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SIMPAVE: Towards Building Interactive Simulations for Planning Pavement Construction

By

George Turkiyyah
Department of Civil and Environmental Engineering
University of Washington
Seattle, WA 98195

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Transportation Northwest (TransNow)
University of Washington
135 More Hall, Box 352700
Seattle, Washington 98195-2700

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ABSTRACT

The goal of this project is to produce a software simulation that enables a user to manage a road construction project from the hot mix asphalt plant operation to the finished paved road. Throughout the simulation, the user is provided with the resources needed to complete a specified road construction task. These resources include raw materials for hot mix production, trucks for transportation of the hot mix asphalt from the plant to the site, equipment to lay, roll, and finish the pavement. In addition, the simulation will include a virtual crew that can be directed to execute the road construction tasks. Built into the simulator is a set of models that emulate real-world constraints on hot mix asphalt construction. These include models of mix design properties, temperature-dependent mix characteristics, resource management to balance production and laydown rates, rolling and compaction, and deployment of available man-hour resources. Computer graphics technology will be used to give the user an omniscient, third-person perspective on the virtual world. Interaction with the visually rich world enables the user to zoom in and examine the individual processes and locations in the simulation or pull back and have a macro view in order to manage the inter-process relationships. From the third-person vantage point, the user can start and stop tasks in order to synchronize dependent tasks or to verify the quality of work. Using a game metaphor, feedback mechanisms will be in place to inform the user of the success of the construction task. This simulator will be useful for training students and workers in the road construction industry, highlighting the necessity of quality control, task coordination, and resource management.

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1. Introduction

Pavement is big business. There are over 3.96 million centerline miles of public roadway in the U.S. Of this, about 2.5 million centerline miles (63 percent) are paved (FHWA, 2002). We spend about $110 billion annually on U.S. highways (Epps et al., 1997), of which $20 to $30 billion is spent directly on pavements (Frojen Marketing, 2000). The HMA material alone is a $500 to $600 million per year industry. On such a large scale, maintaining or upgrading knowledge within the industry can save millions of dollars every year. It is estimated that between 5 and 30 percent of construction contracts are significantly degraded by construction problems (SPTC, 2003). Given the amount of hotmix asphalt pavements built every year, the cost of inferior construction translates to millions of dollars annually. In Washington State alone, this amounts to about $5 to $30 million worth of affected projects each year, many of which could be avoided through better training.

Like many construction processes, HMA manufacturing and construction is a complicated process involving many different stakeholders, materials and equipment, all of which must be effectively managed and coordinated in order to produce a high-quality pavement for the driving public. Pavement construction is a complex, multi-person task that requires careful coordination and proper timing between a sequence of activities ranging from bringing hotmix to the site, laying it on the road being constructed, and compacting it through multiple passes before it reaches a critical cold temperature. Improper execution results both in inefficiencies in the construction process and, more importantly, results in pavements that deteriorate prior to their design life.

Traditionally, it has been difficult to present the HMA manufacturing/construction process, and specifically the inter-relationships of its constituent parts, in a manner conducive to student understanding and learning. Tools that assist trainees in visualizing and understanding the constraints on the construction process are needed. Current computer technology has made it possible to develop three dimensional simulations that provide immersive and interactive training environments where users can perform and experience pavement construction tasks. These environments allow navigation in a realistic 3D world, bring in the time dimension of hotmix laydown and cooling, and allow users to perform construction activities and see their effects in real time. In order for such simulations to more realistically portray real construction scenarios, multiple users need to be able to interact simultaneously with the environment and observe each other's actions and react appropriately.

These interactive training simulations offer multiple benefit to hotmix construction. They allow novices to practice construction tasks in a virtual environment before they execute them on site. Trainees have the opportunity to operate equipment, experience the event sequence in a construction scenario, become sensitive to the timing constraints of a given task, appreciate the effects of wind temperature on compaction density, and interact with other participants in the construction process. In addition, the combination of an accurate geometric representation of the construction site, the time-constraints derived from hotmix cooling physics, and the multi-user interaction in a simulation, gives construction managers insights into the planning, timing, potential bottlenecks, and communication needs of a construction project.

