IMPACT OF LIGHTING ON THE SAFETY AND PRODUCTIVITY OF NIGHTTIME CONSTRUCTION WORKERS

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To my parents.

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ABSTRACT

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Nighttime highway construction work is becoming very common in the U.S. as most of the nation's highway system needs repair and rehabilitation. Most of this work is scheduled to be performed at night so as to avoid increased daytime traffic congestion. Work zone lighting is a very important issue that has to be considered while working at night as it allows workers to be able to see each other and to be aware of their immediate surroundings in order to perform their work in a safe and productive manner. This study's focus is two fold: (1) the analysis of the impact of work zone lighting on nighttime highway construction workers' perceptions of safety and productivity and (2) analysis of the productivity of the operation under different lighting conditions. Surveys were distributed to nighttime construction workers in Indiana to collect data about their perceptions regarding the lighting practices followed in nighttime work zones in which they were working. The workers' perceptions regarding the effectiveness of the current state-of-the-practice of lighting in the areas of safety, productivity, quality, and awareness were also obtained. An econometric analysis of the data obtained showed that the general site lighting affected the perception of safety in a positive way, while the presence of balloon lights that helped improve the lighting around the task area improved worker productivity. A multivariate regression model that determined the impact of the presence of different lighting sources on the ratio of operation productivity achieved during the daytime and nighttime hours was constructed. This enabled the incorporation of the effect of lighting into the duration of activities and, subsequently, the calculation of operation productivity. Four different lighting scenarios were tested using the framework developed and it was found that the scenario which included both roadway and trailer mounted lighting resulted in the highest productivity.

CHAPTER 1. INTRODUCTION

Nighttime construction and maintenance work on highways is becoming very common in the United States. Most of the highways in the U.S. were built in the 1960s and 1970s with a design life of 30 years, it is estimated that about 33% of the nation's highways have exceeded their design lives. According to the Federal Highway Administration (FHWA 2007), the estimated cost to maintain U.S. highways and bridges in order to ensure an efficient roadway system for the use of the traveling public over the 20-year period from 2005 to 2024 would be about US$78.8 billion, stated in constant 2004 dollars.

Construction and maintenance work on highways is now being performed at night in order to reduce the inconvenience that daytime construction poses for the public, especially the problem of congestion. While beneficial to the traveling public, the practice of conducting nighttime highway construction and maintenance operations force contractors to work in a very different environment from their customary daytime operations. Of the many issues which render nighttime construction different from daytime construction, the lighting of the construction work zone is one of the most important. Several factors, such as the safety of the workers, the safety of the motorist travelling through the site, and the productivity of the operation, depend on the lighting strategy adopted in the work zone (Finley and Ullman 2007, Ellis 2001). Safety is one of the chief concerns of the contractor while deciding to work at night and the work may be performed differently from identical daytime operations due to safety reasons (Hancher and Taylor, 2001). Another aspect of the operation that is important to the contractor is the productivity of the operation, which dictates the cost and duration of the project. In order to better understand and evaluate different lighting strategies for highway construction work zones, this study will focus on attempting to link the perceptions of safety and productivity of the workers who work during the night with the lighting that is provided on the site.

1.1. Background and Research Motivation

While the decision to work at night is made mainly as a consideration of the travelling public in mind, the chief concerns of the contractor performing the work are the safety and productivity of the project. There are many factors that can impact the productivity of an operation performed at night in a positive way, such as the cooler temperatures and the reduced traffic experienced at night. However, other factors that adversely affect productivity are also present at night, such as the disruption of the worker's natural circadian rhythms and the absence of natural lighting on the site. etc. In past research (Finley 2008; Hyari and El-Rayes 2006) pertaining to lighting at nighttime construction work sites, it has been noted that one of the major factors that determine the productivity of any nighttime operation is the lighting strategy adopted in the work zone.

In January 2005, Purdue University received a grant from the National Institute of Occupational Safety and Health (NIOSH) to conduct a five-year study to find ways to reduce the number of accidents and fatalities at nighttime construction sites. One of the modules of this project involves the effects of lighting on safety and productivity at nighttime construction sites as lighting is one of the most important aspects of nighttime construction that differentiates it from daytime construction. This assertion is particularly true in the case of highway construction, where the lighting strategy adopted affects the traveling public as well.

This thesis evaluates and identifies the impacts of lighting on the perceptions of the nighttime construction workers with regard to their safety and productivity in the work zone. A framework to analyze the impact of different lighting scenarios on the productivity of the operation that is performed is proposed in this research. The results are illustrated by applying them to a very commonly performed nighttime operation, the milling and repaving of an asphalt pavement. The objective of this research is to develop recommendations for nighttime work zone lighting that will improve the workers' perceptions of safety and the productivity of the workers based on the analysis performed on the data collected.

1.2. Problem Statement

The lighting strategies that are adopted by nighttime construction practitioners are based on general guidelines and specifications developed by various state Departments of Transportation (DOTs). These guidelines are based on literature and lighting standards proposed by agencies such as NIOSH, the Illuminating Engineering Society of North America (IESNA), and the Occupational Safety and Health Administration (OSHA). While these guidelines specify parameters such as the minimum luminance required to perform a particular task, they do not provide information on how to achieve these lighting conditions. Also, since the layout is unique for each work zone, it would be helpful to the contractor to be able to visualize the design of the lighting layout in the two-dimensional space of the work zone, as this would allow him to plan for the types and quantities of lighting equipment which would be required for the project, depending on the lighting needs of that particular project and the layout of the work zone.

Researchers (El-Rayes and Hyari 2002; El-Rayes and Hyari 2005; Hyari and El-Rayes 2006; Nasser 2007) have investigated the topic of nighttime work zone lighting and have developed various tools that would aid the contractor in developing suitable work zone lighting plans. The only quantitative component that is considered in these tools for the comparison of various strategies, however, is the cost of the lighting apparatus used in the different layouts. These tools do not address the importance of the productivity of the operation being performed, which will determine the cost and time taken for the project, in the selection of a lighting layout.

Previous studies (Dunston and Mannering 1998; Lee et al 2000; Ellis and Kumar 2003; Colbert 2003) have compared the productivity of daytime and nighttime constructions, but these studies did not yield results that conclusively state that the productivity of an operation is higher or lower at night than during the day, which could be attributed to the following reasons:

- The night and day operations had different operational objectives (i.e., the project were planned in such a way that different activities were performed during the night and during the day.

- Some studies compared the data for the same operation from different projects. It is not known whether the operation was done in the same manner across the various projects. This method does not factor in the conditions such as the lighting and weather conditions that prevailed on the different project sites.
- There is no uniform and generalized methodology that can be applied to assess and evaluate the productivity of an operation that is performed at night.

This thesis therefore seeks to develop a methodology that can be used to assess and compare the impact of lighting on the safety and productivity of workers and to quantify the impact of different lighting scenarios on the productivity of the operation.

1.3. Research Framework

The main objective of this research was to assess and understand the perceptions of workers in nighttime construction operations regarding the impact of work zone lighting on their safety and the productivity of the operation. To obtain this data, surveys were developed and administered to workers who have worked on nighttime highway construction and maintenance projects in the state of Indiana. The results of the surveys were then analyzed using econometric software to determine the factors that affect the workers' perceptions of safety and productivity.

In order to obtain a comparison of the productivity levels of an operation under different lighting scenarios, the data obtained from the survey regarding the productivity of the operation were analyzed using a multivariate regression model and incorporated into a discrete event simulation model of an asphalt paving operation, which is a construction operation that is commonly performed at night. An analysis of the results of the discrete event simulation model provides a comparison of the productivity of the operation under different lighting conditions. A two-dimensional animation of the operation was also developed in order to communicate the validity of the model to the Subject Matter Experts. Hence, a single and commonly performed operation was studied in order to develop a framework that can be used for similar projects to aid the practitioners of nighttime construction projects in understanding the impact of different lighting scenarios on the productivity of the operation.

1.4. Research Methodology

A state-of-the-art literature review was performed to study and analyze previous research in the areas of lighting of nighttime construction work zones, productivity of nighttime construction operations, and the visualization and simulation of construction operations. Factors which affect the productivity of the operation when it is performed during the night and the various guidelines and standards that are used for setting up lighting in construction work zones were identified from the literature review. This literature review set the stage for the next step in the research, data collection through site visits and surveys.

In order to meet the twin objectives of a) identifying and evaluating the perceptions of nighttime workers regarding the impact of lighting factors on their safety and productivity, and b) quantifying the impact of different lighting scenarios on the productivity of the operation, the research required data to be collected and analyzed for two components, which is described in this section.

To understand the impact of lighting on the workers' perceptions of safety and productivity, surveys were distributed to workers that had worked during the day and during the night on highway construction projects. The survey questionnaires obtained information regarding the characteristics of the respondent, the type of work performed by the respondent, the usual productivity achieved during the day and night shifts, the type of lighting that is available on the work zone, the respondent's perception of the effectiveness of the available lighting in providing the worker with a safe and productive work environment and the problems that were faced regarding lighting. From an econometric analysis of the data collected from the surveys, the factors that significantly impact safety and productivity of operations were identified. An ordered probit model was used to predict which of the factors characteristics of the lighting made the workers feel safer and more productive.

In order to develop the simulation model of the nighttime operation, site visits were conducted to nighttime work zones where asphalt paving was being performed and the following information was obtained: the work breakdown structure of the activity, the duration of each activity in the work breakdown structure, the resources required for each activity, and the minimum lighting required for performing each activity. The cost component for each resource was also noted in order to calculate the unit cost of the operation. The data collected for the productivity were used to generate probability distributions for the durations of the activities in the work breakdown structure. Also, the impact of the lighting on the duration and productivity of the various activities was quantified by using regression. A simulation model of the operation was created in Stroboscope (Martinez 1996) and visualized using Vita2D (Martinez 2009). Once these models were completed, they were shown to the site engineers to validate the model to check if it is a true representation of the nighttime operation that is analyzed. Also, the verification of the model was done by comparing the results from the simulation model with the actual productivity of the operation as observed from the site visits.

1.5. Thesis Organization

This thesis is organized into six chapters. The second chapter provides a review of both the state-of-the-art and state-of-the-practice literature, which includes relevant research, regulations, and guidelines in the areas of work zone lighting for nighttime construction and maintenance operations and the productivity of nighttime construction operations. The third chapter describes the methodology used to achieve the two objectives of the research. The fourth chapter provides a descriptive analysis of the data collected and the econometric analysis conducted on the data to evaluate the impact of lighting factors on the safety and productivity of nighttime workers. The fifth chapter describes the multivariate regression analysis performed to analyze the impact of different lighting scenarios on operation productivity as well as the development and results of the simulation model and two-dimensional animation using Stroboscope and Vita2D respectively. Chapter 5 also details the verification and validation process that was followed to ensure that the tool developed represented the operation conducted in the work zone accurately and to test its efficacy as a decision-making tool for lighting design is also described in this chapter. Finally, the summary and conclusions of the research, its contributions and limitations, and recommendations for future work are presented in Chapter 6.

CHAPTER 2. LITERATURE REVIEW

The volume of construction and maintenance work on U.S. highways has increased from about $13 billion per year in 1985 to about $37 billion per year in 2008 (FHWA 2008), due to the fact that most of the nation's highway system is more than 50 years old and was designed and built with materials that typically last for 30 to 40 years (FHWA 2007). Most of this maintenance and construction work is conducted on roads that are already carrying traffic, which can lead to significant delays and congestion for the travelling public. The total non-recurring delay is estimated to be about five billion hours per year and highway work zones account for 24% of this amount (FHWA 2007), which is ironic, given that one of the objectives of new construction is to reduce congestion on the highways. This situation has led planning agencies and state DOTs to begin performing highway construction and maintenance operations at night instead of during the day, as it would reduce the impact of the operations on the travelling public. The number of nighttime projects being conducted across the country has increased; and in 2002, 22% of all highway projects were performed only at night and about 18% of all highway projects were performed for more than 18 hours per day (FHWA 2008).

However, despite the emergence of nighttime construction in the nation, very little research has been conducted in this area. While there are studies that have addressed the safety aspect of nighttime construction, much is unknown about the effects of working at night on the productivity of the construction operation. It is presently unclear as to whether the productivity and cost of construction increases or decreases when compared to identical daytime work. Previous studies about productivity have not yielded any conclusive results, primarily due to the limited data that were collected.

Another aspect of nighttime construction that is of great interest, primarily to the contractor, is work zone lighting during nighttime construction, which is an important aspect of planning a work zone, as it impacts the safety, productivity and the quality of construction on the work site. While preparing the lighting layout for the site, the contractor also must make sure that the lighting does not cause glare to the motorists using the road.

This chapter discusses and synthesizes the findings of past studies in the area of nighttime construction, focusing mainly on the productivity and lighting aspects. The chapter also discusses the current state-of-the-practice followed by practitioners of nighttime construction.

2.1 Previous Studies in Construction Work Zone Lighting

One of the most important differences between daytime and nighttime construction is the absence of natural lighting during the nighttime hours, which has led to work zone lighting being cited as one of the major factors in nighttime construction (Finley and Ullman 2008). It affects the aspects of safety, cost, quality, and productivity of projects being performed at night. Apart from affecting the construction project that is being performed, lighting also makes the traveling motorists aware of the presence of the work zone and allows for their safe passage through the zone.

2.1.1 Illumination Requirements for Highway Construction and Maintenance Projects

In order to understand work zone lighting, it is necessary to be familiar with the parameters and terms that are associated with lighting. These terms and their definitions are provided below:

- Luminous intensity is defined as the luminous flux that is contained in a unit solid angle (Simons and Bean 2001).
- Illuminance is used as a measure of the intensity of light and is equal to the luminous flux falling on a given area divided by that area (Simons and Bean 2001). The metric unit for illuminance is lux, which is the same as a unit lumen of flux distributed over an area of a unit square meter. It is sometimes expressed in terms of foot-candles, which is equivalent to a unit lumen of flux uniformly distributed over an area of a unit square foot. (Knowledgedoor, LLC 2005).

- Uniformity ratio is defined as the ratio of the average illuminance to the minimum illuminance in that area. This parameter needs to be minimized in order to ensure that the light is evenly distributed in the work zone (El-Rayes and Hyari 2002).
- Glare refers to the visual discomfort that is caused by the direct exposure of the human eye to bright sources of light. It is experienced in nighttime work zones both by the traveling motorists and the construction workers. Glare is quantified using the parameter veiling luminance ratio (El-Rayes and Hyari 2002).
- Veiling luminance ratio is the parameter that is used to quantify glare. IESNA defines the veiling luminance ratio as the maximum value of veiling luminance divided by the average pavement luminance. Average pavement luminance is defined as the overall average luminance of the road surface as observed from a specific point that is 1.45 meters above the pavement surface and 83.07 meters behind each computation point along a longitudinal line parallel to the direction of travel. The line of sight of the observer is 1 degree below the horizontal. Veiling luminance, which is a measure of disability glare, is the luminance superimposed over the eye's retinal image produced by a stray light within the eye. In the IES method, the value is computed at the same points as the pavement from the same observer position as described above (IESNA 2000).

Ellis et al (2003) prepared a report for the National Cooperative Highway Research Program (NCHRP) that detailed guidelines for the illumination of nighttime construction sites. In order to assess the current practices in work zone lighting, the authors conducted a review of existing literature on the subject, reviewed industry practices, and visited numerous nighttime worksites. Common tasks that were performed at night were identified and classified into construction or maintenance activities. From literature reviews and interviews with experts on illumination, the various factors that affect illumination requirements for nighttime highway construction tasks were identified and classified into four categories. These categories and factors included in each are summarized below:

1. Environmental factors: weather conditions, fog, dust, smoke, wetness of surface, ambient glare, and brightness.

2. Human factors: age, visual acuity, response characteristics, experience, and familiarity with the task.
3. Lighting factors: geometric relationships, orientation, power of lamps, gradient uniformity.
4. Task-related factors: equipment characteristics, physical attributes of the task, qualitative attributes of the task, reflectivity and brightness of the background surface, operation attributes.

In order to incorporate the above factors into illumination guidelines for highway construction activities, established illumination guidelines from other industry areas were transferred to the specific area of transportation construction and maintenance. This task was done by comparing the visual requirements of construction tasks to tasks in other industries, such as the automotive and steel industries. For example, the visual requirements for painting stripes and markers on the pavement at night could possibly be obtained by ascertaining the established minimum visual requirements for a similar task (e.g., applying paint to a finished car in the automobile industry).

The lighting required at construction work zones for commonly performed tasks was then divided into three categories with illuminance ranging from 54 lx to 216 lx. The determination of these categories was influenced by several considerations, the most important of which are listed below (adapted from Ellis et al 2003):

1) Minimum illuminance level recommended by IES for visual detection in normal activities from the point of safety is 54 lx (5 fc).
2. IES-recommended levels and uniformity ratios for construction activities, which are 108 lx (10 fc) for general construction and 22 lx (2 fc) for excavation work.
3. OSHA-required minimum illumination intensities for the construction industry, which range from 33 lx (3 fc) to 108 lx (10 fc) for various construction activities.
4. Provisions for lighting requirements and guidelines as included in various state specifications for highway and bridge work. Minimum of 54 lx (5 fc) in Florida, 108 lx (10 fc) in Michigan, 108 to 216 lx (10 to 20 fc) in North Carolina, and 216 lx (20 fc) in Maryland are some of the provisions.

5. Opinions and views of various experts as obtained from the survey and literature review concerning comfortable and practical minimum illuminance values and categories for nighttime highway work.

Table 2.1 shows the categorization of the required minimum illuminance levels required based on the activity that is being performed. As can be seen from the table, three categories have been defined for the illumination of nighttime construction work spaces based on the type of objective that is required from the lighting. The categorization also depends on the level of accuracy desired for the task and the size of the equipment involved. The first category is defined for the general illumination of the work space while the second category is defined for the illumination of the space around the equipment and for the illumination of tasks that do not require a high level of accuracy. The third level is defined for tasks that require a high level of accuracy and involve small objects.

Table 2.1: Recommended minimum illuminance levels and categories for nighttime highway construction and maintenance (Ellis et al. 2003)

Category	Minimum Illuminance Level lx (fc)	Area of Illumination	Type of Activity	Example of Areas and Activities to be Illuminated
I	54 (5)	General illumination throughout spaces	Performance of visual task of large size; or medium contrast; or low desired accuracy; or for general safety requirements	• Excavation • Sweeping and cleanup • Movement area in the work zone • Movement between two tasks
II	108 (10)	General illumination of tasks and around equipment	Performance of visual task of medium sizes; or low to medium contrast; or medium desired accuracy; or for safety on and around equipment	• Paving, milling concrete work around paver, miller, and other construction equipment
III	216 (20)	Illuminance on task	Performance of visual task of small sizes; or low contrast; or desired high accuracy and fine finish	• Crack filling • Pothole filling • Signalization or similar work requiring extreme caution and attention

2.1.2 Decision Support Tools for Work Zone Lighting

A survey of the available lighting standards from all state DOTs conducted by El Rayes and Hyari of the University of Urbana Champaign (2002), indicated that existing specifications listed a range of minimum illuminances from 54 lx to 216 lx for a range of construction activities. It was also found that there was no consensus on the recommendations provided across the various DOTs. For example, the California, Florida and Maryland DOTs have a single minimum requirement (54 lx) for the site illuminance, whereas the North Carolina and Mississippi DOTs have two levels of lighting requirements, 108 lx and 216 lx, depending on the activity being performed. The New York DOT prescribes three levels of minimum illumination depending on the construction activity performed. Also, since these specifications only provide the minimum illuminance that is to be provided on site, it is left to the discretion of the owner to develop the lighting plan for the work zone. Another factor that must be taken into account while designing the lighting plan for a work zone is the glare that the lighting would cause to the workers as well as the motorists. As can be seen above, there is no single unified standard for specifying the lighting required on site, which calls for the development of a scientific framework for the development of lighting plans for nighttime construction work zones.

El-Rayes and Hyari (2002) presented an automated Decision Support System (DSS) that would aid in the design of lighting systems for nighttime construction work zones. The DSS aimed to optimize the following objectives of work zone lighting, namely, maximizing the average illuminance and the lighting uniformity in the work zone and minimizing the glare caused by the lighting and the cost of the lighting apparatus used. A multi-objective evolutionary algorithm called NSGA II was used to optimize the lighting problem, using the following decision variables:

1. Lighting equipment selection
2. Type of lamps used
3. Lamp lumen output
4. Mounting height
5. Lighting towers positioning (Lighting positioning affects the average illuminance and the uniformity of lighting in the work zone.)
6. Luminaries aiming angle, which determines the directional distribution of lighting and affects the coverage area as well as the glare produced by the luminaires.
7. Lighting towers rotation. The towers are rotated in order to direct the lighting intensity towards the intended area and to minimize the lighting spillage to unnecessary directions.

The work zone was divided into a grid and the horizontal illuminance was calculated at each point of the grid using the inverse square law. In order to quantify the lighting uniformity in the work zone, the uniformity ratio was used. The uniformity ratio is the ratio between the average illuminance of the work zone and the minimum illuminance experienced at points in the grid. The veiling luminance ratio was used as a control measure for quantifying glare in the work zone. The cost of the lighting equipment used was calculated from the ownership cost and the operating cost of the equipment. The proposed lighting system was tested for a work zone 27m long and 10m wide, with the following lighting requirements: a minimum average illuminance level of 100 lx to perform the construction activities in the work zone; a maximum average illuminance of 200 lx to avoid light spillage outside the work zone; a maximum allowed uniformity ratio of 6; and a maximum allowed glare (veiling luminance ratio) of 0.4. The lighting model proved to be capable of handling the multiple objectives of the lighting plan that optimized all four design parameters and met all the of the work zone lighting requirements, instead of applying the minimum standards only and by quantifying the glare produced by the lighting.

In 2005, El-Rayes and Hyari developed a new lighting design model called CONLIGHT. This model allowed practitioners to compare and assess various lighting plans and select a practical plan that meets all the lighting requirements of the specific project. The model consisted of two stages: the design stage and the implementation stage. In the design stage, various lighting designs were analyzed prior to the start of construction. In the second stage, CONLIGHT was implemented in three modules to quantify and assess the impact of the various lighting designs on three major lighting criteria, namely, illuminance level, uniformity of light, and glare produced. Figure 2.1 provides a conceptual view of the second stage of CONLIGHT, which shows the various design variables and output parameters.

The design variables were categorized into two major categories: lighting arrangement and lighting equipment parameters. Lighting arrangement parameters represent the various configurations of the lighting equipment used and included parameters such as number of equipment, number of luminaires used, luminaire positioning, mounting height, aiming angle, and rotation angle. The lighting equipment parameters provide information about the type of lighting equipment that is used and includes parameters such as type of lamp, lamp lumen output, and light depreciation. Using the aforementioned parameters as input, the average illuminance, lighting uniformity ratio, and the veiling luminance to quantify glare were computed.

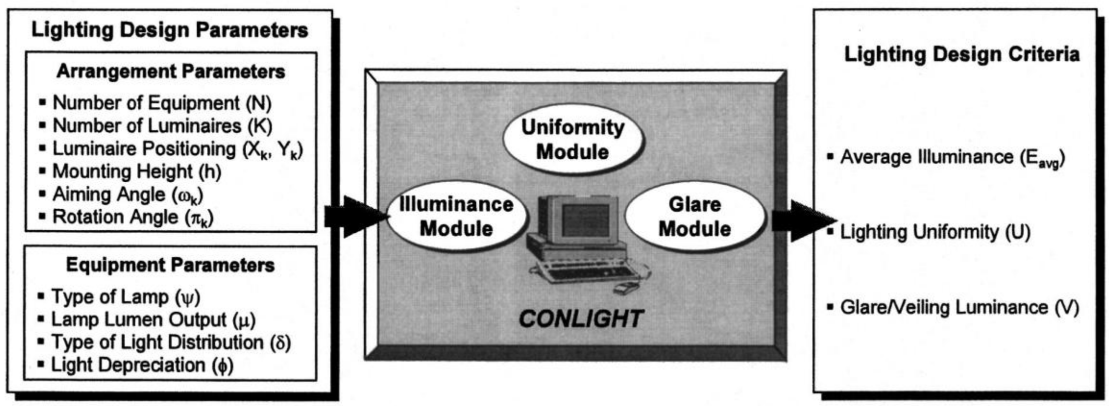


Figure 2.1: Conceptual Model of CONLIGHT (El-Rayes and Hyari 2005)

An application example was analyzed in order to validate the tool for a work zone 90m long and 6m wide. The lighting plan for this work zone required a minimum illuminance of 216 lx and a maximum uniformity ratio of 6 to ensure adequate and uniform lighting of the work zone. A maximum veiling ratio of 0.4 was to be ensured in order to minimize the glare effect for the workers and traveling public. The lighting equipment available to the contractor was three uniform lighting towers, with which he had to realize the above objectives. In order to compare the results of the CONLIGHT model with the actual site data, field experiments were conducted wherein the site was divided into several grids, and the illuminance, the uniformity ratio, and the veiling ratio were measured. The comparison of the results of the model and the actual readings indicated that an accuracy of 88% was achieved for illuminance, 86% for the lighting uniformity ratio, and 84% for the veiling ratio. This proves the efficacy of CONLIGHT as a valuable aid for nighttime practitioners for the design and testing of various lighting plans before their implementation.

