# Computer-Integrated Methodologies for Real-Time Control of Asphalt Paving Operations

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**ABSTRACT**

*A real-time control system is needed for measuring and improving productivity and quality in asphalt pavement operations. This paper presents four computer-integrated methodologies necessary to develop a real-time control system for asphalt paving operation. These methodologies include: (1) simulation modeling for optimal allocation of resources, (2) automatic truck dispatching system to maximize truck productivity, (3) Global Positioning System (GPS) for real-time positional data acquisition, and (4) semi-automated path-planning and real-time guidance system for rolling operations. Interrelating these independent methodologies using a systems approach will allow for the development of a real-time control system for asphalt paving operations. Developing a real-time control system by standardizing construction practices will create a system that is amenable to strict quality and cost control.*

## 1. Introduction

Asphalt paving contractors, public agencies, and researchers share the common objective of properly constructing functional and high-performing asphalt pavements. Meeting this objective requires cost-effective construction, increased productivity, and assurances for quality. Current asphalt paving operations require standardization to meet this objective. Developing a real-time control system by standardizing construction practices will create a system that is amenable to strict quality and cost control.

This paper presents four computer-integrated methodologies necessary to develop a real-time control system for asphalt paving operations in an effort to meet those objectives set forth by the industry. These methodologies include: (1) simulation modeling for optimal allocation of resources, (2) automatic truck dispatching system to maximize truck use and productivity, (3) Global Positioning System (GPS) technology for real-time positional data acquisition, and (4) semi-automated path-planning and real-time guidance system for rolling operation. Interrelating these independent methodologies using a systems approach will allow for the development of a real-time control system for asphalt paving operations.

## 2. Background

The process of constructing a hot-mix asphalt (HMA) pavement is to blend together aggregates and asphalt cement to produce a hot, homogenous mixture according to a specified design. Trucks then transport the HMA from the mix plant to the paving operation for placement by a paver. The paver places the HMA to the desired roadway width and thickness, and rollers compact the mixture to a required density. Upon cooling, the pavement is opened to traffic and expected to perform through many years of service life at the satisfaction of the end-user. While these processes are very fundamental, they lack standardization and an integrated system that is amenable to quality and cost controls.

Compaction is one of the most important factors in this process and is well known to affect the performance of a pavement. Typically, 3 to 8 percent air voids in the final compacted pavement is required for a satisfactorily performing pavement [1]. Under controlled laboratory conditions, it is possible to compact an asphalt concrete mixture to the specified density, or volume of air voids in the mixture. During construction, density can vary and be somewhat difficult to control under changing project conditions.

Types of rollers and number of passes to compact the HMA have a direct affect on the degree of density that can be achieved. Three types of self-propelled compactors widely used are: (1) vibratory rollers, (2) pneumatic-tire rollers, and (3) steel-wheeled rollers. There are several variables that can be adjusted on each roller to achieve desired pavement density. For example, the operator can increase the magnitude of the dynamic force component in vibratory rollers to alter contract with the material. Other variables include changing the tire pressure in a pneumatic roller, or increasing the ballast load in static steel-wheel rollers. Mutual compaction variables found among all types of rollers are speed, number of passes, rolling patterns, rolling zone length, and both temperature and compactibility of the mix. Each of these variables has an effect on the level of density achieved for a given compactive effort.

## 3. Real-Time Control System

A real-time control system for asphalt paving operations requires the measurement and evaluation of key variables influencing production and pavement density that are amenable to strict quality and cost control. This real-time control system must be capable of processing two primary types of data: (1) productivity and (2) quality.

Productivity data are those data used in measuring and monitoring the input and output of material, equipment, and labor resources to maximize production within the constraints of cost and time. Productivity data can be measured and monitored for several key asphalt paving processes including: (1) mix plant in units of tonnage per hour, (2) cycle times of trucks (loading, traveling, unloading, and returning to mix plant), (3) tonnage of HMA hauled by each truck, (4) paver productivity in yield or tonnage of mat produced per hour, and (5) roller productivity in tonnage of pavement compacted per hour.

Quality data can be measured and monitored to ensure that the pavement meets the requirements set forth in the laboratory mix design and standard specifications. Examples of quality data include current density of the mat, mat temperature during compaction, and pavement smoothness immediately behind the various rollers in the paving train.

A central feature of a real-time control system is a computer connected to the environment that sends and receives a variety of productivity and quality data. Both productivity and quality data can be gathered at sites and transferred to the computer using radio modems or other technologies to perform computations and analysis.

The real-time requirement can be expressed quantitatively in terms such that "the average response time will not exceed 20 seconds." In asphalt paving operations, the average response time would be mainly dependent on the required time to measure the productivity and quality data, transmit the data to a computer, perform computations, and report the data in usable terms to a manager or job foreman.

