X528,33/X529,33/X530,34                      109
INITIAL     X531,42/X532,33/X533,33/X534,33/X535,33/X536,33                       110
INITIAL     X537,72/X538,33/X539,34/X540,33/X541,34/X542,33                       111
INITIAL     X543,34/X544,40/X545,45/X546,34/X547,71/X548,33                       112
INITIAL     X549,114/X550,33/X552,38/X551,34/X553,34/X554,64                      113
INITIAL     X555,34/X556,32/X557,33/X558,43/X559,47/X560,47                       114
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              INITIAL    X561,33/X562,72/X563,33/X564,75/X565,32/X566,33
              INITIAL    X567,76/X568,33/X569,33/X570,33/X571,35/X572,32
              INITIAL    X573,32/X574,80/X575,32/X576,33/X577,34/X578,34
              INITIAL    X579,53/X580,33/X581,33/X582,35/X583,40/X584,33
              INITIAL    X585,46/X586,35/X587,59/X588,36/X589,36/X590,37
              INITIAL    X591,37/X592,37/X593,38/X594,37/X595,36/X597,37
              INITIAL    X596,37/X598,37/X599,36/X600,107/X601,98/X602,43
              INITIAL    X603,58/X604,38/X605,36/X606,37/X607,36/X608,37
              INITIAL    X609,36/X610,37/X611,55/X612,37/X613,36/X614,37
              INITIAL    X615,39/X616,49/X617,47/X618,46/X619,46/X620,54
              INITIAL    X621,38/X622,37/X623,36/X624,56/X625,50/X626,51
              INITIAL    X627,35/X628,41/X629,45/X630,45/X631,54/X632,43
              INITIAL    X633,45/X634,47/X635,48/X636,41/X637,35/X638,45
              INITIAL    X639,37/X640,80/X641,36/X642,69/X643,36/X644,36
              INITIAL    X645,37/X646,37/X647,53/X648,36/X649,36/X650,36
              INITIAL    X651,37/X652,36/X653,37/X654,34/X655,37/X656,36
              INITIAL    X657,37/X658,36/X659,36/X660,50/X661,62/X662,38
              INITIAL    X663,37/X664,40/X665,50/X666,49/X667,51/X668,46
              INITIAL    X669,45/X670,45/X671,41/X672,38/X673,36/X674,37
              INITIAL    X675,36/X676,37/X677,49/X678,37/X679,36/X680,37
              INITIAL    X681,37/X682,38/X683,37/X684,59/X685,51/X686,83
              INITIAL    X687,36/X688,37/X689,37/X690,100/X691,98/X692,44
              INITIAL    X693,36/X694,36/X695,36/X696,37/X697,36/X698,37
              INITIAL    X699,37/X700,36/X701,37/X702,37/X703,45/X704,173
              INITIAL    X705,36/X706,99/X707,44/X708,36/X709,36/X710,36
              INITIAL    X711,37/X712,56/X713,55/X714,51/X715,53/X716,51
              INITIAL    X717,52/X718,57/X719,53/X720,55/X721,54/X722,56
              INITIAL    X723,52/X724,41/X725,56/X726,42/X727,56/X728,54
              INITIAL    X729,60
              INITIAL    X730,729
        *
        *
        ***********************************************************************
        *                                                                     *
        *         THIS PORTION OF THE PROGRAM CAUSES THE STANDARD             *
        *            GPSS TABLE OUTPUT TO BE PRINTED IN TABLE 1               *
        *                                                                     *
        ***********************************************************************
        *
        *
         1    TABLE      X*1,30,5,100
1             GENERATE   ,,,1
2             ASSIGN     1,X730
3        XXX  TABULATE   1
4             LOOP       1,XXX
5             TERMINATE  1
              START      1
        *
        *
        ***********************************************************************
        *                                                                     *
        *             THE FOLLOWING PROGRAM SEGMENT PRINTS THE                *
        *              HISTOGRAM OF THE FREQUENCY OCCURRENCE                  *
        *                                                                     *
        ***********************************************************************
        *
        *
```

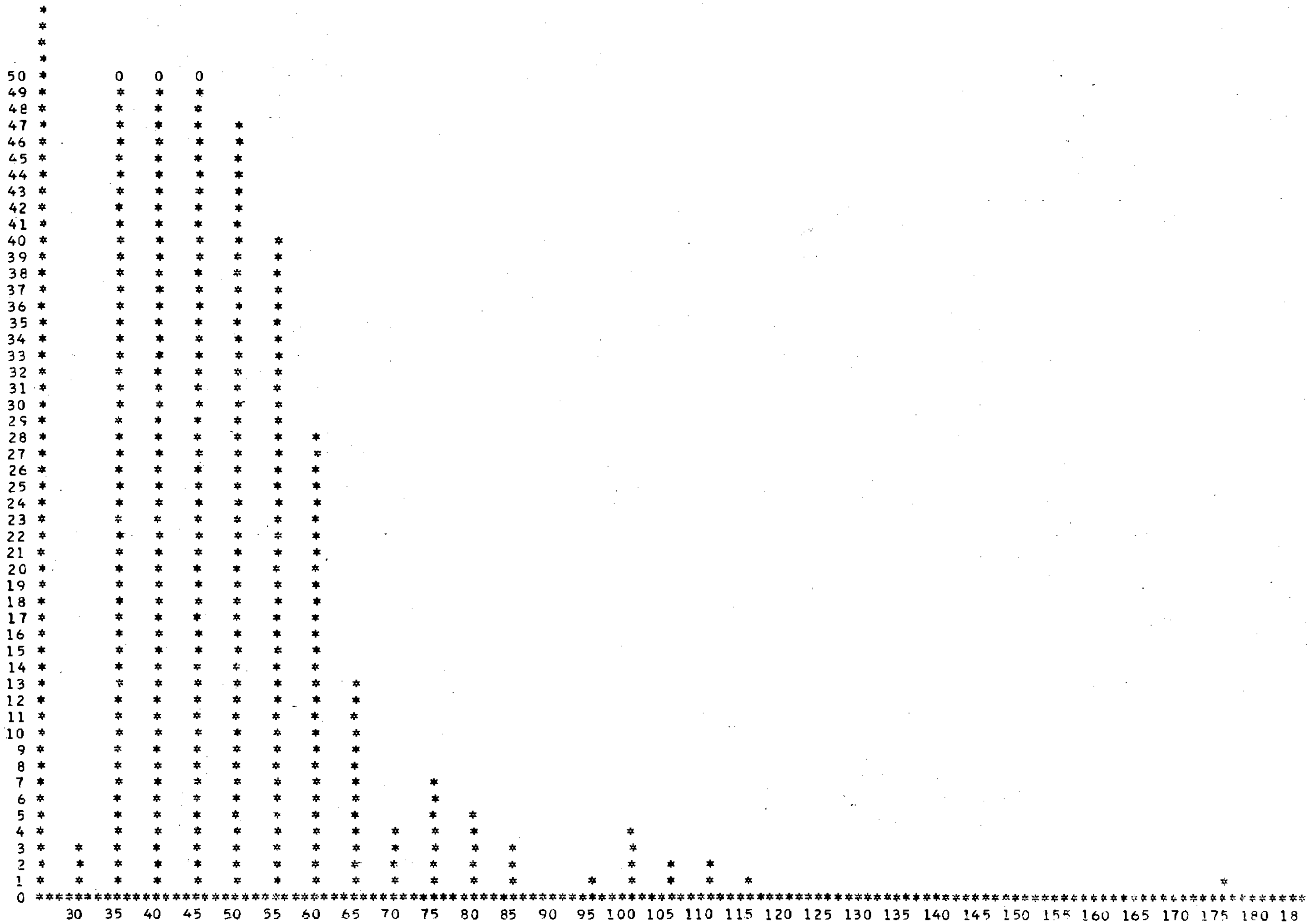
```
       REPORT
       EJECT
 TAB   TITLE      1,THE MEAN AND STANDARD DEVIATION OF PUGMILL CYCLE TIM
ME AND THE PROBABILITY OF CYCLE TIME OCCURRENCE.
       EJECT
       GRAPH      TF,1
       ORIGIN     56,3
       X          ,1,3,30,1,32
       Y          0,1,50,1
 47    STATEMENT  58,29,PLOT OF FREQUENCY OCCURRENCES
       ENDGRAPH
       END
```