Another tool called CONVISUAL was developed by El-Rayes and Hyari in 2006. CONVISUAL aimed to quantify the lighting requirements for various visual and construction tasks that were performed at night. The main objective of CONVISUAL is to provide a scientific framework for determining the lighting conditions required by workers for performing a construction activity satisfactorily and safely, by integrating concepts from construction engineering and vision science.

CONVISUAL is implemented in five phases, which are described as follows:

- Phase 1: Construction Work Breakdown Structure: An analysis of the operation to be performed is conducted and the operation is broken down into various activities and sub-activities in order to determine the visual and lighting requirements for each sub-activity.
- Phase 2: Identification of Critical Construction Details: In this phase, the tasks that are to be performed are analyzed in order to identify all the critical details that need to be seen by the workers while performing the task.
- Phase 3: Field Measurement of Visual Attributes for Construction Details: The visual attributes of the construction details are measured in this phase. The attributes measured are target size, contrast, and reflectance factor.
- Phase 4: Determining Required Task Luminance: In this phase, analytical visual performance models from vision science are used to identify the required minimum visual acuity level for each task, based on the visual attributes that were measured in the field. This minimum level is then adjusted by factoring in a comfort factor, which will enable the workers to perform their task comfortably.
- Phase 5: Recommending Illuminance Level: In this phase, the luminance level that is obtained in the previous phase is converted into an illuminance level, after factoring in the age of the worker and the reflectance factor of the target object so that older people can also comfortably perform their visual tasks.

The prototype of CONVISUAL was tested for a pavement marking operation and a required illuminance of 110 lx was obtained. This required illuminance was greater than those specified by the various DOTs and hence meets the standards specified. It proves that the CONVISUAL tool can serve as a tool for determining scientifically the lighting requirements and minimum illuminance levels that need to be provided on a worksite for conducting various tasks.

The lighting design tools discussed thus far are all quantitative models that provide the user with output on the various lighting attributes on a construction site. However, none of them allow the user to visualize the lighting arrangement and layout. Nor do they account for the dynamic nature of construction work zones, which involves the movement of traffic through the work zone. Nasser (2007) developed a lighting design framework, which enables the users to design, model, and visualize various lighting layout plans. A prototype of the software tool called NiteLite was developed using discrete event simulation software called STROBOSCOPE and a three-dimensional modeling and rendering software called 3DMax.

The framework of the tool (Figure 2.2) consists of the simultaneous development of two distinct modules: the work zone modeling module and the construction activity module. The work zone modeling module includes the 3D modeling of the work zone as well as the lighting plans. This can be developed using an easy-to-use drag and drop interface and allows the user to develop the model of the work zone by selecting common objects like cones, barriers, etc. from a menu and places them in the model of the work zone. The lighting plans include lighting equipment that are commonly used in construction work zones (e.g., lighting tower, equipment mounted lighting, etc.). This module also allows the user to select certain viewing planes of interest, at which the lighting conditions can be studied. The construction activity module involves building a discrete event simulation model of the construction activity that is being performed in STROBOSCOPE. Additionally, STOBOSCOPE also allows the incorporation of the traffic around the site, which will allow the user to accurately visualize the work zone conditions. MAXScript is then used to connect the data from STROBOSCOPE to 3DMax, in order to generate an accurate 3D simulation model of the work zone.

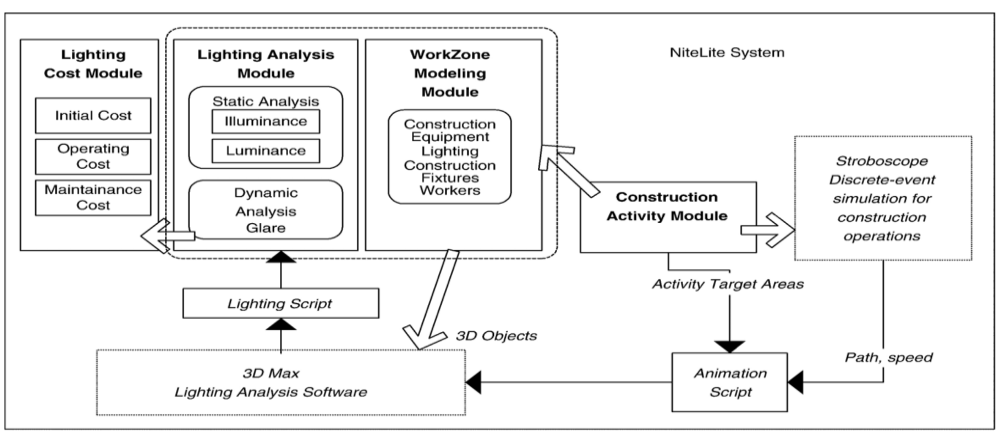


Figure 2.2: Framework of NiteLite (Nasser 2007)

Once this model is developed, lighting analysis can be done for the viewing planes of interest that were specified in the 3D model. Three important metrics are measured at each plane, including the uniformity ratio, the veiling luminance, and the glare rating. The results of NiteLite were verified by comparing them to actual measurements taken on the worksite. It was found that the average illuminance as calculated by NiteLite was 92.9% accurate, the lighting uniformity ratio was 93.0% accurate, and the veiling luminance ratio was 91.6% accurate.

NiteLite allows the user to analyze lighting on a site by varying the configuration of the lighting equipment and its layout. There is no need for complex calculations of the metrics, such as illuminance and the uniformity ratio, using many parameters such as the angle of luminaire and number of luminaires etc., as these can be understood from the iso-flux chart at points of interest. Also, the software allows the user to study the dynamic nature of lighting at a highway construction site by considering the movement of various objects in the work area as well as the movement of traffic through the site.

2.1.3 Summary of Lighting Tools

The tools discussed in the above sections described the research that is being undertaken in the area of lighting as it relates to nighttime construction work. While the automated DSS seeks to help the contractor choose lighting equipment, the CONLIGHT tool determines the value of average illuminance, the lighting ratio, and the veiling ratio based on the lighting equipment used and the layout adopted. CONVISUAL is a framework that can be used to determine the lighting requirements of various construction tasks by considering factors such as the visual acuity of the worker and the visual requirements of the task itself. NiteLite is a tool that provides a visualization of the work zone and has an easy to use graphical interface to aid in designing lighting layouts. Table 2.1 summarizes the studies in the area of lighting in highway construction work zones.

Table 2.2: Studies related to lighting in nighttime construction work zones

Researchers/ Year	Areas of Emphasis related to lighting	Research tools used, data collected and analysis preformed (Methodology)	Main findings and/or contributions	Shortcomings/ Aspects not considered in the study
José Holguín-Veras (2003)	Most of the lighting issues mentioned in this article are explored from the perspective of the effect that lighting has on workers in nighttime construction projects.	Interviews with workers and field surveys.	According to the researchers: -Proper lighting is an issue because, even in those cases in which lighting strictly adheres to specifications, "it is not the same as during the day." - There was agreement that nighttime work involves challenging conditions with not enough work space for proper equipment movement and inadequate lighting.	- No methodology for better lighting practices discussed. - Focus of the study was on the effect of nighttime work on the sleep patterns and social lives of the workers, not the effect of lighting on their safety and productivity.
Khalied Hyari and Khaled El-Rayes (2002)	Development of a DSS to optimize four lighting related parameters including illuminance, uniformity ratio, glare, and cost of lighting apparatus.	Non-Dominated Sorted Genetic Algorithm-II (NSGA-II), which is a pareto-based approach that handles multi-optimization problems.	The DSS provides lighting recommendations after optimizing the four objectives.	- Since it a multi-objective optimization problem, an increase in the importance of one parameter would lead to a decrease in the emphasis on another.

Table 2.3: Studies related to lighting in nighttime construction work zones (Continued)

Khalied Hyari and Khaled El-Rayes (2005)	Development of a construction work zone lighting tool called CONLIGHT that tests the performance of various lighting plans by considering requirements of the work zone.	The tool was implemented using C++ programming language.	The tool provides illuminance, uniformity ratio, and veiling luminance ratio values on the work zone for different lighting tools that are tested.	- A graphical user interface is absent, which makes testing of different plans cumbersome.
Khalied Hyari and Khaled El-Rayes (2006)	Development of a practical framework for identifying the lighting requirements for nighttime highway construction activities- Construction Visual Requirements, "CONVISUAL," and is designed to consider and quantify the varying lighting needs for different visual and construction tasks.	The framework is developed to determine adequate lighting conditions on site that enable workers to properly see and perform their tasks safely and with satisfactory quality. CONVISUAL determines the required luminance level for each construction activity based on its required visual tasks and the visual capacity of construction workers.	- Methodology for determination of required luminance level of lighting is presented. - Age of the operator as well as the lighting requirements for operations is factored in to get the required lighting. - Methodology uses an inter-disciplinary approach that uses concepts from Vision Science and Construction Engineering to provide lighting requirement for specific construction operations in nighttime construction zones.	- While the age of the worker is considered, other aspects could also be factored into the methodology. - Glare to motorists is not considered while calculating lighting requirements.
Khaled Nassar (2007)	Development of a tool that aids in visualizing the lighting requirements of a nighttime construction work zone.	The tool uses 3D Max to render the layout of the construction work zone and the lighting layout. It also uses Stroboscope to model the construction activity.	- Provides a realistic and physical based model for work zone lighting. It takes the luminance values and calculates the uniformity ratio and glare rating at recurring times during the simulation.	Developing the 3D work zone model takes too much time and reduces the tool's effectiveness for making decisions.

It can be seen how successive tools and frameworks build on work that has been done previously in the lighting area. However, while these tools do help in determining the cost of lighting strategies, none of them describe the effect of lighting on the other aspects of nighttime construction, such as safety or productivity. Research is need that looks into the relationships between lighting and other aspects of nighttime construction such as productivity and safety.

2.2 Previous Studies in Nighttime Productivity

The productivity of the operation dictates the time taken to complete the project, which also has a major impact on the cost of the operation. However, the productivity of nighttime construction is an area that has not received a lot of attention from researchers, which could be due to the fact that the primary reason for performing the work at night is to reduce the traffic congestion during the daytime, and not necessarily to increase productivity and lower costs. Even so, an understanding of the impact of nighttime work on the construction operation could help during the planning phases of the project and also aid in making the decision to work at night, given the option to do so. This subsection discusses the previous work that has been conducted on productivity as it relates to nighttime construction.

Ellis and Kumar (1993) analyzed eight different activities in Florida in order to determine the influence of nighttime operations on construction cost and productivity. The activities that were focused on were chosen on the basis of their presence in typical daytime and nighttime highway projects, their significant contribution to project costs, and their large quantity. The following were the activities that were selected for comparing the costs of daytime and nighttime operations:

- Removal of existing pavement
- Regular excavation
- Bituminous material-prime coat
- Bituminous material-tack coat
- Milling of existing asphalt pavement
- Class I concrete-miscellaneous
- Type S asphalt concrete-including bitumen

- Asphalt concrete friction course-including bitumen

Costs for these activities were collected from all the projects completed by the Florida Department of Transportation in the year 1990. The data were then subjected to statistical and correlation analysis to quantify the difference in unit costs between daytime and nighttime projects. The results obtained indicated that seven out of the eight activities (all except Class I Misc Concrete) had lower mean unit costs during nighttime construction, which indicated a trend that it is less expensive to work at night than during the day. However the results cannot be conclusive as the standard deviations were very high, which proved that the unit costs were dependent more on project-related conditions than on the time of day the work was completed.

In order to compare the productivity of daytime and nighttime operations, productivity data were obtained for both nighttime and daytime projects. Data for daytime projects were obtained from another study by the University of Florida for FDOT and nighttime production data were obtained from a construction project in progress on I-95 in St John's County in Florida at the time of the study (1990). Data were collected for activities, namely, plant-mixed surface and milling of existing pavement. Statistical analysis was performed on the data using t-tests on independent samples of data. The tests failed to confirm any significant difference between nighttime and daytime productivity levels. Project to project variations occurred because of project-specific conditions.

Another study that provides some insight into the comparison of daytime and nighttime construction productivity was conducted by Dunston and Mannering in 1998, which sought to evaluate and compare the strategy of closing a single direction of freeway traffic over the entire weekend, with the customary practice of frequent night closures of one or two lanes. The project which was used as a case study for this purpose was the reconstruction of an approximately 5.5-mi. (8.85-km) section of Interstate 405 in the state of Washington (from Coal Creek to Sunset Boulevard), which was completed over two weekends in 1997. The contract specified a 0.15 feet Asphalt Concrete Pavement (ACP) Class A overlay on the pavement. The productivity of the operation was used as an indication of the cost of the project and was compared to a similar I-5 project (C4250) from the Nisqually River to the

Gravelly Lake Interchange, also in Washington. The I-5 project overlay was constructed with nighttime closures during the 1993 and 1994 paving seasons. It was found that the shift production rate of the I-405 project was 350 tons per hour, which was 23% greater than the productivity experienced in the I-5 project, which used a mass transfer device. The higher productivity could be explained by the fact that since construction was allowed to continue uninterrupted for the entire weekend of the I-405 project, valuable setup and shutdown time were saved, resulting in greater productivity.

This study focused on assessing the impact of the different closure policies on construction quality and costs and the impacts on the road users, but did not intend to compare nighttime and daytime productivities, such as Ellis and Kumar (1993). However, the data collected during the course of this research proved to be very useful in the comparison of nighttime and daytime construction. Since the weekend closure afforded the construction crews a 24-hour workday, the productivity data can be separated to get the productivity experienced during the day and during the night. Tables 2.3 and 2.4 provide a comparison of the daytime and nighttime productivity levels that were achieved during the I-405 project.

Table 2.4: Productivity of day operations for the I-405 project (Dunston and Mannering 1998)

Daytime Shifts				
Day	Paving Direction	Time for Mainline Paving Work (hrs)	Production [tons (tonnes)]	Rate (tons/hr) (metric tons/hr)
Saturday	South	12	4955.85 (4495.0)	412.98 (374.6)
	North	10.5	4181.65 (3792.8)	398.25 (361.2)
Sunday	South	2.5	849.45 (770.4)	339.78 (308.2)
	North	0.5	167.1 (151.5)	334.20 (303.0)
Average Daytime Productivity:				371.30 (338.7)

Table 2.5: Productivity of night operations for the I-405 project (Dunston and Mannering 1998)

Nighttime Shifts				
Day	Paving Direction	Time for Mainline Paving Work (hrs)	Production [tons (tonnes)]	Rate (tons/hr) (metric tons/hr)
Friday	South	10.5	3716.5 (3370.9)	353.95 (321.0)
	North	11.25	4105.45 (3723.6)	364.92 (330.9)
Saturday	South	11.5	3185.58 (2889.3)	277.00 (251.2)
	North	11	3498.35 (3173.0)	318.03 (288.4)
Average Nighttime Productivity:				328.48 (296.9)

As shown in Table 2.4, the average productivity experienced on the project during the day was 371.30 tons/hour, which was 13% higher than the productivity that was acheieved for the same project during the night. An issue that prevents the results from being conclusive is the fact that the data for the project was collected from the project time sheets. Since this data are particular to this project alone and were collected under the conditions existing at the project site at the time, it cannot necessarily be held to be valid while extrapolating it to other similar projects, which might be performed under very different conditions.

Colbert (2003) conducted an independent research study with the aim of providing a quantifiable comparison of nighttime and daytime productivity for heavy highway construction projects. The research also investigated the safety approaches to nighttime construction operations and their costs. The data for calculating the productivity levels obtained from the time sheets, which were maintained by the contractor for the project. The time sheets contain very important information about the project regarding the type of work performed, the amount, the number of workers, and the time spent on a particular operation, etc.

Productivity was calculated and expressed in terms of units per man-hour in order to permit the comparison of productivity across different projects which utilize different resources. The productivity data calculated from the time sheets were compared to the productivity that was estimated using empirical formulae to see if there was a gain or loss of productivity during the daytime and nighttime operation. In order to compare between the daytime and nighttime productivity levels, a combination of statistical methods of analysis (e.g., hypothesis testing, analysis of variance and confidence intervals) was performed. Hypothesis testing is a method that determines how well the experimental data support the assumed hypothesis, which in the case of this research, is that there is no difference in the productivity levels of nighttime and daytime operations. The magnitude of the difference in the productivity of daytime and nighttime operations can be determined using the analysis of variance and confidence interval.

Two different construction operations were analyzed in this research – earthwork moving and asphalt paving operations. The hypothesis analysis for both the projects resulted in the rejection of the null hypothesis, indicating that the data collected showed that there was a significant difference in the daytime and nighttime productivity levels for the two projects. The first earthwork moving operation was the US-60 Superstition Freeway project between Tempe and Mesa, Arizona. This project was conducted in 2002 and data were collected for 30 day shifts and 30 night shifts between July and August of 2002. The two shifts for this project were between the hours of 6:00 am to 4:30 pm and 7:00 pm to 5:00 am. An analysis of the data proved that the nighttime productivity was 96% higher than that experienced during the day. One of the reasons attributed to this large variation was that the project had different operational objectives for day and night. It was planned to perform most of the mass excavation work at night when there was less traffic, and focus on butting the ground to the proper level and set it up for the night work during the day.

The second earthwork project that was performed was the Interstate 70 Fast Track project, performed in 2003 in Indianapolis, Indiana, for which work was conducted in two shifts between 7:00 am to 5:00 pm and 7:00 pm to 5:00 am. In this project, it was found that the dayshift outperformed the night shift, which was due to the fact that the project was conducted in Indianapolis during a very harsh winter, and most of the nighttime work was done in temperatures well below freezing. Also, a lack of lighting in the "cut" portion was observed, and that the "cut" portion had a very steep grade, both of which could adversely affect productivity. For earthwork operations, it is seen that two different projects provide two contradicting answers to the question of whether working at night improves or decreases construction productivity. This result is due to the fact that each project is unique and has its own set of variables, which dictate project cost and productivity.

Two projects, both in the Mendota California area were studied to analyze the asphalt paving operation and compare the daytime and nighttime productivity. It was found that there was no significant difference in the productivity levels of daytime and nighttime operations for both these projects, given the data collected. The first project consisted of paving a five-mile section of Highway 180 from the Union Pacific Railroad crossing to the Four Mile Slough Bridge, and the second project involved the completion of a five-mile stretch of pavement from the Four Mile Slough Bridge to Yuba Avenue. For the Highway 180 project, data were collected for 22 day shifts and seven night shifts between August and December of 2001. It was found that the day-shift productivity averaged 12.9 tons/MH over the timeframe considered and the night-shift productivity averaged 15.1 tons/MH. The next asphalt paving project was the paving of a five-mile section of Highway 180 near Mendota, California. For this project, data were collected for 14 day shifts and 10 night shifts between September and October of 2002. It was found that the day-shift productivity averaged 17.0 tons/MH over the timeframe considered and the night-shift productivity averaged 15.6 tons/ MH. From this research study, it is seen that there is a significant difference in the daytime and nighttime productivity levels of earthwork moving operations but was not the case for asphalt paving operations. Table 2.5 summarizes the previous research done in the area of nighttime highway construction.

Table 2.6: Studies done in nighttime construction

Researchers/ Year	**Area of Emphasis**	**Location and Time of Research**	**Tools Used and Reasons for using these tools**	**Issues/Metrics Analyzed**	**Analysis Performed**	**Main Findings**	**Shortcomings and Issues Not Considered**
Donn E. Hancher Timothy R. B. Taylor 2007	Nighttime construction issues	Research was conducted among state DOTs nighttime construction practitioners in Kentucky in the year 2000.	Surveys, questionnaires and interviews were used to determine issues faced by nighttime construction practitioners.	The various factors while working at night were analyzed and a new form of lighting technology, Airstar Balloon Light was discussed.	Surveys were conducted to determine the issues of nighttime construction, its effect on quality and productivity.	The main issues faced during nighttime construction were identified and ways to improve construction and public awareness were provided.	It is purely qualitative and does not quantify any aspect of nighttime work vis-à-vis daytime construction.
Ossama Abd Elrahman Robert Perry 2008	Nighttime construction operations	Performed by Transportatio n Research and Development Bureau in 2008.	A synthesis of the past studies in nighttime construction was presented.	The various parameters that affect nighttime construction were analyzed.	The paper synthesized the findings of previous research in nighttime construction.	A framework for evaluating and quantifying the impacts of nighttime construction was provided.	It does not have any case study or actual data.
Ralph D. Ellis Ashish Kumar 1993	Influence of nighttime operations on construction cost and productivity	The research focused on eight common operations in Florida in the year 1990.	Statistical analysis was used for comparing cost productivity of daytime and nighttime operations.	The effect of nighttime construction on cost and productivity was analyzed.	Productivity and cost data for daytime and nighttime operations in Florida were collected.	Unit price was found to be lower for nighttime work than for daytime work.	Data collected is too limited to arrive at conclusions regarding productivity.

Table 2.7: Studies done in nighttime construction (Continued)

Researchers/ Year	**Area of Emphasis**	**Location and Time of Research**	**Tools Used and Reasons for using these tools**	**Issues/Metrics Analyzed**	**Analysis Performed**	**Main Findings**	**Shortcomings and Issues Not Considered**
Phillip S. Dunston Fred Mannering 1998	evaluation of the full weekend closure strategy for highway reconstruction projects I-405	The research focused on a roadway project in Washington during 1997.	Statistical comparison of construction productivity and quantitative assessment of smoothness, densities, etc.	The feasibility of closing all lanes in a single direction instead of the customary nighttime operations was analyzed.	Productivity of I 405 project, done during the weekend was compared with a I-5 nighttime project.	The productivity on the I-405 project was approximately 21 percent higher than that of the I-5 nighttime project.	Study does not specifically compare nighttime and daytime operations.
Douglas Colbert 2003	Productivity and safety implications for night-time construction cperations	The research focused on earthwork moving projects in Mesa, AZ and Indianapolis, IN in 2003 and asphalt paving operation in Mendota CA in the year 2001.	Combination of hypothesis testing, analysis of variation, and confidence intervals was performed on time sheet data.	By analyzing operations that were conducted during both the day and night, conclusions could be drawn about the productivity and safety of nighttime construction.	Statistical analysis to determine presence of significant difference between nighttime and daytime productivity.	No significant difference found for asphalt paving but earthwork operations experienced increased productivity in some cases or decreased productivity in others.	Only time sheet data of completed project were considered, not taking into account other factors.

2.3 Link between Lighting and Productivity

The effect of the illuminance levels present on the productivity of workers has been studied extensively in office (Hedge et al 1990, Boyce et al 2003) and industrial settings (Juslen 2006). These studies were carried out in settings where the productivity of the worker was linked directly to his/her visual performance, alertness, and motivation. The effect of lighting on the productivity of workers in outdoor settings, such as construction sites, has not been given enough attention by previous researchers.

In the studies conducted by Juslen on several assembly units in warehouses in Europe, it was concluded that the quality and level of lighting available in the work space does influence the productivity of the workers if that productivity is linked with human performance. On the basis of a literature review focusing on biology, light, and psychology, Juslen developed a model that could be used to describe the effect of a change of lighting on human performance and productivity, which in turn affects the profitability of an operation (Juslén and Tenner, 2005). This link or change is caused by a combination of mechanisms, including visual, photo-biological, and process of change mechanisms. These mechanisms are discussed below.

Lighting affects the visual performance, comfort, and ambience of the workers and this can affect their productivity. Also, it influences the way that people see and perceive each other, which can impact teamwork and hence productivity. Light has an effect on the biological clock which controls the circadian rhythms and also stimulates physiological processes that can affect productivity. The change process mechanism describes the effect that a change in lighting will have on the morale and satisfaction of the workers. Improving the lighting and paying attention to the complaints of the workers has an effect on the wellbeing and motivation of the employees. Juslen also states that being able to better see the work that is being done under better lighting leads to better appreciation of the work that is done and hence boosts the job satisfaction of the employees, which in turn could motivate them to be more productive in the workplace. A “halo effect” is also described, wherein the belief in the superiority of new technologies could improve the productivity of workers. While the visual and photo-biological effects last for a long time, the change process mechanism comes into play only when there is a change in the lighting levels and, with time, this effect could wear off. More lasting productivity improvements are observed when workers are given the autonomy to control the lighting in the workplace to a configuration with which they are comfortable.