Current GPS technology employed in related research can measure and transmit a maximum of five positional data per second, equating to a lag time of about 0.2 seconds [2]. Current time durations to measure and transmit density data are within several seconds using a Density-On-The-Run (DOR) nuclear gauge [3]. The repeatability of density readings using the DOR are considered to be highly variable and have precluded widespread use throughout the industry. However, as the real-time density technology continues to develop, measuring density in real-time will satisfy the needs of the industry.

## 4. Framework for Real-Time Control System

The framework of a real-time system for controlling asphalt paving operations is developed with individual work components consisting of *tasks* or *processes*, that are organized hierarchically using *multitasking* or *multiprocessing*. Each task or process is a stand-alone program capable of independent execution. Data is input within each tasks at a specified or available rate. Each task performs a calculation on the data after measurement and sampling. In this system, tasks are subdivided into: (1) data filtering, (2) simulation, (3) optimization, and (4) control.

The data filtering task is required to obtain relatively reliable data. In some cases, incorrect data can be transmitted to the system propagating errors. The simulation task includes the Automatic Truck Dispatching (ATD) system. Instant dynamic simulation will be used to predict the productivity of trucks under the current situation. The optimization task will perform calculations

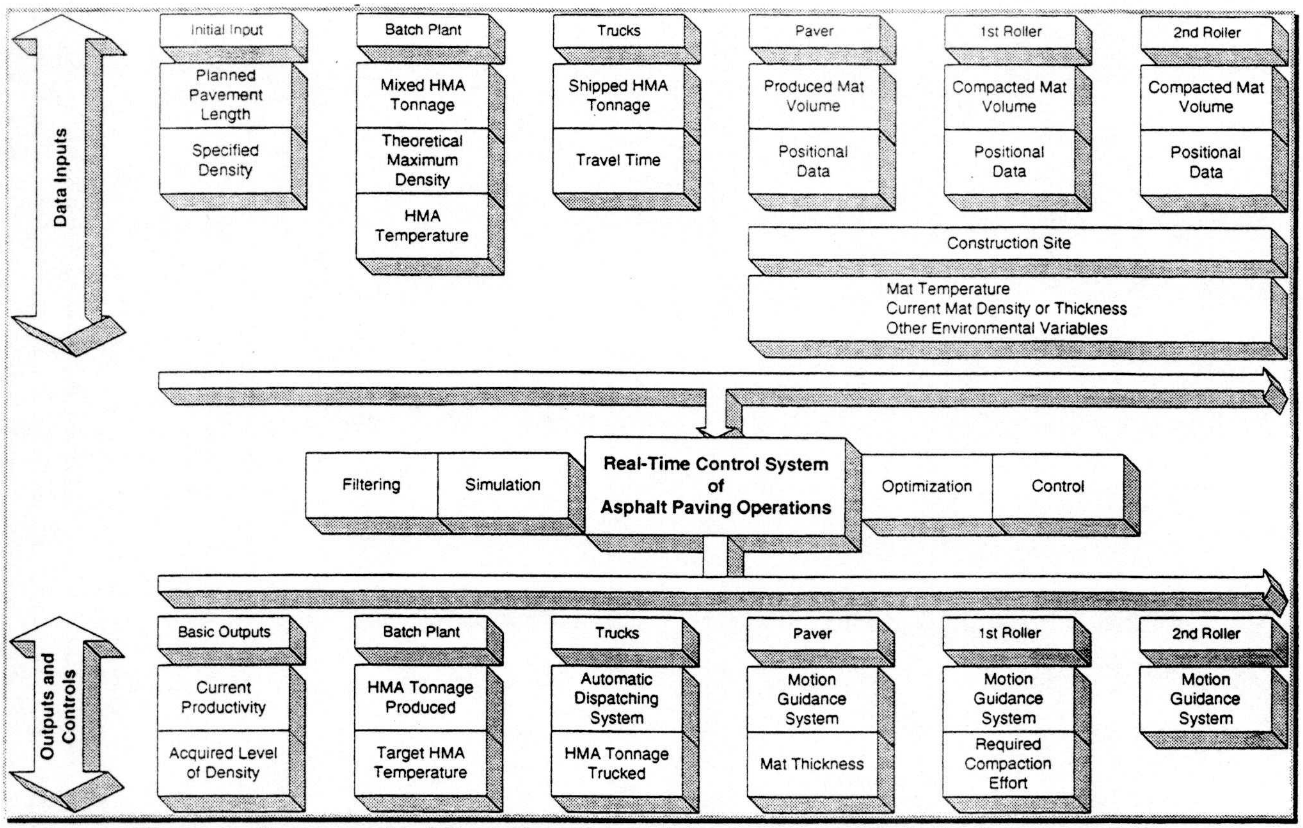


**Figure 1. Framework of Real-Time Control System for Asphalt Paving Operations**

to update the optimal setup of process components. The control task will continuously monitor the operations and send guidance to operators to achieve the specified productivity and quality.