```
THE MEAN AND STANDARD DEVIATION OF PUGMILL CYCLE TIME AND THE PROBABILITY OF CYCLE TIME OCCURRENCE.

TABLE    1
ENTRIES IN TABLE          MEAN ARGUMENT          STANDARD DEVIATION          SUM OF ARGUMENTS
          729                   42.588                        22.812                31047.000          NON-WEIGHTED

           UPPER        OBSERVED        PER CENT        CUMULATIVE        CUMULATIVE        MULTIPLE        DEVIATION
           LIMIT        FREQUENCY       OF TOTAL        PERCENTAGE        REMAINDER          OF MEAN        FROM MEAN
              30              3             .41                .4              99.5            .704            -.551
              35            294           40.32              40.7              59.2            .821            -.332
              40            199           27.29              68.0              31.9            .939            -.113
              45             71            9.73              77.7              22.2           1.056             .105
              50             47            6.44              84.2              15.7           1.174             .324
              55             40            5.48              89.7              10.2           1.291             .544
              60             28            3.84              93.5               6.4           1.408             .763
              65             13            1.78              95.3               4.6           1.526             .982
              70              4             .54              95.8               4.1           1.643            1.201
              75              7             .96              96.8               3.1           1.761            1.420
              80              5             .68              97.5               2.4           1.878            1.639
              85              3             .41              97.9               2.0           1.995            1.859
              90              0             .00              97.9               2.0           2.113            2.078
              95              1             .13              98.0               1.9           2.230            2.297
             100              4             .54              98.6               1.3           2.348            2.516
             105              2             .27              98.9               1.0           2.465            2.735
             110              2             .27              99.1                .8           2.582            2.955
             115              1             .13              99.3                .6           2.700            3.174
             120              0             .00              99.3                .6           2.817            3.393
             125              0             .00              99.3                .6           2.935            3.612
             130              0             .00              99.3                .6           3.052            3.831
             135              0             .00              99.3                .6           3.169            4.050
             140              0             .00              99.3                .6           3.287            4.270
             145              0             .00              99.3                .6           3.404            4.489
             150              0             .00              99.3                .6           3.522            4.708
             155              0             .00              99.3                .6           3.639            4.927
             160              0             .00              99.3                .6           3.756            5.146
             165              0             .00              99.3                .6           3.874            5.365
             170              0             .00              99.3                .6           3.991            5.585
             175              1             .13              99.4                .5           4.109            5.804
             180              0             .00              99.4                .5           4.226            6.023
             185              0             .00              99.4                .5           4.343            6.242
             190              0             .00              99.4                .5           4.461            6.461
             195              0             .00              99.4                .5           4.578            6.681
             200              1             .13              99.5                .4           4.696            6.900
             205              0             .00              99.5                .4           4.813            7.119
             210              1             .13              99.7                .2           4.930            7.338
             215              0             .00              99.7                .2           5.048            7.557
             220              0             .00              99.7                .2           5.165            7.776
             225              0             .00              99.7                .2           5.283            7.996
             230              0             .00              99.7                .2           5.400            8.215
             235              1             .13              99.8                .1           5.517            8.434
             240              0             .00              99.8                .1           5.635            8.653
             245              0             .00              99.8                .1           5.752            8.872
             250              0             .00              99.8                .1           5.870            9.092
             255              0             .00              99.8                .1           5.987            9.311
             260              0             .00              99.8                .1           6.104            9.530
             265              0             .00              99.8                .1           6.222            9.749
             270              0             .00              99.8                .1           6.339            9.968
             275              0             .00              99.8                .1           6.457           10.187
             280              0             .00              99.8                .1           6.574           10.407
             285              0             .00              99.8                .1           6.691           10.626
             290              0             .00              99.8                .1           6.809           10.845
             295              0             .00              99.8                .1           6.926           11.064
             300              0             .00              99.8                .1           7.044           11.283
```

