SIMULATION IN GPSS/360 OF A HIGHWAY PAVING OPERATION USING A MOBILE CENTRAL-MIX PLANT WITH DIFFERENT HAUL TRUCK SPEEDS AND FLEET SIZE COMBINATIONS

Author: Edwin L. Bidwell

University of Michigan
Ann Arbor, Michigan

Summary

The simulation program was written to describe a concrete highway paving operation using mobile central-mix plant and slip form paver, in combination with different truck haul fleet sizes and truck speeds. The trucks queue at the plant, load, travel to the slip form paver, queue, unload, and then complete the cycle by returning to the plant. Because the distance, plant to paver, first decreases and then increases as the paving strip moves toward the plant, passes in front, then moves away in the other direction, the trucks' mean arrival rate is not constant. The program is completely probabilistic and provides for truck fleet size, truck haul speed and rate of paving progress to be treated as variables.

Introduction

In recent years a method of concrete highway paving using mobile central-mix plants (1) and slip form paving equipment (2) has become popular with paving contractors. Both the contractors and the equipment manufacturers have spent considerable time developing better equipment. However little time and effort has been spent developing least cost (3) configurations (4) and procedures (5) for using this equipment. Because of this void in configurations and methods criteria, an analytical study was conducted in which simulation played an important role.

Description of the Paving Method

Equipment for this paving method includes a mobile central-mix plant, a paving train (6), and a fleet of trucks to haul the concrete from plant to paving train. The plant is set up a predetermined distance from one end of the strip to be paved and then the paving train starts paving from that end. As the paving train moves toward the plant, the haul distance decreases; and then, as the paving train moves on by the plant, the haul distances increase. When the paving train has moved beyond the plant a distance equal to the distance, starting point to plant, the plant is disassembled, moved down the strip a distance equal to twice the aforementioned distance and then reassembled (see Figure 1). Now the process starts all over again.

MOVING AND PAVING SCHEDULE
FOR SINGLE STRIP PAVING

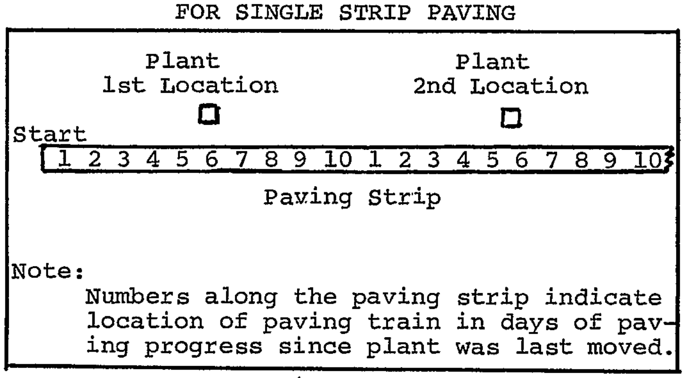

Figure 1

(1) Central-mix plant both weighs and mixes all ingredients of concrete at a central location. The resulting concrete is then hauled to the paving site in trucks. Mobile central-mix plants are easily disassembled, moved to a new location and reassembled - usually in less than two days.

(2) Slip form paver is a machine that extrudes concrete shaped to final line and grade. Only 6 to 8 ft. of side forms are used and they move with the paver forming the sides of the paving as they go. Line and grade are transferred from a wire on the shoulder to the self contained side forms by means of electronic sensing equipment.

(3) Least cost is defined here in dollars per cubic yard of concrete placed.

(4) Configuration refers to number, size and location of equipment a paving contractor uses in the paving process.

(5) Procedure refers to the way the paving contractor uses the equipment configuration decided on.

(6) Paving train includes all pieces of equipment at the paving site which move over the pavement helping to shape, finish and cure the concrete. This equipment usually includes spreader, slip form paver, float and curing sprayer.

The decision variables of interest to the simulation include:

1) Average rate of paving progress
2) Plant locations
3) Haul truck fleet size
4) Average speed of haul trucks

Cost-wise there is a trade-off between cost of extra trucks or cost of running plant at less than capacity, and cost of moving the plant. Therefore there is a least cost configuration and procedure, and the contractor is behooved profit-wise to find and use it.

Why Simulation

In order to derive the least cost combination analytically, it was necessary to estimate the production rate under different combinations of average truck speed, average rate of paving progress, truck fleet size, and distance between plant and paving train. The paving process described is stochastic and has the possibility of queues at both plant and paving train. It however differs from classic finite queueing models because the distance plant to paving train is not constant and therefore the travel time probability distribution is not constant. There was even some question whether the system ever reached a steady state condition. A search of the literature failed to reveal any previous work on this problem although Saaty[1] did mention it as being of interest. When the literature didn't turn up a solution, it was necessary to decide whether an attempt should be made at deriving a direct mathematical solution or whether simulation should be used. Because the problem had been recognized by at least one very qualified queueing expert and there was not a published solution, it was reasoned the solution must be more than trivial. Therefore, simulation was the choice as estimated production rates were not the main point of the study but rather a means to an end. GPSS/360 was chosen as the programming language because it was the only simulation program language available at the computer center during the period of the study and there was strong sentiment by others with better simulation programming experience to use some simulation programming language if at all possible.