In this report, we describe the design of a pavement construction project simulator. The design is based on our experience in the development and testing /evaluation of prototype interactive simulations, as well visualizations of various pieces of the HMA construction process. The development of a compelling instructional user experience requires the integration of a number of technologies including path planning for material-hauling trucks to the job site, realistic physics-based models for hotmix cooling from the plant to final compaction, operations models for construction equipment including pavers, rollers, etc., as well as stochastic elements to simulate the random elements that affect pavement construction (temperature, wind, traffic, etc.). We describe the methods and tools that must be integrated to build the next-generation of pavement construction simulators.

2. Background

Simulation in the construction of transportation facilities has a long history. Project activity networks and bar charts have been a staple of construction planning for a long time. They still are the main tools for high levels description and presentation of project tasks, time constraints, resource usage, and related tools for effective management. The advent of powerful graphical rendering hardware and software tools has recently opened the door for more detailed graphical representations of the construction process.

Koo and Fischer (Koo and Fischer, 2000) describe what they term a 4D CAD system. A 4D model is a sequence of 3D graphical models showing the evolution in time of a constructed facility, allowing planners and various stakeholders to visualize the construction process as it would be built. Using a specific project as a case study they showed the benefits of such a system in increasing the comprehensibility of projects schedule, timing and dependencies. Kamat and Martinez (Kamat and Martinez, 2001, 2005) describe a construction visualizer that accepts a simple command language to generate animations of construction subtasks (e.g., a dump truck unloading material). The system allows planners to analyze a construction tasks at the operation level of detail and verify/simulate required construction operations. Models of construction equipment (cranes, backhoes, trucks, etc.) can operate on terrain maps to provide 3D graphical feedback on the time evolution of a construction operation to provide additional insight insight into the subtleties of construction operations that are otherwise nonquantifiable and presentable. Zhang et al (Zhang et al, 2002) describe the development of an animation tool for activity-based construction modeling and simulation. The tool uses an activity-based network diagram as the animation background image, and uses pre-created two-dimensional iconic images for simulation entities (e.g., resources). The animation process displays the queuing status and dynamic movements of 2D iconic images on the background image to allow users to better understand the dynamic nature of the construction process.

While these simulators are very useful additions to the arsenal of tools for construction simulation, they provide limited or no real-time interactivity. Users (planners, managers, trainees, etc.) cannot steer these simulations interactively and see the effect of their decisions on the construction process. The simulations are set up as pre-scripted and pre-designed playbacks of one or more scenarios. Our goal has been to incorporate an interactive element in pavement construction simulation.

3. Problem Statement and Objectives

This project seeks to develop a second-generation real-time interactive pavement construction simulation system based on our experience with, and tests/evaluations performed on, previous prototypes. In particular, we have developed a compaction simulator that provides users with a virtual paver and one or more virtual compactors in simulated pavement construction sites. Users can take on multiple roles in the simulation including controlling the laydown of hotmix, and driving the rollers in order to achieve optimal pavement compaction. Visual feedback using realistic 3D graphics provides the user with real time information as to the current temperature of the cooling pavement and the degree of compaction of the road. The simulations can be run either in a stand-alone single-user mode or, by using the provided a simulation server, multiple users can participate in the simulation over a network. The network simulation includes a passive observer role and a text messaging feature that allows the participants to communicate over the network.

While these prototypes allow detailed simulations and visualization at the operation level, our evaluations indicate the need for broader simulations that provide information at the strategic level, to enhance users' understanding of the entire hot mix asphalt (HMA) construction process through the use of similar interactive, entertaining and realistic computer simulations. In order to allow for better understanding of the overall HMA road construction process, the simulation should provide the mechanisms and feedback for users to appreciate and evaluate the various roles and tasks that need to be managed, time and resource constraints, material variability, working in variable weather conditions, effect of traffic on haul time from plant to job site, cost of equipment use, and the influence of these factors on the quality of the finished product.

The overall objectives of the current system being designed are to allow users to control major resource allocations and expenditures during a project, and be able to visualize, at all times during construction, the effects of these decisions on the budget, schedule, and quality of the placed and compacted hotmix. The resources to be controlled include the number and type of equipment vehicles to use (trucks, rollers, etc.), speed of paver and rollers, time of operations, crews on site, etc. These resources must be adjusted *dynamically* in response to various factors including non-uniform initial hotmix temperatures, traffic that prevents trucks from reaching the paver at deterministic intervals (particularly during the morning and evening rush hours), change in ambient temperature and wind speed during a typical 24-hour period, as well as major events such as rain, plant malfunction, road closures due to accidents, etc. The budget and schedule are readily measurable quantities while the quality of the resulting pavement (measured by compaction density) is a distributed measure and requires taking into account initial temperature when material is first laid down, cooling physics, wind/temperature effects, compaction time, etc. Quality/density are spatially varying and must be computed in real-time and presented to the user. In addition, and as in real settings, multiple users must be able to participate, communicate and coordinate their actions, and their interactions must be synchronized.

