

SIMULATING HAUL DURATIONS FOR LINEAR SCHEDULING

David J. Harmelink

Division of Const. Engr. and Mgmt.
Purdue University
West Lafayette, IN 47907, U.S.A.

Maria Andrea Bernal

Baker Concrete
Houston, TX 77027, U.S.A.

ABSTRACT

A major portion of highway construction work is comprised of linear activities. A linear activity is one that progresses along a path (non-stationary), as it does it is complete and another activity can proceed. Traditional scheduling methods model linear activities as having constant production rates. Linear scheduling allows an activity to be modeled as a line with dimensions of time and location. The slope of the line at any point represents the planned productivity rate of the activity. Predicting the productivity of linear activities is a scheduler's most difficult task. Simulation can be used to give planners greater insight into the factors that influence an activity's production rate.

1 INTRODUCTION

Linear scheduling techniques have been applied to the analysis of highway construction projects for several years. Unlike traditional scheduling methods (such as CPM), linear scheduling techniques offer several advantages including a visual environment. The visual aspect allows a close analysis of the activities that take place at every location of the project and the inclusion of productivity rates in the schedule format, a useful tool that facilitates schedule control.

Linear Scheduling Method is one of the scheduling techniques that offer a practical way to model linear projects as well as an efficient framework to monitor their progress. It not only allows positioning the activities in a time/space format but also presents a method to determine the controlling activity path for the project. The production rates for the activities are also included in the schedule in the form of the slope of the lines (curves) that represent the activities.

The activity production rate, should reflect the real behavior of the activity in order to present the construction operation in a realistic form and facilitate the control process. With a reliable production rate, the planner can

make better decisions to maintain a specific production rate for an operation, to expedite the process or to delay it until a certain condition or milestone is met.

This paper studies the variation in productivity rates for a non-stationary operation, concrete paving. Linear activities must be modeled as non-stationary operations. In this case, as the paver progresses along the path of the roadbed the distance traversed by trucks hauling the concrete changes. The paver completes a short segment of the road as each truck delivers a load of concrete. The simulation model must account for the change in haul distances to provide reliable results. The following sections describe the paving process, the project prototype, the model development, and the model analysis and results.

2 THE PAVING PROCESS

The construction operation selected for the productivity analysis was a linear concrete paving operation carried out using a slipform system. This system utilizes equipment, which moves in a continuous fashion along the road placing concrete in its final position and providing the final texture required. The paving train consists of several machines performing a series of operations such as placing, texturing, finishing, dragging and curing. In some situations, a machine called placer or spreader is used ahead of the paver to alleviate the hydraulic pressure created by the paver on the concrete and to achieve uniformity in the concrete distribution on the road surface. The spreader receives the concrete from the truck and delivers it very close to its final position by using a conveyor or belt arm. This process allows the slipform to perform only the consolidation and extrusion functions so the entire operation can move at a higher rate.

The slipform paver extrudes and shapes the concrete into the correct dimensional shape. The paver has a two piece auger in front, which helps to spread the concrete material. Then, a strike-off mechanism controls the amount of concrete that enters the zone called "the grout box". In this zone, a set of vibrators removes the air bubbles and

consolidates the mix. Later, a tamper bar densifies the concrete and finally a profile pan shapes the surface of the slab and provides the smoothness required.

A final finisher tool can be added to the rear part of the paver to reduce any surface irregularities and reduce the hand finishing work. In general, the forward motion of the paver machines should be maintained at 3 to 7 feet per minute with uniform concrete delivery in front of the paver to guarantee a uniform and even work. Paver speed should be adjusted to match changes in concrete delivery rates.

When a complete paving train is used, a machine with a special finishing tool follows the paver. This tool can be a tube finisher or a drag attachment. The last equipment of the paving train is a machine that provides a specified texture and applies the curing compound on the surface and edges of the road. The texture is accomplished by using a rake that travels across the slab from one side to the other grooving the surface. This gives the road the roughness desired to meet requirements like rainwater drainage. Finally, the curing compound is sprayed over the concrete surface.

The horizontal and vertical alignment of the paving train is controlled using a stringline set by the surveyors before starting the paving process.