The Simulation Program

The simulation program may be thought of as containing four sections. Section 1 has to do with simulation of the truck cycle, section 2 takes care of the trucks' interfailure rates and downtimes, section 3 takes care of interfailure rates and downtimes for plant and paving train, and section 4 handles data collection, printout and variable changes. Figures A-1, A-2, A-3 and A-4 in the appendix give the macro-flow charts of these sections. Section 1 is the heart of the program and collects the estimated production rate data by counting trucks (transactions) as they unload at the paving train (facility). By obtaining the estimated production rate in number of trucks, truck size is not a limiting factor during simulation.

Each computer run simulated 40 iterations of the paving train moving from in front of the plant to five 8 continuous hour days of paving production away from the plant, for one average rate of paving progress, one truck fleet size, and three average truck speeds (15, 30 45 mph). There were 28 runs made for basic data collection, one for each of seven haul fleet sizes (3, 6, 9, 12, 15, 18 and 21 trucks) in combination with each of the four average rates of paving progress (1/2, 1, 1 1/2, and 2 miles per day). There were also 5 runs made of eighty iterations each as a rough check on the size of the sample (iterations) needed. It was found the sample mean varied by less than $\pm$ 0.2 trucks per hour after 35 iterations 95% of the time so 40 iterations were considered sufficient.

Every effort was made to make the simulation as realistic as possible. The contractor's practices of starting the paving train after the plant so that the paving train would not be idle so long in the morning and closing down the plant first in the evening so that loaded trucks could move to the paving train before it shut down, were included in the program. Consideration was also given to such realities as allowing faster trucks to pass slower ones on the haul road and starting subgroups of trucks in the morning so the whole fleet of trucks will not queue at the plant first thing in the morning. Each truck is assigned a number (1 to N) so it can retain its uniqueness for such aspects as interfailure rates (time between failures) and down times. Provisions are made for the possibility that one or more trucks might break down in either queue, that trucks are parked and drivers sent home when plant or paving train are going to be down any length of time, and that trucks will not start up until later in the day if the repair of plant or paving train runs into another work day. Contractors' plants contain either one or two channels but the program considered only the one channel variety.

The haul cycle routine contained a number of probability distributions: load time at plant, travel time loaded, unloading time at the paving train, and return travel time empty. The data for these distributions and the distributions used in Sections 2 and 3 came from time studies done by the Bureau of Public Roads during the Summers 1963 through 1966. Because the objectives of the Bureau's studies were different from those of this study, all necessary data for some of the distributions used in the program could not be obtained from a single project or even from a single equipment spread. Rather, truck travel times and corresponding probability distributions came from one study, plant loading times from another, and so forth. A summary of all probability distribution information used in the simulation program is included in Table 1.

Programming the moving of haul trucks, plant to paving train and back, was one of the more difficult problems in Section 1. The Bureau of Public Roads' time studies showed both the mean and variance varied for this probability distribution. The distribution was nearly normal with a slight skew to the right when the paving train was near the plant and a slight skew to the left when it was four miles or more from the plant. It was therefore decided to use the normal zero, one cumulative probability distribution to simulate truck travel times. Floating-point variable cards were used to write the following equation (in this case truck speed 30 mph and rate of advance 1 mile per day):

(V1*92+(4*W$HOL1))/100)+FNI*15(3*W$HOL1)/6

where:

V1 is the deterministic cycle time calculated as follows:

(900+(5280*W$HOL1)+((C1*1833)/10000))/44

W$HOL1 is the number of days the haul trucks have advanced from the plant

C1 is the time in seconds since start of the work day

FN1*15(3*W$HOL1)/6 is the standard deviation

FN1 is the normal zero, one cumulative probability distribution

The 900 included in V1 was arbitrarily selected as the distance, in feet, from the plant's loading bay to the start of the haul road. The average rate of advance was 1 mile per day, which can also be written as 5280 ft/day, or for an 8 hour day, as 0.1833 ft/sec. The deterministic cycle time, V1, was modified by first multiplying by the factor $\frac{92+(4*W\$HOL1)}{100}$. This was done to approximate the skew effect found in the Bureau of Public Roads' data. Adding the standard deviation made the travel time probabilistic. It should be noted seconds were used for the time increment as it allowed both the required precision and a large enough time integer (999,999 seconds or a little over 11 days).

The problem of a maximum allowable holding time for concrete was another of the real life situations that was troublesome to incorporate in Section 1 of the program. Some agencies, such as the city and county of Los Angeles, are very strict and require concrete be placed within 30 minutes of the time water is originally introduced to the mixture or be refused as unacceptable. While City, State and Federal regulations vary on this time limit all have some regulation. This restriction is included in the simulation program first by not allowing the truck to unload if it arrives at the paving train; finds the paving train down, and it remains down for a length of time specified by the programmer. Second, this is accomplished by not allowing any trucks to load at the plant if the paving train is down. The handling of this allowable time restriction is certainly one of the more significant shortcomings in the program, because it does not allow for the fact that occasionally some trucks take longer total time (haul road and in the paving train queue) than this time restriction allows. The only justification for not directly considering this other possibility is that investigation showed in "real world" situations it amounts to less than 3% of daily production in about 95% of the cases.