4. System Design

In this section we briefly describe the overall design of the simulator. Figure 1 shows the main elements of the system. One or multiple users can control the resources available for achieving a pavement construction task and can observe, through a 3D graphical interface, the effects of their decisions on the evolution of the task. The behaviors of the various agents that are involved in the construction operations (trucks, hotmix plants, pavers, rollers, etc.) are automatically generated in response to environment factors, with an element of randomness to provide realistic scenarios.

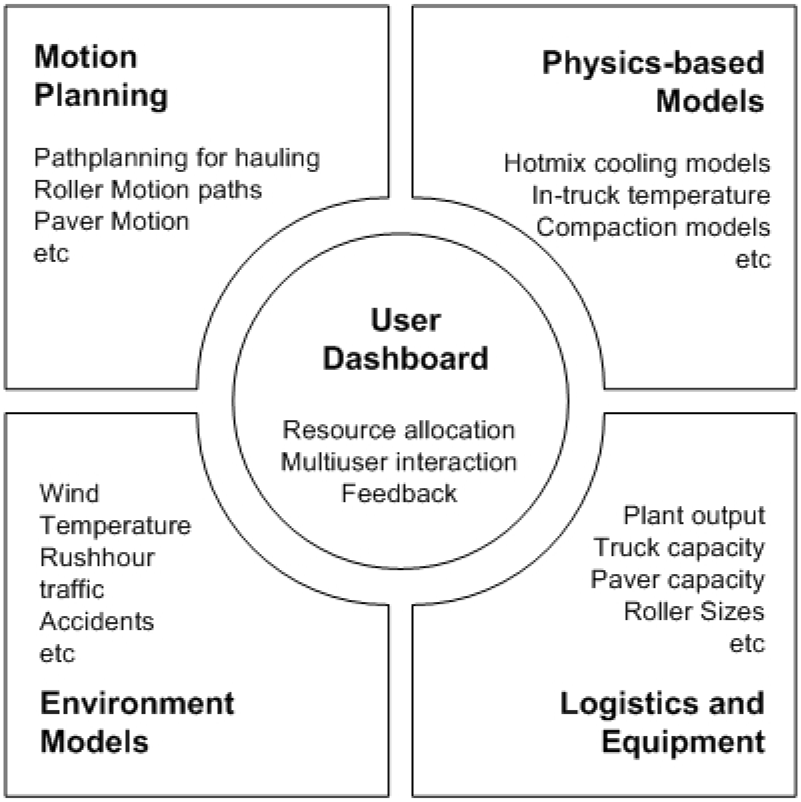

Figure 1. System Architecture

Scenarios for the construction tasks are specified in xml files and can be loaded at runtime. These definition files specify the construction task to be executed (plan geometry of the road that needs to be paved/ overlayed), plant locations that the user can choose from, the road network available for transporting material from the plants to the job site, and baseline climate data. Loading these data files at run time from xml files provides a flexible design and allows users and trainers to develop their own construction scenarios.

The user's primary view in the dashboard is a 3D display of the site as it is evolving. Closeup operation-level views are possible and are useful to the extent that individual paver, roller, or truck operations need to be simulated and visualized. A more global view of the site is more appropriate when making resource allocation decisions. Such views allow the extent of the jobsite to be seen with repect to its surroundings.