After completing these steps, the verification of this system follows by comparing estimated system results and actual field testing results. If the verification shows that the system does not accurately represent the actual operations, each step should be carefully examined and re-performed to modify the system. Figure 1 shows the framework of the real-time control system for asphalt paving operations. The upper portion of the figure shows the required data inputs, primarily consisting of both productivity and quality data. The lower portion shows the data outputs and controls that the system is expected to generate.

The following sections provide an overview of four methodologies and areas of research necessary within a real-time control system for asphalt paving operations. These methodologies include: (1) simulation modeling, (2) automatic truck dispatching, (3) Global Positioning System, and (4) real-time guidance system. Each methodology contributes to the goal of a real-time control system.

## 5. Methodology 1 - Simulation Modeling

Simulation modeling of asphalt paving operations has been performed previously to predict the productivity of the constituent components [4]. The objectives of this study were to: (1) evaluate various productivity methods available for asphalt paving operations, (2) model the asphalt paving operation with simulation, (3) evaluate productivity by applying collected field data to the model, and (4) describe a concept for the future that uses GPS to collect data in real-time and simulate the data to determine actual productivity. The research demonstrated that simulation can be used during the estimating process and planning paving operations to evaluate multiple alternatives.

Simulation is a useful computer-aided tool for modeling the network of interrelated work cycles in the construction operation [4]. The mutual use of resources is the primary feature of the simulation models, allowing a detailed analysis of resource interaction. A given work task that requires two or more resources can be easily modeled. If one or more resources are unavailable to perform a work task, a delay situation is created allowing construction managers to evaluate the cost implications of the delay, and design a construction system that can remove the delay and increase the productivity rate.

Fixed or variable work duration data are entered into the simulation model to generate an output that reflects actual construction conditions.

Another application of simulation for asphalt paving is to show the complete operation on computer screens using a visualization software package. The visualization of the simulation model can enable users to see and understand the process, thus making it easier to recommend improvements. Figure 2 shows the required steps to simulate and visualize the model.

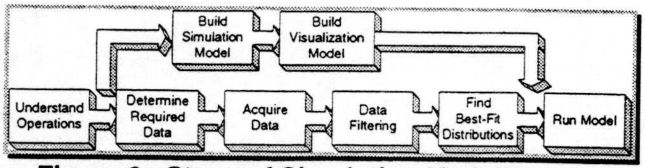


**Figure 2. Steps of Simulation Modeling and Visualization**

Simulation modeling can be programmed with the use of common computer languages such as C, FORTRAN, and BASIC. Special simulation software packages have been developed to offset the difficulty that may be encountered when writing detailed computer code. Languages such as GPSS/H™ of MicroCYCLONE™, can be used to perform these simulations. The simulation language GPSS/H™ has many advantages, one of which is the speed of writing programs to simulate complex systems. Since programming in GPSS/H™ is very rapid, more time can be spent in studying and possibly improving the model as opposed to spending significant time and effort developing a model using C code. However, GPSS/H™ is DOS-based, and the Microsoft Windows™ version is not available at this time. Since the real-time control system will be based on Microsoft Windows™, common programming languages, such as C or Microsoft Visual Basic™, can be used for a real-time system [5].

In the GPSS/H™ simulation modeling, work durations for loading, traveling, unloading, and rolling were considered variables. All variables were expressed in time units and were directly measured from the time-consuming and labor intensive work activities. The future study is expected to provide this information automatically in real-time with the help of GPS, bar-code, or magnetic card. Figure 3 shows the flowchart of the program.

During initial research with this program, simulations were run for one day's production, and the daily working hours were assumed to be eight hours. One hundred replicated runs were first executed and data from average daily productivity were analyzed to obtain the required number of runs under the permissible error of one ton with 95 percent confidence level. In this study, 3,182 replications were conducted to obtain the expected accuracy.

The visualization of this model was performed with the general and flexible visualization software, Proof Animation™. The software runs an animation trace file and a layout file. An animation trace file contains a sequence of commands that specifies dynamic events that take place on the screen. Everything that moves, changes, appears, or disappears in the animation, does so as the result of a command in the animation trace file.