Section 2 handles the interfailure and down time routines for the trucks. While all trucks are assigned interfailure times and down times uniquely, all interfailure times come from a single distribution as do all down times.

When a truck breaks down (its interfailure time is completed) it is moved to the queue at the repair area until a mechanic (channel) is free to work on it. The programmer can designate the number of channels desired. Truck repair is programmed to continue on a 24 hour a day basis when there are still trucks to be repaired. Down time varies from several minutes to several days. Down time includes all time from the moment the truck fails until it is back in the queue in front of the plant or in the night parking area as the case may be. All down time distributions closely resembled an exponential except that there were a few repair times when parts had to be ordered from some distance. These few lengthy down times dictated using an empirical distribution rather than multiplying the mean time by the random variable obtained from a 1,1 cumulative exponential distribution.

The interfailure rate distribution obtained from the Bureau's time study data only included times when the trucks were working. Therefore each truck's interfailure time had to be preempted when there was a long delay at plant or paving train and when the trucks were parked for the night.

Section 3 of the program handled the interfailure times and down times for plant and paving train. The programming procedures were approximately the same as those used for the trucks in Section 2, including using a preempting routine on the interfailure rates, when the other facility was down during the day and when both were down for the night. While the paving train includes several pieces of equipment (spreader, slip form paver, float, and curing sprayer), they were handled as one piece of equipment in constructing the probability distributions from the Bureau's data. That is, the paving train was considered down if either spreader or slip form paver was down, but down time on float and curing sprayer was considered of no significance because these pieces of equipment could be worked overtime after their repair or their work could be done by hand when necessary.

Section 4 of the program provides for the collection of necessary data, programs this data's printout and provides a means of changing the average truck speed during the run. During the time the program was being debugged, field C of a PRINT block was used to obtain the normal statistical printout of GPSS/360 (once each hour of simulated time). This snap interval count gave rapid access to hourly production figures and allowed the tracing of most transactions hour by hour, but also showed a serious flaw. It became apparent that some method of suppressing the normal statistical printout was needed, or

GPSS/360 would have to be abandoned as the simulation language. The normal printout for each hour snapped was 927 lines. As there were to be 40 iterations with 9 hourly snaps for each of the 5 days simulated, 7 different truck sizes, and 4 different average rates of advance, the printout would total (927)(40)(9)(5)(7)(3)(4) or 156,848,400 lines. The computer center's printer was barely able to handle 1000 lines a minute which meant total printout time alone would be over 43 hours. The program requires a 200K memory and an average running time of 50 minutes. Therefore both the memory requirement and the running time for the main program are excessive; the printout time astronomical! The printout problem was reduced 100 fold by using START NP cards in combination with the data collection and printout routines. RESET, CLEAR, CHANGE, and ADVANCE cards appropriately placed were used to correctly keep the block counts, and change the average truck speed.

GPSS/360 has no direct means for obtaining card printouts. The program therefore used the conventional printout procedure and then the 5 x 9 matrices were punched manually onto cards for later data reductions. The only justification for doing this was timing. Because of the large memory and running time requirements the program's priority on the system suffered. It was therefore necessary to do the runs between Summer and Fall quarters. The card printout routine was not debugged when it was time to start the runs so it was decided to run now and suffer the consequences of having the matrices punched onto cards manually later.

Reduction of Data

After the computer runs were completed, it was very apparent the cost of computer time was going to be a limiting factor in contractor acceptance and use of the study. That is, if a contractor was interested in finding his least cost configuration and procedure, data from his equipment spread would have to be used in the simulation. Say he simulated nineteen different haul fleet sizes (1 - 18 and 21 trucks), four different rates of paving progress (1/2, 1, 1 1/2 and 2 miles per day), and three average truck speeds (15, 30, 45 mph), he would have more than 200 hours of simulation time involved. It was therefore necessary to reduce the data obtained in simulation, study it and then either find a direct mathematical solution or some relationships that would greatly shorten the simulation time.

The data was first reduced to hourly production rates and plotted on rectangular coordinate paper. Figure 2 is such a plot. The plot suggested steady state might be reached. The other plots verified this fact and showed steady state is usually reached between the second and third hours. Figure 2 also showed the production rate might be constant over some part of the region. It was determined that this occurs when the number of trucks working in the system is equal to or greater than the average round trip time divided by the average loading time.

It was decided hourly increments would cause problems in later use because each fleet size was not represented by one continuous curve but rather by 5 curves. Therefore the data was reduced to daily averages and again plotted on rectangular paper. Figure 3 is a plot of this type. In Figure 3 each curve was seen to consist of two identifiable regions, the horizontal region and the decreasing region. It has already been stated the horizontal region can be represented by a general equation.

$$\text{Number of trucks per hour} = \frac{60}{\text{average trip time in minutes}}$$

Where: number of trucks working in the system is equal to or greater than $\frac{\text{average trip time}}{\text{average load time}}$

It was conjectured the decreasing region could also be represented by a general equation. To investigate this further the daily totals were plotted on other types of graph paper. Figure 4 is such a plot on log-log paper. As the different fleet sizes plot as straight lines, the curves must be of the general hyberbolic form. Unfortunately the slope changes with either a change of truck speed or truck advance (1).