Besides the paving train equipment, a concrete plant is needed to produce and supply the large amounts of concrete required. Generally, the batch plant is portable to satisfy job location conditions. The capacity of the batch plant can directly affect the productivity of the paving operation. If a concrete batch plant with a production capacity lower than the paving train production capacity is chosen, the whole process will suffer stoppages due to a lack of concrete material. The location of the concrete plant in the project is also one of the most important decisions that the planner has to make in the resource allocation stage. Considerations in siting the batch plant are space availability, environmental regulations, access to haul roads, and the distance from the paving operation.

Another factor that plays a very important role in the paving process is the concrete mix. Workability conditions and consistency affect the productivity of the process causing stoppages or low production when the mix is not appropriate. The requirement of the slipform paver is a dried mix with a slump able to produce sharp pavement edges while responding to the extrusion process. Common slumps vary between 1 and 2 inches. It is also important to mention that unfavorable conditions in the concrete mix can be caused not only by dosage problems but also by delays in the delivery process.

3 PROJECT PROTOTYPE

The prototype project was developed using data from past projects and from vendors to design a typical paving scenario. The prototype project is meant to demonstrate the simulation model not represent actual project conditions. Specific dimensions and rates used for the prototype project are given in Table 1.

Table 1: Project Specifications

Parameter	Value
Road to be paved	10 Mi
Volume of the concrete batch	10 cy
Thickness of the Road	12 in (1 ft)
Width of the road	30 ft
Paving Train Capacity	350 cy/hr
Batch Plant Capacity	360 cy/hr
Truck Speed	25 Mi/hr
Position of Batch Pant (X coordinate)	-1 Mi
Position of Batch Plant (Y coordinate)	1 Mi

The layout for the prototype project is shown in Figure 1.

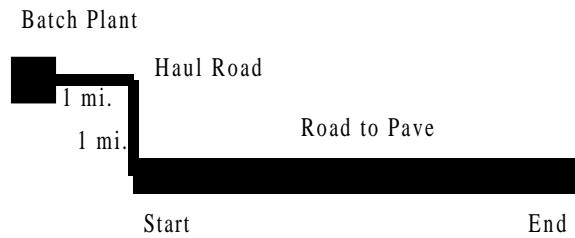


Figure 1: Project Layout

4 MODEL DEVELOPMENT

A discrete-event system simulation was used to analyze the concrete paving process studied. Under this type of modeling, the state variables - which are defined as the variables that describe the state of the system at any moment - change at a discrete set of points in time. The model was developed to investigate the relationships between the different entities – system components - and the overall response of the system to different situations.

The simulation was performed using STROBOSCOPE (Martinez, 1996) - STate and ResOurce Based Simulation of COnstruction ProCesses-, which is a general purpose

simulation programming language designed to model construction operations.

The analysis of the system was done using an algorithm able to perform different simulation runs, varying every time the number of resources employed. Each run simulates the paving process for the total length of the project. The productivity data for the operation was obtained from multiple replications, which allowed data to be gathered from independent simulations (runs). This process was accomplished by changing the seed value used to generate the random numbers for the stochastic processes of the model. The data generated by the model was stored in text files to facilitate further manipulations. A flowchart showing the algorithm logic used in the STROBOSCOPE Model is included in Figure 2.

A network is used to define the simulation model. In this type of representation, a description of the different entities of the system and the flow of resources through them are depicted. A standard set of elements is used to reflect the logic of the process and the relationship between the different activities. The elements used to construct the network in STROBOSCOPE are shown in Table 2, and the network is shown in Figure 3.

Table 2: Model Input Variables

Variable	Description
NumberTrucks	Number of concrete trucks used in the paving operation
RoadToBePavedMi	Total length of the road to be paved (mi)
BatchVolume	Volume of the concrete batch produced by the concrete plant
RoadThick	Thickness of the road to be paved (in)
RoadWidth	Width of the road to be paved (feet)
PavingTrnCapacity	Paving train capacity (cy/hr)
BatchPlantCapacity	Batch plant capacity (cy/hr)
TruckSpeed	Truck speed allowed (mi/hr)
XdistanceBatchPlant	Parallel distance of the batch plant to the road
YdistanceBatchPlant	Perpendicular distance of the batch plant to the road
nsamples	Number of samples used for multiple replications