Five case studies were carried out by Juslen in assembling units in various countries in Europe to determine the effect of illuminance on the productivity and the number of errors made in the assembly units, with the objective of describing the effects of a change in illuminance on the productivity of the worker in a real industrial environment, based on the mechanism model described earlier. The case studies aimed to minimize the effect of the change process mechanism by conducting the studies over a long period of time as this effect would quickly wear off. Also, since the studies focused on the manual assembly of electronic items, the effect of interpersonal relationships was not investigated during the course of the studies.

In all the studies, the productivity of the workers was measured under different illuminance conditions and ANOVA (Analysis of variance, $r<0.05$) was used to determine whether there was a significant difference in productivity in four out of five cases. No statistical method was employed in the final study. In three of the case studies the results were compared to those of a reference group. Table 2.6 summarizes the key findings of the five case studies.

Table 2.8: Summary of case studies (Juslen 2006)

Work, Location	Lighting change	Methodology used	Result of study
Luminaire assembly, Finland	A new overhead controllable lighting system was installed, which allowed users to set the illuminance between 100 lx to 3000 lx.	The assembly time of the test group was compared with the productivity of a reference group provided with a workplace illumination level of 700 lx.	The productivity of the test group increased by 4.6% when measured against the reference group and there was a weak statistically significant correlation between illuminance and the productivity.
Luminaire assembly, Germany	A new controllable task lighting system was installed, allowing users to adjust the illuminance in the range of 100 lx to 900 lx. The illumination was selectable as a color temperature of 3500 K or 4400 K.	The users could modify the level of illuminance but not the color temperature. The color temperature was varied between high and low.	It was found that the higher color temperature had a positive effect of 5.7% on productivity, while the illuminance did not have a significant effect.
Electronics assembly, Netherlands	The illumination levels at the assembly desks were re-set for different shifts to a level of either 800 lx or 1,200 lx	The productivity (assembly time and number of errors) was measured for each shift for a given illuminance level.	The productivity was found to have increased by 3% during the day shift and 7% during the night shift with increased illumination.
Machine maintenance, Netherlands	A lighting system that set the level of local lighting set alternately to 50 lx or 1,700 lx on a weekly basis was installed.	The repair time on the machines was recorded as representative of the productivity levels of the employees.	The rates of absenteeism of the test group were 17% lower than that of the reference group. The productivity was found to have increased by 3%.
Luminaire assembly, Netherlands	A local illumination system was installed that increased the illuminance from 500 lx to 1,050 lx.	Productivity was measured for the test group and compared with a reference group before and after the change.	The productivity was found to have increased by 5.5% after the lighting change.

From the studies described above, it can be concluded that an improvement in the lighting provided in the workplace can improve a worker's productivity. It was also shown that the productivity of a person increases with an increase in the illuminance. However, it is difficult to quantify the effect that lighting has on the performance of the people as it depends very much on the type of operation being performed, the visual acuity of the people performing the work, the type of change that is brought about. However, the studies do show that an improvement in lighting quality and illuminance has a positive effect on the performance of the workers.

2.4 Chapter Summary

A variety of lighting design technologies were discussed in this chapter and it can be seen how these technologies build upon previous research efforts to improve the design of lighting in construction work zones. While, there are many methods available for the design of lighting, the effect of a particular lighting arrangement on the operation is an aspect of nighttime construction that is yet to be studied. Apart from lighting, previous studies in nighttime productivity has also been discussed. It can be seen how using data from time sheets has yielded data that are very project-specific, depending very much on the conditions existing at the site, which has led to the lack of any conclusive results regarding the effect that working at night has on the productivity of the operation.

This study investigates the perceptions of nighttime highway construction workers and seeks to develop a framework that can be used to quantify and compare the impact of different lighting scenarios on the productivity of the operation. The framework will build upon concepts that have been studied by previous researchers and use them to form a link between the various aspects of nighttime construction. Apart from studying the past research work that has been done in nighttime construction, hands-on experience working in a highway construction work zone at night would be helpful to understand the factors and conditions that prevail in nighttime work zones from the perspective of the people who know it best - the workers.

CHAPTER 3. RESEARCH METHODOLOGY

This chapter provides a description of the methods and analysis used in this research to study the impact of lighting on the safety and productivity of nighttime highway construction operations, focusing on asphalt paving operations. The first section discusses the general research framework and methodology followed during the research. The second section identifies the factors that affect lighting in nighttime highway construction work zones. The third section discusses the site visits that were conducted for the research. The various methods used to collect data for determining the perception of workers regarding the impact of lighting on their safety and productivity as well as the collection of data required for developing the simulation model of the paving operation will be described. The method used to gauge the perception of the workers using an ordered probit model then will be discussed, as well as the process used to develop the simulation model and the animation of the paving operation and the lighting tool used to calculate the illuminance and uniformity of different lighting configurations.

3.1 Research Framework

The research methodology (shown in Figure 3.1) can be broadly classified into four main phases. The first phase involves identification of the research questions and establishing the basis for the study, consisting of a review of the current state-of-the-practice and research in the area of nighttime construction with a focus on the lighting of nighttime highway construction work zones. Previous tools that have been developed to analyze the lighting of work zones are also studied along with the identification of factors that affect the safety and productivity of nighttime construction operations.

The second phase is the data collection phase, where the data for determining the perspectives of the workers regarding the impact of lighting on their safety and productivity and for the development of the simulation model are collected. These data were collected through the administration of surveys to nighttime construction workers and site visits, where an asphalt paving operation was observed and duration data for the activities involved were collected. Data were also gleaned from interactions with the workers and operators during the site visits.

The third phase consists of the data analysis phase, wherein two different types of models were created. Two different econometric models for the analysis of the workers' perceptions of the impact of lighting on their safety and productivity were created. These models help in providing a descriptive and statistical analysis of the factors related to lighting that affect worker safety and productivity. A lighting tool was developed which uses a graphical user interface to calculate the illumination and uniformity ratio of different lighting configurations using the point-by-point method (El-Rayes and Hyari 2005).

In order to quantify the impact that lighting conditions in the work zone have on the productivity of the operation, a multivariate regression model was constructed, which has the ratio of nighttime and daytime productivity for different activities as the dependent variable. The independent variables indicate the presence of different lighting sources in the work zone. The ratio of nighttime and daytime productivity levels are calculated using the equation obtained for different lighting scenarios and then incorporated into a discrete event simulation model to obtain the operation productivity under different lighting scenarios. The discrete event simulation model and an animation of the paving operation was developed using the discrete event simulation software STROBOSCOPE (Martinez 1996) and Vita2D (Martinez 2009). The development of the discrete event simulation model also provided the researcher with a systematic approach to collecting the data and studying the operation. Factors that affected the performance of activities were understood during the course of the site visits and the development of the model. This also helped in the preparation of the worker surveys. The results of the simulation model and the animation of the paving operation were finally verified and validated by Subject Matter Experts (SMEs), who are either workers or engineers working in companies that perform nighttime paving operations.

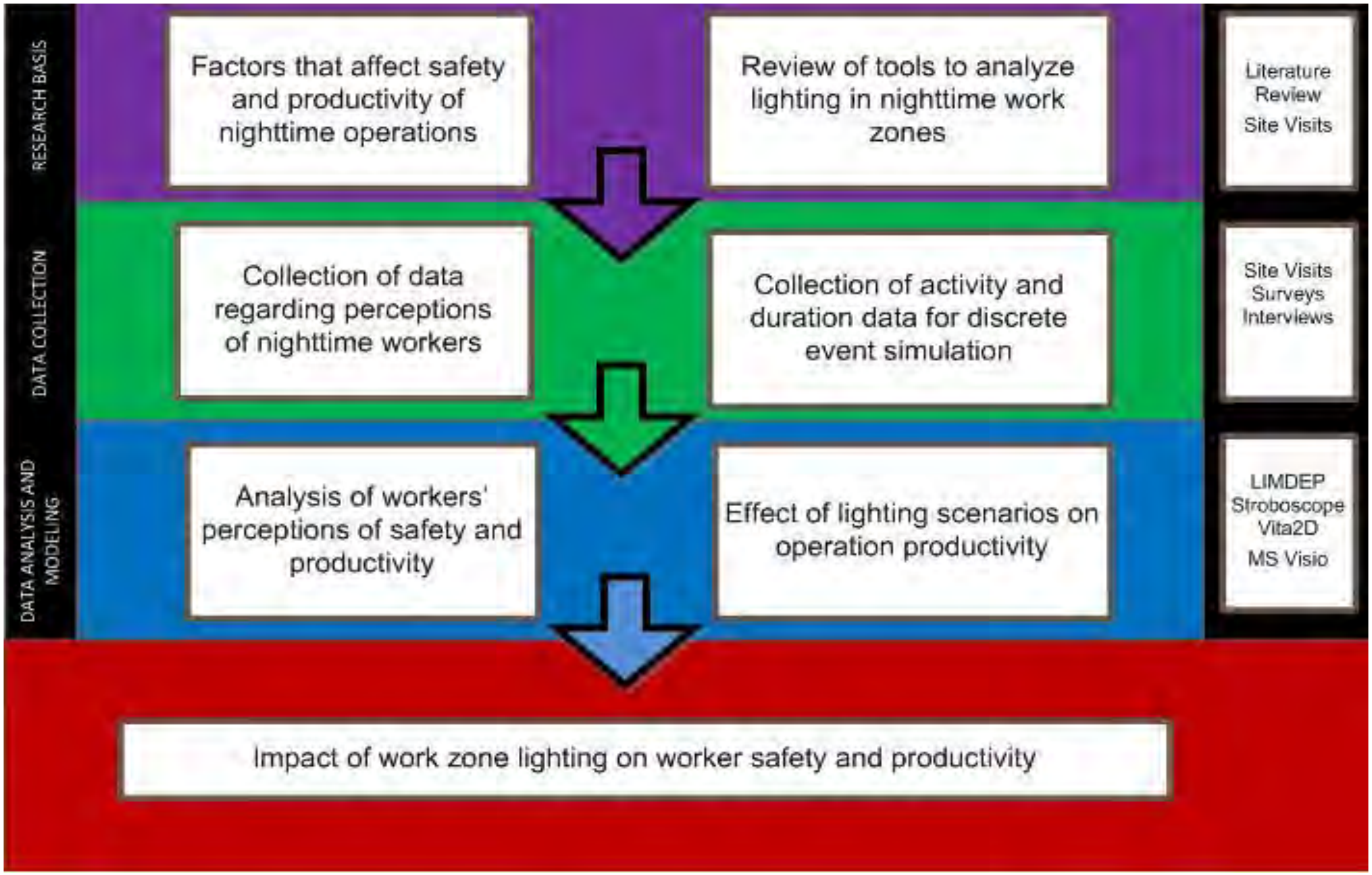


Figure 3.1: Research Methodology

3.2 Identification of Factors Affecting Lighting in Nighttime Construction Work Zones

A literature review was conducted to identify the parameters that determine the quality and effectiveness of a lighting plan and the factors that affect lighting in a construction work zone. Currently, contractors refer to non-highway construction standards and regulations and state DOT requirements for guidelines on the illumination requirements of their tasks. These standards are not always in consensus (El-Rayes et al. 2003; Hyari 2004) and leave much of the lighting planning to the discretion of the contractor. A scientific tool for calculating the visual requirements of a construction operation are needed which takes into account all the factors that affect the lighting requirement of the work zone. As discussed in Chapter 2, these factors have been categorized into four different classes: human factors, environmental factors, task-related factors, and lighting factors. Based on these four factors, it is possible to adjust the minimum requirement of the illuminance and adjust it based on the visual acuity of the worker and the weather and environmental conditions existing at the site. This new target illuminance will be a closer approximation to the actual illumination that is provided on the site. A tool that considers these factors was discussed in Chapter 2.

Factors that affect the outcome of the lighting plan depend on the type of the luminaires chosen and the design of the lighting layout plan (El-Rayes and Hyari 2002). The factors are listed below:

- Lighting equipment selection
- Types of luminaires
- Lamp lumen output
- Mounting height
- Lighting towers positioning
- Aiming angle of luminaires
- Lighting tower rotations

Other factors that determine the visual requirements of an activity that is performed at night and affect the lighting on a site were explained in Chapter 2. These factors could be broadly classified under the following groups:

- Environmental factors
- Human factors
- Lighting factors
- Task-related factors

The above factors were taken into consideration while designing the survey that sought to evaluate the perceptions of nighttime workers on the effectiveness of the existing lighting conditions on their safety and productivity.

3.3 Visits to Nighttime Highway Construction and Maintenance Sites

The primary purpose of site visits was to observe the paving operation conducted at night and to collect data related to the productivity and lighting of the operation. The site visits also provided the researchers with an opportunity to interact with the site supervisors and workers and to learn about the particular activity from their experience. Data were collected by interviewing the workers and by measuring the time taken to complete different tasks in the paving operation.

Seven site visits were conducted between May and October of 2009 to construction and maintenance projects located on Indiana interstates, six of which were construction projects and one was a maintenance project. Table 3.1 describes the key features of the sites.

Table 3.1: Site visits conducted

Date of visit	Project Name	Location of site visit	Activity observed	Equipment/ tools in use
May 2, 2009	INDOT Maintenance	I-70 N, Mile marker 271	Patching concrete pavement	Concrete truck, Jack hammer, Blower
July 6, 2009	HMA overlay on I-65	I-65 S, Between mile-markers 152 and 150	Milling and paving of shoulder with 1.5" asphalt coat	Wirtgen W2000 Milling Maching with one balloon light ; Paver: Roadtec RP150 with 2 balloon lights; Material Transfer: Roadtec SB-2500C with 1 balloon light; Roller:2 Ingersoll Rand DD118
July 9, 2009	HMA overlay on I-65	I-65 S, Between mile-markers 150 and 148	Milling and paving of shoulder with 1.5" asphalt coat	Wirtgen W2000 Milling Maching with one balloon light; Paver: Roadtec RP150 with 2 balloon lights; Material Transfer: Roadtec SB-2500C with 1 balloon light; Roller:2 Ingersoll Rand DD118
July 15, 2009	HMA overlay on I-65	I-65 S, Between mile-markers 146 and 144	Placing the previously milled asphalt outside the shoulder	Front End Loader
August 5, 2009	HMA overlay on I-65	I-65 S, Between mile-markers 144 and 142	Base repair	
August 25, 2009	HMA overlay on I-65	I-65 N, Between mile-markers 142 and 144	Milling and paving of shoulder with 1.5" asphalt coat	Wirtgen W2000 Milling Maching with one balloon light; Paver: Roadtec RP150 with 2 balloon lights; Material Transfer: Roadtec SB-2500C with 1 balloon light; Roller:2 Ingersoll Rand DD118
October 31, 2009	HMA overlay on I-69	I-69 N, Between 106th and 116th Street	Milling and paving of shoulder with 1.5" asphalt coat	Wirtgen W2000 Milling Maching with one balloon light; Paver: Roadtec RP150 with 2 balloon lights; Material Transfer: Roadtec SB-2500C with 1 balloon light; Roller:2 Ingersoll Rand DD118

The first site visit was conducted to observe a maintenance operation of patching concrete pavements by a nighttime crew. This crew is a dedicated nighttime crew that mainly performs maintenance activity like concrete patching and bridge deck repair. The crew works at night throughout the year to maintain and repair state highways in and around Indianapolis, Indiana.

On the night that the site visit was conducted, the crew was performing bridge deck repair and concrete patching on I-70. The concrete patching operation (see site layout in Figure 3.2) is described as follows (INDOT 2008). Areas where the concrete is to be replaced is first determined and marked for removal. Some areas on the pavement which need to be replaced can be identified visually, such as pot holes and areas with spider-web cracking. Areas where the defects are not obvious on the surface are identified by sounding the concrete, wherein a heavy chain or a section of rebar is bounced on the surface of the concrete. Unsound concrete will produce a dead sound when sounded. This aids in the identification of areas to be patched in a concrete pavement. Once the area of concrete to be replaced has been identified and marked, the perimeter of the area is sawed a minimum of 1 inch in depth. After this, the unsound concrete from within the perimeter is removed using a hand-held jack hammer, operated at a maximum of 45 degrees to the surface of the pavement. This procedure prevents undue stress and damage to the underlying concrete, while removing the unsound concrete from the surface. The process of sounding is repeated on the remaining concrete to determine whether all the unsound concrete has been removed. Once the unsound concrete has been removed using the jackhammer, the dust and debris is cleared from the patch using a compressed air jet. Once all the debris has been removed and the patch is cleaned, an epoxy adhesive is applied to the hole, taking care to prevent the mixture of the adhesive and the dust from the debris. After coating the hole with the adhesive, fresh concrete is placed and vibrated to ensure compaction. The freshly placed concrete is then finished by hand. A layer of curing compound is sprayed on the concrete soon after the finishing work is complete.

The minimum recommended illumination level for performing this activity is 108 lx (Ellis et al 2003). The lighting fixtures used in the operation were a trailer mounted lighting tower, consisting of four incandescent lamps, each 700W. The light from the trailer mounted lights also served to alert the traveling public of the presence of the work zone. Permanent lighting was available in the vicinity in the form of high mast lighting towers. The following figure shows the layout of the site and the lighting equipment used. It also indicated measurements of illuminance values taken at various points in the site.

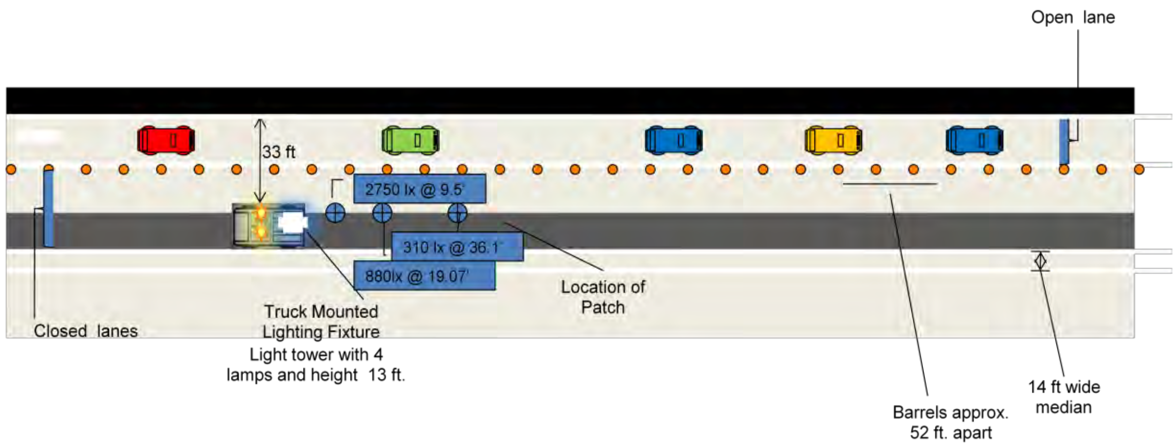


Figure 3.2: Layout of the concrete patching site.

The second project that was visited was a paving operation that was conducted by Milestone LLP on Interstate-65. The project involved paving both lanes and the shoulder in both directions on I-65, on a 10-mile stretch of the highway between mile marker 142 and 152. Due to current interstate lane closure policies, any maintenance work that is conducted can only be done at night, between the hours of 9:00 pm and 6:00 am, which includes the set up time for the site and traffic control devices such as cones and barriers. The lane to be paved that night could be closed only at 9:00 pm and it had to be reopened to the traveling public at 6:00 am. Failure to do so would entail a heavy fine for the contractor.

The functional objective of the project was to replace the existing surface of the road with a new coat of Hot Mix Asphalt (HMA). A description of the main steps involved in the process is provided below:

a) Milling of the existing pavement: The existing surface of the road is removed with the help of a milling machine and loaded onto waiting dump trucks. The milling machine consists of a rolling drum at its bottom, which is fitted with several rows of sharp teeth. The thickness and the width of the pavement to be milled can be adjusted by the operator. The trucks then haul the milled debris to an asphalt plant where it is dumped. Usually about five to seven trucks, each of 20-ton capacity, are used for transporting the debris to the dump-site in order to ensure that the miller does not have to stop milling to wait for a truck. This milling can be recycled to make asphalt and is also used to lie along the shoulder of the road. Milling is an activity for which lighting is a critical component, as the surface that is milled must be in alignment with the road. Hence, the miller has lighting fixtures mounted on it. About once during a work shift, a water truck is used to replenish the water that is used to cool the grinding drum. Figure 3.3 shows the milling machine filling up a truck with the milled asphalt.

Figure 3.3: Milling of the asphalt pavement (photo taken during Site Visit # 3, I-65 S Mile Marker 150 on July 9, 2009)

b) Cleaning of the milled surface: Once a certain distance of the road to be paved is milled, a sweeper with a broom attached to it follows up to clean the milled surface of the debris. The distance by which the miller leads the sweeper is based on the judgment of the operator of the sweeper and it is usually between 100 to 200 feet. Two passes of sweeping are performed before the tack coat can be applied. Lighting is not a critical issue for the cleaning activity and no extra lighting fixtures are mounted onto the sweeper. Figure 3.4 shows the sweeper brushing up the pavement after the miller has milled the pavement.

Figure 3.4: Sweeping the debris after milling is complete (photo taken during Site Visit # 3, I-65 S Mile Marker 150 on July 9, 2009)

c) Tacking of the cleaned surface: The activity that follows the cleaning activity is the tacking activity. This involves laying the cleaned surface with a layer of tack coat. The tack coat is applied to ensure a strong adhesive bond between the old surface and the freshly laid coat of hot mix asphalt. The tack coat is laid using a tacking truck, which has a row of nozzles at its rear end, through which the coat is applied, while the truck moves along the pavement at a constant speed. Lighting is not a critical issue for this task as the tack coat is applied only along the path on which the truck moves, which is well illuminated by the headlights of the truck. No extra lighting equipment is mounted on the truck.

d) Once the tack coat is laid, the pavement is ready to be surfaced with hot mix asphalt. The equipment that is required for this activity is a screed paver and a material transfer vehicle and dump trucks. Fresh asphalt that is made at the asphalt plant is transported to the worksite in 20-ton dump trucks. The hot mix asphalt is dumped into the hopper of the material transfer vehicle, which has a conveyer that transfers the asphalt to the paver, which follows the material transfer vehicle. The paver then lays the asphalt onto the tacked surface. The thickness and the width of the coat of asphalt that is being applied can be adjusted by the operator of the paver by adjusting the screed of the paver. It is desirable to ensure that the paver does not have to stop, as this would cause the formation of joints in the surface of the road, which are critical points. Hence, the number of trucks used in the operation must be enough to ensure a steady supply of asphalt to the paver. Once the surface of asphalt is laid, a crew member, walking behind the paver visually checks to ensure that the proper thickness of asphalt has been laid. Another important factor to be considered while paving is the slope of the coat applied. Lanes slope away from the center line of the road in order to drain the water off the roads during rain and to alert drivers while they are changing lanes. Hence the slope is also checked to ensure that the paver is laying the coat correctly. The operator of the paver must also ensure that the coat being applied is aligned with the road. Hence, lighting is a critical component for the paving activity and lighting fixtures are mounted on the paver. Figure 3.5 shows the paver laying the HMA coat on the pavement.

Figure 3.5: Laying the HMA coat on the pavement (photo taken during Site Visit # 3, I-65 S Mile Marker 150 on July 9, 2009)

e) Rolling and compaction of the asphalt: After the asphalt coat is laid, it is compacted by two rollers that follow each other. Compaction is necessary to ensure that the asphalt achieves the required density. Lighting is a critical component for the rolling activity and equipment-mounted lighting was present on the rollers. Figure 3.5 shows the roller compacting the freshly laid HMA coat.

Figure 3.6: Compacting the HMA coat (photo taken during Site Visit # 3, I-65 S Mile Marker 150 on July 9, 2009)

On two of the site visits (July 15, 2009 and August 5, 2009), operations other than the mainline paving operation were observed. They were:

- Base repair: This activity was conducted along a stretch of road before paving it. Weak spots along the pavement were identified and repaired by patching it with asphalt. The activity is very similar to the mainline paving activity described earlier, with the main difference being that the repair work was not a continuous operation, but was instead done in only certain sections.
- Laying the milled asphalt along the shoulder. On certain nights, the previously milled asphalt was transported back to the site and laid along the shoulder.