A closer study of Figure 4 revealed the lines are parallel and that there is a constant distance between lines where fleet sizes are doubled. So the distance between lines is logarithmic and there is no reason to run a simulation for each fleet size. Rather a simulation can be run for, say, fleet sizes of 3 and 6 and the other fleet size lines constructed from these. Figure 5 is a plot constructed in this manner. In this case 19 fleet sizes can be plotted after simulating only two fleet sizes, so the number of simulations has been cut by a factor of 9.5. As the simulation times for the larger fleet sizes are 3 or 4 times those of the smallest fleet sizes, it is possible that simulation time may be cut by a factor of 18 or more. Therefore, while the need to simulate for different fleet size values has not been eliminated, it has been greatly reduced.

Next it seemed reasonable to investigate the other two main variables, rate of

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(1) Rate of truck advance is defined as the difference in distance the first and last truck travel each day. The rate of truck advance and the rate of paving progress may or may not be the same. They are the same only when the haul road runs parallel to the paving strip for its total length and the haul trucks are of sufficient capacity. Therefore, while rate of paving progress is the variable included in the discussion so far, rate of truck advance is really the variable used in the simulation program. These rates were tied together later in the study but the procedure used is not relevant to this paper.

truck advance and average truck speed, with the same objectives in mind. It was discovered that for all constant values of speed divided by rate of advance (designated a "B" value) and the same fleet size, the plot lines coincide. That is, for a fleet size of say 3, the line for speed 15 mph and rate of advance 1/2 mpd, the line for speed 30 mph and rate of advance 1 mpd, the line for speed 45 mph and rate of advance 1 1/2 mpd, and the line for speed 60 mph and rate of advance 2 mpd all coincide. Figure 6 shows this fact for "B" values of 7.5, 15, 30 and 60.

A closer examination of Figure 6 reveals any line drawn perpendicular to the "B" value line of slope 1 shows equal distance between all double "B" values. The distance along this line between "B" values of 15 and 30 will be the same as between 30 and 60. Therefore, the relationship between lines drawn perpendicular to the "B" value line of slope 1 is logarithmic. By simulating for two "B" values and one fleet size, one graph can be drawn which will include lines for one fleet size and all the speed, rate of advance combinations desired. Figure 7 is such a graph for a truck fleet size of 3 and selected "B" values. There are 35 "B" values on this graph and theoretically they can all be drawn after two simulations, say, one for fleet size 3, speed 30 mph, rate of advance 1 mpd, and a second for fleet size 3, speed 60 mph, rate of advance 1 mpd. This would allow the simulations to be cut by a factor of 17 1/2 times. Here the simulation time is approximately constant as long as the fleet size does not change, so the computer time saving would also be about 17 times.

While the relationships found in Figure 4 and 6 do not allow complete elimination of simulation, the number of simulations and resulting computer time have been greatly reduced. A complete set of graphs like Figure 7 can theoretically be drawn for all fleet sizes with only three simulations, one for a "B" value of 30 and fleet size 3, one for a "B" value of 30 and a fleet size 6, and one for a "B" value of 60 and a fleet size of 3. As the "B" value is the speed divided by the rate of advance, it should be noted that Figure 5 is also a graph for the "B" value 30 and fleet sizes 1 through 18 and 21. Therefore, by superimposing the "B" value 30 line of the desired fleet size of Figure 7 type on Figure 5, a complete set of graphs can be produced.

Theoretically was used in the aforementioned discussion because not every point in Figures 4 and 6 falls exactly on the lines drawn. It would probably be better, therefore, to use three simulations (say "B" value 30 and truck fleet sizes of 3, 6 and 12) in drawing a graph of the Figure 5 type. A graph of the Figure 7 type should probably be drawn from data collected during six simulations (say "B" values of 15 and 30 and three combinations of truck speed and rate of truck advance for each). So with nine simulations and computer time of less than 180 minutes, graphs that might otherwise have taken over eight days of continuous computer simulation can be constructed. All computer time estimates are based on use of an IBM Model 360/65 computer.

Conclusions

1) Simulation seems a worthwhile means of obtaining the estimated production data needed for any analysis of paving spread configurations and procedures. There has been only one "real world" test on the accuracy of simulated data. If all plant and paving train delays over one half hour are ignored, the simulated and "real world" data compare within seven percent 85 percent of the time. When these delays are not ignored, the data compare within twelve percent 85 percent of the time. While the first test was encouraging, it was felt the sample was too small to draw a definite conclusion.

2) Simulation must be used in conjunction with plots on log-log graph paper to be economically feasible.

3) Simulation shows steady state is reached in the system and usually between the second and third hour after production starts.

4) Although not part of this paper, sensitivity analysis of the least cost combinations, determined through mathematical modeling, found the least cost combination was very sensitive to production and fleet size changes.