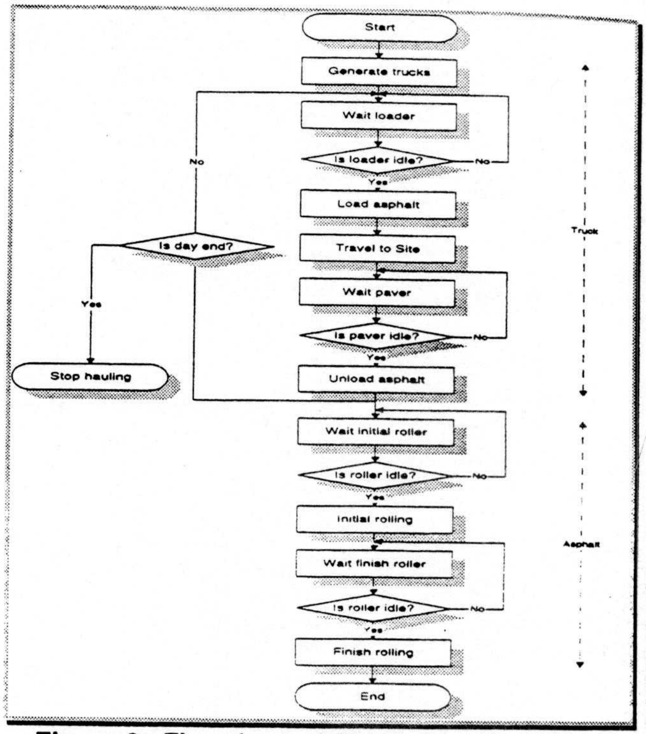


**Figure 3. Flowchart of Simulation Model for Asphalt Paving Operations [5]**

A layout file contains all of the background texts and graphics for an animation. It also contains definitions of shapes, messages, plots, and paths. Layout files are normally constructed and saved within Proof Animation™. They may also be derived from data generated by other programs such as CAD programs. Animation trace files are usually generated by other language programs or modeling packages, such as FORTRAN, BASIC, GPSS/H™, and SIMAN. Controlling output command in the above programs will produce animation trace files, that have simple motion control commands in ASCII format. Currently, GPSS/H™ is being used in the research to produce the animation trace file. Figures 4 and 5 show the visualized screens for the asphalt paving operation [5].

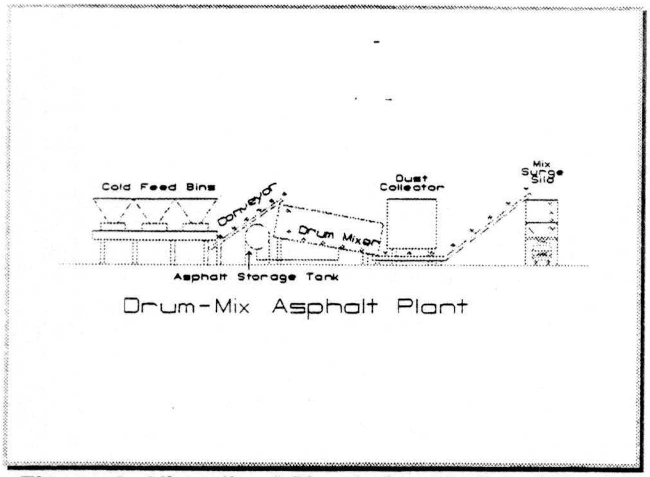


**Figure 4. Visualized Simulation Model of Plant Operation [5]**

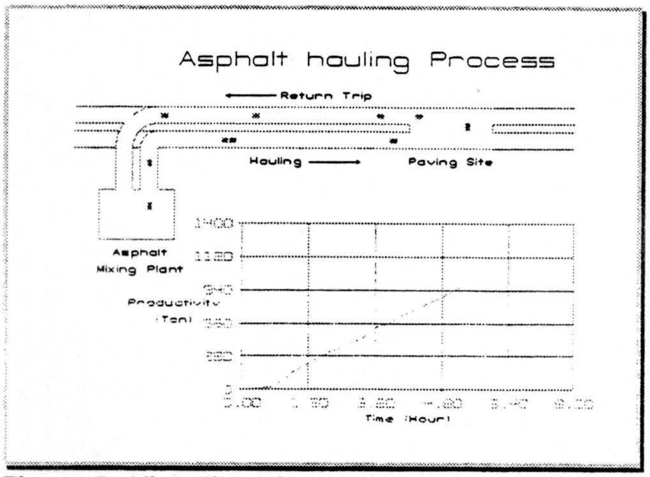


**Figure 5. Visualized Simulation Model of Asphalt Paving Operations [5]**

## 6. Methodology 2 - Automatic Truck Dispatching System

The previous simulation modeling will be further enhanced to develop an automatic truck dispatching system for asphalt paving operations. Prior research and development with automatic truck dispatching is available from the mining industry. The mining industry has widely used a real-time automatic truck dispatching system for (1) determining the optimum cycle paths for trucks, (2) determining the optimum number of trucks, (3) providing day to day records for production, maintenance and repairs for each truck, and (4) dispatching trucks to minimize production costs. With the successful employment of the dispatching system, mining operations have achieved production increases from 10 to 16 percent [6,7]. Similar benefits can be expected in the asphalt paving industry. The primary difference between dispatching trucks in mining and asphalt paving operations is the traveling zone. In mining operations, trucks travel within a limited or controlled area. The travel within a mine is typically not affected by external variables such as public traffic or railroad crossings. In asphalt paving operations, trucks travel in an "open" environment where external variables influence travel distances and speeds. The distance between the mix plant and the construction site is continually changing as the paving operation proceeds down the roadway. The haul cycle time from fluctuations in traffic volumes or patterns.

The work duration or travel time for each operation can be expressed as a statistical distribution. It is possible to obtain a distribution for varying travel distances and time of day. Once travel times for a specific distance are measured, the distribution can be used to predict the travel time distribution for the next travel distance.