This project was chosen to serve as the basis for studying the effect of lighting on the productivity of the operation for the following reasons. The paving operation, which is continuous in nature, allows for the calculation of the cost and the productivity of the operation with respect to time. From the perspective of the lighting designer, the lighting plan can be designed to illuminate the entire site, or just the section of the work zone where the work is being done, using the various lighting equipment available. These different objectives can be tested using the proposed lighting tool to find the most efficient and economical lighting plan.

Another site visit was conducted to a different asphalt paving project site on I-69 on the night of October 31^{st} 2009. Work was being done on the left lane on the northbound side of I-69 between the 106^{th} Street and 116^{th} Street in Indianapolis. This work was also done by Milestone Contractors and was very similar to the project observed on I-69.

3.4 Data collection

Most of the data for developing the simulation model and the lighting tool were collected during the site visits by either taking measurements on the site or by interviewing the project manager and the workers at the site. A description of the methods of data collection, the type of data collected, and the analysis performed on the data will be discussed in this section.

3.4.1 Development of Worker Survey

Surveys were the primary tool used in order to gauge the perception of the impact of lighting strategy on the safety and productivity of the workers. The information that was obtained was analyzed to identify the lighting factors that most significantly affected the workers' perceptions of safety and productivity at night. The workers at the work zones are the people who are most affected by the lighting strategy adopted as they will be working under the given conditions. They are therefore valuable sources of information regarding the effectiveness of current lighting practices adopted. The worker is expected to complete his portion of the operation in a safe and efficient manner and in turn, expects the contractor to provide him with a safe work environment.

The survey (Appendix A) that was distributed to the workers collected information regarding the workers' perceptions of the importance of different factors that render nighttime construction different from daytime construction. The workers were also asked to rate the importance of issues that proved to be obstacles to achieving a well illuminated work zone and were asked to rate the effectiveness of current lighting practices that were adopted for the work zone with regard to their safety, productivity, awareness, and quality of work performed. The workers were also asked about the activities that they perform most often on the site. Data about the activity, such as the lighting that is provided to illuminate the activity and the time that it takes to perform that activity under nighttime and daytime conditions, were obtained using the survey.

The surveys were distributed in spring 2010 to paving and construction companies in Indiana and Illinois. Subjects were recruited for the survey by contacting engineers at the companies' office and requesting them to distribute the surveys among the workers who had worked on highway projects during the day and night shifts. Of the six companies that were contacted, responses were received from three companies. Surveys were either dropped off in person at the field offices or emailed to the office of the company, where it would be printed out and distributed. A total of 42 completed surveys were returned and available for analysis from the three companies. This subsection describes the population of the sample of respondents.

Two of the contractors from which surveys were received mainly perform paving work in Indiana. Both of these companies are headquartered in Indianapolis and have offices around the state. The third company is a general contracting company headquartered in Chicago that performs nighttime paving operations. A majority of the respondents were between the ages of 36 and 43 years old and had worked in the construction industry for a range of 10 to 20 years. The average age of the respondents was 42 years and the mean for the number of years of experience in construction for the respondents was 16.3 years. Figure 3.7 shows the ages of the respondents and Figure 3.8 shows the number of years of experience of the respondents.

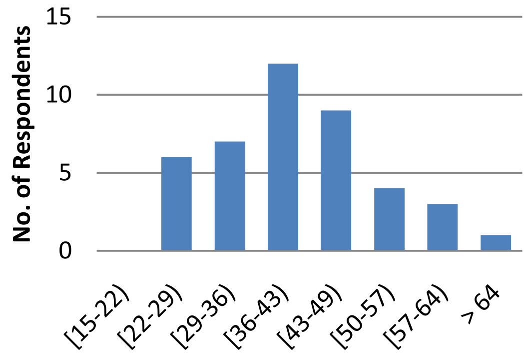


Figure 3.7: Workers' Ages

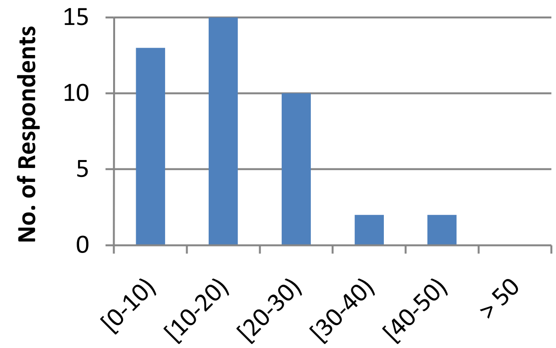


Figure 3.8: Workers' Experience

All of the respondents had worked both during the day and during the night. Forty-five percent of the respondents were operators of various types of equipment including the paving machine, tacking truck, sweeping machine, and roller-compactor; 33% of them were work managers on the site such as a site supervisor or foreman; and the remaining 22% were laborers. Fifty-one percent of the respondents replied that they worked night shifts often (more than once a year), 32% of the respondents said that they did not work on nighttime projects often (less than once a year), and 17% said that they worked on nighttime jobs very often (more than three projects a year). Out of the 42 responses obtained, only two of them were females. Figures 3.10 and 3.11 show the breakdown of the respondents by the nature of their work and by the frequency with which they have worked at night respectively.

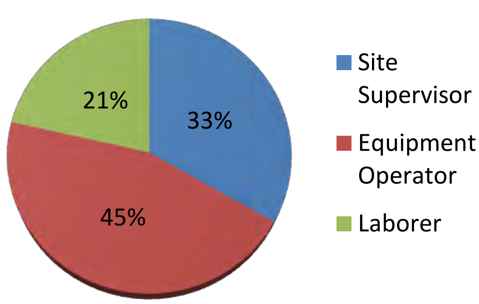


Figure 3.9: Nature of Work

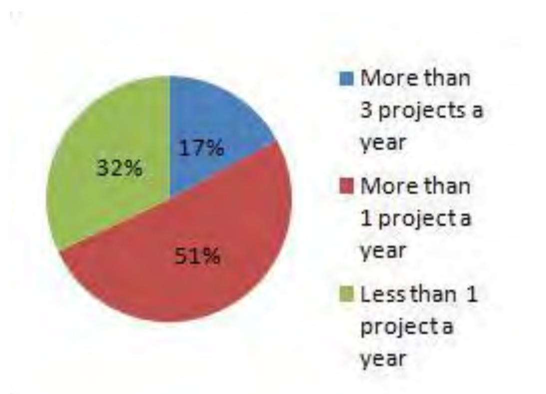


Figure 3.10: Frequency of Nighttime Work

3.4.2 Human Subjects Review

In order to use human research subjects in this investigation, this researcher, the principal investigator, and secondary research personnel were required to complete the Purdue University Collaborative Institutional Review Board (IRB) Training Initiative (CITI) Basic Course for Investigators and Key Personnel. This review process ensures the safe and ethical conduct of research involving human subjects and complies with all applicable state and federal statutes and regulations concerning research with human subjects. After completing the certification, a research protocol was submitted to Purdue University's Committee on the Use of Human Research Subjects, also known as the Institutional Review Board (IRB), for review and approval. Since the workers take the survey anonymously, an expedited review was sought and was received.

3.4.3 Data for the Discrete Event Simulation Model

There were two steps in preparing a discrete event simulation model of the paving operation. The first step was to obtain the details of the operation, such as the sequencing of activities and the number and type of equipment and resources required for each of the activities that make up the operation, and to identify problems or other "out-of-the-ordinary" situations that could disrupt the flow of the simulation and affect the time and productivity of the operation. The second step in the development of the simulation model was to collect the data that would allow the modeler to determine the duration of each activity. A characteristic of duration-related data in the field of construction is the degree of uncertainty that exists in the duration of an activity because it depends heavily on a number of factors that are unique to the circumstances under which the activity is being performed. For example, the time taken by a truck to haul soil from the excavation site to the dump site could be different depending on the traffic on the haul route at the time of hauling, the condition of the haul road, the weather, and the skill of the driver. In order to enable the modeler to model this uncertainty in the data, the software package allows for the duration of the activity to be entered as a probabilistic distribution.

These probabilistic distributions are generated by first collecting durations of the activity to be modeled, checking to ensure that the durations collected are Independent and Identically

Distributed Data (IID), selecting the distribution and estimating its parameters based on the data, and testing for goodness of fit (Law and Kelton 2001). To check if the data collected were IID requires that the data collected come from the same source under identical conditions and that the data points are not dependent on one another. However, as will be explained in Chapter 5, the data were found to be correlated and not independent. This required measures to be taken regarding the treatment of the data collected as well as the development of the simulation model.

Prior to visiting the site to observe the operation and collect data, the researcher performed a thorough review of the Indiana Department of Transportation (INDOT) Certified Technician Program Training Manual for Hot Mix Asphalt Paving (INDOT 2008), which is used by INDOT to train their site engineers and inspectors. This review of the manual provided the groundwork upon which the methods for collection of data on the site could be effectively planned. Milestone LLC, a general contractor based in Indiana, agreed to have the researcher on the site of their paving project on I-65 to observe the paving operation and collect data about the nighttime paving operation. During the site visits, the work breakdown structure of the asphalt paving operation, the sequence of activities in the operation, and the resources needed to perform activities were noted. Data about the duration of different activities were collected using one of the following methods: a) by recording multiple observations of the duration of an activity and b) by interviewing workers on the site to obtain a subjective distribution of the time that it takes to perform an activity. The analysis of the data collected and the development of the simulation model will be discussed in Chapter 5.

3.4.4 Lighting Data

Data regarding the lighting plan for the construction sites were collected in order to develop the lighting analysis tool. The lighting parameters to be analyzed are the illuminance, the lighting uniformity ratio and the veiling luminance ratio. These parameters were calculated at points along which the construction equipment moves by taking into consideration the following characteristics of the lighting plan (El-Rayes and Hyari 2002):

a) Lighting equipment selection: The different types of lighting equipment commonly used at construction sites are lighting towers, portable towers mounted on trailers, and equipment-mounted luminaires.

b) Types of luminaires: the different types of luminaires used are metal halide lamps, high pressure sodium vapor lamps, halogen lamps, and low pressure sodium vapor lamps.

c) Lamp lumen output: This represents the power and intensity of the lamp used in the luminaire and it affect the illuminance and glare in the surrounding area. The lamp lumen output is calculated from the photometric data table that is provided by the manufacturer.

d) Mounting height: This parameter refers to the distance of the centre of the luminaire from the ground.

e) Lighting towers positioning: This parameter refers to the X and Y coordinates of the luminaire with respect to the layout of the construction site.

Illuminance measurements were taken using a light-meter at different distances from the luminaire along the surface of the ground. The measurements were taken in the vicinity of the miller and the paver, the two activities for which lighting was a critical component. These readings helped to test the lighting tool and to validate and verify the results obtained from the lighting tool. Figure 3.8 shows the layout of the work zone and the illuminance values measured at the work zone.

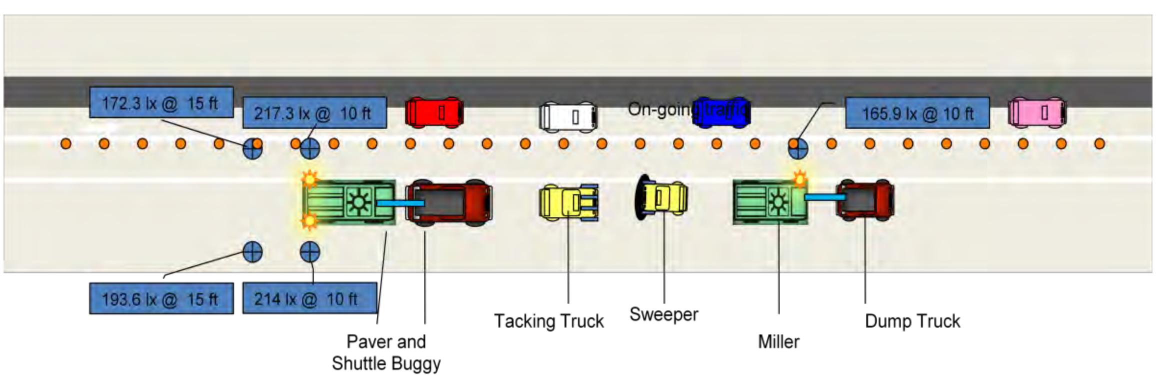


Figure 3.11: Layout of the work zone on I-65 S

As seen in Figure 3.8 the main type of lighting fixture used was the equipment-mounted light fixtures, which consist of a 1000W halogen lamp enclosed in a balloon and mounted at a height of 12" from the ground. This new lighting technology is glare-free as it diffuses the light to an ambient and uniform glow through the balloon. One lamp was mounted on the milling machine and two lamps were mounted on the paver. No additional light fixtures were attached to the sweeper and tacking truck.

3.5 Data Analysis

A descriptive and statistical analysis of the data collected from the surveys was conducted. Different models were developed in order to find the best representation of the data and to find the factors related to lighting that significantly affect the safety and productivity of a nighttime operation. The data were first analyzed using graphic, tabular, and summary statistics. From this preliminary analysis, the models for gauging the worker's perceptions of the impact of lighting on the safety and productivity of the operation were determined.

The impact of lighting on the safety of nighttime operations was modeled using an Ordered Probit model. This model considers the dependent variable to be the response to a question where the respondents are required to give an ordered opinion ranging from "Strongly Disagree" to "Strongly Agree" to indicate whether or not the overall lighting provided makes them feel safe. The Ordered Probit model is also used to model and analyze the impact of lighting conditions on the productivity of the worker. Here, the dependent variable was taken as the response to a question wherein the respondents are asked to give an ordered opinion ranging from "Strongly Disagree" to "Strongly Agree" to whether or not the lighting provided makes them feel that they can be as productive and complete the task at the same rate as can be completed during the daytime, under natural lighting.

3.5.1 Ordered Probit Model with Random Effects

The Ordered Probit model considers an ordered set of discrete outcomes denoted as 1, 2, 3, 4, or 5; which in this case refers to whether the respondent strongly disagrees, disagrees, is neutral to, agrees, or strongly agrees, respectively, with the statement that the lighting provided on the site makes them feel safe and allows them to work as productively as they would during the day. From Washington et. al. (2003), the ordered probit model (Eq. 3.1) is derived by a variable, Z_{in}, that determines discrete outcome *i* for observation *n,*

$$Z_{in} = \beta_i X_{in} + \varepsilon_{in} \tag{3.1}$$

where βi is a vector of estimable parameter coefficients for discrete outcome *i*, and X is a vector of variables that determine the discrete ordering outcomes for observation *n* and ε is a random disturbance. These parameters determine the discrete response for the observation, and in this case, they are related to the characteristics of the lighting configuration used, the perceptions of workers with regards to the problems associated with visibility at night, etc. The addition of the disturbance term ε_{ix} emerges because of the possibility that some important variables could have been omitted, the form of Eq. 3.1 may not be linear, or (3) variations in βi are not accounted for (Washington et al. 2003). Using Eq. 3.1, the ordered ordinal data, *y,* for each observation are defined as:

$$y = 1 \; if \; Z_i \leq \mu_0$$

$$y = 2 \; if \; \mu_0 < Z_i \leq \mu_1$$

$$y = I \; if \; Z_i \leq \mu_{I-2}$$

where the μ are referred to as thresholds that define the *y*, that correspond to integer ordering of the dependent variable, and I is the highest ordered integer response (in this case, I = 5). Washington et. al (2003) states that if the disturbance term ε is assumed to be normally distributed with mean = 0 and variance = 1, the ordered probit model results with ordered selection probabilities:

$$P(y=1) = \Phi(-\beta X)$$

$$P(y=i) = \Phi(\mu_{i-2} - \beta X) - \Phi(\mu_{i-1} - \beta X) \text{ for } i > 1. \tag{3.2}$$

$$P(y=I) = 1 - \Phi(\mu_{I-2} - \beta X)$$

In Eq. 3.2, μ_0 can be set to 0 without a loss of generality and Eq. 3.2 becomes:

$$P(y=i) = \Phi(\mu_i - \beta X) - \Phi(\mu_{i+1} - \beta X) \quad (3.3)$$

where μ_i and μ_{i+1} become the upper and lower thresholds for outcome i.

The likelihood function then becomes:

$$L(y|\ \beta, \mu) = \Pi\Pi[\Phi(\mu_i - \beta X) - \Phi(\mu_{i+1} - \beta X)]^{\delta}_{in} \quad (3.4)$$

Where $\delta = 1$ if the observed discrete outcome for observation *n* is *i*, and 0 otherwise. This leads to a log-likelihood of:

$$LL = \sum\sum \delta in \mathrm{LN}\ [\Phi(\mu i - \beta X) - \Phi(\mu i + 1 - \beta X)] \quad (3.5)$$

In order to get the best model, the log- likelihood of the model needed to be maximized, and variables were added and then removed from each of the different models if their t-statistics were lower than 1.0. The log-likelihood value was used to compare the different models developed and to choose the model that better fits the data. A positive value of a coefficient in the final model implies that an increase in that variable will decrease the probability of that respondent agreeing with the statement that the lighting provided makes him feel safe and productive, respectively and vice versa. The overall fit and validity of the model is measured using the X^2 (Chi-squared) and the P^2 (Rho-squared) statistic.

3.5.2 Multivariate Regression Analysis

From the surveys obtained from the respondents, the data from the activity section and the type of lighting present on the work zone were used to create a regression model to study the impact of the presence of different lighting scenarios on the operation productivity. The ratio of the productivity of the respondent at night under the type of lighting that is usually provided and the productivity achieved during the day shift was taken to be the dependent variable and regressed using the indicator variables that indicated the presence of different types of lighting equipment. The ratio of nighttime to daytime productivity was chosen to be the dependent variable as this would enable the comparison of the effect of working at night across different activities.

After the regresson analysis, the ratio of nighttime to daytime productivity was obtained as a relationship with the type of lighting equipment. Using this relationship, the ratio of nighttime to daytime productivity could be obtained for different lighting scenarios. The inverse of this ratio gives the ratio of the nighttime to daytime duration that is required to perform a unit amount of the work (hereafter referred to as lighting duration factor, LDF). Once the LDF was obtained for different lighting scenarios, it was normalized using the LDF value for the lighting conditions that were present during the collection of the data that was used in the simulation model. Assuming that the duration of the activity is dependent on the lighting conditions, the modified duration of the activity could be obtained by applying the normalized LDF value. This modified duration value could be used in the discrete event simulation developed to obtain the productivity of the operation after considering the lighting conditions prevailing on the site. The development of the simulation model is described in Section 3.5.3. The results of the regression analysis and the description of the different lighting scenarios are described in Chapter 5.

3.5.3 Development of the Simulation Model

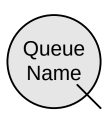
The next step in the methodology is the development of a simulation model of the paving operation. The data required for the simulation model were obtained during the site visits as described in Section 3.4. The model was built using a discrete event simulation package called STROBOSCOPE (Martinez 1996). This software is a construction-oriented discrete event simulation package that has a very intuitive and user-friendly graphical user interface and it also allows the user to write code to manipulate the various programming elements of the model. Discrete event simulation is a method of modeling an operation as a chronological sequence of events.

STOBOSCOPE allows the user to model a wide array of different operations in varying degrees of detail. It allows the use of different resources types, which give the modeler a greater control of running of the simulation by allowing control of the various properties of the resources.

STROBOSCOPE allows two types of resources: characterized and generic resources. Characterized resources are resources that represent unique and individual entities. For example, a particular hauler at a construction site can be thought of as a characterized resource. These characterized resources can have several properties attached to them, such as the capacity of the hauler and the driving speed of the hauler. On the other hand, generic resources are the types of resources that are in bulk and cannot be uniquely identified. An example of a generic resource would be asphalt material. Thus, generic resources have no properties attached to them.

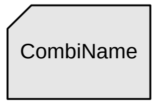
The nodes used in the DES can be of the following types:

a) Queues are nodes that hold idle resources until the resource is drawn away by an activity. At any point during the simulation, the modeler can access the number or amount of resources residing in the queue, the total amount of resources that entered the queue, and the average waiting time of each resource in the queue. These values can be used in the model. It is required to specify the type of resource that is held in the queue. A particular queue can hold resources of only one type and it is required to specify the type of resource held by the queue at the time it is defined. A queue is represented by the following symbol in STROBOSCOPE:

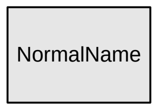


b) Activities are nodes that represent the tasks to be performed in the model using the required resources. Activities typically have durations associated with them. At any point during the simulation, the following information can be obtained about an activity: number of current instances of activity, total number of instances of the activity until that point, information about the resources currently being used by the activity (e.g., amount of a certain general resource or the name of a characterized resource). No specific resource type needs to be selected for activities as they can hold different types of resources. Activities can be of the following two types:

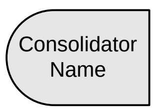
a. Combi is an activity that can start only when certain conditions are met. Combis are usually preceded by queues and are represented by the following symbol.



b. Normal is an activity that starts as soon as the preceding activity is complete. A normal cannot immediately succeed a queue and can be preceded only by another activity. The following is the symbol used for a normal.



c) Consolidator collects resources until they satisfy certain conditions. Upon the end of the consolidation, the accumulated resources are released into the succeeding node. The following is the symbol used to represent the consolidator in the model.



The different nodes in the network are connected by links. A link can carry only one type of resource through it. If a link connects a queue and an activity, the resource type for the link is the same as the resource that is contained in the queue. However, if the link connects two different activities, the modeler will have to specify the resource type of the link.

Once the skeletal model has been developed using the graphical user interface, the model can be enhanced by adding code. This can be done by double clicking on the node of interest or by right clicking over an empty part of the page.

Writing code in STROBOSCOPE is very easy and a wide range of commands are provided to aid the modeler. Some of these commands include flow control statements like the IF and WHILE statement. STROBOSCOPE also allows the user to define variables that can store values. In order to run the simulation of the model, the user needs to include the SIMULATE command in the Control Section of the Global Code. Statistics about the operation can be viewed by entering the keyword REPORT after the SIMULATE command.

3.5.4 Developing the Two-Dimensional Animation

The two-dimensional animation of the operation was prepared using Microsoft Visio and a software developed to animate objects created in Visio by Dr. Julio Martinez called Vita2D (www.ezstrobe.com). This section of the chapter explains how the simulation model created in STROBOSCOPE can be used to generate a trace file containing commands that can be used to animate shapes that represent different entities in a highway construction work zone, created in MS Visio. Microsoft Visio is diagrammatic programming software that allows the user to manipulate the properties of shapes. Vita2D provides a means by which a trace file can be used to change and manipulate the shapes on the page. This trace file is generated by printing Vita2D commands onto a text file during a simulation run. Since the commands are written as the simulation is running, they will be generated in a chronological order. This would enable the user to animate the shapes, created in Visio, according to the operation that is represented by the simulation model.

The commands in Vita2D allow the user complete control over the shapes in the Visio drawing and any kind of animation is possible by using Vita2D. The commands that are used to manipulate the properties of shapes in Visio are as follows:

a) CREATE: This command creates an instance of a master shape that is present in the stencil.
b) PATH: This command names a path that has been created using a one-dimensional drawing tool.
c) MOVE: This command moves an object that has been created along the path defined by the PATH command in a particular amount of time.
d) SETOBJCELL: This command allows the user to set the formula of a property cell of an object.
e) DYNUPDATECELL: This command updates the value of a cell from an initial value to a final value in a specific amount of time.

Using the above commands, it is possible to manipulate the shapes created in Visio as desired.

The shapes need to first be created in Visio by using the different drawing tools available. Paths are created using one-dimensional drawing tools like the line tool, arc tool, and free-form tool. It must be noted that the objects that are to be moved along the paths must be created using the CREATE command. When these objects are invoked by the CREATE command, a copy is made from the master object available on the stencil of the Visio document.

3.6 Chapter Summary

This chapter discussed the research framework and the methodology that were used to analyze the impact of the lighting factors on the nighttime workers' perceptions of safety and productivity. The site visits conducted to nighttime work zones were described along with the activities that were observed. The development and administration of the survey were described along with the characteristics of the sample of respondents. The process that was used to evaluate the impact of different lighting scenarios on the operation productivity by using a multivariate regression analysis and a discrete event simulation was also explained in this chapter; and the methods of data collection employed and the tests conducted on the data to ensure that it could be used in the simulation were presented. A description of the site visits that were conducted to collect data and the details of the paving operations that was modeled was provided.

Chapter 4 will provide a descriptive and statistical analysis of the nighttime workers perceptions of work zone lighting. Chapter 5 will then describe the results of the regression model and the development of the discrete event simulation model and the two-dimensional animation of the paving operation. A comparison of the results of the simulation under different lighting scenarios also will be provided in Chapter 5.