Four resources are needed to start the paving operation: road to pave, the paving train, the batch plant and the truck to deliver the concrete material. The “amount of road” that needs to be paved is determined by the total length of the project. The production rate of the paving process is controlled by the paver which sets the pace for

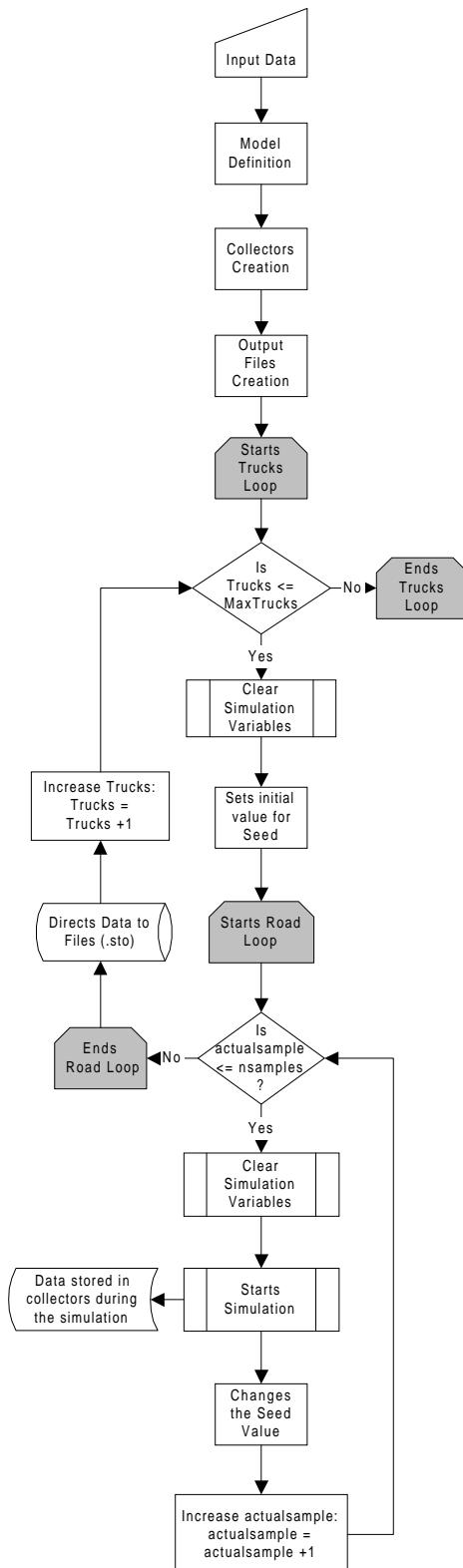


Figure 2: Model Flowchart

accomplishing the following operations such as texturing and curing. In the model development the paving activity includes all the subsequent activities that take place immediately after the paver equipment moves forward. The non-stationary effect of the travel of the concrete trucks to the batch plant is included in the model network. Every time a truck is loaded with concrete, it travels to the work zone to load the spreader (or dump the concrete in the ground). This haul distance changes according to the progress of the work along the road. The duration of the travel of the concrete trucks to the batch plant was obtained from the location of the batch plant with respect to the road and the speed at which the concrete truck is able to travel along this path. The same procedure was used to determine the duration of the travel from the batch plant to the work area in the road.

To account for the stochastic effect inherent in construction operations, statistical distributions were used to model the duration times. Table 3 includes the statistical distributions and parameters used for the activities involved in the operation.