Further quantitative description of haul times, such as log-normal or square-root functions, will help the system to predict the travel time for a specific distance. Trucks spend considerable amount of total travel time in acceleration and deceleration modes. Also, the travel time can increase logarithmically or at a square root function as the travel distance lengthens. Figure 6 is a simple plot showing the relationship between haul time and distance traveled. The original data was obtained at 16-km point and a log-normal function was used for the stochastic data conversion.

To successfully develop a dispatching system for asphalt paving operations, it is important to consider the localized traffic volume for a given time of day. If there is small levels of traffic at or along the travel route, or traffic is fairly constant throughout the day, this consideration can be ignored. However, when trucks pass the route where the traffic volume changes periodically, this will decrease the accuracy of the system. Several approaches can be applied; one solution is to divide the day into several time zones, such as hours, and to use separate travel time distribution for each time zone. Before this step it is useful to observe the entire daily traffic pattern, or obtain compiled traffic data, and determine a method of subdividing the day into time zones.

## 7. Methodology 3 - Global Positioning System

The Global Positioning System (GPS) satellite network was initiated in 1978 and achieved its initial operating capability in 1993 when 24 orbiting GPS satellites were successfully operating simultaneously. This satellite system is deployed and operated by the U.S. Department of Defense, where over $12 billion has been invested in the system. GPS can be classified into three primary types [5]:

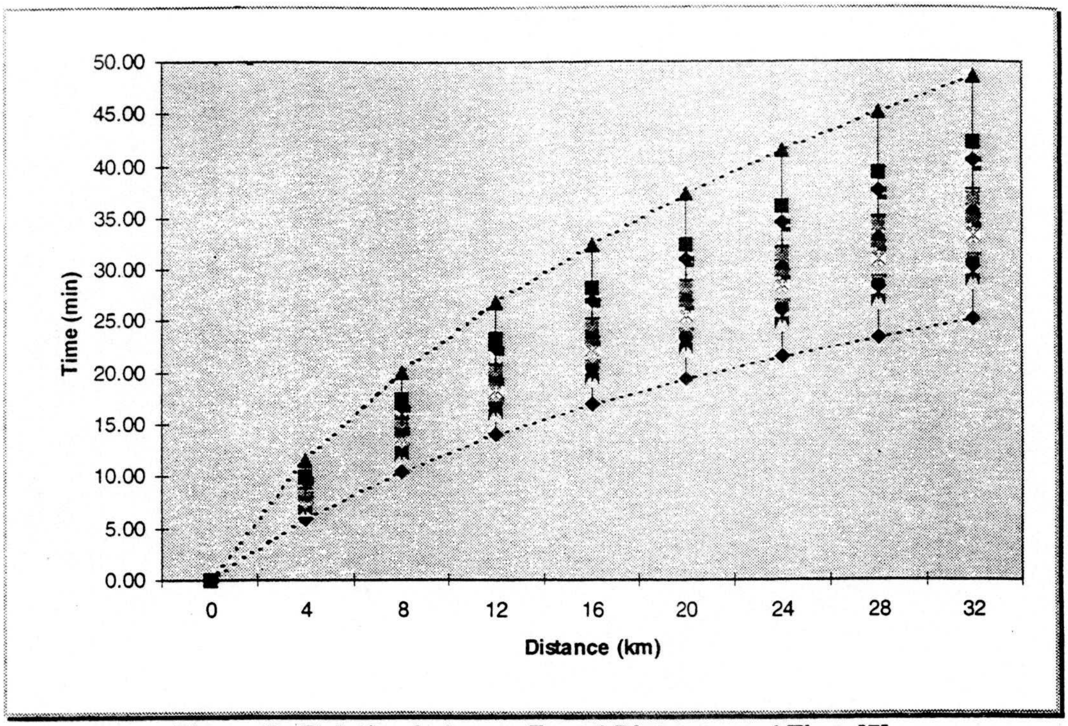


**Figure 6. Relation between Travel Distance and Time [5]**

- Standard GPS
- Differential GPS
- Kinematic GPS

Standard GPS has about 100-meter position accuracy, and can be operated with only one receiver. Differential GPS can achieve measurement accuracy of less than one meter. This measurement accuracy is achieved within fifteen minutes of GPS data collection using a stationary location, precise knowledge of a reference point, and the use of a complex computer program to triangulate the precise position of the receiver. This system requires at least two receivers for initial location and point referencing.

Kinematic GPS can achieve 10-centimeter accuracy. This measurement technique is based on the principle that if a GPS receiver is put at a known location, it can be used to determine the errors contained in the satellite data. It transmits an error correction message to other GPS receivers to correct their position. This system requires at least two receivers, similar to Differential GPS.

The adaptation of GPS to asphalt paving operations has been successfully performed in several field studies [2]. The objective of the research was to construct a real-time guidance system for the roller operator. The system basically consists of GPS hardware, computer software, and the actual paving equipment. The overview of the GPS employed in the system is shown in Figure 7.