```
           305            0          .00          99.8           .1        7.161        11.502
           310            0          .00          99.8           .1        7.278        11.722
           315            0          .00          99.8           .1        7.396        11.941
           320            0          .00          99.8           .1        7.513        12.160
           325            0          .00          99.8           .1        7.631        12.379
           330            0          .00          99.8           .1        7.748        12.598
           335            0          .00          99.8           .1        7.865        12.818
           340            0          .00          99.8           .1        7.983        13.037
           345            0          .00          99.8           .1        8.100        13.256
           350            0          .00          99.8           .1        8.218        13.475
           355            0          .00          99.8           .1        8.335        13.694
           360            0          .00          99.8           .1        8.452        13.913
           365            0          .00          99.8           .1        8.570        14.133
           370            0          .00          99.8           .1        8.687        14.352
           375            0          .00          99.8           .1        8.805        14.571
           380            0          .00          99.8           .1        8.922        14.790
           385            0          .00          99.8           .1        9.040        15.009
           390            0          .00          99.8           .1        9.157        15.228
           395            0          .00          99.8           .1        9.274        15.448
           400            0          .00          99.8           .1        9.392        15.667
           405            0          .00          99.8           .1        9.509        15.886
           410            0          .00          99.8           .1        9.627        16.105
           415            0          .00          99.8           .1        9.744        16.324
           420            0          .00          99.8           .1        9.861        16.544
           425            0          .00          99.8           .1        9.979        16.763
           430            0          .00          99.8           .1       10.096        16.982
           435            0          .00          99.8           .1       10.214        17.201
           440            0          .00          99.8           .1       10.331        17.420
           445            0          .00          99.8           .1       10.448        17.639
           450            0          .00          99.8           .1       10.566        17.859
           455            0          .00          99.8           .1       10.683        18.078
           460            1          .13         100.0           .0       10.801        18.297
REMAINING FREQUENCIES ARE ALL ZERO
```



PLOT OF FREQUENCY OCCURRENCES

APPENDIX F

PROGRAM FOR SURGE ANALYSIS

```
************************************************************************************************
*                                                                                              *
*  PROC REGR   :  S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                        *
*                                                                                              *
*  DATA SET    :  SURGE         NUMBER OF VARIABLES =  2       NUMBER OF CLASSES =  0          *
*                                                                                              *
*  VARIABLES   :  LOAD TIME                                                                    *
*                                                                                              *
************************************************************************************************
```

```
S T A T I S T I C A L   A N A L Y S I S   S Y S T E M                                14:13 FRIDAY, OCTOBER 12, 1973

                DATA SURGE;
                INPUT LOAD 3-7 TIME 9-12;
                CARDS


                 124 OBSERVATIONS IN DATA SET SURGE          2  VARIABLES

                PROC REGR ;
                MODEL TIME=LOAD/P CLI;
                MODEL TIME=LOAD/NOINT P CLI
```

```
                    S T A T I S T I C A L   A N A L Y S I S   S Y S T E M

ANALYSIS OF VARIANCE TABLE , REGRESSION COEFFICIENTS , AND STATISTICS OF FIT FOR DEPENDENT VARIABLE TIME


SOURCE               DF    SUM OF SQUARES        MEAN SQUARE        F VALUE     PROB > F      R-SQUARE          C.V.

REGRESSION            1     6287.77718261      6287.77718261     1202.46904       0.0001    0.90788752     12.26650 %

ERROR               122      637.94475287         5.22905535
                                                                                                  STD DEV     TIME MEAN
CORRECTED TOTAL     123     6925.72193548
                                                                                               2.28671278      18.64194



SOURCE               DF     SEQUENTIAL SS         F VALUE    PROB > F        PARTIAL SS         F VALUE     PROB > F

LOAD                  1     6287.77718261      1202.46904      0.0001     6287.77718261      1202.46904       0.0001



SOURCE              B VALUES          T FOR H0:B=0          PROB > |T|           STD ERR B       STD B VALUES

INTERCEPT         1.48938711               2.78091              0.0064          0.53557568        0.0
LOAD              1.56226615              34.67664              0.0001          0.04505241        0.95283137


         OBS              OBSERVED           PREDICTED            RESIDUAL         LOWER 95% CL       UPPER 95% CL
        NUMBER              VALUE              VALUE                             FOR INDIVIDUAL     FOR INDIVIDUAL