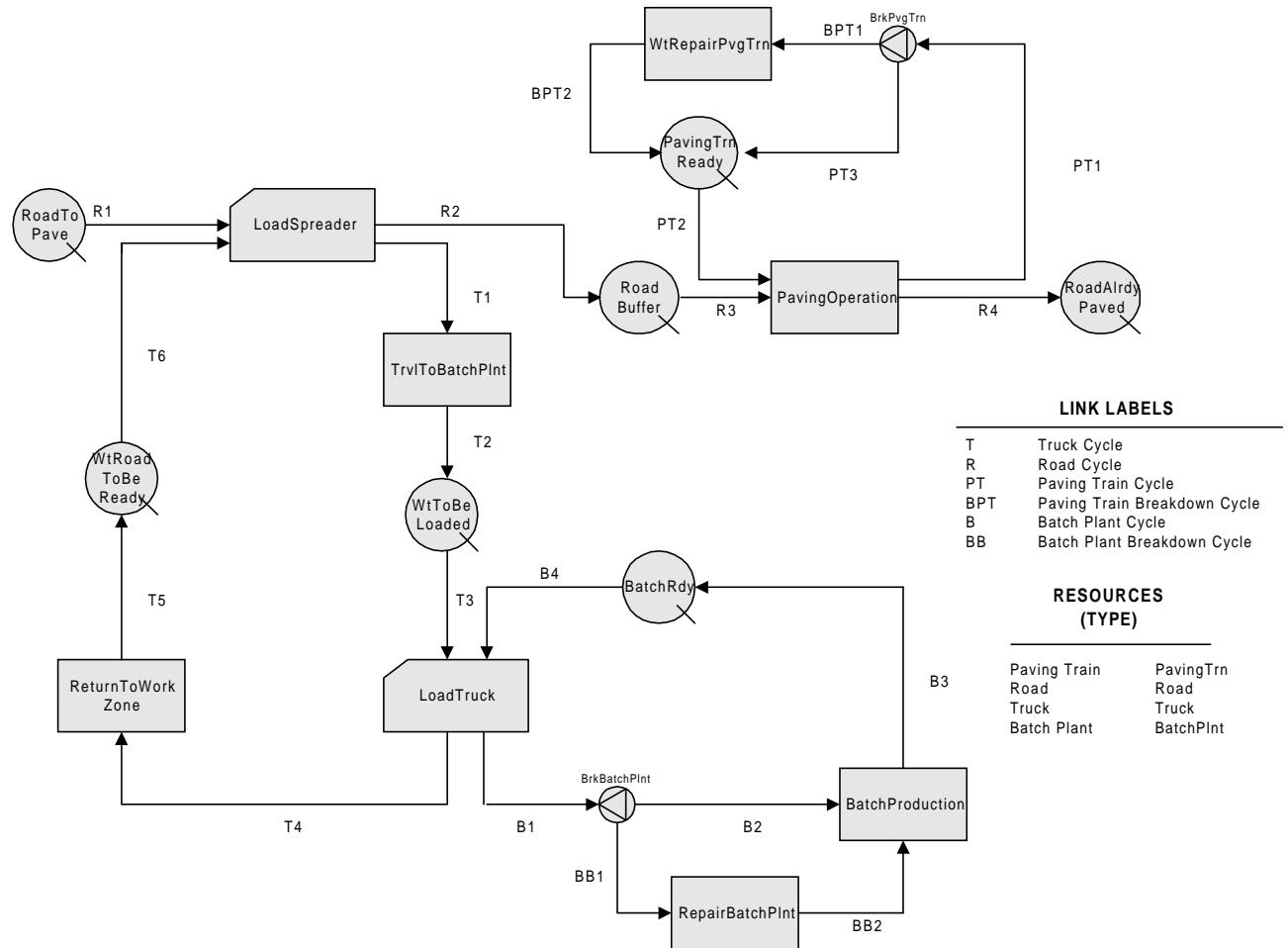


Figure 3: Concrete Paving Operation (Network Model)

5 MODEL ANALYSIS AND RESULTS

The size of the sample, which is the number of simulation runs or replications needed to determine an accurate estimator of the parameter studied, should be determined based on the error criterion “•” specified, and the confidence interval selected for the process. For an appropriate analysis of the output data, a proper number of independent simulations must be provided.

For a stochastic stationary process, any average obtained with respect to time along any member of an ensemble is exactly equal to the corresponding average across the ensemble at an arbitrary time “t” (Clough and Ponzion, 1975). This concept is known as ergodicity, and it is applicable to the paving process modeled due to the small variation that two consecutive road sections exhibit between them, compared with the size of the overall process. The variation of data for consecutive road sections is very small when compared with the data variation for the whole process. This concept allows a high reduction of the number of runs needed, due to the great amount of data that is being collected from the different sections along the road. Based on this characteristic, a total of 50 runs were selected to perform the simulation of the paving operation modeled.