CHAPTER 4. ANALYSIS OF WORKERS' PERCEPTIONS OF LIGHTING

Understanding the importance of different lighting factors and the problems commonly encountered on the worksite regarding lighting would help in the assessment of the effectiveness of current lighting practices and to provide recommendations to improve the state of lighting in nighttime construction work zones. It is important to understand the perceptions of the workers on the site as they are the people who are most affected by the lighting condition. This chapter presents a descriptive and econometric analysis of the perceptions of the construction workers who responded to the surveys distributed during the data collection. The purpose of administering the surveys was to gain an insight into the common lighting practices in highway construction work zones and to understand the perceptions of the workers and supervisors as to the effectiveness of the lighting provided. The responses from the surveys will be discussed by first providing a descriptive analysis of the data, followed by an econometric analysis of the data. The data are presented using graphical, tabular, and summary statistical descriptions. Econometric analysis was conducted using LIMDEP 7.0 Software (Econometric Software Inc 2009).

4.1 Descriptive Analysis of the Survey Results

This section of the chapter provides a descriptive analysis of the perceptions of the respondents regarding the effect of lighting on their safety and performance at work. The results of the survey are summarized using histograms and tables.

4.1.1 Issues Related to Nighttime Construction Work Zones

The respondents were asked to rate, on a scale of 1 to 5 (with 1 being very unimportant to 5 being very important), different aspects of nighttime highway construction, such as visibility in the work zone, awareness of hazards at night, traffic through the work zone, and lighting in the work zone. The basis for rating these factors was the importance the factors had in rendering nighttime work different from daytime work.

Seventy-four percent (74%) of the respondents felt that visibility in the work zone was very important, 64% of the respondents felt that lighting and the awareness of hazards were very important, and 57% of the respondents felt that traffic was a very important issue in nighttime construction. Only 14% of the respondents felt that temperature was a critical issue in nighttime construction. The objective of this question was to determine the factors that the workers and supervisors felt were most important in a nighttime construction work zone. Figure 4.1 shows the perception of the respondents with regard to the importance of various issues that differentiate nighttime construction from daytime construction.

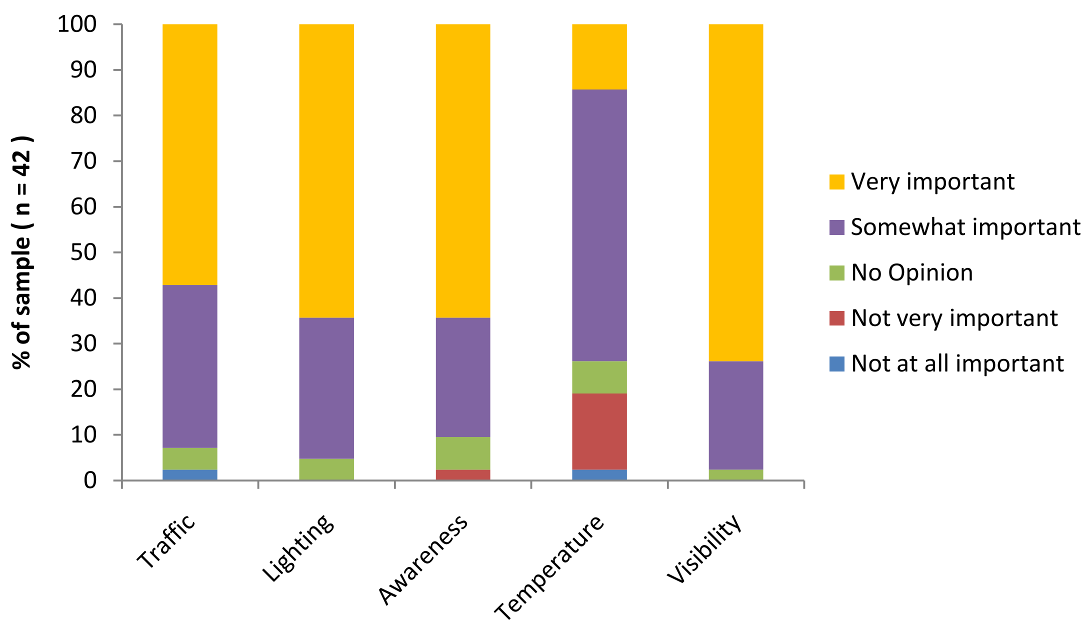


Figure 4.1: Workers' perceptions of the importance of issues in nighttime construction

The top three issues, namely, visibility in the work zone, lighting, and awareness of hazards in the work zone are directly affected by the lighting strategy that is adopted in the work zone. Hence, improving the lighting in the work zone can greatly enhance the work environment for the workers.

4.1.2 Effectiveness of Lighting

To determine the effectiveness of the current lighting practices, the respondents were asked to describe the lighting equipment used in the work zone and then rate the lighting strategy used on the basis of the following aspects: safety, productivity, quality of finished work, awareness of surroundings, and ability to do work without making errors. The respondents rated the effectiveness on a scale of 1 to 5 (ranging from 1, which indicates that they strongly disagree with the fact that the lighting provided is effective,; to 5, which indicates that they strongly agree with the fact the lighting provided is adequate and effective with regard to the previously mentioned issues).

In order to determine the lighting conditions in which the respondents are accustomed to working under, they were asked to indicate which of the following lighting equipment was usually provided for the illumination of the general and task areas in the work zone:

- Roadway lighting
- Light from surrounding buildings, etc.
- Trailer-mounted lighting towers
- Other lighting
- Balloon lights fixed on equipment
- Lights fixed on the equipment by the manufacturer
- No lighting is provided for the illumination of the work zone sometimes

Sixty-nine percent (69%) of the respondents said that they worked with balloon lights fixed on the equipment. Several comments were received which referred to the ability of the balloon lights to diffuse the light uniformly and thus greatly reduce the glare produced by conventional lighting sources. Balloon lights seemed to be very popular with the respondents, primarily because of the ability to reduce glare and due to the ease of installation on the equipment. Equipment-mounted balloon lights are also very effective with paving operations as it is an operation that continuously moves along the length of the work zone.

Sixty percent (60%) of the respondents claimed that they sometimes work in areas where only task illumination is provided. This is particularly true in operations like paving, where it is not feasible for the entire work zone to be illuminated. Fifty percent (50%) of the respondents answered that they usually worked in areas that were illuminated by roadway lighting. An equal percentage replied that they were accustomed to the lighting provided by the manufacturer to illuminate the task area. Fifty five percent (55%) of the respondents said that they used trailer-mounted lighting towers on the work zone. Only 21% of the respondents said that they received light from buildings surrounding the work zone. Figure 4.2 summarizes the use of lighting equipment among the respondents.

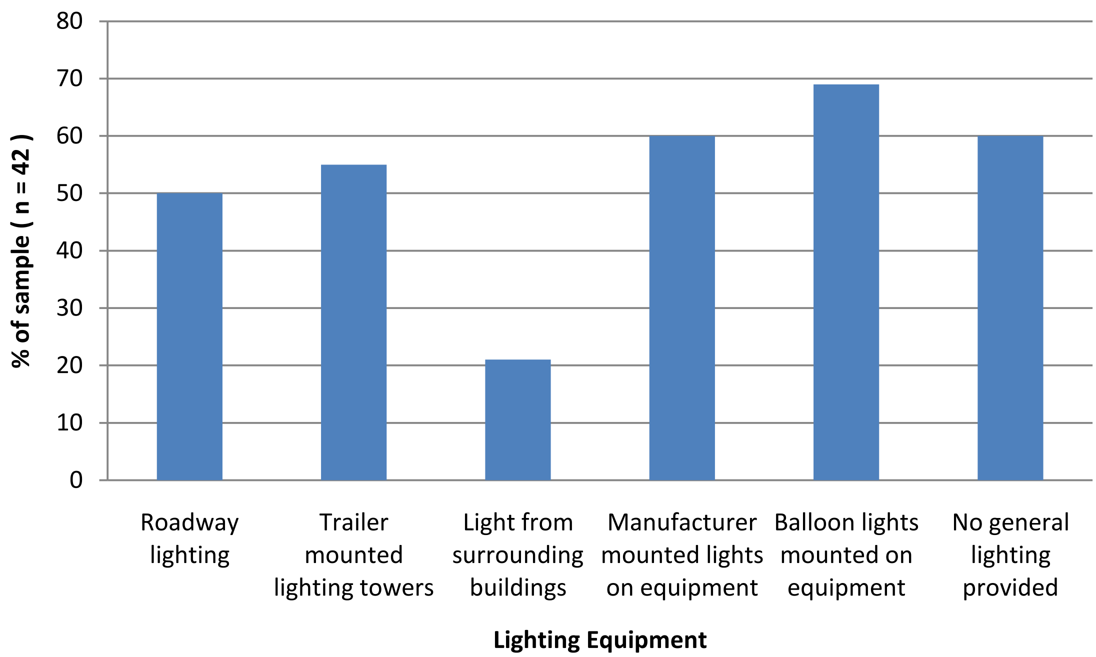


Figure 4.2: Lighting equipment used on nighttime construction work zones

The respondents were then asked to rate the effectiveness of the lighting strategy that was used in the work zone with regards to safety, productivity, quality of work, ability to do work without making errors, and awareness of the surrounding area. The data collected from the surveys revealed that the quality of work was the aspect that was most affected by the poor lighting. Seventy-four percent (74%) of the respondents said that the lighting available to them in the work zone does not allow them to achieve the same quality of work as during the day. This problem can be circumvented by scheduling tasks for which quality is not the highest priority, such as excavation and earth moving, to be performed at night whenever possible. Forty-three percent (43%) of the respondents indicated that the lighting available does not prevent them from making mistakes, and 39% of the respondents believed that the available lighting prevents them from achieving the same productivity as during the day.

Regarding safety, 66% of the respondents agreed with the statement that the lighting provided does make them feel safe while doing their work at night. Since safety is of the highest concern to the practitioners of nighttime construction, it would seem that the lighting that is provided is adequate. However, improvements can be made in the lighting strategies that can greatly affect the productivity and quality of the work conducted at night. The econometric analysis that is discussed Section 4.2.3 describes the factors that influence the workers' perception of lighting. The analysis performed helped to identify areas of lighting which can be improved. Figure 4.3 summarizes the workers' responses regarding the effectiveness of the current state of practice of lighting.

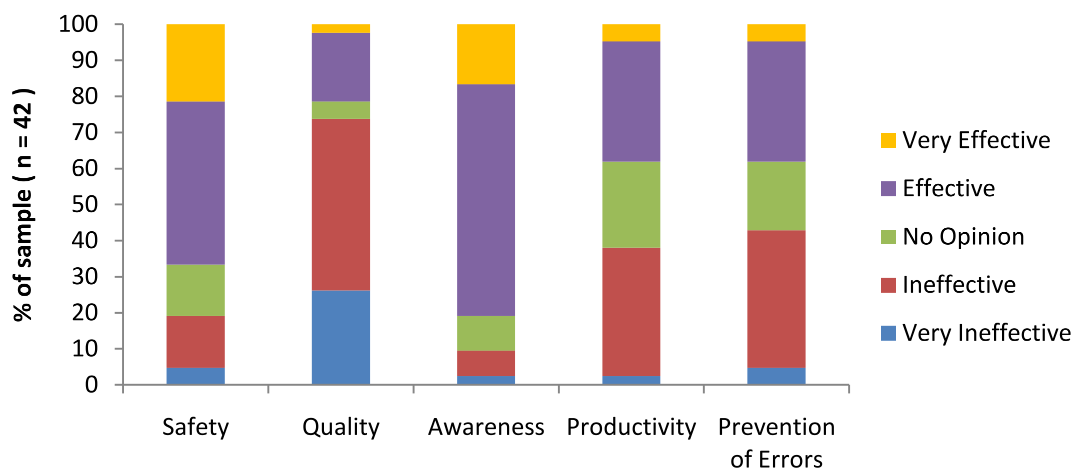


Figure 4.3: Workers' perceptions about the effectiveness of work zone lighting

4.1.3 Issues Related to Work Zone Lighting

The following issues were discussed in the survey: shadows in the work zone, visual communication with workers, inadequacy of illumination, and glare. The respondents were also given the option to list any other lighting issues that they may have faced in the work zone.

The presence of shadows in the work zone was one of the most commonly faced problem regarding lighting, as 84% of the respondents selected “Agree” or “Strongly Agree.” Difficulty in visually communicating with fellow workers in the work zone also was an issue for 84% of the respondents. Seventy-seven percent of the respondents agreed that glare was issue, and 67% of the respondents said that the illumination provided was not adequate.

It is important to illuminate the work zone uniformly and reduce the presence of shadows in the work zone. The balloon lights that diffuse the light uniformly are becoming a preferred choice of lighting fixture for the workers as it does not focus a high intensity beam of light over a small area. Rather, it lights the area to be illuminated with a uniform glow, which also reduces the problem of glare. The elimination of shadows would also reduce the difficulty in visually communicating with workers as it is much hard to communicate with workers standing in the shadows. Figure 4.4 summarizes the responses of the workers regarding their perceptions of the lighting issues in nighttime work zones.

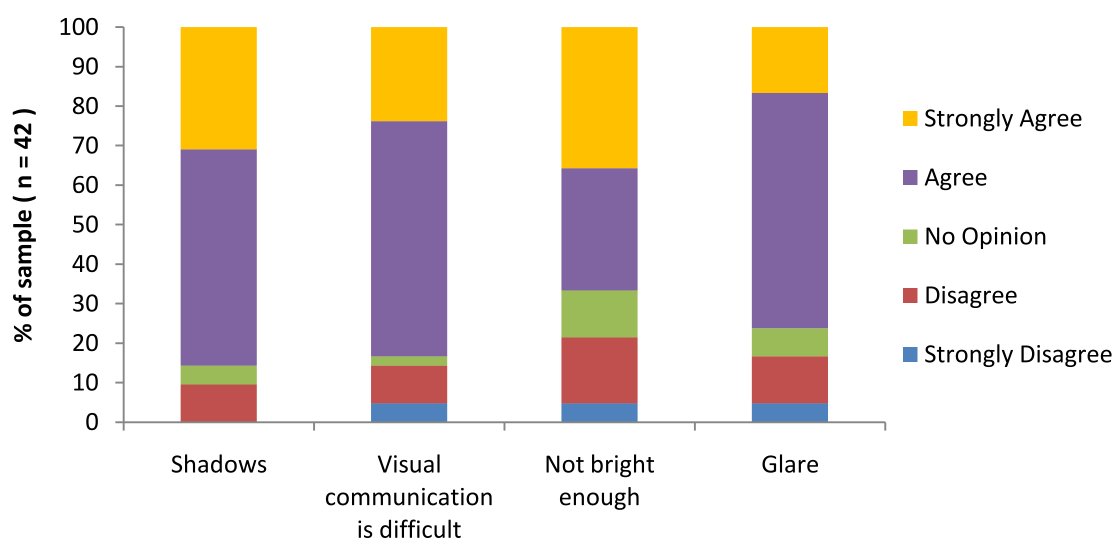


Figure 4.4: Workers’ perceptions about the importance of lighting

4.2 Econometric Analysis of the Survey Results

In order to correctly understand the factors that had a significant impact on the respondents' perceptions of the effectiveness of lighting on their safety and productivity, two different ordered probit models were created using the variables that were used in the surveys that were distributed. Descriptions of the respondents' choices for the variables were provided in the preceding subsection, and Table 4.1 provides this information as well as a list of possible answers.

Table 4.1: Variables available for model

Variable Mnemonic	**Description of variable (answer choices)**
Years	Number of years of experience in construction.
Day	Worked on projects during the day (1 if yes, 0 if no)
Night	Worked on projects during the night (1 if yes, 0 if no)
ImpTraffic	Importance of traffic as a nighttime construction issue (1 if not at all important, 2 if not very important, 3 if no opinion, 4 if somewhat important, 5 if very important)
ImpLight	Importance of lighting as a nighttime construction issue (1 if not at all important, 2 if not very important, 3 if no opinion, 4 if somewhat important, 5 if very important)
ImpAware	Importance of awareness of hazards (1 if not at all important, 2 if not very important, 3 if no opinion, 4 if somewhat important, 5 if very important)
ImpTemp	Importance of temperature as a nighttime construction issue (1 if not at all important, 2 if not very important, 3 if no opinion, 4 if somewhat important, 5 if very important)
ImpCom	Importance of visual communication (1 if not at all important - 5 if very important)
Role	Role performed on site (1 if laborer, 2 if supervisor, 3 if operator of equipment)
LtRoad	Presence of roadway lighting in work zone (1 if yes, 2 if no)
LtBld	Presence of light from surrounding buildings in work zone (1 if yes, 2 if no)
LtTrl	Presence of trailer mounted lighting towers in work zone (1 if yes, 2 if no)
LtNon	Sometimes no general lighting is provided (1 if yes, 2 if no)
LtOth	Presence of other lighting sources not mentioned above in work zone (1 if yes, 2 if no)
LtMan	Presence of manufacture mounted lights on equipment (1 if yes, 2 if no)
LtBal	Presence of balloon lights mounted on equipment (1 if yes, 2 if no)
EfSaf	Effectiveness of lighting regarding safety (1 if strongly disagree - 5 if strongly agree)
EfQty	Effectiveness of lighting regarding quality (1 if strongly disagree - 5 if strongly agree)
EfAwr	Effectiveness of lighting regarding awareness (1 if strongly disagree - 5 if strongly agree)
EfPdy	Effectiveness of lighting regarding productivity (1 if strongly disagree, - 5 if strongly agree)
EfErr	Effectiveness of lighting regarding error prevention (1 if strongly disagree - 5 if strongly agree)
Shd	Perception of importance of shadows (1 if strongly disagree - 5 if strongly agree)
VisCom	Perception of importance of visual communication (1 if strongly disagree, 2 if disagree, 3 if no opinion, 4 if agree, 5 if strongly agree)
Int	Perception of importance with intensity of lighting (1 if strongly disagree - 5 if strongly agree)
Glr	Perception of importance of glare (1 if strongly disagree - 5 if strongly agree)
Age	Age of the respondent
Gender	Gender of the respondent
Freq	Frequency of working at night (1 if often, 2 if not often, 3 if very important)

Two ordered probit models were constructed using the variables EfSaf and EfPdy as the dependent variables. Both of these variables ask the respondent for an ordered response in a range of 1 to 5, which indicates a range of responses from "Strongly Disagree" to "Strongly Agree." The responses to this variable indicate how effective the lighting strategy adopted in a work zone is in keeping the respondent safe and productive. The two ordered probit models that were developed are discussed below.

4.2.1 Ordered probit model for the perception regarding safety

To understand the factors affecting the perception of safety in nighttime work zones, an ordered probit model was constructed using the variable EfSaf as the dependent variable. The survey asked the respondents to select one of the following answers to the question "Do you feel that the lighting that is provided for the illumination of the worksite and the activity is adequate in making you feel safe?" - Strongly disagree, Disagree, No Opinion, Agree, or Strongly Agree.

Five percent (5%) of the respondents answered "Strongly Disagree" and 14% of the respondents answered to each "Disagree" and "No Opinion" respectively. Forty-five percent (45%) of the respondents agreed with the statement and 22% of the respondents responded with "Strongly Agree." The histogram of the responses to this question is shown in Figure 4.5.

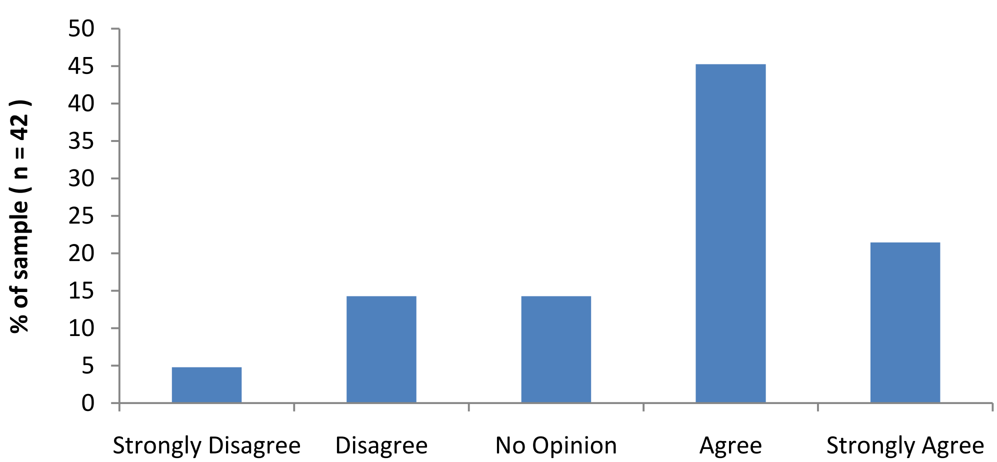


Figure 4.5: Workers' perceptions regarding effectiveness of lighting with respect to safety

4.1.1.1. Discussion of Ordered Probit Model for Workers' Perceptions of Safety

The variables that were used in the model, along with the parameter estimates and t-stats, are summarized in Table 4.7. The model converged from an initial LogLikelihood of -59.422 to -54.384, resulting in a Rho-Squared value of 0.083. This is a low value for the Rho Square, which is largely due to the insufficient number of observations. The sample size required for a 95% confidence level of obtaining a confidence interval of 10 was found to be 96 observations, but only 42 responses were obtained for the surveys distributed. The selected variables were chosen only if their t-stats were significant (greater than 1) after repeated trials of the models with different combinations of variables. Various combinations of the available variables were used in the model and were rejected if their t-statistic value was less than 1. This indicated that the respective variables were not significant.

Table 4.2: Ordered Probit model for effect of lighting on safety

Independent Variables	**Symbol**	**Estimated Coefficient**	**t statistic**
Constant		1.311	2.715
No general lighting provided (1 if yes, 0 if no)	*LtNon*	-0.395	-1.101
Balloon lights mounted on equipment (1 if yes, 0 if no)	*LtBal*	0.909	2.115
Supervisor (1 if yes, 0 if no)	*Superv*	0.584	1.348
Number of observations			42
Initial Log likelihood			-54.384
Log likelihood at convergence			-59.422
P- Squared			0.083

Table 4.2 provides the summary statistics about the ordered probit model developed to analyze the workers' perceptions of safety.

- No general lighting provided (LtNon): 60% of the respondents said that in some projects there was no general illumination of the work zone, which is most often the case in operations like paving, where different activities occur at different areas of the work zone and where it is not feasible to have any general illumination for the entire work zone. This variable has a parameter estimate of -0.395, which indicates that if the respondent has worked in an area where there is no general lighting provided, the probability of the respondent agreeing with the fact that the provided lighting makes him feel safe.

- Balloon lights mounted on equipment (LtBal): Sixty-nine percent (69%) of the respondents answered that the task area in which they work is illuminated by balloon lights that are affixed to the equipment. Comments received during the surveys also indicate that the balloon lights are popular with the workers because they help diffuse the light uniformly and reduce the glare that is produced. This variable has a positive parameter estimate of 0.909, which indicates that the presence of balloon lights on the equipment increases the probability of the respondent giving a higher score to the safety of the work zone.
- Supervisor (Superv): The model included an indicator variable, which took into account the role of the respondent in the work zone. This particular variable takes the value of 1 if the role of the respondent is that of a supervisor. The positive value of the parameter estimate suggests that the respondent is more likely to feel safe in the work zone if he is a supervisor. This could stem from the knowledge and confidence that the supervisor has in the lighting strategy that is adopted and used on the site and due to the fact that he is responsible for the safe execution of the operation.

4.1.1.2. Marginal Effects of Selected Variables in Model

While the sign of the parameter estimate gives an idea about how an increase or decrease in the variable affects the workers' perceptions of safety, it does not give information about the rate of change that occurs. This information is provided by the marginal effects for that variable. Table 4.3 provides the summary of the marginal effects of the variables included in the model.

Table 4.3: Marginal effects

Variable	Mnemonic	Strongly Disagree	Disagree	No Opinion	Agree	Strongly Agree
Constant		-0.086	-0.223	-0.168	0.135	0.343
No general lighting provided (1 if yes, 0 if no)	*LtNon*	0.026	0.067	0.05	-0.04	-0.103
Balloon lights mounted on equipment (1 if yes, 0 if no)	*LtBal*	-0.059	-0.154	-0.116	0.094	0.237
Supervisor (1 if yes, 0 if no)	*Superv*	-0.038	-0.099	-0.075	0.06	0.153

A look at the marginal effects values for the indicator variable that represents the fact that workers have experienced times when no general lighting (LtNon) was provided on the site suggests that the absence of general lighting in the work zone decreases the probability of the respondent answering "Strongly Agree" when asked about the effectiveness of the work zone lighting to make them feel safe by 0.103, while increasing the probability of selecting "Strongly Disagree" by 0.026. The marginal effects values for the "Balloon" indicator variable indicate that the probability of the respondent answering with "Strongly Agree" is increased by 0.237 and the probability of "Strongly Disagree" reduces by 0.059 when there is no balloon lighting mounted on the equipment. The marginal effects values for the "Superv" indicator variable indicate that the probability that the respondent will answer with "Strongly Agree" is increased by 0.153 and the probability of "Strongly Disagree" reduces by 0.038 when the respondent is a supervisor.