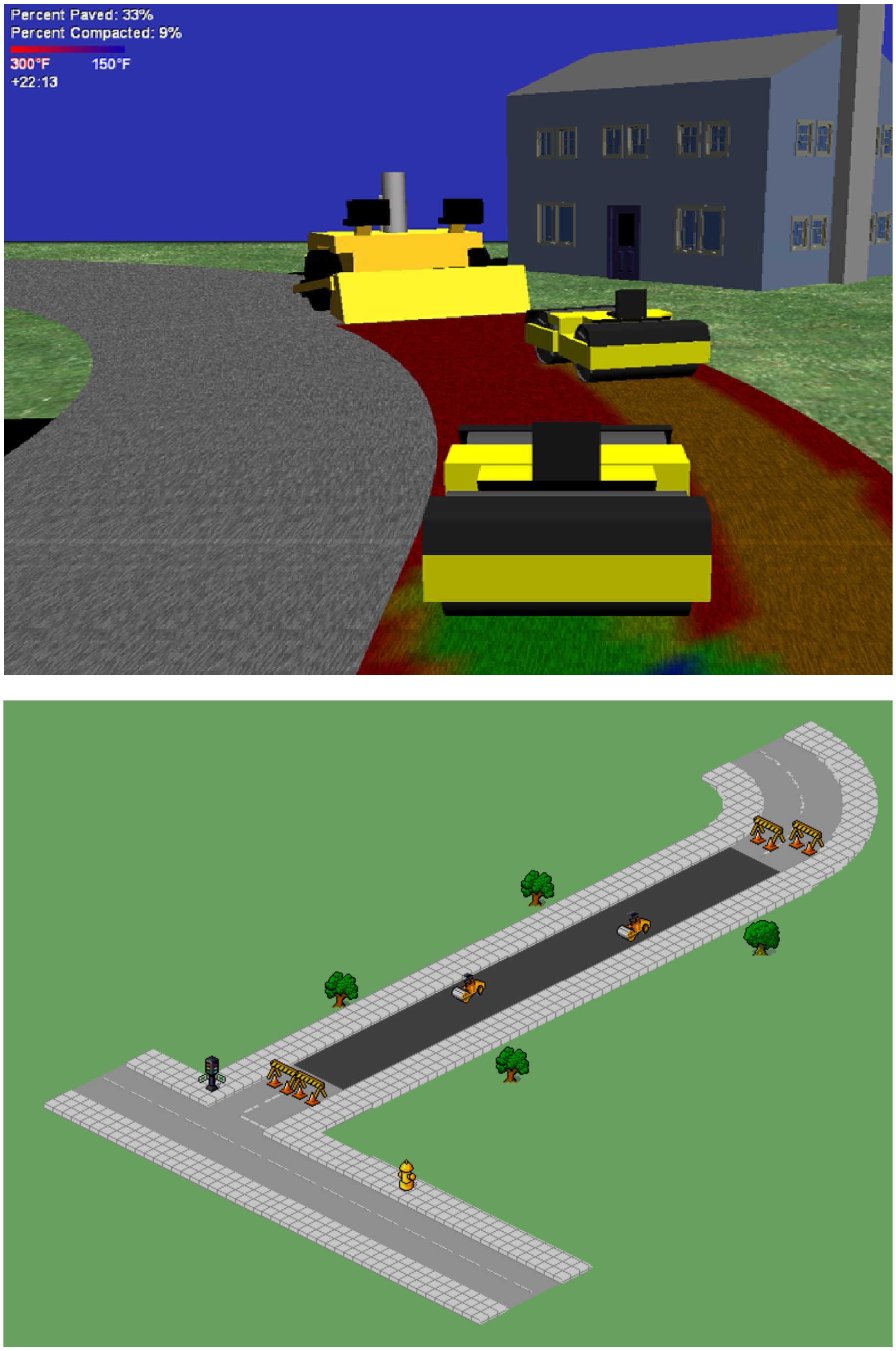

Figure 2. Sample user views of job site

Fig 2 show screenshot examples of these views. Naturally, controls allow the user to zoom in and out of the scene as needed. Our early prototypes allowed users to view the job site from any perspective. However as the complexity of the job site increased, we generally noticed a slowdown in performance on the generally-modest hardware available for people running these simulations. Fixed 3D perspectives appear to be at this stage a reasonable compromise between realism and performance. The next generation of 3D graphics hardware will allow for richer and more general navigation around the job site.

Motion Planning

One of the important modules of the global simulator is a motion planner that allows moving equipment to have the "intelligence" to traverse the road network and job site. Hauling trucks need to find their way from a plant to the job site. Static routes are not possible nor realistic because of traffic, closures, etc. Dynamic path finders endow the trucks with the necessary logic to find the fastest route to the site, and to replan the path in the face of slowdown due changing traffic patterns. Similarly, rollers need not be individually moved and steered by the user. High-level commands can be issued ("compact lane behind paver with 3 passes") and the path planner finds the sequence of passes depending on paver and roller widths to cover the appropriate region behind the paver.