A number of runs, between 10 –30, is suggested to predict the mean of a steady-state simulation (Schmeiser, 1982). This guideline is also adequate for inferring the underlying mean of a transient simulation (AbouRizk and Halpin, 1990).

The paving operation was first analyzed under optimal conditions, which means that no equipment breakdowns were considered. The model network includes the breakdown cycles, but to guarantee a proper operation of the equipment, a probability of 0 was assigned to the breakdown cycle links

An estimate of the duration of the process for every section of the road and its standard deviation was obtained from the simulation. For this project, every road section is 9 ft long according to the specifications previously defined. These results were obtained for every set of trucks (1, 2, 3, etc.) in the form of a text file.

The results of the simulation analysis were collected for each set of trucks and plotted in a Linear Schedule Model framework. This was done using a spreadsheet application. Under the LSM framework, the productivity of the paving operation can be easily analyzed and its variation for different zones of the road can also be identified. The sequence of activities along the project, the starting and ending dates, the location of the activities and the production rates in terms of stations are some of the advantages that the LSM offers for the analysis of highways (Harmelink, 1995).

For the linear schedule creation 8 hour-days were used to plot the data. This permits planning the activities in terms of standard days which offers a more realistic view of the project. Also a theoretical production was plotted based on the paving train ideal capacity. This production assumes 0 delays and perfect conditions. The slope of the curve is given by the following Equation (1).

$$\begin{aligned} \text{Productivity} &= ((10 \text{ cy} / 350 \text{ cy/ hr}) / 9 \text{ ft}) \\ &/ (8 \text{ hr} / 1 \text{ day}) = 0.000397 \text{ days/ft} (2520 \text{ ft/day}) \end{aligned} \quad (1)$$

The productivity for the linear concrete paving operation and truck sets of 1, 3, 6, 9, etc. is included in Figure 4.

The influence of the amount of resources on the total production is very easy to see. The productivity rate is given by the slope of the curve. The steeper the curve the lower the productivity. This effect is very useful to determine changes in productivity rates and select a specific productivity depending on the requirements of the planner. For example, in some cases it may be useful to increase the productivity rate of the process to save time or update an activity that is behind schedule, while in other cases the planner may decide to slow down the production to satisfy a certain condition like a project milestone.

The effect of the stochastic nature of the activities involved in the paving process is easy to observe in the graph when analyzing the relation of the different production curves with the theoretical one. For a set of 30 trucks an ideal productivity will be achieved under deterministic conditions. However, although in this case the productivity rate (0.00044 days/ft) is close to the theoretical one the cumulative effect of this rate leads to a completion date 3 days later than the one achieved with the theoretical production (21 days). This difference in production rates along the different areas of the project is a direct consequence of the random variables involved in the process.

The first aspect that should be pointed out is the direct relation between the number of resources used and the production achieved. The larger the amount the better the productivity. This seems reasonable due to the increment in the travel distance from the batch plant to the work zone every time a progress takes place in the paving operation. When more trucks are used the availability of resources increases and in this way some trucks are available when the others are traveling to the batch plant. However, this positive effect diminishes for large number of resources. It can be seen that the time saved when increasing the number of trucks from 27 to 30 is almost negligible. Although there is a change in production, the final decision must be taken by the planner in terms of cost-revenue

ratios. Paying for three more trucks to save 0.2 days may not be cost worthy for the project.

From the chart it is possible to see that the project can be completed in 23 days with 30 trucks which can be considered a logical time according to the project specifications. Also, if fewer trucks are used for the entire project the total duration will be larger, as is the case with 12 trucks which leads to 37 days completion. However, using the same number of trucks for the whole project is not a wise decision when the same productivity can be achieved for different road zones using less resources. The critical point of the analysis is determining when (where) the number of resources must be increased to keep the same productivity rate or to satisfy a specific one.

The maximum productivity achievable is given by the lowest production line of the chart, which is in this case, the 30 trucks production line. A flatter line closer to the theoretical may be obtained with a larger number of resources but was not considered in the analysis due to realistic considerations. The positive effect on productivity that a resource increment brings is every time smaller as was explained before, so larger number of trucks than 30 will produce very small increments in production. From test runs,

it was determined that the theoretical productivity could be achieved with 78 trucks, which is an unreasonable amount of resources.