The implications of the marginal effects for the ordered probit model can help the contractor make decisions regarding the use of lighting resources should he ever be in such circumstances. From the above analysis, it can be seen that if the contractor had to choose between providing general lighting or providing balloon lights, he would rather select the option of providing balloon lights, as it has results in a greater increase in the probability that the worker would tend to "Strongly Agree" that it makes him feel safe in the work zone.

4.2.2 Ordered probit model for the perception of productivity

To understand the factors affecting the perception of productivity in nighttime work zones, a second ordered probit model was constructed using the variable EfSaf as the dependent variable. The survey asked the respondents to select one of the following answers to the question "Do you feel that the lighting that is provided for the illumination of the worksite and the activity is adequate and allows you to achieve the same productivity as achieved during the day?" - Strongly Disagree, Disagree, No Opinion, Agree, or Strongly Agree

Two percent (2%) of the respondents answered "Strongly Disagree," 36% of the respondents answered "Disagree," and 24% answered "No Opinion." Thirty-three percent (33%) of the respondents agreed with the statement and 5% of the respondents responded with "Strongly Agree." The histogram of the responses to this question is shown in Figure 4.6.

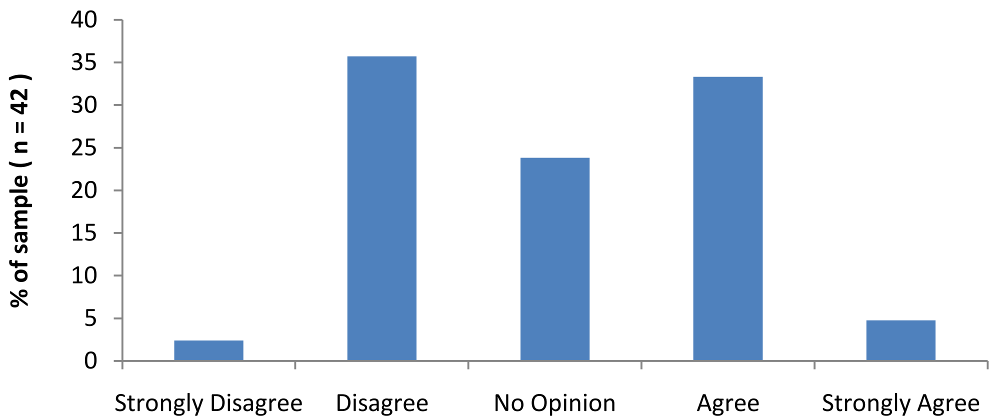


Figure 4.6: Workers' perceptions regarding effectiveness of lighting with respect to productivity

4.1.1.3. <u>Discussion of the Ordered Probit model for workers' perceptions of productivity</u>

The variables that were used in the model, along with the parameter estimates and t-stats are summarized in Table 4.7. The model converged from an initial Log Likelihood of -57.218 to

-50.809, resulting in a Rho- Squared value of 0.112. This is a low value for the Rho Square and can be attributed to the to the small sample size of the data collected and the resulting low number of variables with a significant t-stat that were included in the model. The selected variables were chosen only if their t-stats were significant (greater than 1), after repeated trials of the models with different combinations of variables. Table 4.4 provides the summary statistics about the ordered probit model developed to analyze the workers' perceptions of productivity.

Table 4.4: Ordered Probit model for effect of lighting on productivity

Independent Variables	**Symbol**	**Estimated Coefficient**	**t - statistic**
Constant		1.163	1.767
Presence of roadway lighting	*LtRoad*	-0.582	-1.494
Balloon lights mounted on equipment	*LtBal*	0.712	1.684
Presence of other lighting sources	*LtOth*	0.688	1.219
Perception of importance of intensity of lighting	*Int*	0.833	2.085
Number of observations			42
Initial Log likelihood			-50.809
Log likelihood at convergence			-57.218
Rho Squared Value			0.112

The final model included four independent variables. An analysis of the selected variables and their effect on the perception of productivity in the work zone is provided below:

- <u>Presence of roadway lighting (LtRoad):</u> Fifty percent (50%) of the respondents answered that there was roadway lighting that was present at the work zone. A negative parameter estimate indicates that the presence of roadway lighting has a negative effect on the productivity of the respondent. The result obtained here seems to be counterintuitive to the fact the roadway lighting should help to improve the productivity of the worker. It could be attributed to the fact the presence of general lighting in the work zone could compromise the task lighting required for seeing objects clearly in the area where the task is being performed. The presence of roadway lighting may provide the contractor with the option of not requiring other lighting equipment for task lighting, which may impact the overall productivity of the activity.

- Presence of balloon lights on equipment (LtBal): The presence of balloon lights has a strong positive influence on the productivity of the worker, as evidenced by its parameter estimate of 0.712. The balloon lights' advantages were discussed earlier and were found to be a significant factor affecting the workers' perceptions of safety as well. The ease with which the balloon lights can be set up and dismantled from the equipment is another added advantage over other lighting fixtures, such as portable lighting towers, also affects the productivity of the operation in a positive manner.
- Perception of the importance of the intensity of light provided (Int): When asked about the importance of the intensity of light being an issue in nighttime work zones, 36% and 31% of the respondents respectively answered "Strongly Agree" and "Agree." The intensity of light provided enables the workers to see their work area clearly, thus helping them to avoid errors.

4.1.1.4. Marginal Effects of Selected Variables in Model

While the sign of the parameter estimate indicates how an increase or decrease in the variable affects the workers' perceptions of productivity, it does not provide information about the rate of change that occurs. This information is provided by the marginal effects for that variable. Table 4.3 provides a summary of the marginal effects of the variables included in the model.

Table 4.5: Marginal Effects

Variable	Mnemonic	Strongly Disagree	Disagree	No Opinion	Agree	Strongly Agree
Constant		-0.086	-0.223	-0.168	0.135	0.343
No general lighting provided (1 if yes, 0 if no)	*LtNon*	0.026	0.067	0.05	-0.04	-0.103
Balloon lights mounted on equipment (1 if yes, 0 if no)	*LtBal*	-0.059	-0.154	-0.116	0.094	0.237
Supervisor (1 if yes, 0 if no)	*Superv*	-0.038	-0.099	-0.075	0.06	0.153

The marginal effects values for the indicator variable that indicates the presence of roadway lighting (LtRoad) shows that the probability that the respondent answers with "Strongly Agree" when asked about the effectiveness of the work zone lighting in allowing them to achieve the same productivity as achieved during the day is decreased by 0.343 and the probability of "Strongly Disagree" increases by 0.338. The marginal effects values for the variable that indicates the presence of balloon lights on the equipment indicate that the probability that the respondent answers with "Strongly Agree" is increased by 0.048 and the probability of "Strongly Disagree" reduces by 0.041 by the presence of balloon lights. The marginal effects values for the variable that provides the respondent's perception of the importance of intensity of light at the work zone indicates that a person who feels that the intensity of light is an important problem that is faced on the work zone with regards to the lighting provided is more likely to agree with the fact that he can achieve the same productivity as during the day.

The information provided by the marginal effects of the different variables could be used by the contractor to make decisions regarding the choice of lighting equipment to be used in order to improve the workers' perception of productivity. In a hypothetical scenario, if the contractor had to choose between providing balloon lighting and another source of lighting (indicated by the variable LtOth), he would choose balloon lighting as it would provide a greater change in the worker's perception of productivity as indicated by the higher marginal effect for the LtBal variable when compared to the LtOth variable.

4.2.3 Validity of the Ordered Probit models for workers' perception of safety and productivity

The significance of the independent variables included in the model is approximated using the one tailed t test (Washington et al 2001), which is represented by the t statistic. Only variables that had a t-stat that was greater than 1 is included in the model.

Two common measures of a model's fit were applied to test the validity of the ordered probit models. These measures are the P^2 statistic and the X^2 statistic (Washington et al 2001). The P^2 statistic is calculated as follows:

$$P^2 = 1 - \frac{LL(\beta)}{LL(0)}$$

Where LL (β) is the log likelihood at convergence with the parameter vector β and LL (0) is the initial log likelihood (with all the parameters set to 0).

The P^2 statistic has a value that lies between 0 and 1. A perfect model would have a P^2 that is equal to 1, which means that it is able to predict all selected outcomes with a probability of 1. The closer the P^2 value is to 1, the more certain the model is to predict the outcome correctly (Washington et al 2001).

The ordered probit model for the workers' perceptions of safety had a P^2 value of 0.083 while the ordered probit model for the workers' perceptions of productivity had a P^2 value of 0.112. The low values of the P^2 statistic are due to the low number of variables that are used in the model (Washington et al 2001). This was done in order to ensure that only variables with a t statistic greater than 1 were included, so as to avoid the presence of irrelevant variables, which are variables that do not have a significant impact on the dependent variable.

The X^2 statistic is calculated for the two ordered probit models using the following formula:

$$X^2 = 2 * [LL(\beta) - LL(0)]$$

Where LL (β) is the log likelihood at convergence with the parameter vector β and LL (0) is the initial log likelihood (with all the parameters set to 0). This statistic is X^2 distributed with a degree of freedom equal to the number of parameters in the model.

The X^2 statistic for the ordered probit models for the workers' perceptions of safety had a value of 10.084 with 4 degrees of freedom. At 4 degrees of freedom, the value of the critical X^2 at 95% levelconfidence level is 9.488. We therefore can accept the hypothesis that the model at convergence is significantly different from the model with all its parameter estimates set to 0.

The ordered probit model for the workers' perceptions of productivity safety was found to have a X^2 statistic of 12.818. This model had 5 degrees of freedom. The critical value of the X^2 statistic at 5 degrees of freedom and 95% confidence level is11.071. Here too, we can accept the hypothesis that the model at convergence is significantly different from the model with all its parameter estimates set to 0.

4.2.4 Summary of the econometric analysis

The econometric analysis to determine the perceptions of the workers regarding the effect of lighting on their safety and productivity was conducted with the data obtained from the surveys distributed to practitioners of nighttime construction. The models that were constructed for safety and productivity contained three and four variables respectively. The variables were selected based on the respective t-stat value that was obtained in the model.

While running the ordered probit model, it was found that the absence of any general lighting on the worksite had a negative impact on the workers' perceptions of safety. However, the presence of general roadway lighting reduced the respondents' perceptions of their productivity during the nighttime work. Balloon lighting mounted on equipment was found to have a significant positive impact on the workers' perceptions of both the safety and productivity, as explained in Section 4.2.3. Balloon lights are a relatively new product (Airstar 2007) and are being adopted by practitioners of nighttime work in Indiana as was observed during the site visits. The intensity of light was found to be a significant factor that affected the productivity of nighttime work. Thus, the illumination provided for the task is very important in the perception of productivity of the workers and to ensure optimal productivity, the task lighting provided must be sufficient.

The implications of the econometric analysis to the state-of-the-practice could be illustrated by a hypothetical situation. In the event a contractor has limited resources to provide lighting for a project, he could channel the funds to provide general lighting in order to eliminate shadows and improve the workers' perceptions of safety in the work zone. The presence of supervisors or foremen who could coordinate the work better could also improve the workers' perceptions of safety. If the work zone is illuminated by roadway lighting, for instance), he could invest the resources to obtain balloon lighting which could greatly improve the illumination of the task area.

4.3 Chapter Summary

This chapter described the analysis performed on the data obtained from the surveys distributed to the nighttime construction workers in order to understand their perceptions of the effectiveness of the lighting conditions in which they work. A descriptive analysis and an econometric analysis of the data were discussed in this chapter. The descriptive analysis of the responses of the surveys provided insights into the perceptions of the practitioners regarding the various aspects of lighting in nighttime construction work zones, such as the importance of various factors in nighttime construction, the type of lighting that is usually available in nighttime highway construction work zones, the effectiveness of said lighting in terms of providing the workers with a work environment so they can perform their work in a safe and productive manner. The problems that workers commonly face in the work zone regarding lighting were also discussed. The econometric analysis of the data collected identified the variables that significantly affected the perceptions of the respondents regarding the effect of lighting on their safety and productivity. The analysis performed in this chapter provides insights into the general perceptions of the effectiveness of lighting from the perspective of the workers who work in the nighttime construction work zones.

Chapter 5 will describe the development of the regression model and the discrete event simulation of the paving operation in order to quantify the effect of different lighting scenarios on the operation productivity. The conclusions, limitations, and contributions of the research will be discussed in Chapter 6.

CHAPTER 5. IMPACT OF LIGHTING SCENARIOS ON OPERATION PRODUCTIVITY

This chapter describes the multivariate regression analysis performed on the survey data and the development of the simulation model and animation that form the framework for evaluating the impact of different lighting strategies on the productivity of the operation. The first section describes the regression analysis performed to obtain the relationship between the lighting duration factor (LDF) and the type of lighting available in the work zone. The second section describes the development of the discrete event simulation model and the animation that is used to calculate the operation productivity. The incorporation of the LDFs for different lighting scenarios and the method used to compare the corresponding productivity levels are discussed in Section 5.2.5.

5.1 Multivariate Regression Analysis and Calculation of LDF

This section describes the results of the regression analysis that was performed on the data regarding the effect of different lighting equipment on the nighttime to daytime productivity ratio and the use of the equation obtained from the regression to calculate the Lighting Duration Factors (LDFs) for different lighting scenarios.

5.1.1 Results of Multivariate Regression Analysis

Out of the 42 responses that were obtained from the surveys, only 11 respondents answered the section regarding the activities correctly. The remaining respondents either misinterpreted the question or left it unanswered. Although, the sample size used for the regression model is very small, the analysis was nevertheless performed in order to illustrate the framework that could be used to quantify and compare the impact of different lighting strategies on operation productivity. This section describes the results and implications of the multivariate regression model that was constructed using the 11 data points obtained from the respondents who did answer the question regarding the daytime and nighttime productivity levels. The independent variables available for regression model are variables which indicate the presence of the following types of lighting equipment in the work zone:

- Roadway lighting
- Trailer-mounted lighting
- Balloon lights mounted on equipment
- Manufacturer-affixed lights on equipment

The results of the simulation model are summarized in Table 5.1.

Table 5.1: Results of multivariate regression model

Variable Description	Mnemonic	Parameter Estimate	t-statistic
Constant		0.563	2.604
Roadway Lighting (1 if present, 0 if not)	LtRoad	0.324	2.123
Trailer Mounted Lighting (1 if present, 0 if not)	LtTrl	0.105	0.926
Manufacturer Installed (1 if present, 0 if not)	LtManuf	-0.215	-1.974
Balloon Lighting (1 if present, 0 if not)	LtBal	0.084	0.617
R Square			0.536
Adjusted R Square			0.227
Observations			11

The resulting equation for the ratio of nighttime to daytime productivity is given below:

$$\frac{NP}{DP} = 0.563 + 0.324 * LtRoad + 0.105 * LtTrl - 0.215 * LtManuf + 0.084 * LtBal$$

Where NP = Nighttime Productivity and DP = Daytime productivity.

The lighting duration factor (LDF) is obtained follows:

$$LDF = \frac{1}{\frac{NP}{DP}}$$

As can be seen from Table 5.1, the ratio of nighttime to daytime productivity increases when there is the presence of roadway lighting, trailer-mounted lighting, and balloon lighting, but it decreases when there is manufacturer-installed lighting present. It must be understood that these results and the analysis performed in the succeeding sections are based on the sample of data that was available, and hence the results obtained is specific to the sample of respondents. However, the analysis performed illustrates the use of the framework that is proposed for the comparison of operation productivities achieved under different lighting scenarios.

5.1.2 Calculation of LDFs for Different Lighting Scenarios

Lighting duration factors were calculated for the four different scenarios listed below using equations 5.1 and 5.2:

1. Presence of balloon lighting for mill and pave activity and manufacturer-mounted equipment for the sweeping and tack activity (the lighting conditions that existed while the data for the simulation model were collected)
2. Presence of balloon lighting for mill and pave activity, manufacturer-mounted equipment for the sweeping and tack activity and roadway lighting
3. Presence of balloon lighting for mill and pave activity, manufacturer-mounted equipment for the sweeping and tack activity and trailer-mounted lighting
4. Presence of balloon lighting for mill and pave activity, manufacturer-mounted equipment for the sweeping and tack activity and, roadway and trailer-mounted lighting

The first scenario was the one that was observed on the site visit when the data collection took place. Balloon lights were provided for task illumination of the miller and paver, while the sweeper, tacker, and roller used the lights that were mounted on the equipment by the manufacturers. There was no general lighting present. The three remaining scenarios included different type of extra lighting equipment and are hypothetical in that they were not observed and have been included only for the purpose of illustration of the methodology used.

Once the LDFs for these scenarios were obtained for the different activities, they were normalized with the LDF obtained for the first scenario considered – the presence of balloon lights, and equipment manufactured lights in the case of the sweeper, tacker, and roller. This was the lighting that was observed on the site while the duration data were collected. These normalized LDFs could be used to modify the duration of the activities in the simulation model, depending on the lighting scenario that is being considered. The ratio of nighttime to daytime productivity levels, the LDFs, and the normalized LDFs for the above lighting scenarios are summarized in Table 5.2:

Table 5.2: Summary of Lighting Duration Factors

Sl No	**Lighting Scenario Considered**	**NP/ DP**	**LDF**	**Normalized LDF**	**Activities**
1	Balloon lights on miller and paver	0.65	1.54	1.00	Mill , Pave
2	Balloon lights on miller and paver and roadway lighting	0.97	1.03	0.67	
3	Balloon lights on miller and paver and traile- mounted lighting	0.75	1.33	0.86	
4	Balloon lights on miller and paver, roadway lighting and trailer mounted lighting	1.08	0.93	0.60	
1	Manufacturer-mounted lights on sweeper, tacker, and roller.	0.35	2.87	1.00	Sweep, Tack and Roll
2	Manufacturer-mounted lights on sweeper, tacker ,and roller and roadway lighting	0.67	1.49	0.52	
3	Manufacturer-mounted lights on sweeper, tacker, and roller and trailer mounted lighting	0.45	2.20	0.77	
4	Manufacturer-mounted lights on sweeper, tacker and roller, roadway lighting and trailer-mounted lighting	0.78	1.28	0.45	

The normalized factors were used in the discrete event simulation model to obtain the operation productivity under different lighting conditions. The following section describes the development of the discrete event simulation of the paving operation.

5.2 The simulation model and animation of the nighttime paving operation:

The asphalt paving operation was modeled using the discrete event simulation software STROBOSCOPE (Martinez 1996). The elements that make up the model were described in Chapter 3. While the simulation is running, commands are written to a trace file, which are later used to animate shapes created in MS Visio using the Vita2D post processing animation software (EZStrobe 2009). This section describes the data collection process for the simulation model, the development of the simulation model, and the animation of the asphalt paving operation.

5.2.1 Data Collection and Preliminary Analysis

It was decided to collect activity duration data for the mill and pave activities since lighting was a critical component for these activities, as they required the operators of the respective equipment to judiciously align the path of the machines so that it was aligned with the existing lane of road. Since the two activities are continuous by nature and were going to be modeled in discrete event simulation software, it was necessary to break up the continuity of the operation into small discrete bits. On this project, white poles were planted in the median at a distance of 100ft apart. Hence, for the sake of convenience of collecting data, it was decided to collect the time taken to mill and pave 100 feet of pavement. The data collected during the site visits conducted on July 9 2009, and August 25, 2009 were used to generate the distributions. The objective during both visits was to pave approximately two miles of shoulder on I-65 South.

The data collected is included in Appendix D. In order to fit the data to distribution so that it later can be used during simulation, it was necessary to determine if the data were Independent and Identically Distributed (IID) (Martinez 2009), which means that the data collected need to be independent of each other and come from the same distribution. If the data are not IID, then the underlying reasons need to be understood so that it then can be modeled appropriately (i.e., the data need to be explained in terms of other variables that are IID and the state of the model). The IID nature of the data can be assessed using auto correlation plots and by comparing ordered and randomized scatter plots of the data. The following section describes the nature of the data collected and the analysis done in order to use the data in the simulation model.

Two hundred thirteen (213) data points were collected for the mill activity. Each data point represented the time that it took for the milling machine to traverse the distance of 100 ft between the white poles planted on the median. A visual examination of an ordered plot of the data (Figure 3.6) showed that there seemed to be two different sets of data.

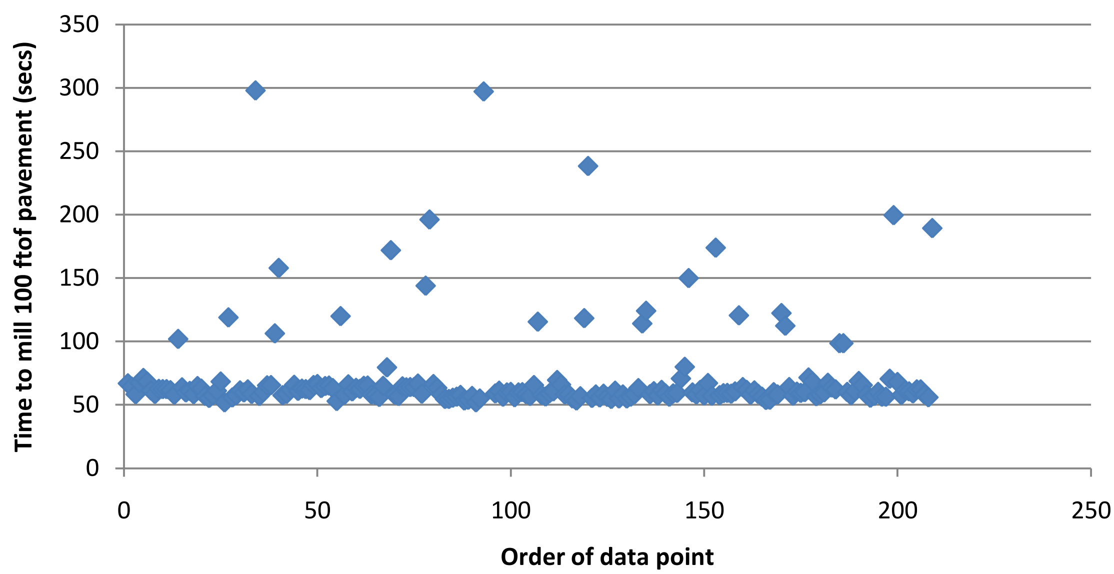


Figure 5.1: Ordered Plot of milling data

The presence of outliers in the data could be explained by the fact that the time that was measured also included the time that the milling machine stopped in the middle of the activity or slowed down. Since the milling machine and the milling truck had to work and move in a synchronized manner, there were times when the miller had to slow down and even come to a halt, when the truck had to align itself with the milling machine and when a truck was almost full. Hence, the outliers in the data were selected by identifying data points that were collected when a break in the above nature occurred. These data points were separated from the other points and they were analyzed separately. It was found that there were 25 of these "extraordinary" points and 188 of the data points collected under normal conditions of the milling activity.

On subjecting the 25 points of data that were collected when there was a break in the operation to the same analysis, the coefficient was found to be -0.08. At this value, it is reasonable to assume that the data is uncorrelated.

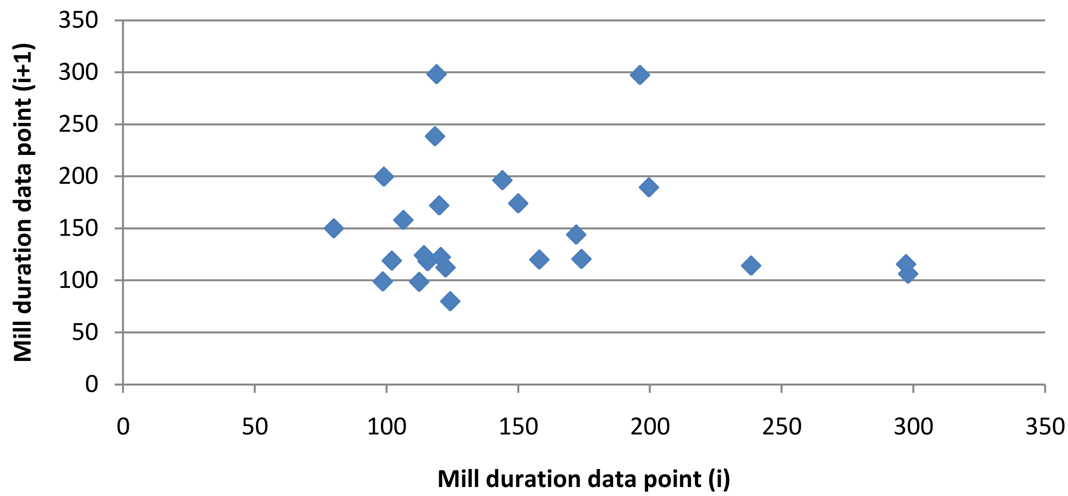


Figure 5.2: Scatter plot of mill duration with breaks

The data set was analyzed after removing the outlier data points. A visual observation between a random and an ordered plot of the data revealed that there was a discernable trend in the ordered plot, which meant that the data could be correlated.