Reference

1. T. Saaty, "Elements of Queueing Theory," McGraw-Hill Book Co., 1961

Appendix

(on following pages)

Macro-Flow Chart for Section 1

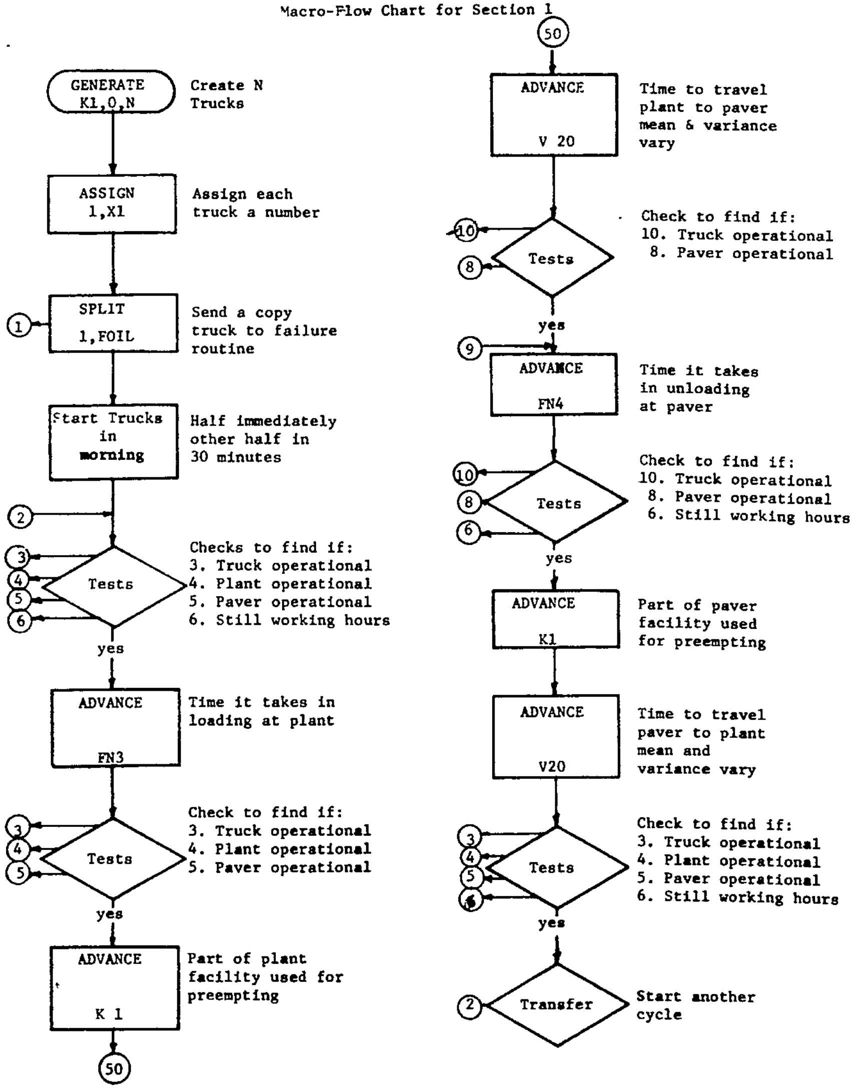


Figure A-1

Macro-Flow Chart for Section 2