If a theoretical productivity rate is used, a length of 2520 ft will be paved daily, this means that analyzing the process every 900 ft (~1260 ft) allows the planner to change the number of resources in a daily basis, even more to suit morning and afternoon requirements. A higher precision may not be needed because daily data provides enough accuracy to satisfy planning requirements.

The curves depicted in Figure 4 allow us to identify those points where an abrupt change in productivity takes place. From these points, and on, the operation will deviate from the “ideal” production line leading to larger duration times and lower productivity rates. To find the points where the slope changes in a radical manner and not only due to the “noise” produced by the stochastic analysis, a central difference formula was used. The change in slope for the production curve can be found by Equation (2).

$$P''_1 = (t_0 - 2t_1 + t_2) / \Delta d^2 \quad (2)$$

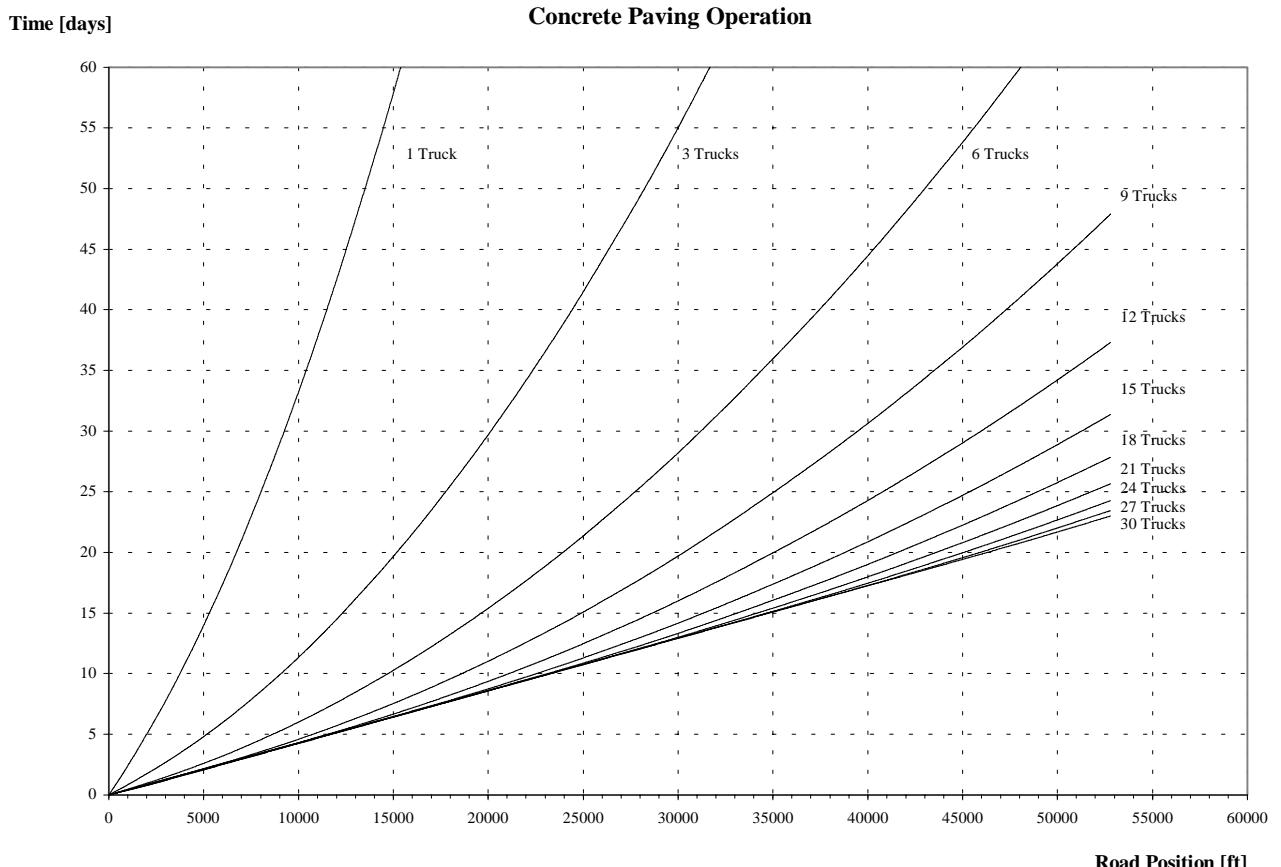


Figure 4: Paving Production Curves

Where t_0 , t_1 and t_2 is the time value or process duration for the position p_0 , p_1 and p_2 respectively and Δd indicates the increment in distance between those positions (Jürgen-Bathe et al., 1976).