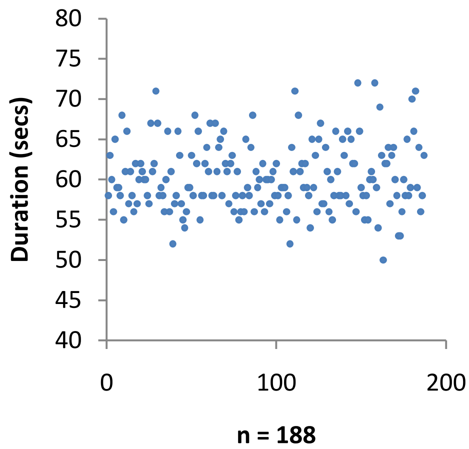


Figure 5.3: Random plot of milling durations

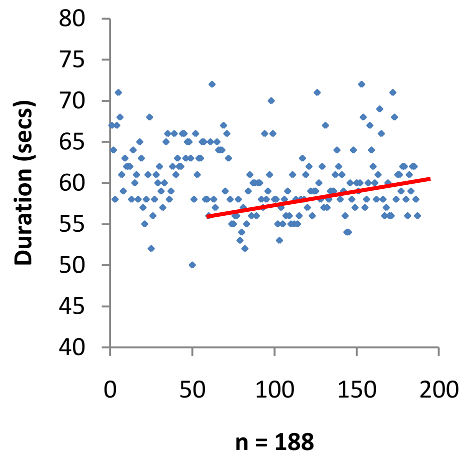


Figure 5.4: Ordered plot of milling durations

A correlation plot was plotted with the data by using the correlation coefficients at different lags as the data points. It was found that the coefficient exceeded the limit of correlation for 188 points (Cryer and Chan 2008) as seen in the correlation plot below.

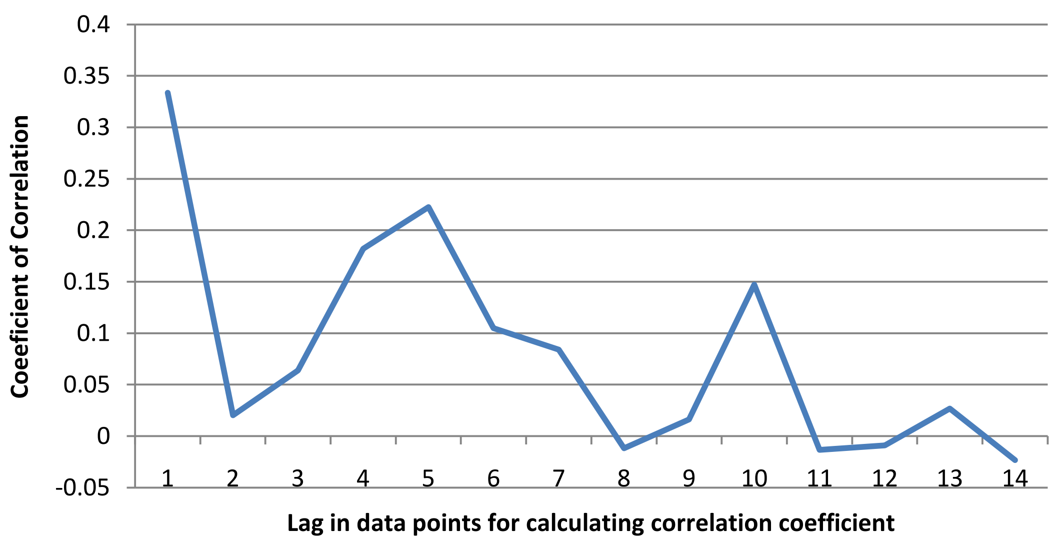


Figure 5.5: Correlation plot for milling data

The lag 1 correlation coefficient for the data was 0.382, which is greater than the acceptable limit for the coefficient of correlation, which is 0.145. This indicates that the data are correlated, which is to be expected, as the activity that is being modeled here is of a continuous nature and it is therefore natural that consecutive data points will be related to each other in some way. This is punctuated by random occurrences where the milling machine slows down considerably or even comes to a halt, which result in the high valued data points that occur. On further examination, it was found that the outliers occurred during the times when the milling machine had to slow down. This occurred whenever an empty truck had to position itself in front of the miller or when the miller had to stop due to unforeseen circumstances. These conditions were already incorporated into the model and it was hence necessary to ensure that whenever a truck was positioning itself in front of the miller or whenever the miller had broken down, the distribution built from the outliers would be used for the duration of the milling activity.

In the case of the paving activity, the data that were collected during the August 25, 2010 visit were used in the simulation model. The data were collected for the paving of a total of 3,100 feet of pavement. The difference between the pave and mill activity is that the continuity needs to be maintained for the proper execution of the pave activity. If the paving were to stop or slow down, the HMA mix that is lais down will not be uniform throughout. To ensure minimal disruptions to the pave activity, there is a material trasfer vehicle that moves in front of the paver and feeds it with HMA at a steady rate. Since the trucks dump the HMA into the material transfer vehicle, the problems that used to cause disruptions in the mill activity are negated. Hence, the paving is carried out at a steady rate.

The duration varied from 98 seconds to 158 seconds and had a mean of 120 seconds. On inspection of the data collected (included in the appendix), the correlation was found to be 0.387. The correlation limit for this set of data was calculated to be 0.359 (based on 31 observations). The high value shows that the data are indeed correlated and cannot be considered to be IID. This is true given that the operator tries to maintain the speed of the paver to be constant in order to lay the HMA properly. In order to be able to model the operation correctly and factor in the variation of the data, it was necesssary to understand the nature of the activity. On interaction with the operator of the paving machine, it was found that, although he tries to maintain a steady speed, there are indeed fluctuations in the speed that are caused by the varying conditions in the work zone. Since these fluctuations are independent, they could be synthesised using a probabilistic distribution.

In order to do this, the fluctuation were determined from the data by subtracting the (i+1) th value from the ith value. This provides the difference in the time it takes to pave consecutive stretches of 100 feet. This variation was found to have values ranging from -40 seconds to +56 secs. The correlation coefficient for this data was found to be -0.269, which is lower than the limit calculated earlier. It is therefore possible to model the paving operation by generating random values and adding them to the duration of the previous instance of the paving activity.

5.2.2 Interviewing Workers on Site

Interviews were conducted with the workers on site to extract useful information about the various activities. This process, known as probability encoding (Spetzler and Von Holstien 1975, Martinez 2009), seeks to quantify an expert's knowledge of an activity and can yield much more useful information than can be obtained from limited field observations. It was decided to pursue this line of obtaining information about the sweep, tack, and roll activities as these were activities that were performed solely on the basis of the operator's judgment. For instance, the sweep activity was carried out after the miller had milled about 100 to 200 feet and the sweep machine was sitting idle. Hence, there would be times when the machine would be idle while it waited for a sufficient length of pavement to be milled before it started sweeping away the milled debris. This distance was determined by the operator of the sweeping machine based on past experience and based on the speed with which he could sweep away the debris and prepare the pavement for the tacking truck. As an example, a construction worker may not be able to provide the duration of the time it takes for the milling machine to fill a truck with milled concrete. However, by framing the questions in an effective and simple way, it is possible to glean information that could help determine the distribution.

It was first required to "condition" the interviewee to ensure that his answers anchored on recent experiences with performing the activity. Also, it was necessary to remove any bias that the interviewee might have towards answering the questions by communicating to him the nature of how the information will be used. Once the interviewee was thus conditioned so as to remove any bias that might be present, appropriately framed questions were asked which could yield valuable information about the activity. For instance, with the above example, questions could be of the following nature:

- "How long does it usually take for the miller to fill a truck?"
- "Do you think that there is a lot of difference in the time it takes to load different trucks of the same capacity?"
- "What is the shortest time that it has taken to fill the truck that you have noticed?"
- "Have there been times when you had to stop the miller, due to some situation that was beyond your control, and if so, does it happen often?"

The answers to the first and second questions could reveal the mean and spread or standard deviation of the distribution. Similar questions could be used to determine the mode. The information that was obtained in the above described manner included the distance or lead that was given to the equipment in front of the sweeper, tacking truck, paver, and roller before starting to perform the respective activity and the speeds at which the equipment is operated. One must be careful, though, while using the information extracted from these interviews, as the minimum and maximum values observed by a person cannot be the absolute endpoints of the distribution, but are, rather, the 5th and 95th percentiles of the distribution (Perry and Greig 1975). Information about the operation that was gleaned in this manner is summarized in Chapter 4.

Technical specifications about the equipment were determined by studying the technical literature of the machine, which is available on the companies' websites and by interviewing the operators of the respective equipment. The websites also contained the drawings of the equipment, which were used to develop shapes to represent the equipment in the 2-D animation. The development of these shapes was discussed in Chapter 4.

5.2.2.1 The discrete event simulation model

The simulation model was broken down into different sub-networks based on the resource that flows through the particular network, which was done for the sake of convenience in explaining the flow of the different types of resources throughout the model. Table 4.1 lists the different resources that are used in the model:

Table 5.3: List of resources used in the model

S.No	Name of resource	Description	Type of Resource	Total Amount/Quantity and units
1	Length	Length of the road	General	12,000 feet (4000 m)
2	Amount	Amount of milling and asphalt	General	NA
3	MTruck	Truck used for hauling milled asphalt	Characterized	5
4	ATruck	Truck used for hauling fresh hot mix asphalt	Characterized	5
5	MillMach	Milling Machine	Characterized	1
6	SweepMach	Sweeping Machine	Characterized	1
7	TackMach	Tacking Truck	Characterized	1
8	PaveMach	Asphalt Paver	Characterized	1
9	MTV	Material Transfer Vehicle	Characterized	1
10	RollMach	Rolling Compactor	Characterized	1
11	Loader	Loader at the asphalt plant	Characterized	1

5.2.2.2 Flow of the 'Length' Resource:

The *Length* resource refers to the length of the road that is to be paved and is expressed in terms of linear feet. Table 4.2 lists the various user-defined variables that are used in this network, which are related to the *length* resource.

Table 5.4: List of User Defined Variables in the Network

S No	Name of Variable	Description	Value
1	nTotLenFeet	Total Length of road to be paved.	12000 ft (4000 m)
2	LnthPerPaveFt	Length that is performed in one instance of the activity.	100 ft (33.3 m)
3	MinSweepLength	Lead given by the sweeper to the miller.	Uniform[100,150] ft
4	MinTackLength	Lead given by the tacker to the sweeper.	Uniform[100,150] ft
5	MinPaveLength	Lead given by the paver to the tacker.	Uniform[100,150] ft
6	MinRollLength	Lead given by the roller to the paver.	Uniform[100,150] ft
7	SpeedMiller	Speed of the miller.	100 ft/min
8	SpeedSweeper	Speed of the sweeper.	Uniform[60,70] ft/min
9	SpeedTacker	Speed of the tacker.	60 ft/min
10	SpeedRoller	Speed of the roller.	50 ft/min

The total length of the road that is to be paved is represented by the variable nTotLenFeet. In this case, we assume that the entire operation takes place by breaking up the bulk resources into discrete parts expressed by the variable LnthPerPaveFeet. The variables MinSweepLength, MinTackLength, MinPaveLength, and MinRollLength refer to the lead given by the various machines to the machine that is immediately preceding them. This distance is subjective and based mostly on the operator's judgment, but the values used above were the most commonly cited values by the operators. The variables SpeedMiller, SpeedSweeper, SpeedTacker, SpeedPaver, and SpeedRoller represent the average speeds of the different equipment. These variables are used to calculate the duration of each activity. Figure 4.1 shows the network through which the Length resource is being passed.

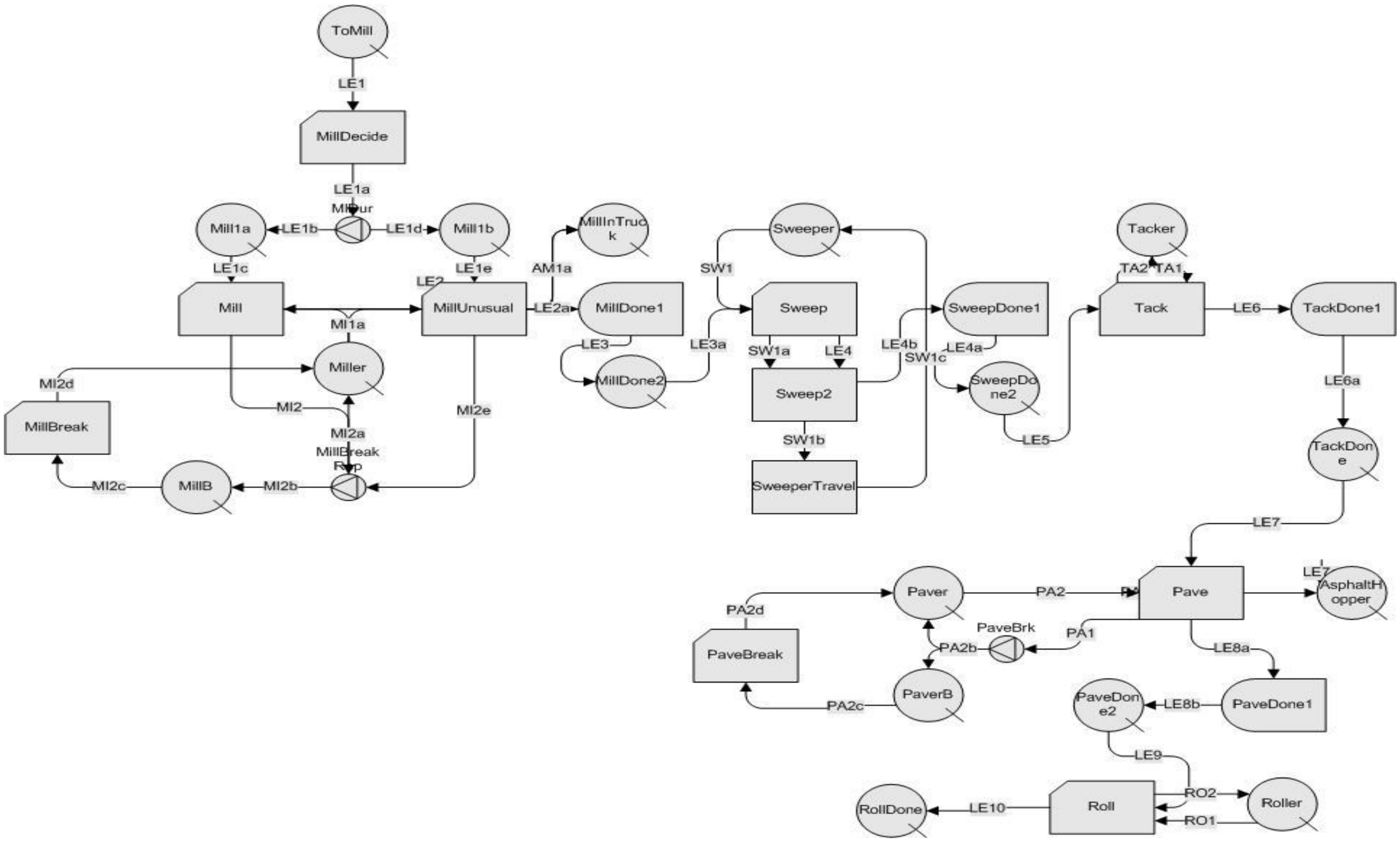


Figure 5.6: Flow of the Resource Length

5.2.2.2.1 "Mill" Activity

The queue called "ToMill" is first initialized with the variable "nTotLenFeet." All the equipment required to perform the activities in the network reside in the queues that bear their names: "Miller," "Sweeper," "Tacker," "Paver," "MTV," "Roller." These queues are initialized with one characterized resource each at the beginning of the simulation.

On analysis of the duration data that were collected for the time that it takes to mill 100 feet of pavement, it was found that the data belonged to two different distributions, which was explained in the data collection section in Chapter 3. It was established that the majority of the data points were collected when there was no break in the milling activity and when the miller was operating at its usual speed. However, there were instances when the miller had to slow down and/or stop for a few seconds, which resulted in the time taken to mill 100 feet of pavement becoming significantly larger than usual. These instances caused the outliers in the ordered plot of the duration data. As described in Chapter 3, distributions were built for both the usual and unusual circumstances of the milling activity. It was noted that these unusual times occurred during the times when the truck was taking its position in front of the miller and whenever the miller was starting from rest. This was modeled appropriately, mimicking the real world when the mill activity was subject to the unusually long durations when the was positioning itself in front of the miller and when the miller slowed down.

Initially, there are a sufficient number of resources in both queues that precede the "MillDecide" combi, allowing it to be instantiated. An amount of the length resource equal to a random number from the distribution variable LnthPerPaveFt is drawn from the ToMill queue. And the sole characterized resource is drawn from the "Miller" queue. The "MillDecide" activity decides which activity will occur by using a probability fork. At the conclusion of the instance of the mill activity, the amount of the "Length" resource is released into the "MillDone1" consolidator and the characterized resource of the MillMach type is released back into the "Miller" queue. Having the miller reside in a separate queue is important as it prevents multiple instances of the "Mill" activity from starting simultaneously. The "MillDone1" consolidator collects the resources until the amount of the resources of type "Length" is greater than the minimum distance required before the succeeding "Sweep" activity can start. Once this condition is reached, all of the resource is passed on to the "MillDone2" queue.

5.2.2.2.2 "Sweep" Activity

It was observed that the sweeper does two passes of the sweeping activity, one in either direction of the road before following the miller. The sweeping activity is modeled using one combi and two normal activities. When there is enough resource in the "MillDone2" queue and an idle resource in the "Sweeper" queue, the "Sweep" activity can be initiated. Once this activity is completed, the "Sweep2" normal, which represents the second pass of the sweeping process, is initiated. Once the "Sweep2" activity is complete, the sweeper resource is released back to the "Sweeper" queue and the amount of the "Length" resource is passed on to the "SweepDone1" consolidator, where it is consolidated until it exceeds the minimum distance before the "Tack" activity can start.

5.2.2.2.3 "Tack" Activity

The "Tack" activity takes place in the same way as the "Mill" and "Sweep." Once the "Tack" activity is complete, it releases the sweeper resource back to the "Tacker" queue and the amount of the "Length" resource is passed on to the "TackDone1" consolidator, where it is consolidated until it exceeds the minimum distance before the "Pave" activity can start.

5.2.2.2.4 "Pave" Activity

Duration data were collected for the paving of 100 feet of pavement similar to the data collected for the milling of the pavement. The analysis of the data and the method used to obtain the duration of each instance are described in Chapter 3. The following are the conditions to be fulfilled for the paving to be performed.

a) There is sufficient amount of "Length" resource in the TackDone2 queue.
b) The paver is idle in the "Paver" queue (i.e. there is no instance of "Pave" happening at the moment).
c) There is a sufficient amount of asphalt in the hopper of the material transfer vehicle. This is represented by the "AsphaltHopper" queue.

If all of these conditions are satisfied, the "Pave" activity can begin. At the start of the pave activity, it draws resources from the "Paver," "TackDone2," and the "AsphaltHopper" queues. The amount of resource that is drawn from the "AsphaltHopper" queue is measured in terms of cubic feet and it is calculated by multiplying the cross sectional area of the road being paved by the length of road that the particular instance of the activity is paving. It is of the resource type "Amount". The duration of the activity is calculated by dividing the length of road being paved with the speed of the paver. When the "Pave" activity is complete, the combi releases one characterized resource into the paver queue and the length paved into the "PaveDone2" queue.

5.2.2.2.5 "Roll" Activity

The "Roll" activity takes place when there is enough "Length" resource in the "PaveDone2" queue and there is a roller idle in the "Roller" queue. It is again very similar to the "Sweep and "Tack" activities. On the completion of the "Roll" activity, the amount of the "Length" resource that was in the "Roll" activity is released into the "RollDone" queue.

This marks the end of the network that uses the "Length" resource. The condition given in the model to end the simulation is that the amount of "Length" resource in the "RollDone" queue reaches the objective length of the road that was to be paved.

5.2.2.3 <u>Flow of the "Amount" Resource:</u>

The "Amount" resource refers to the volume of asphalt that is involved in the operation. Table 4.3 lists the variables that are associated with this resource. Since this resource is carried by trucks, some of the variables will be associated with the trucks and the haul paths of the trucks.

Table 5.5: List of user defined variables in the "Amount" network

	Name of Variable	**Description**	**Value**
1	LaneWidthFt	Width of the lane that is being paved.	12 ft (4 m)
2	MillDepthFt	Thickness of the asphalt surface.	1.5" (3.75 cm)
3	SpeedTruck	Average Speed of the Truck.	3960 ft/min (1320m/min)
4	SpeedDumper	Average Speed of the Dumper.	50 cuft/min (1.8 m3/min)
5	MillTruckCapCuFt	Volume Capacity of the truck hauling the milled asphalt.	600 cu ft (22.2 m3)
6	AsphaltTruckCapCuFt	Volume Capacity of the truck hauling the hot mix asphalt.	600 cu ft (22.2 m3)
7	Actualhaulpathlength	Length of the haul road, from the work site to the asphalt plant.	52800 ft (17,600 m)
8	Actualreturnpathlength	Length of the return road, from the asphalt plant to the work.	63360 ft (21120 m)
9	nMTruck	Number of trucks used to haul milled asphalt.	5
10	nATruck	Number of trucks used to haul hot mix asphalt.	7

The value of the "Amount" resource is closely related to that of the "Length" resource, since "Amount" refers to the volume of milled asphalt generated after milling a certain section of the road, or the volume of hot mix asphalt required to pave a certain length of the road. Hence, the value of "Amount" is calculated from the following formula.

Activity.Amount.Count = *Activity*.Length.Count *MillDepthFt*LaneWidthFt cubic feet

Since the "Amount" resource refers to both milled asphalt and hot mix asphalt, each cycle will be described separately.

5.2.2.3.1 The Milled Asphalt and the Milling Truck Cycle:

Milled asphalt is generated after the completion of the mill activity. This material is dumped by the miller into the back of a waiting haul truck, here forward referred to as milling truck. Once the milling truck reaches its capacity of 20 tons, the truck hauls the milled asphalt to a dump site, which is located inside the asphalt plant, where it dumps the milled asphalt. After dumping the asphalt, the milling truck returns to the work site and waits in a queue until it can be filled. The milling activity then continues until the truck reaches its capacity, at which time it proceeds to the dump site and repeats the cycle. This operation is represented by the network shown in Figure 4.2.

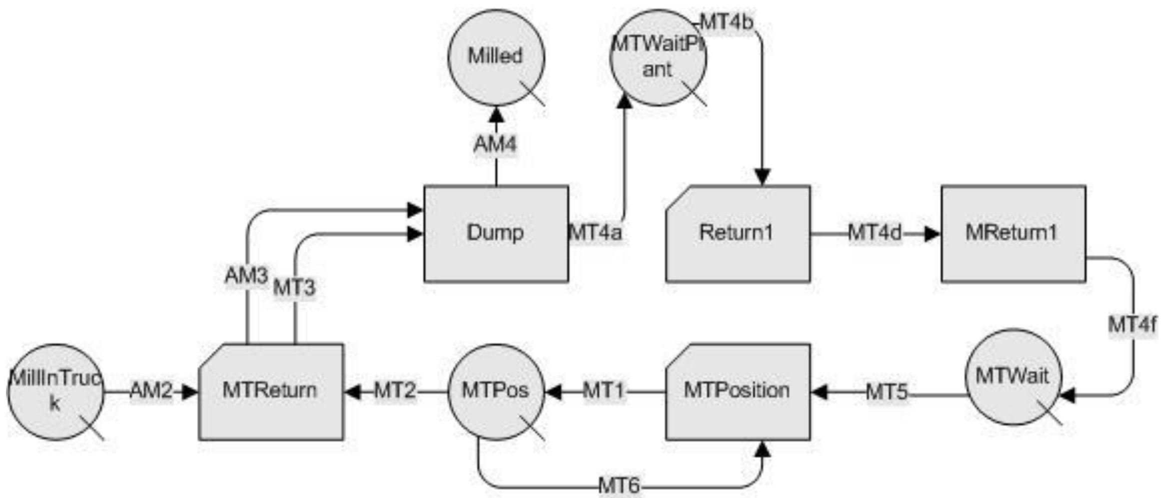


Figure 5.7: Milled Asphalt and Milling Truck Cycle

5.2.2.3.2 Positioning the truck:

Initially, all the milling trucks are initiated into the "MTWait" queue. The trucks that are not being filled by the miller or that are not on the haul road wait by the shoulder in front of the milling machine. The "MTPosition" activity selects the first truck in the queue and places it in front of the miller to be filled. The "MTPosition" activity can start only when there is no truck being filled by the miller and when there are idle trucks waiting in the "MTWait" queue. It is only when there is a truck in the "MTPos" queue that the mill activity can start. After each instance of the "Mill" activity, the "Mill" combi releases "Amount" resource to the "MillinTruck" queue. This represents the amount of milled asphalt that is in the truck that is being filled by the miller.