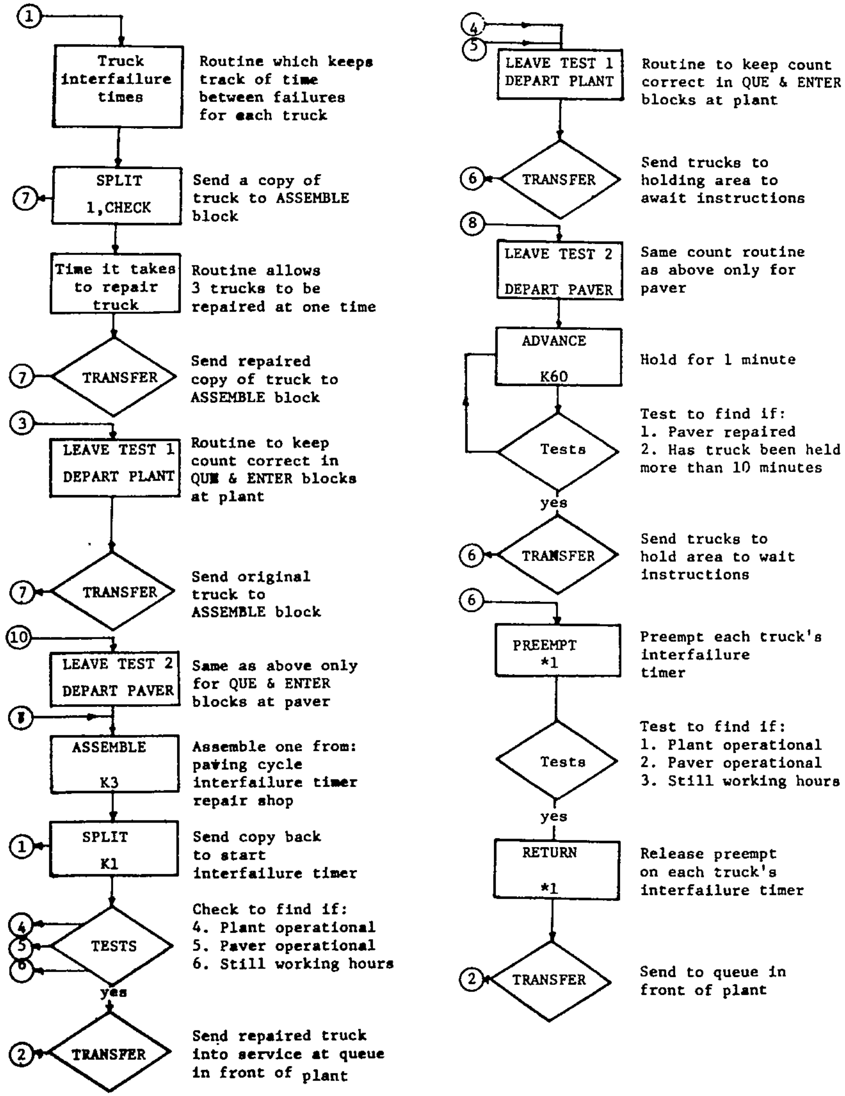
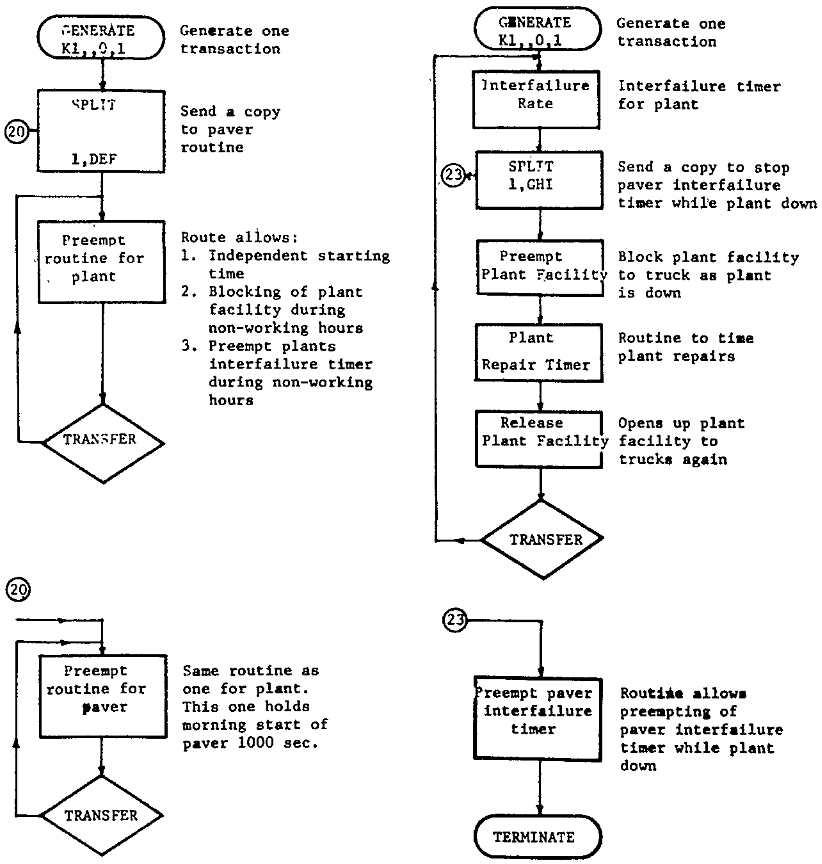


Figure A-2

Macro-Flow Chart for Section 3



Note: Macro-flow chart for paving train portion of section 3 not shown because same as plants.