          1             33.00000000        33.43772978         -0.43772978        28.81488245        38.06057711
          2             31.50000000        33.35961647         -1.85961647        28.73758184        37.98165110
          3             22.00000000        27.23553318         -5.23553318        22.66410613        31.80696024
          4             26.50000000        26.95432528         -0.45432528        22.38459316        31.52405740
          5             27.00000000        26.87621197          0.12378803        22.30694077        31.44548317
          6             27.00000000        26.87621197          0.12378803        22.30694077        31.44548317
          7             27.20000000        26.87621197          0.32378803        22.30694077        31.44548317
          8             27.40000000        26.40753213          0.99246787        21.84093597        30.97412829
          9             26.50000000        26.32941882          0.17058118        21.76325341        30.89558423
         10             25.40000000        26.01696559         -0.61696559        21.45248002        30.58145116
         11             25.00000000        25.54828575         -0.54828575        20.98619033        30.11038116
         12             23.00000000        25.54828575         -2.54828575        20.98619033        30.11038116
         13             25.40000000        25.31394583          0.08605417        20.75298710        29.87490455
         14             27.00000000        25.31394583          1.68605417        20.75298710        29.87490455
         15             23.00000000        25.31394583         -2.31394583        20.75298710        29.87490455
         16             23.00000000        25.31394583         -2.31394583        20.75298710        29.87490455
         17             32.00000000        25.31394583          6.68605417        20.75298710        29.87490455
         18             25.50000000        25.23583252          0.26416748        20.67524403        29.79642101
         19             26.00000000        25.31394583          0.68605417        20.75298710        29.87490455
         20             25.00000000        25.15771921         -0.15771921        20.59749663        29.71794179
         21             25.20000000        25.07960590          0.12039410        20.51974490        29.63946691
         22             21.00000000        24.92337929         -3.92337929        20.36422844        29.48253014
         23             26.00000000        24.92337929          1.07662071        20.36422844        29.48253014
         24             25.00000000        24.92337929          0.07662071        20.36422844        29.48253014
```

```
25      25.00000000     24.92337929      0.07662071     20.36422844     29.48253014
26      23.00000000     24.92337929     -1.92337929     20.36422844     29.48253014
27      26.00000000     24.92337929      1.07662071     20.36422844     29.48253014
28      26.00000000     24.92337929      1.07662071     20.36422844     29.48253014
29      21.00000000     24.92337929     -3.92337929     20.36422844     29.48253014
30      28.00000000     24.92337929      3.07662071     20.36422844     29.48253014
31      24.50000000     24.76715268     -0.26715268     20.20869463     29.32561072
32      24.50000000     24.53281275     -0.03281275     19.97536141     29.09026410
33      22.50000000     24.45469945     -1.95469945     19.89757499     29.01182391
34      21.00000000     24.14224622     -3.14224622     19.58638589     28.69810655
35      25.00000000     23.59545307      1.40454693     19.04163769     28.14926845
36      22.80000000     23.51733976     -0.71733976     18.96379912     28.07088040
37      24.00000000     23.36111314      0.63888686     18.80810894     27.91411735
38      26.00000000     23.36111314      2.63888686     18.80810894     27.91411735
39      26.00000000     23.36111314      2.63888686     18.80810894     27.91411735
40      22.00000000     23.36111314     -1.36111314     18.80810894     27.91411735
41      18.00000000     23.36111314     -5.36111314     18.80810894     27.91411735
42      22.00000000     23.36111314     -1.36111314     18.80810894     27.91411735
43      21.50000000     23.36111314     -1.86111314     18.80810894     27.91411735
44      22.00000000     22.97054661     -0.97054661     18.41880731     27.52228591
45      24.00000000     22.57998007      1.42001993     18.02939678     27.13056337
46      24.00000000     22.57998007      1.42001993     18.02939678     27.13056337
47      24.00000000     22.57998007      1.42001993     18.02939678     27.13056337
48      20.50000000     22.57998007     -2.07998007     18.02939678     27.13056337
49      21.00000000     22.57998007     -1.57998007     18.02939678     27.13056337
50      22.00000000     22.18941354     -0.18941354     17.63987727     26.73894981
51      21.00000000     22.18941354     -1.18941354     17.63987727     26.73894981
52      25.00000000     22.18941354      2.81058646     17.63987727     26.73894981
53      20.00000000     22.18941354     -2.18941354     17.63987727     26.73894981
54      20.50000000     22.18941354     -1.68941354     17.63987727     26.73894981
55      20.50000000     22.18941354     -1.68941354     17.63987727     26.73894981
56      20.00000000     21.79884700     -1.79884700     17.25024870     26.34744530
57      24.50000000     21.79884700      2.70115300     17.25024870     26.34744530
58      25.00000000     21.79884700      3.20115300     17.25024870     26.34744530
59      22.00000000     21.79884700      0.20115300     17.25024870     26.34744530
60      19.00000000     21.79884700     -2.79884700     17.25024870     26.34744530
61      22.00000000     21.79884700      0.20115300     17.25024870     26.34744530
62      20.00000000     21.79884700     -1.79884700     17.25024870     26.34744530
63      20.50000000     21.01771393     -0.51771393     16.47066414     25.56476371
64      26.50000000     21.01771393      5.48228607     16.47066414     25.56476371
65      25.00000000     21.01771393      3.98228607     16.47066414     25.56476371
66      26.00000000     21.01771393      4.98228607     16.47066414     25.56476371
67      21.00000000     21.01771393     -0.01771393     16.47066414     25.56476371
68      21.00000000     21.01771393     -0.01771393     16.47066414     25.56476371
69      18.00000000     21.01771393     -3.01771393     16.47066414     25.56476371
70      20.80000000     21.01771393     -0.21771393     16.47066414     25.56476371
71      21.00000000     20.39280747      0.60719253     15.84668192     24.93893201
72      20.50000000     20.23658085      0.26341915     15.69064266     24.78251905
73      27.00000000     20.23658085      6.76341915     15.69064266     24.78251905
74      27.00000000     20.23658085      6.76341915     15.69064266     24.78251905
75      19.00000000     19.45544778     -0.45544778     14.91018392     24.00071165
76      18.50000000     19.06488125     -0.56488125     14.51979052     23.60997198
77      18.00000000     19.06488125     -1.06488125     14.51979052     23.60997198
78      21.50000000     19.06488125      2.43511875     14.51979052     23.60997198
79      18.50000000     18.67431471     -0.17431471     14.12928774     23.21934168
80      21.50000000     18.67431471      2.82568529     14.12928774     23.21934168
81      14.00000000     14.37808281     -0.37808281      9.82654272     18.92962290
82      14.50000000     14.14374289      0.35625711      9.59146775     18.69601803
83      19.00000000     13.98751627      5.01248373      9.43472933     18.54030322
84      12.00000000     13.98751627     -1.98751627      9.43472933     18.54030322
85      13.00000000     13.20638320     -0.20638320      8.65077618     17.76199022
86      11.00000000     12.81581667     -1.81581667      8.25863662     17.37299671
87      13.00000000     12.81581667      0.18418333      8.25863662     17.37299671
88      12.50000000     12.81581667     -0.31581667      8.25863662     17.37299671
89      11.00000000     12.81581667     -1.81581667      8.25863662     17.37299671
90      10.00000000     12.81581667     -2.81581667      8.25863662     17.37299671
```