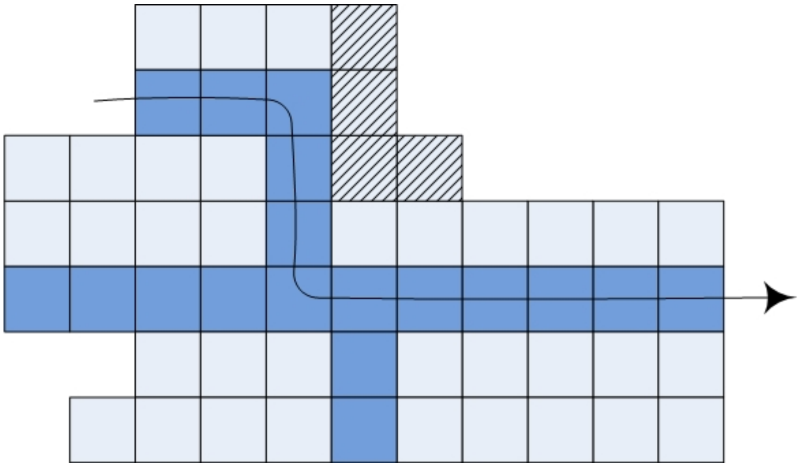

Figure 3. Grid structure used in path planning

The algorithms for the automatic generation of motion paths are based on the A* algorithm (Russel and Norvig, 03). A* is a heuristic graph search algorithm to find paths between a start and goal nodes. The graph we use for the search is generated by overlaying a Cartesian grid on the overall site and using the tiles that cover roads as the nodes of the graph (Fig 3). The nodes are connected by arcs in the direction of travel. Each arc is weighted by the traffic density along it, and this traffic density (average speed) changes continuously depending primarily on time of day. The shortest (fastest time) path from the plant to job site can then be found in this graph, and forms the initial planned route for the truck. At regular intervals, this route can be updated by running the algorithm again from the current truck position to the job site. Depending on conditions, this may change the truck's path en-route. A*'s performance is sufficient for small and medium sized spatial domains. For large simulations, its performance may be a bottleneck. Hierarchical and dynamic versions of the algorithm (Stentz, 2002) are available to still allow it to run continuously with real-time performance.

Planning the path of rollers has to occur at a finer level of resolution. For planning these paths, the regions behind the paver are discretized using a finer tiling and the algorithm reduces to finding the shortest path to cover the whole graph. Because of the simple and predictable geometry of the region of compaction, template solution paths can be readily instantiated and used. No dynamic replanning is necessary during compaction.