Figure 4 indicates that for 9 trucks, 5409 ft marks the road position where the productivity of the operation starts going down affecting the completion of the overall project. Knowing these points gives the planner the benefit of scheduling the amount of resources needed along the project, not only in terms of location but also in terms of dates. Table 4 shows an example of resources needed, in terms of location and time to, provide an expected rate of production.

Table 4: Resource Schedule

Road Position Starting	Road Position End	From day	To day	Number of Trucks
0 ft	909 ft	0	0.5	6
909 ft	5409 ft	0.5	2.5	9
5409 ft	10809 ft	2.5	5.0	12
10809 ft	17109 ft	5.0	8.0	15
17109 ft	22509 ft	8.0	10.5	18
22509 ft	29709 ft	10.5	13.5	21
29709 ft	38709 ft	13.5	17	24
38709 ft	42309 ft	17	19	27
42309 ft	52800 ft	19	23.5	30

6 CONCLUSIONS AND RECOMMENDATIONS

With the model developed it was possible to show the effect of the non-stationary process on the productivity rates for a paving operation. The reduction in production could be easily observed in the linear schedule format as well as its consequences on the overall process (e.g. completion date). This tool enables the planner to determine when and where a change in resources must take place to satisfy the goals set for the project.

Following the previous result a resource schedule can be developed in terms of feet or stations (100 ft) to facilitate the control and coordination of the activities involved in the paving process. The planner is able to perform "what-if" analysis to determine the best site layout versus resource utilization. The amount of resources and when and where they are needed can also be determined given a specific

layout and set of project conditions. In a situation where resources (i.e. trucks) are limited, a more realistic projection of productivity can be made instead of a generalized assumption.

For this technique to be widely adopted by industry a significant amount of further research must be done to establish more realistic models and input data. A user-friendly interface or application to facilitate this type of analysis would also need to be established to gain industry acceptance.

This work does, however, demonstrate the potential benefit that could be derived from this type of analysis. This technique combined with recent advances in linear scheduling could provide an analysis tool more powerful and dynamic than any currently used by the industry.

REFERENCES

- AbouRizk, S. M. and Halpin D. W. (1990). "Probabilistic simulation studies for repetitive construction processes" *Journal of Construction Engineering and Management*, ASCE, 116(4), 575-593.
- Clough, R. W, and Powzion, J. (1975) *Dynamics of Structures*. McGraw-Hill, New York. Random Processes. Chapter 23. Page 443.
- Harmelink, D. J. (1995). "Linear scheduling model: the development of a linear scheduling model with microcomputer applications for highway construction control" Ph.D. thesis, Iowa State University, Ames, Iowa.
- Jürgen-Bathe, Klaus and Edward L. Wilson, (1976) *Numerical Methods in Finite Element Analysis*. Prentice Hall, New Jersey. Chapter 8.
- Martinez, J. C. (1996) "STROBOSCOPE State and Resource Based Simulation of Construction Processes" Ph.D. thesis, University of Michigan, Michigan.

AUTHOR BIOGRAPHIES

DAVID J. HARMELINK is an assistant professor in the Division of Construction Engineering in the School of Civil Engineering at Purdue University. He received a B. S. degree in construction engineering, an M.S.C.E and Ph.D. degrees in civil engineering from Iowa State University. He also has 11 years of experience in the heavy mechanical construction industry.

MARIA ANDREA BERNAL is a project engineer for Baker Concrete in Houston, Texas. She received a B.S. degree in civil engineering from Universidad de Los Andes, Bogota, Columbia, and an M.S.C.E degree from Purdue University.