The GPS used in the research was Real-Time Kinematic GPS, a product of Differential GPS, that features one-centimeter horizontal accuracy, and two-centimeter vertical accuracy. The system can track up to five positions per second, and enables the system to observe movements almost instantly.

The GPS transmits positional data that can be used to calculate the current production rate of paver and rollers, as well as to control the motion of rollers. It is possible to obtain productivity data by tracking forward progress of the paving train. The GPS system can be readily applied to trucks to monitor their current position, travel speed, and productivity.

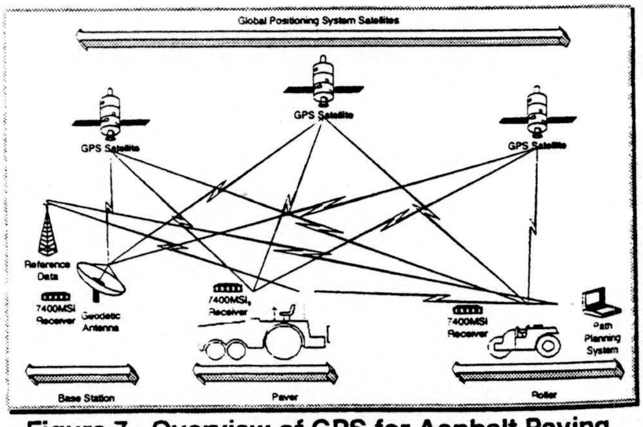


**Figure 7. Overview of GPS for Asphalt Paving Operation [5]**

## 8. Methodology 4 - Real-Time Guidance System

A primary objective of this computer-aided research is to develop a semi-automated path-planning and guidance system for real-time control. This system accepts relevant paving project inputs, generates appropriate path plans for the compactor, performs a graphical visualization of the generated path plan, and offers real-time guidance capabilities using GPS technology [2]. The real-time guidance system was developed in *Microsoft Visual Basic*™ programming language and can be implemented on all Microsoft Windows™ platforms. This system was tested on several actual paving projects, and many operational issues related to the functioning of the system were successfully overcome.

The system monitors and graphically displays the real-time roller and paver paths, current coordinates, number of passes made, overlap areas, and other current rolling zone information. Additionally, the system guides the operator with appropriate visual and audio guidance throughout the operation, to follow the planned motion path as closely as possible. An illustration of the plan view of the semi-automated system is shown in Figure 8.

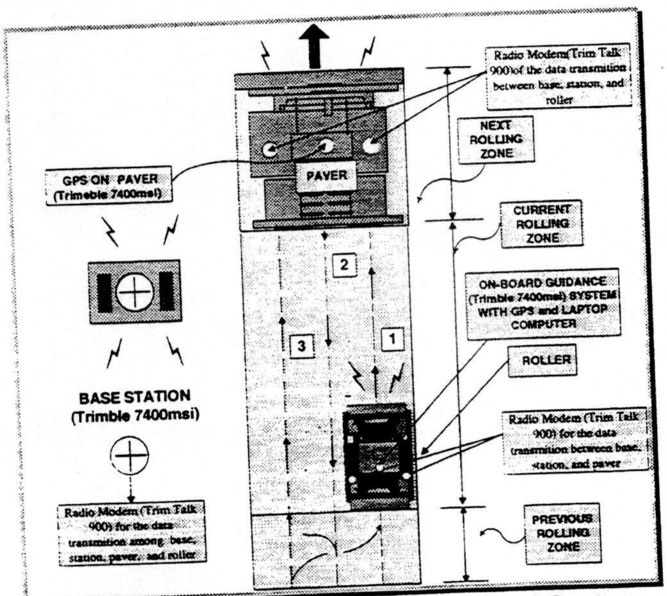


**Figure 8. Plan View of Semi-Automated System [2,8]**

Primary variables are entered into the system before the start of the paving operation, such as overall width of the pavement, key dimensions of the roller and paver, equipment operating characteristics, width of the mat, maximum allowable overlap value, minimum and maximum allowable rolling zone lengths, desired pavement mat thickness, and compaction pattern to be followed. The inputs are used by the program to implement the computational algorithms for path planning and real-time control.

Once all the relevant inputs are declared and entered into the system, the various input dimensions are first converted to common field dimensions, then from real-world dimensions to local screen dimensions, by applying suitable scale factors. An angular transformation is applied with a rotational transformation matrix to adjust from the orientation alignment of real-world coordinates to local screen coordinates. The angle can be determined in the field by automatic calculation or trial and error.

The appropriate motion model for a given project is determined from various project inputs. This algorithm suggests the suitable number of passes to provide a complete and nearly uniform coverage of the rolling area. This simplified algorithmic procedure is an independent unit in the program, and is modularized to accommodate future algorithms that take into account other influencing variables. This important feature allows system versatility for changing project conditions. The procedure actually implements the specific path planning algorithm currently used for determination of the appropriate motion model.