Physics-based Models

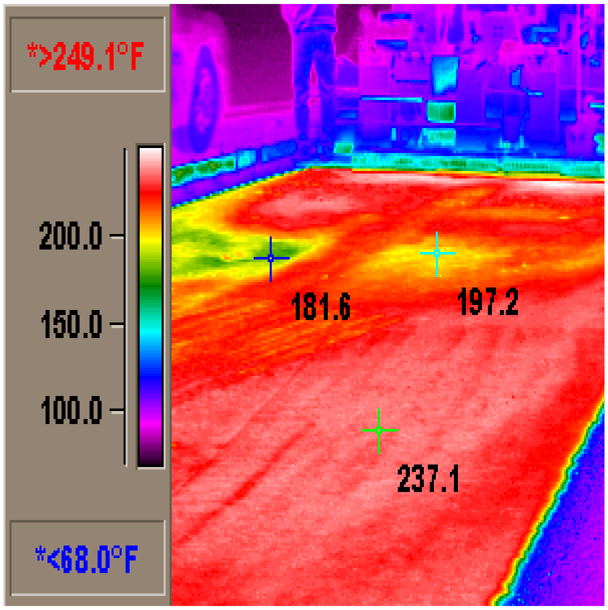

Figure 4. Infrared image of mat temperature behind paver

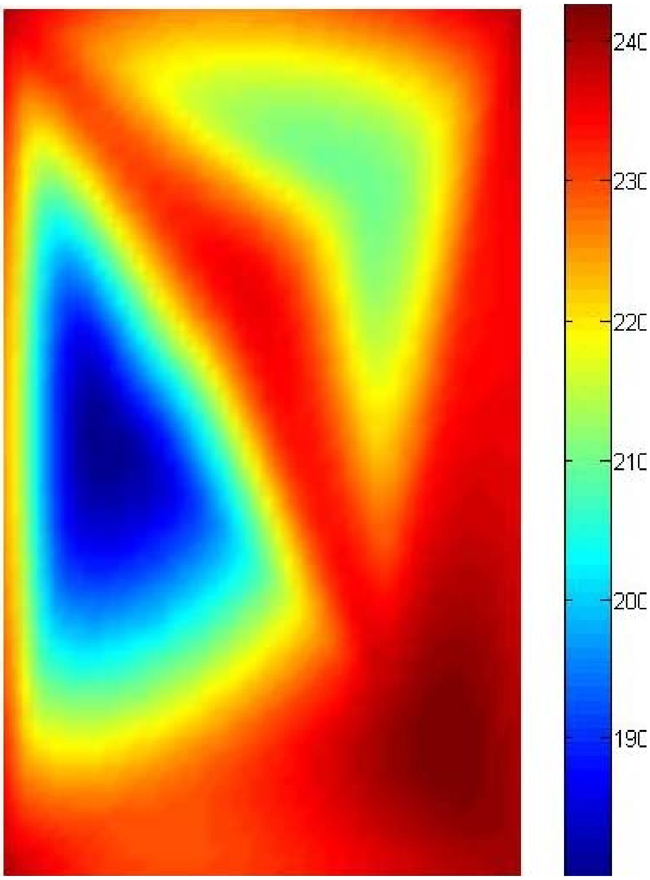

Figure 5. Synthetically-generated mat temperature

The main feedback on the quality of the hma construction comes from compacted density, which is directly correlated with the temperature at which the compaction takes place. Therefore, the mat temperature must be conveyed to the user continuously. It is reasonable to assume that the temperature at the plant is controlled and constant, and that the heat losses occur during hauling (mostly convective losses due to air effects) and from the conduction, convection and radiation from the mat after the hma is deposited (Chadbourn at al, 1998). There are a number of difficulties in modeling temperature changes in a simulator. The mat temperature even right after the hotmix is deposited by the paver is not always uniform (Figure

4) due to a variety of factors including the nonuniform temperature in the hauling truck. If the temperature were spatially uniform, then the solution of a one-dimensional heat equation with the nonlinear radiation boundary condition is possible to perform continuously during the simulation. However the three-dimensional version of the conduction-convection-radiation equation is far too computationally intensive and is not practical for near real-time applications. Our solution is to combine the 1-d solutions at a few specified points and perform spatial interpolation using a Delaunay triangulation (Preparata and Shamos, 1985) of the mat geometry. Figure 5 shows the results that can be obtained in real-time. Cold spots can be realistically injected in the simulation at random locations and would presumably prompt the user of the simulation to get compacters to those regions in time before the cessation temperature is approached. Heat loss during hauling may be modeled simply by a constant decrease in temperature with time. While this does not properly take into account the differential cooling of the outer shell of the hotmix volume, the random seeding of cold spots during deposition on the mat is a proxy to simulate that effect without the expensive 3d simulation of convective losses in transit.

Logistics and Environment Models

The environment models (weather, traffic) and logistics/equipment models (plant production rate, truck sizes, compactor widths, etc.) represent the parameters of the simulated world. Values of these parameters automatically change the results of the prediction algorithms for travel paths, haul times, temperature and spatial non-uniformity of deposited hotmix, severity of cold spots, cooling rates, etc. It is against this background that the user must make decisions on using resources to mitigate potential problems (use more crews, pave during night-time, avoid rush hours, pay for tarps to cover trucks, use a secondary mixing device on-site, etc.). Because of their parameter-setting role, relatively simple environment models may be used. For example, the traffic model need not rely on a sophisticated demand-based (trip generation) traffic simulator. Changes in traffic patterns during the day are reasonably predictable and the average speed may be modeled by a bimodal curve as a function of time of day. With the addition of a randomly generated speed fluctuation component, this provides a realistic background for path planning. Similarly ambient temperature and wind speeds are modeled by random fluctuations super-imposed on average curves. Injection of cold spots is done at a random location at every truck load dump in the paver. These simplified models allow the simulation to proceed in real-time while still preserving the necessary realism.

5. Conclusions

This report presented the overall design of a pavement construction simulation system that can provide a user with an environment to experiment with the effect of resource and equipment allocation on the schedule, budget, and quality of a pavement construction task. The key enabling feature of the simulation is endowing the various agents of the simulation with internal logic so they they can autonomously make progress from a high-level task specification, and react to dynamically changing operating conditions. The environment and logistics plant production models are kept simple to strike a balance between the real-time performance needs and the realism of the simulation. The algorithms presented can run smoothly on modest hardware even with reasonably-sized simulated job sites.

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