```
 91      13.60000000      12.58147674       1.01852326       8.02330080      17.13965269
 92      12.00000000      12.58147674      -0.58147674       8.02330080      17.13965269
 93      10.80000000      12.58147674      -1.78147674       8.02330080      17.13965269
 94      11.00000000      12.42525013      -1.42525013       7.86638856      16.98411170
 95      17.00000000      12.42525013       4.57474987       7.86638856      16.98411170
 96      16.00000000      12.42525013       3.57474987       7.86638856      16.98411170
 97      17.00000000      12.42525013       4.57474987       7.86638856      16.98411170
 98      10.80000000      12.42525013      -1.62525013       7.86638856      16.98411170
 99      12.00000000      12.42525013      -0.42525013       7.86638856      16.98411170
100      10.50000000      11.25355052      -0.75355052       6.68899457      15.81810647
101       8.00000000      11.25355052      -3.25355052       6.68899457      15.81810647
102      15.00000000      10.86298398       4.13701602       6.29631375      15.42965422
103       9.00000000      10.86298398      -1.86298398       6.29631375      15.42965422
104       9.00000000      10.86298398      -1.86298398       6.29631375      15.42965422
105       9.00000000       9.45694445      -0.45694445       4.88177111      14.03211780
106       8.20000000       9.37883115      -1.17883115       4.80314458      13.95451771
107      11.50000000       9.30071784       2.19928216       4.72451377      13.87692191
108      11.00000000       9.30071784       1.69928216       4.72451377      13.87692191
109      11.00000000       9.30071784       1.69928216       4.72451377      13.87692191
110       6.00000000       8.51958477      -2.51958477       3.93797013      13.10119941
111       7.50000000       7.73845169      -0.23845169       3.15099937      12.32590402
112       6.00000000       7.73845169      -1.73845169       3.15099937      12.32590402
113       9.00000000       7.73845169       1.26154831       3.15099937      12.32590402
114       6.50000000       7.34788516      -0.84788516       2.75735433      11.93841598
115       5.00000000       6.17618555      -1.17618555       1.57578314      10.77658796
116       4.00000000       5.00448594      -1.00448594       0.39326269       9.61570919
117       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
118       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
119       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
120       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
121       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
122       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
123       4.00000000       4.61391940      -0.61391940      -0.00112061       9.22895942
124       4.50000000       4.61391940      -0.11391940      -0.00112061       9.22895942