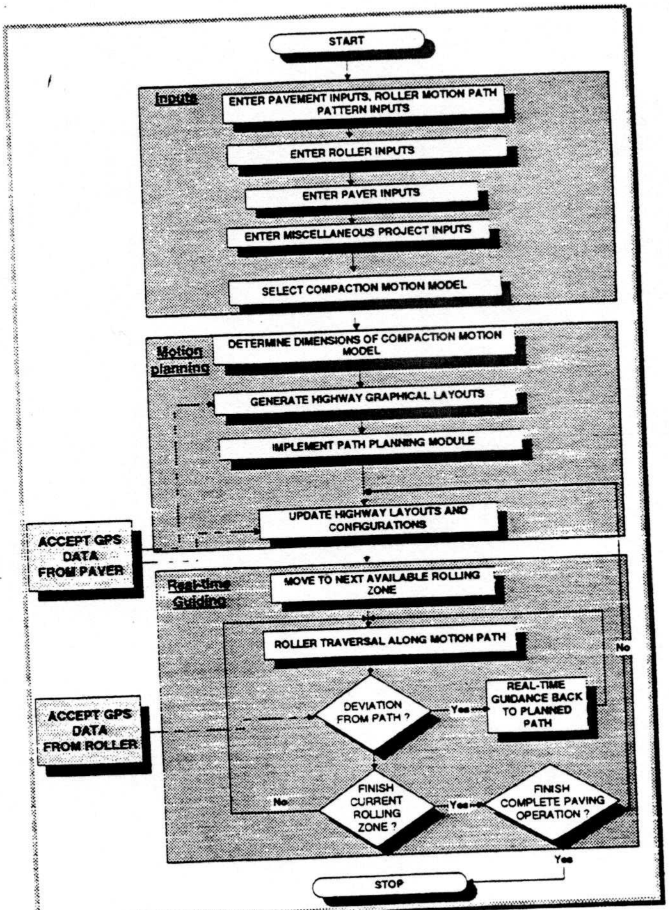


**Figure 9. Flowchart of Semi-Automated System [2]**

It is invoked by both the path-planning and real-time control procedures. A flowchart describing the crucial steps and significant stages in the computational process is presented in preceding Figure 9.

Based on the relationship of recommended minimum laydown temperature, mat thickness, base temperature, and available time for compaction, comprehensive computational algorithms can be developed representing the conditional relationships between these influencing variables. The future of this system is to automatically calculate an optimal number of transverse roller lanes, number of passes, rolling pattern, rolling zone, and speeds of the paver and rollers based on these inputs. Figure 10 provides the flowchart for the compaction module of the semi-automated system.