Figure A-3

Macro-Flow Chart for Section 4

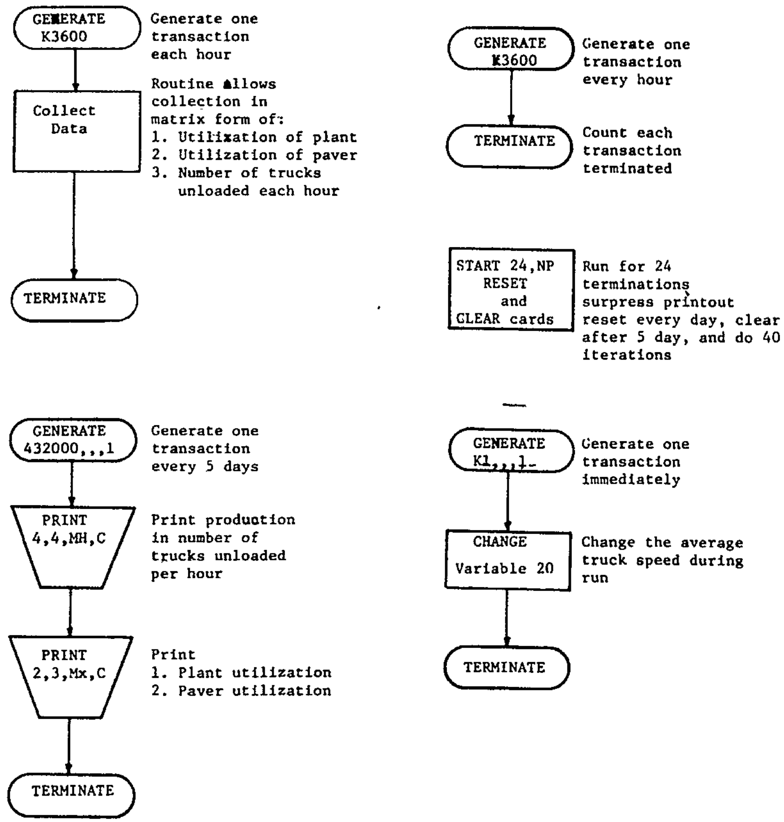


Figure A-4

HOURLY PRODUCTION CURVES FOR SELECTED FLEET SIZES

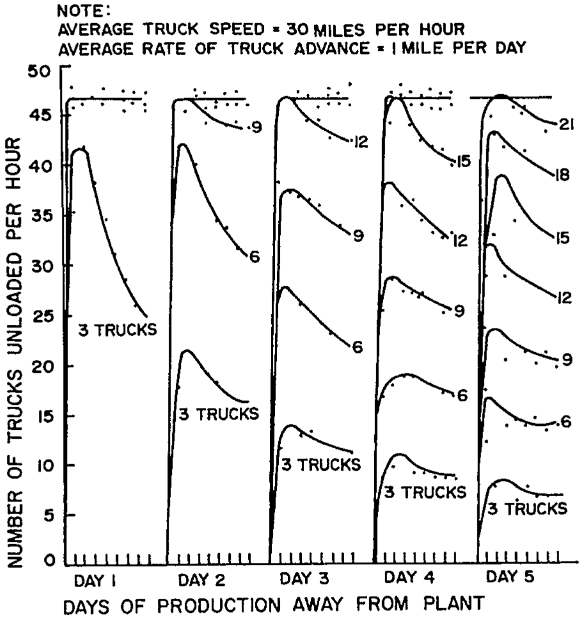


Figure 2

DAILY PRODUCTION LINES FOR SELECTED TRUCK FLEET SIZES

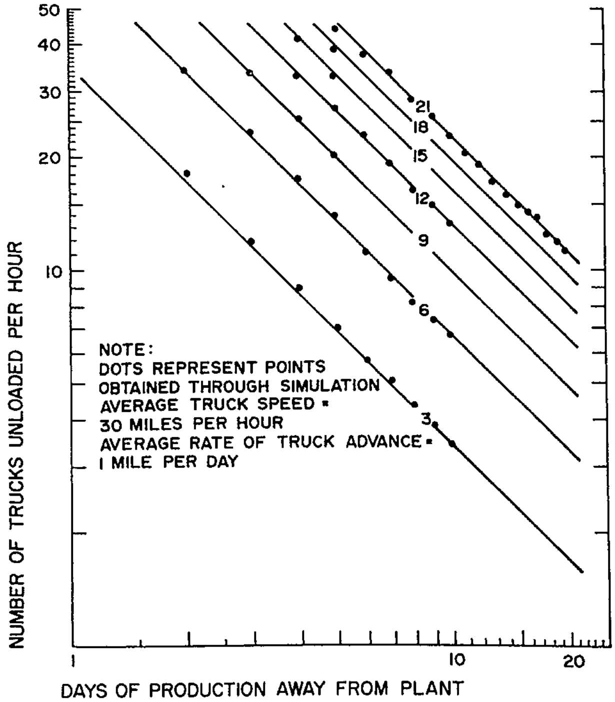


Figure 4

DAILY PRODUCTION CURVES FOR SELECTED TRUCK FLEET SIZES

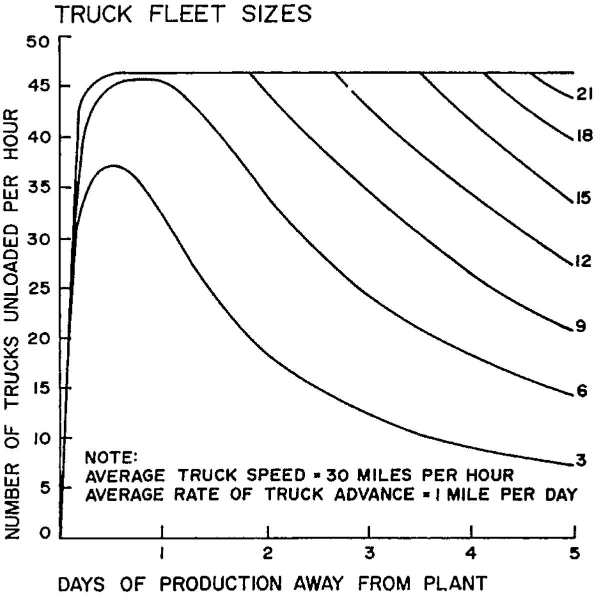


Figure 3

DAILY PRODUCTION LINES FOR TRUCK FLEET SIZES 1-18 AND 21

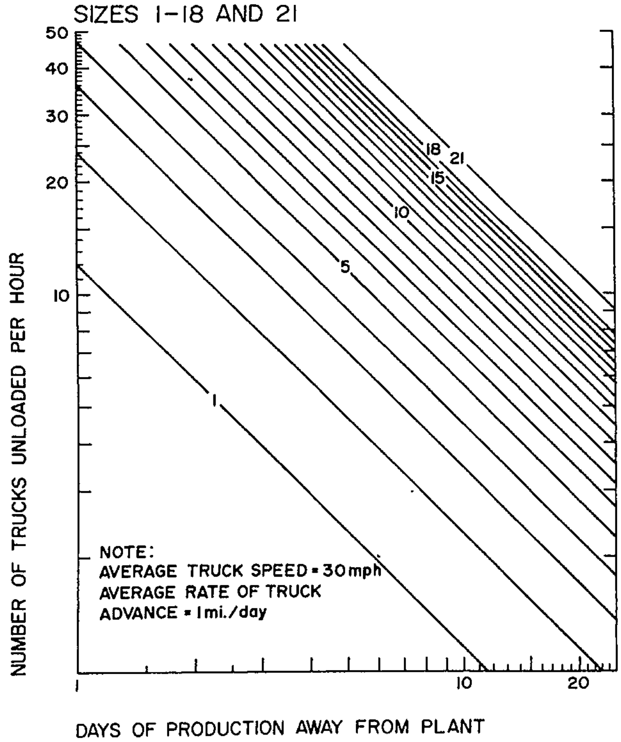


Figure 5

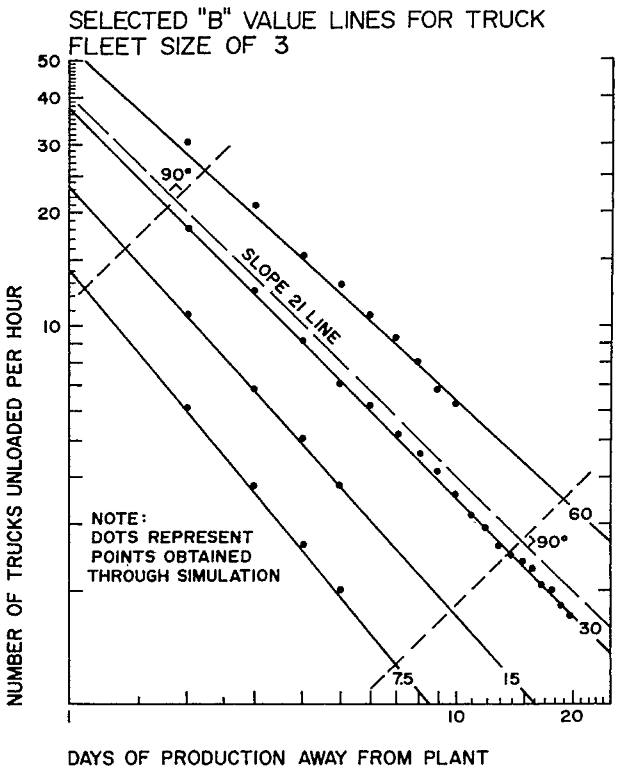


Figure 6

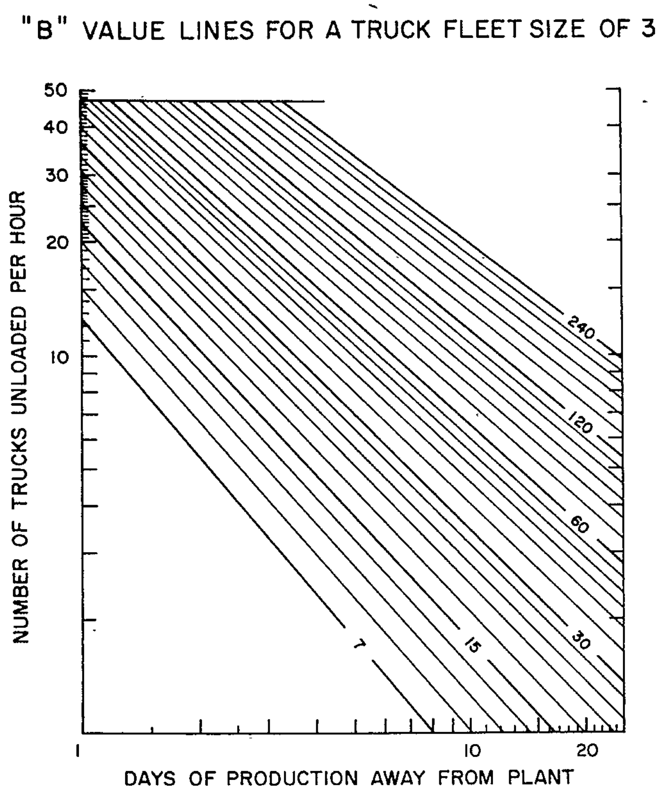


Figure 7

TABLE OF PROBABILISTIC DISTRIBUTION INFORMATION
USED IN THE SIMULATION PROGRAM

Use	Distribution Type	Parameters
Truck loading times	Empirical	mean = 73 secs
Truck travel times (plant to paving train)	Normal 0,1 with corrections	mean = variable variance = variable
Truck travel times (paving train to plant)	Normal 0,1 with corrections	mean = variable variance = variable
Truck unloading times	Empirical	mean = 62 secs
Trucks' interfailure rate	Empirical	mean = 15.1 hrs
Trucks' down time	Empirical (closely resembles exponential except for a few lengthy delays)	mean = 1786 secs
Plant interfailure rate	Empirical	mean = 6.9 hrs
Plant down time	Empirical (closely resembles exponential except for a few lengthy delays)	mean = 1920 secs
Paving train interfailure rate	Empirical	mean = 5.9 hrs
Paving train down time	Empirical (closely resembles exponential except for a few lengthy delays)	mean = 2142 secs

Table 1