         SUM OF RESIDUALS                          =           0.00000000

         SUM OF SQUARED RESIDUALS                  =         537.94475287

         SUM OF SQUARED RESIDUALS - ERROR SS       =          -0.00000000

         FIRST ORDER AUTOCORRELATION OF RESIDUALS  =           0.15432332

         DURBIN-WATSON  D                          =           1.69108216
```

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                    S T A T I S T I C A L   A N A L Y S I S   S Y S T E M

ANALYSIS OF VARIANCE TABLE , REGRESSION COEFFICIENTS , AND STATISTICS OF FIT FOR DEPENDENT VARIABLE TIME


SOURCE               DF      SUM OF SQUARES        MEAN SQUARE          F VALUE    PROB > F       R-SQUARE           C.V.

REGRESSION            1      49340.03659003     49340.03659003       8946.00960      0.0001     0.98643733       12.59778 %

ERROR               123        678.38340997         5.51531228
                                                                                                   STD DEV      TIME MEAN
UNCORRECTED TOTAL   124      50018.42000000
                                                                                                2.34847020       18.64194


SOURCE               DF       SEQUENTIAL SS          F VALUE     PROB > F       PARTIAL SS           F VALUE     PROB > F

LOAD                  1      49340.03659003       8946.00960       0.0001   49340.03659003        8946.00960       0.0001


SOURCE              B VALUES          T FOR H0:B=0          PROB > |T|          STD ERR B          STD B VALUES

LOAD              1.67797742              94.58335              0.0001         0.01774073            1.02340406


       OBS            OBSERVED            PREDICTED             RESIDUAL          LOWER 95% CL        UPPER 95% CL
     NUMBER            VALUE                VALUE                                 FOR INDIVIDUAL      FOR INDIVIDUAL

        1          33.00000000          34.31463816          -1.31463816          29.61080737         39.01846894
        2          31.50000000          34.23073929          -2.73073929          29.52717625         38.93430233
        3          22.00000000          27.65306782          -5.65306782          22.96849505         32.33764059
        4          26.50000000          27.35103188          -0.85103188          22.66723581         32.03482796
        5          27.00000000          27.26713301          -0.26713301          22.58355119         31.95071483
        6          27.00000000          27.26713301          -0.26713301          22.58355119         31.95071483
        7          27.20000000          27.26713301          -0.06713301          22.58355119         31.95071483
        8          27.40000000          26.76373979           0.63626021          22.08142989         31.44604968
        9          26.50000000          26.67984091          -0.17984091          21.99774074         31.36194109
       10          25.40000000          26.34424543          -0.94424543          21.66297763         31.02551323
       11          25.00000000          25.84085221          -0.84085221          21.16081348         30.52089093
       12          23.00000000          25.84085221          -2.84085221          21.16081348         30.52089093
       13          25.40000000          25.58915559          -0.18915559          20.90972263         30.26858856
       14          27.00000000          25.58915559           1.41084441          20.90972263         30.26858856
       15          23.00000000          25.58915559          -2.58915559          20.90972263         30.26858856
       16          23.00000000          25.58915559          -2.58915559          20.90972263         30.26858856
       17          32.00000000          25.58915559           6.41084441          20.90972263         30.26858856
       18          25.50000000          25.50525672          -0.00525672          20.82602438         30.18448906
       19          26.00000000          25.58915559           0.41084441          20.90972263         30.26858856
       20          25.00000000          25.42135785          -0.42135785          20.74232548         30.10039022
       21          25.20000000          25.33745898          -0.13745898          20.65862593         30.01629203
       22          21.00000000          25.16966124          -4.16966124          20.49122488         29.84809760
       23          26.00000000          25.16966124           0.83033876          20.49122488         29.84809760
       24          25.00000000          25.16966124          -0.16966124          20.49122488         29.84809760
       25          25.00000000          25.16966124          -0.16966124          20.49122488         29.84809760
```

```
26          23.00000000       25.16966124       -2.16966124       20.49122488       29.84809760
27          26.00000000       25.16966124        0.83033876       20.49122488       29.84809760
28          26.00000000       25.16966124        0.83033876       20.49122488       29.84809760
29          21.00000000       25.16966124       -4.16966124       20.49122488       29.84809760
30          28.00000000       25.16966124        2.83033876       20.49122488       29.84809760
31          24.50000000       25.00186350       -0.50186350       20.32382123       29.67990577
32          24.50000000       24.75016689       -0.25016689       20.07271086       29.42762291
33          22.50000000       24.66626802       -2.16626802       19.98900611       29.34352992
34          21.00000000       24.33067253       -3.33067253       19.65418057       29.00716449
35          25.00000000       23.74338044        1.25661956       19.06821080       28.41855008
36          22.80000000       23.65948157       -0.85948157       18.98449822       28.33446491
37          24.00000000       23.49168382        0.50831618       18.81707112       28.16629653
38          26.00000000       23.49168382        2.50831618       18.81707112       28.16629653
39          26.00000000       23.49168382        2.50831618       18.81707112       28.16629653
40          22.00000000       23.49168382       -1.49168382       18.81707112       28.16629653
41          18.00000000       23.49168382       -5.49168382       18.81707112       28.16629653
42          22.00000000       23.49168382       -1.49168382       18.81707112       28.16629653
43          21.50000000       23.49168382       -1.99168382       18.81707112       28.16629653
44          22.00000000       23.07218947       -1.07218947       18.39849194       27.74588700
45          24.00000000       22.65269512        1.34730488       17.97989644       27.32549379
46          24.00000000       22.65269512        1.34730488       17.97989644       27.32549379
47          24.00000000       22.65269512        1.34730488       17.97989644       27.32549379
48          20.50000000       22.65269512       -2.15269512       17.97989644       27.32549379
49          21.00000000       22.65269512       -1.65269512       17.97989644       27.32549379
50          22.00000000       22.23320076       -0.23320076       17.56128462       26.90511691
51          21.00000000       22.23320076       -1.23320076       17.56128462       26.90511691
52          25.00000000       22.23320076        2.76679924       17.56128462       26.90511691
53          20.00000000       22.23320076       -2.23320076       17.56128462       26.90511691
54          20.50000000       22.23320076       -1.73320076       17.56128462       26.90511691
55          20.50000000       22.23320076       -1.73320076       17.56128462       26.90511691
56          20.00000000       21.81370641       -1.81370641       17.14265647       26.48475635
57          24.50000000       21.81370641        2.68629359       17.14265647       26.48475635
58          25.00000000       21.81370641        3.18629359       17.14265647       26.48475635
59          22.00000000       21.81370641        0.18629359       17.14265647       26.48475635
60          19.00000000       21.81370641       -2.81370641       17.14265647       26.48475635
61          22.00000000       21.81370641        0.18629359       17.14265647       26.48475635
62          20.00000000       21.81370641       -1.81370641       17.14265647       26.48475635
63          20.50000000       20.97471770       -0.47471770       16.30535112       25.64408428
64          26.50000000       20.97471770        5.52528230       16.30535112       25.64408428
65          25.00000000       20.97471770        4.02528230       16.30535112       25.64408428
66          26.00000000       20.97471770        5.02528230       16.30535112       25.64408428
67          21.00000000       20.97471770        0.02528230       16.30535112       25.64408428
68          21.00000000       20.97471770        0.02528230       16.30535112       25.64408428
69          18.00000000       20.97471770       -2.97471770       16.30535112       25.64408428
70          20.80000000       20.97471770       -0.17471770       16.30535112       25.64408428
71          21.00000000       20.30352673        0.69647327       15.63545973       24.97159374
72          20.50000000       20.13572899        0.36427101       15.46798033       24.80347765
73          27.00000000       20.13572899        6.86427101       15.46798033       24.80347765
74          27.00000000       20.13572899        6.86427101       15.46798033       24.80347765
75          19.00000000       19.29674028       -0.29674028       14.63054403       23.96293654
76          18.50000000       18.87724593       -0.37724593       14.21180129       23.54269057
77          18.00000000       18.87724593       -0.87724593       14.21180129       23.54269057
78          21.50000000       18.87724593        2.62275407       14.21180129       23.54269057
79          18.50000000       18.45775158        0.04224842       13.79304216       23.12246100
80          21.50000000       18.45775158        3.04224842       13.79304216       23.12246100
81          14.00000000       13.84331368        0.15668632        9.18560701       18.50102036
82          14.50000000       13.59161707        0.90838293        8.93423508       18.24899906
83          19.00000000       13.42381933        5.57618067        8.76665049       18.08098817
84          12.00000000       13.42381933       -1.42381933        8.76665049       18.08098817
85          13.00000000       12.58483062        0.41516938        7.92868798       17.24097326
86          11.00000000       12.16533627       -1.16533627        7.50968198       16.82099055
87          13.00000000       12.16533627        0.83466373        7.50968198       16.82099055
88          12.50000000       12.16533627        0.33466373        7.50968198       16.82099055
89          11.00000000       12.16533627       -1.16533627        7.50968198       16.82099055
90          10.00000000       12.16533627       -2.16533627        7.50968198       16.82099055
91          13.60000000       11.91363965        1.68636035        7.25827045       16.56900885
```