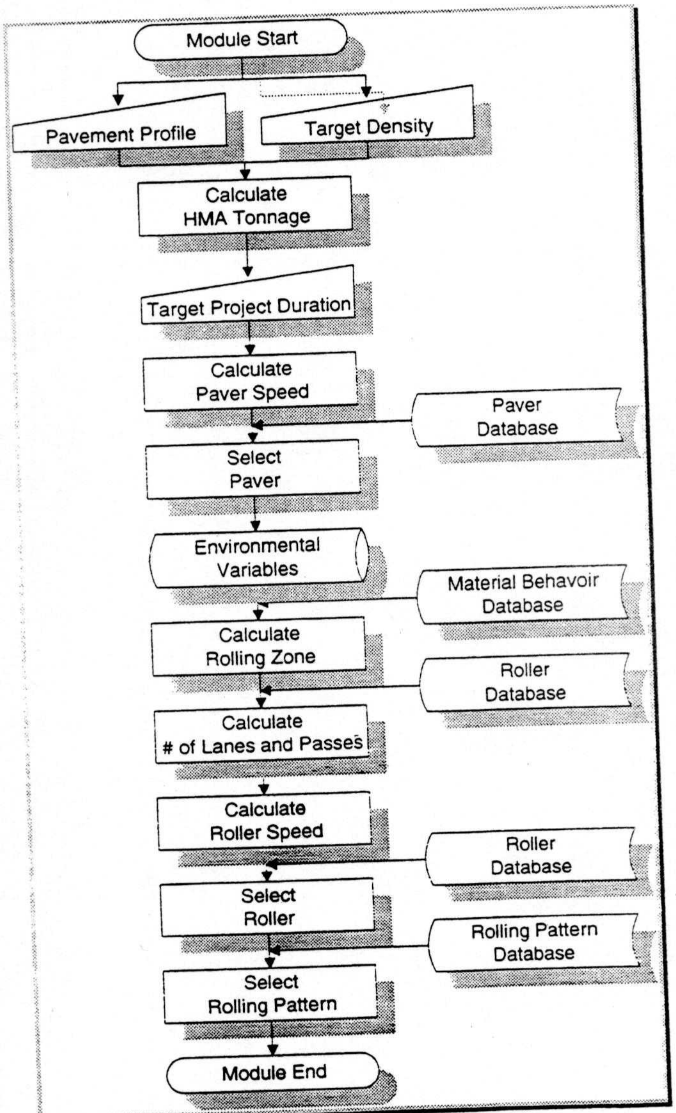


**Figure 10. Flowchart of Compaction Module**

The system's computer screen includes several icons for performing specific functions as shown in Figure 11. Clicking the "Path Plan" icon enables the system to implement the algorithms to determine the appropriate motion model for the current paving project. This module also displays a graphical visualization of the motion path to be followed by the compactor, using the motion pattern specified earlier in the project inputs. Clicking the "Real-Time" icon invokes the real-time control and guidance module. This module performs the actual motion tracking, graphical display and real-time calculations of overlap, and speed calculations.

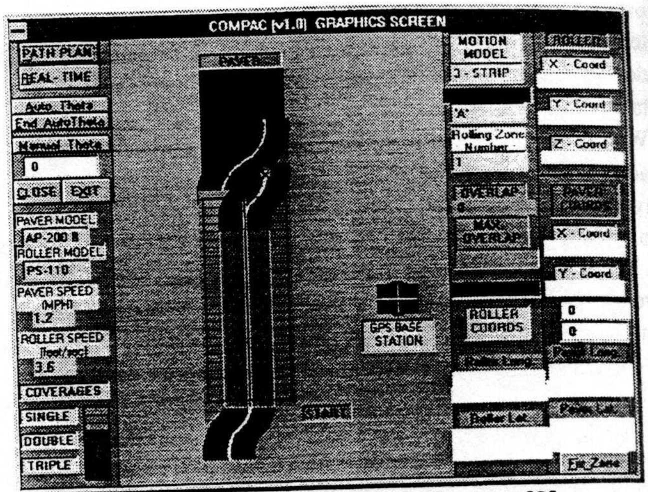


**Figure 11. Main Graphics Screen [2]**

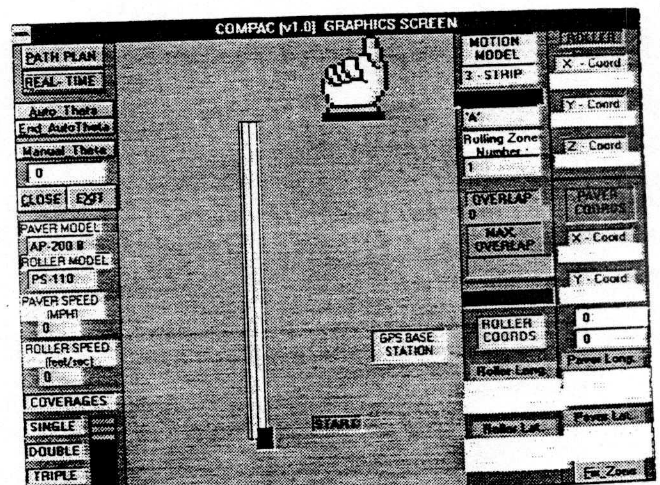


**Figure 12. Real-Time Guidance Graphics Screen [2]**

Operator ergonomics were given prime consideration while designing the real-time guidance module. Audio instructions were found to be more favorable among operators for guidance. Several audio files with simple instructions were recorded and integrated into the computer program to provide audio instructions to guide the operator throughout the operation. These include instructions to begin the rolling for current zone, turn left or right, maintain straight movement, end of current pass, end of current rolling zone, begin of next rolling zone, and the end of the paving operation. In addition to audio guidance, the system also has complete visual guidance capabilities through message prompts, dialog boxes, icons, and graphical images as shown in the preceding Figure 12. The current status of the screen in Figure 12 prompts the operator to start a straight forward pass.

## 9. Conclusions

This paper provided methodologies to develop a real-time control system for measuring and improving productivity and quality in asphalt paving operations. These four computer-integrated methodologies include: (1) simulation modeling and visualization, (2) automatic truck dispatching system to maximize truck productivity, (3) Global Positioning System for real-time positional data acquisition, and (4) semi-automated path-planing and real-time guidance system for rolling operations.

Simulation modeling provides information for optimal allocation of available resources, with the goal of improving productivity. Visualization will enable users to see and understand the operations effectively and to verify the simulation model. Simulation modeling can be upgraded to real-time dynamic simulation with the help of GPS technology. Automatic truck dispatching system will enable the cost-effective use of trucks in asphalt paving operations by minimizing costs and maximizing productivity.

A computer-integrated path-planning and real-time guidance system with operation planning potential, incorporating the state-of-the-art GPS positioning technology, was provided for the rolling operation. This system offers an interactive, user-friendly, graphical interface with real-time tracking and path guidance features that incorporates both visual and audio guidance capabilities. This system provides an expandable software base, firm program infrastructure for further additions and modifications, all towards the development of a real-time control system of asphalt paving operations.

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