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  92      12.00000000     11.91363965      0.08636035      7.25827045     16.56900885
  93      10.80000000     11.91363965     -1.11363965      7.25827045     16.56900885
  94      11.00000000     11.74584191     -0.74584191      7.09065947     16.40102436
  95      17.00000000     11.74584191      5.25415809      7.09065947     16.40102436
  96      16.00000000     11.74584191      4.25415809      7.09065947     16.40102436
  97      17.00000000     11.74584191      5.25415809      7.09065947     16.40102436
  98      10.80000000     11.74584191     -0.94584191      7.09065947     16.40102436
  99      12.00000000     11.74584191      0.25415809      7.09065947     16.40102436
 100      10.50000000     10.48735885      0.01264115      5.83349286     15.14122484
 101       8.00000000     10.48735885     -2.48735885      5.83349286     15.14122484
 102      15.00000000     10.06786450      4.93213550      5.41440428     14.72132471
 103       9.00000000     10.06786450     -1.06786450      5.41440428     14.72132471
 104       9.00000000     10.06786450     -1.06786450      5.41440428     14.72132471
 105       9.00000000      8.55768482      0.44231518      3.90554850     13.20982114
 106       8.20000000      8.47378595     -0.27378595      3.82171690     13.12585500
 107      11.50000000      8.38988708      3.11011292      3.73788463     13.04188953
 108      11.00000000      8.38988708      2.61011292      3.73788463     13.04188953
 109      11.00000000      8.38988708      2.61011292      3.73788463     13.04188953
 110       6.00000000      7.55089837     -1.55089837      2.89952556     12.20227119
 111       7.50000000      6.71190966      0.78809034      2.06110027     11.36271905
 112       6.00000000      6.71190966     -0.71190966      2.06110027     11.36271905
 113       9.00000000      6.71190966      2.28809034      2.06110027     11.36271905
 114       6.50000000      6.29241531      0.20758469      1.64186280     10.94296782
 115       5.00000000      5.03393225     -0.03393225      0.38405100      9.68381349
 116       4.00000000      3.77544919      0.22455081     -0.87390989      8.42480827
 117       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 118       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 119       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 120       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 121       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 122       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 123       4.00000000      3.35595483      0.64404517     -1.29326334      8.00517300
 124       4.50000000      3.35595483      1.14404517     -1.29326334      8.00517300

           SUM OF RESIDUALS                              =          27.15120651

           SUM OF SQUARED RESIDUALS                      =         678.38340997

           SUM OF SQUARED RESIDUALS - ERROR SS           =          -0.00000000

           FIRST ORDER AUTOCORRELATION OF RESIDUALS      =           0.20616664

           DURBIN-WATSON  D                              =           1.58411276
```
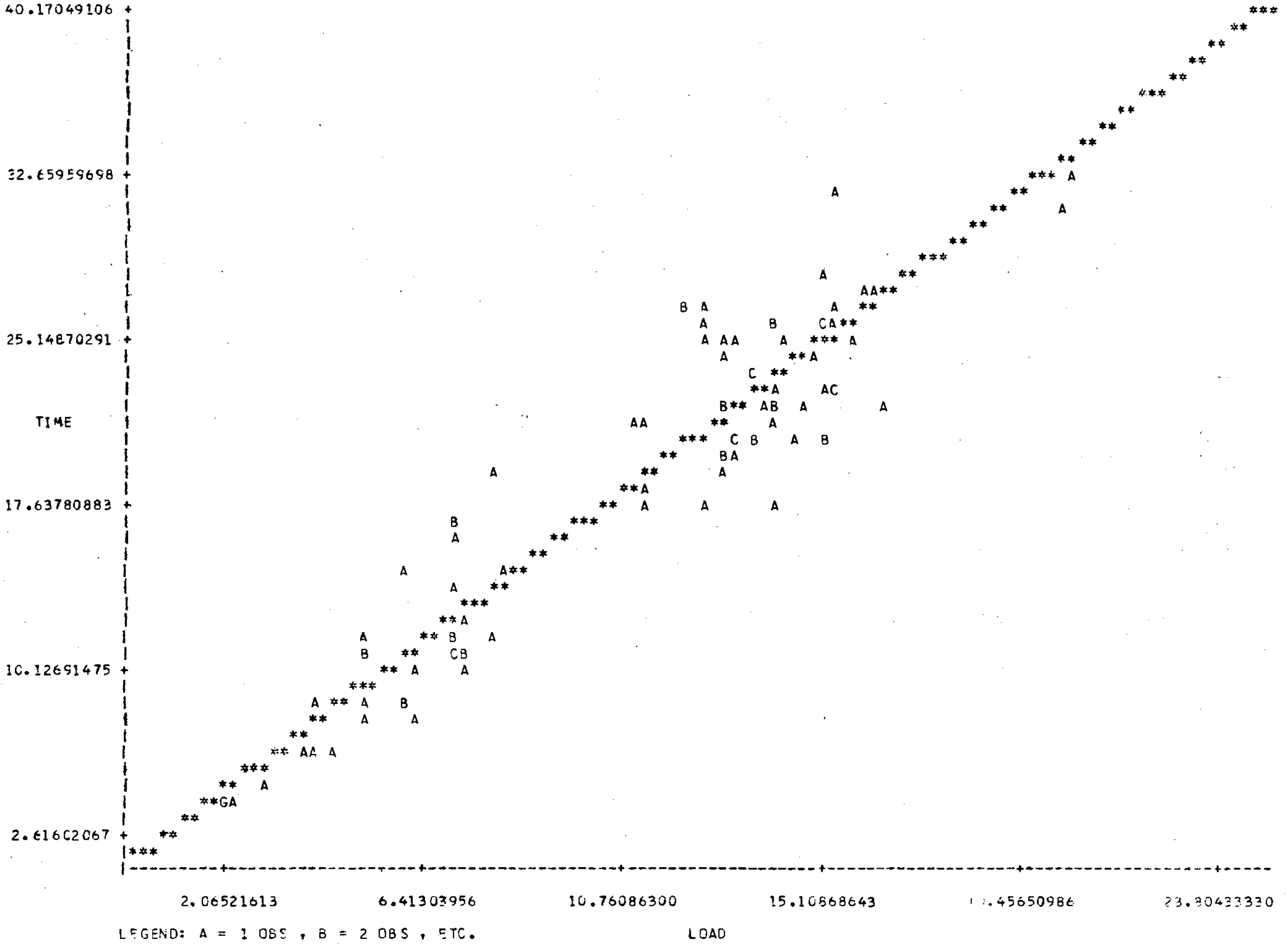

```
DATA ANALYSIS FOR SURGE LOADING                                                              14:17 FRIDAY, OCTOBER 12, 1973

                TITLE 'DATA ANALYSIS FOR SURGE LOADING' ;
                INPUT LOAD 3-7 TIME 9-12 ;
                TYPE=0 ;
                CARDS


                INPUT ;
                TYPE=1 ;
                INCRMENT = (25 - 0)/114 ;
                LOAD = 0 ;
                LINE: TIME=1.489387+1.562266*LOAD ;
                      OUTPUT ;
                      LOAD = LOAD + INCRMENT ;
                      IF LOAD <= 25 THEN GO TO LINE ;
                DROP INCRMENT ;
                CARDS


                 239 OBSERVATIONS IN DATA SET DATA0001        3  VARIABLES

                PROC PLOT ;
                VAR TIME LOAD ;
                ID TYPE ;
                TITLE 'SURGE TIME (SEC) VS ASPHALT LOADED (TONS)'
```

SURGE TIME (SEC) VS ASPHALT LOADED (TONS)

PLOT OF TIME VS LOAD



LEGEND: A = 1 OBS , B = 2 OBS , ETC.

VITA

Robert K. Hughes

Candidate for the Degree of

Doctor of Philosophy

Thesis: A STOCHASTIC APPROACH FOR THE ECONOMIC ANALYSIS OF ASPHALTIC CONCRETE PRODUCTION

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Memphis, Tennessee, July 8, 1936, the son of Mr. and Mrs. C. A. Hughes.

Education: Civilian - Graduated from North Augusta High School, North Augusta, South Carolina, in May, 1954; received the Bachelor of Science degree in Civil Engineering from The Citadel in 1958; received the Master of Science degree from Oklahoma State University in 1963, with a major in Civil Engineering; completed requirements for the Doctor of Philosophy degree from Oklahoma State University in December, 1973, with a major in Civil Engineering. Military - Completed the Engineer Officers Basic Course in 1958; completed the Engineer Officers Advanced Course in 1964; completed twelve months of study at the Defense Language Institute in 1966 in Indonesian language; graduated from the U. S. Army Command and General Staff College in 1970.

Professional Experience: Entered the United States Army in 1958 as a Second Lieutenant; served four years as a Combat Engineer troop leader; one year as the Area Engineer, Sondestrom, Greenland; one year as Deputy Post Engineer, Fort Gordon, Georgia; one year as Assistant Army Attache, Djakarta, Indonesia; and one year as Assistant Division Engineer, 101st Airborne Division (Airmobile), Hue, South Vietnam.

Professional Activities: Member of American Society of Civil Engineers; Society of American Military Engineers; Association of the U. S. Army; Phi Kappa Phi; Chi Epsilon.