5.2.2.3.3 Hauling the Milled Asphalt to the Asphalt Plant:

Once the count of the "Amount" resource in the "MillinTruck" queue exceeds the capacity of the truck, the "MTReturn" combi is instantiated. This represents the hauling activity of the milling truck. The duration of this activity is calculated by dividing the distance of the haul road by the average speed of the truck. When this activity starts, the value of the "Amount" resource in the "MillinTruck" queue is set to zero, so that the counter can start for the next truck that enters. Also, the sole resource from the "MTPos" queue is removed, which triggers the start of the "MTPosition" activity, provided there are trucks waiting to be loaded.

5.2.2.3.4 Dumping the Milled Asphalt and Returning to the site:

The "Dump" activity represents the act of the milling truck dumping the milled asphalt at the asphalt plant. After dumping the milled asphalt, the truck returns o the construction site. This is represented by the MReturn1 and the Return1 activities. The return activity is divided into two different activities to separate the travel on the haul road and travel in the construction work zone. The distance along the return haul path remains the same throughout, but the distance that the truck has to travel inside the work zone increases as the miller keeps moving along the roadway in the work zone. Once the truck reaches the miller in the work zone, it joins the end of the queue of trucks that are waiting on the shoulder for their turns to get filled. This is represented by the milling truck resource being released into the "MTWait" queue at the end of the "MReturn1."

5.2.2.3.5 The Hot Mix Asphalt and the Asphalt Truck Cycle:

The hot mix asphalt is produced at the asphalt plant and is used to surface the road. The hot mix asphalt is transported from the asphalt plant by a fleet of dedicated 20-ton trucks to the work site. Once it reaches the worksite, the trucks dump the asphalt into the hopper of the material transfer vehicle, which has a conveyer belt that will feed the paver at an approximate rate of 2 tons/minute. The paver moves closely behind the material transfer vehicle and it paves the road as it moves along. Figure 4.3 illustrates the cycle of the hot mix asphalt and the asphalt trucks:

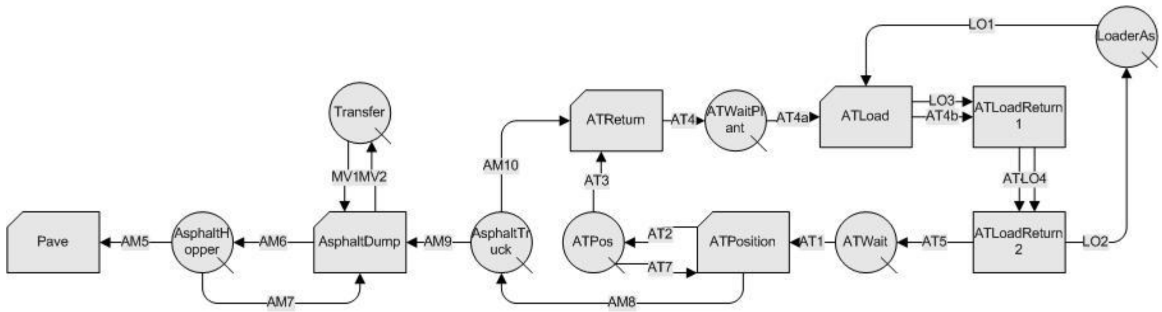


Figure 5.8: Hot Mix Asphalt and Asphalt Truck Cycle

5.2.2.3.6 Loading the asphalt at the plant:

The cycle starts at the asphalt plant, where the asphalt is loaded into the truck. The queue called "ATWaitPlant" is initialized with the "nATruck" number of trucks. The fleet of trucks usually contains about seven to 10 trucks that are used to transport asphalt to the site. However, not all of them are loaded at the same time.

5.2.2.3.7 Hauling the asphalt to the work site:

Once the asphalt truck is loaded with asphalt, the truck starts hauling it to the work site. This is represented by the activities ATLoadReturn1 and ATLoadReturn2. The haul activity is represented by two normals to break up the haul path into a fixed length and the variable length. The length that the truck has to travel inside the work zone increases as the paver keeps moving along the work zone. Once the truck reaches the work zone, it joins the queue of trucks that are waiting to load the material transfer vehicle. In the simulation model, this is represented by the queue ATWait.

5.2.2.3.8 Positioning the Truck to Dump:

When the truck that is currently dumping the hot mix asphalt into the material transfer vehicle has completed this task, the truck that is waiting at the beginning of the queue slowly moves and positions itself to dump the hot mix asphalt into the material transfer vehicle. This is represented by the activity ATPosition and ATPos. The ATPosition activity takes place only when the ATPos queue is empty (i.e., after the truck that was dumping the hot mix asphalt into the hopper of the material transfer vehicle has finished dumping and starts to return to the asphalt plant. After the ATPosition activity takes place the activity releases one

"Amount" of resource in to the ATPos queue. This is to prevent other trucks waiting in the queue from positioning themselves in front of the material transfer vehicle. It also releases the "Amount" resource to the "AsphaltTruck" queue, which contains the amount of asphalt that is in the truck that is currently dumping hot mix asphalt into the material transfer vehicle.

5.2.2.3.9 Dumping the Hot Mix Asphalt:

The activity that takes place after positioning the truck is the "AsphaltDump" activity, which represents the dumping of the hot mix asphalt into the hopper of the material transfer vehicle. For this activity to take place, it is required that there is enough space in the hopper to accommodate the new material, there is enough asphalt in the truck , and there is a truck positioned in front of the material transfer vehicle. Also, to ensure that this activity does not takes place multiple times simultaneously, there is another queue representing the material transfer vehicle, which is initiated with one resource that is used in the start of the "AsphaltDump" and the returned to the queue once the activity is over. The "Amount" resource that is dumped into the hopper is added to the "AsphaltHopper" queue, which indicates the amount of hot mix asphalt that is available in the hopper of the material transfer vehicle which can be used for paving.

5.2.2.3.10 Asphalt Truck Return:

The asphalt truck returns to the asphalt plant to get loaded with fresh hot mix asphalt after it has dumped all the hot mix asphalt into the hopper of the material transfer vehicle. The "ATReturn" activity represents the return of the asphalt truck to the asphalt plant. This happens when the count of the asphalt in the "AsphaltTruck" queue is less than 2 cubic feet, which indicates that the truck is also empty. The "ATReturn" activity also removes resource from the "ATPos" queue, which allows the "ATPosition" activity to take place. At the conclusion of the "ATReturn" activity, the truck resource is released into the "ATWaitPlant," where the truck waits to get loaded with hot mix asphalt.

5.2.3 Animation of the Operation:

An animation of the operation described in Section 3.3 was created using Vita2D, a scripting language that is used to animate shapes in Microsoft Visio. This is done by writing Vita2D commands during the simulation. These commands are written to a text file which will be used as a trace file to manipulate the properties of various shapes in the Visio page.

5.2.3.1 Creation of Shapes in Visio:

The first step in animation is the creation of the shapes in MS Visio that represent elements of the work zone and the equipment used in the operation. MS Visio has a number of drawing tools that can be used to prepare 2D shapes.

5.2.3.1.1 Creating the Work Zone:

The paving operation modeled in this study was conducted on one lane of a two-lane interstate road. The dimensions of the road in MS Visio correspond to the standards specified by the American Association of State Highway and Transportation Officials (AASHTO). The width of each lane is 12 feet and the median width is 30 feet.. For the sake of representing the highway is a manner that is convenient to view on the screen, the scale of 1:5 has been used in the X- axis and a scale of 1:10 has been used along the length of the road. Also, the road has been drawn as a curved path with seven alternating straight and semicircular segments. This has been done in order to fit the plan view of the road on the computer screen. Figure 4.4 shows the plan view of the road as developed for the tool in MS Visio.

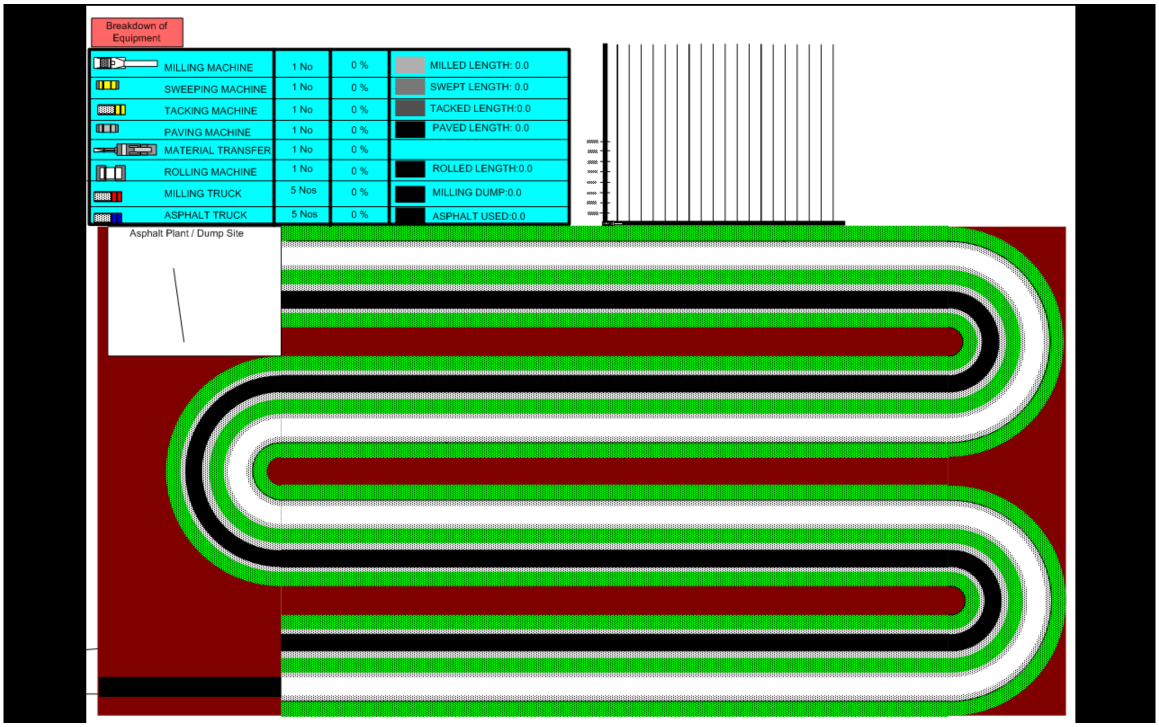


Figure 5.9: Diagram of road developed in MS Visio

The right lane, shown as white in color, is the lane that is to be paved. As the operation progresses, the color of the lane changes depending on what activity has been completed over that length of the road. Table 4.4 lists the colors that the lane changes into and the stage of the operation that it represents.

Table 5.6: Colors that represent the various stages of completion of the paving activity

Color	Activity
	Milling completed
	Sweeping of the debris completed
	Applying the tack coat completed
	Paving completed
	Rolling and compaction completed

5.2.3.1.2 Creation of the Construction Equipment shapes in MS Visio:

During the site visits, the details of the construction equipment that were used to perform the various activities were noted. The dimensions of these pieces of equipment were acquired from the manufacturers' websites and these specifications were used to create the two-dimensional shapes in MS Visio. This section describes the shapes that were created in MS Visio to represent the various types of equipment that were used in the operation.

Master copies of all these shapes were created by dragging the shapes onto the MS Visio shape stencil. This is done so that instances of these master shapes could be created using the CREATE command in Vita2D, which is written to the trace file initially:

CREATE *ObjectName MasterName X Y*

Eg: CREATE miller1 miller 0 0

The above command creates a shape called "miller1" from the master shape called "miller" and places it at (0,0) n the drawing.

5.2.3.1.3 Creating Paths in MS Visio:

One-dimensional paths, along which the hauling trucks will travel, are created in MS Visio. The paths can be created using the one-dimensional drawing tools that are available in MS Visio. The tools that were used to create the path include the line tool, the arc tool, and the free-form tool. The shapes were then named and later these names were associated to other path names using the PATH command in Vita2D.

PATH P*athName ShapeName*

5.2.3.2 Creating the Trace File for the Animation:

A trace file is generated while the STRBOSCOPE model is running and contains the commands that are used to create and animate shapes in the MS Visio drawing. This trace file is a text document that is created at the beginning of the simulation. Commands are written to this trace file by printing Vita2D statements preceded by the time of the simulation at which that command should be executed in the animation. The following command ensures that every time the simulation clock advances, the statement shown below is executed:

AFTERTIMEADVANCE PRINT V2D "TIME %.2f\n"SimTime;

V2D is the handle to the text file to which we are printing the trace commands. The "%.2f" indicates that a floating point number rounded off to two decimal places is added to the statement. At the start of the simulation (i.e., when the SimTime =0.00 sec, the following line is written into the trace file):

TIME 0.00

The following example illustrates how commands are written to the trace file.

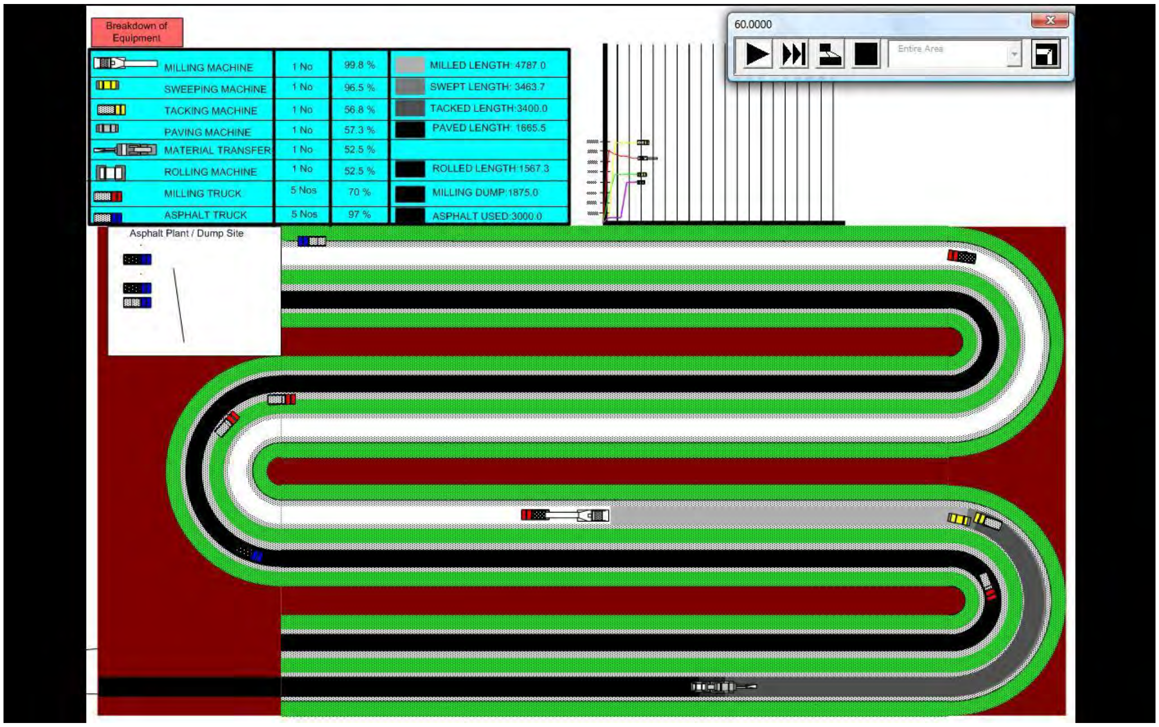
ONSTART Mill PRINT V2D "DYNUPDATECELL stat User.milled %.3f FROM %.3f TO %.3f\n" Mill.Duration millerst milleren;

"ONSTART Milll" indicates that this command is executed every time that the Mill Activity starts. The words "millerenst" and "milleren" are variables that taken up different values during the course of the simulation. If the Mill activity starts at SimTime=4.56 secs, the following line is written to the trace file:

TIME 4.56

DYNUPDATECELL stat User.milled 5.332 FROM 10.123 TO 15.231

The above command DYNUPDATECELL updates the value of the cell from 10.123 to 15.231 over a time 5.322 seconds starting at 4.56. This is how various commands are written to the trace file. The following figure shows a snapshot of the animation:



5.10: Snapshot of the Animation

5.2.3.3 <u>Verification and validation of the animation</u>

It is essential that the simulation model and the animation developed are subject to the twin process of verification and validation to ensure that they are a true representation of the system that was modeled and that the results obtained serves the purpose for which the model was built. This section discusses the steps taken to verify and validate the models developed.

Verification is the process that is performed to ensure that the developed model is a true representation of the system as perceived by the modeler. Debugging the model to identify logical errors is the most important part of the verification process. The animation developed helped greatly with the debugging as it visually enabled s the modeler to identify inconsistencies between the model and the real world system. The multiple site visits also greatly contributed to the verification of the model by increasing the understanding of the operation and allowed for changes to be made in the model.

Validation is the process of comparing the verified model with real world system that was modeled. The comparison is done with respect to the logic used in the model, the input parameters, the assumptions used and the output parameters (Martinez 2009). The logic used in the model is compared to the real world system to ensure that the operation performed in the model is as it is performed in the real world. A very important assumption that was made in the development of the simulation model of the paving operation is that the continuous activities of milling and paving are considered to be discrete events. Hence, the duration of each instance of the activity is dependent upon the length that was being milled or paved respectively.

It must be ensured that these input variables are a inputs to the model are a true representation of the corresponding values that can be observed during operation in the real world. The output of the model must represent what can be expected out in the real world. However, there will be a variance in the outputs of multiple simulation runs due to the uncertainty that has been modeled into the simulation model with the use of probabilistic distributions. Hence, it is important to understand and recognize this variability in the output (Martinez 2009). Since various lighting configurations are being compared in the model, the outputs for different lighting configurations must reflect the effect of the particular configuration on the operation productivity.

For the validation of the model, it is essential to bring in Subject Matter Experts (SMEs) to examine and corroborate the model. The model of the operation can be effectively communicated to the stakeholders by displaying the animation of the model. The SMEs can also check the validity of the input and output parameters. Visits were conducted to the Milestone office in Indianapolis and Lafayette, where the animation and the model was demonstrated to workers and the project managers, who provided the researchers with recommendation on how to improve upon the model.

The verification and validation of the paving operation model can be discussed in terms of the following four attributes (Aegis Technologies Group 2007):

a) Completeness: The developed model represents the complete paving operation, from the start of the milling activity to the finishing of the rolling activity. It does not consider the placement and removal of traffic control devices and channelizing devices at the start and on the end of the operation. All activities performed are modeled and entities that are involved with the activities are represented in the model.

b) Consistency: The elements and activities in the simulation model are consistent in the use of dimensions and units. Also, there is a consistency in the animation with regards to the scale and the coordinate system of the objects in the animation.

c) Coherence: No part of the model is extraneous and every item that is represented in the model is relevant to the model.

d) Correctness: The model was checked for correctness in the use of its logic, input parameters, assumptions and output parameters. The model was verified and validated to ensure that it was a true representation of the paving operation observed.

Visits were conducted to the offices of Milestone in Lafayette and Indianapolis to demonstrate the lighting tool and the simulation model to Subject Matter Experts. The SMEs were then asked to rank the model and the results, mentioned above on an opinion scale ranging from Strongly Agree to Strongly Disagree. Table 5.7 summarizes the response obtained from the SMEs. All of the SME's selected either "Agree" or "Strongly Agree" to the test of completeness, consistency, coherence and correctness of the model.

Table 5.7: Results of verification and validation visits

Criterion	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Completeness	1	5	0	0	0
Consistency	4	2	0	0	0
Correctness	2	4	0	0	0
Coherence	2	4	0	0	0

5.2.4 Results of the simulation

The objective of the regression analysis and the simulation model is to quantify the impact of different lighting scenarios on the operation productivity and to compare the values obtained from the productivity across the different lighting scenarios. The normalized LDFs for four different lighting scenarios were incorporated into the duration of the respective activities and the simulation was run to achieve the above objective. The probability that a particular lighting scenario resulted in a higher productivity level than that achieved under another scenario was calculated for different pairs of the lighting scenarios obtained. This section discusses the process undertaken to compare the productivity of the operation under the different lighting scenarios.

5.2.4.1 Setting up the model

It was necessary to synchronize the simulation runs by using Common Random Numbers (Law and Kelton 2000, Martinez 1996) in order to compare the productivity levels between the different alternatives that were available. This process ensures that the differences that may be observed in the productivity levels of the operation across the various lighting scenarios are caused due to the effect of the lighting scenario and not due to the fact that the productivity levels that are being compared were obtained under different conditions. In order to achieve the synchronization of the model across the different alternatives, it is necessary that all the probabilistic distributions in the model sample the same set of random numbers.

This is implemented in the STROBOSCOPE model by specifying a seed for the model and specifying different streams for the various distributions. In order to to preserve the independence of subsequent replications of the model, it is necessary to ensure that the random numbers sampled do not overlap with those generated during the previous runs. This is implemented in the model by offsetting the seed by *n**100,000 positions, where *n* is the number of the streams used in the model. Each stream is allotted 100,000 random numbers and offsetting the seed would ensure by a sufficiently large number of positions that the random numbers that are retrieved during the simulation have not already been used by the succeeding stream.

It was necessary to run the simulation multiple times in order to obtain the expected value of and the variability of the productivity obtained. It was hence required to estimate the number of replications that would be required to obtain a 95% confidence interval that the standard deviation of the change in productivity across the various pairs of lighting scenarios would be less than 10%. Ten synchronized runs of the simulation model were conducted and the number of replications required to obtain a half width of 5% change in productivity was calculated. It was found that 109 replications were required. Hence, 109 sets of productivities were obtained for the four different lighting scenarios.

From the four different lighting scenarios that were tested, six different pairs of lighting scenarios were obtained. The ratio of the productivity of one scenario to the other was obtained for each run of the synchronized run and the histogram of the results obtained was plotted. From the histograms, the probability that a particular lighting scenario resulted in a higher productivity level than the other could be calculated by the area under the graph on either side of the unity abscissa

5.2.4.2 Results of Synchronised Simulation Runs

This section describes the results of the simulation model that was run to calculate the change in productivity obtained. As mentioned in the preceding section, the 109 synchronized replications of the simulation model were run for the four different lighting scenarios that were tested. Table 5.8 provides the 95% confidence interval of the productivity under the different lighting conditions.

Table 5.8: Summary of Synchronised Simulation Runs

Lighting Scenario	**95% Confidence Interval of Productivity (fpm)**
No General Lighting (1)	[25.81, 26.26]
Roadway Lighting (2)	[43.23, 44.56]
Trailer Lighting (3)	[33.14, 33.73]
Roadway and Trailer Lighting (4)	[46.42, 48.10]

The lighting scenarios will hitherto be referred to by the number provided in paranthesis. Table 5.9 summarizes the 95% confidence intervals of the ratios of the productivity between the different pairs of lighting scenarios, which is of interest to this research as it provides the comparison between the different lighting scenarios used.

Table 5.9: Summary of productivity ratios

Productivity of Lighting Scenario (i)/ Productivity of Lighting Scenario (j)	95% Confidence Interval of Ratio of Productivities
(2) / (1)	[1.65, 1.73]
(3) / (1)	[1.25, 1.29]
(4) / (1)	[1.75, 1.85]
(3) / (2)	[0.74, 0.78]
(4) / (2)	[1.04, 1.10]
(4) / (3)	[1.38, 1.46]

Table 5.9 provides the summary statistics of the ratio between the productivity levels obtained under different lighting scenarios. The ratios from the 109 simulations were tabulated and a histogram was plotted for each pair of lighting scenarios that were compared. The area of the curve to the left and right of the 1 on the x-axis (indicated by the red line) were calculated and used to find the probability that the productivity obtained under one lighting scenario was greater than or lesser than the other. Figures 5.11 to 5.17 show the distribution of the ratio of the productivity achieved under a particular lighting scenario to the productivity achieved under another lighting scenario.

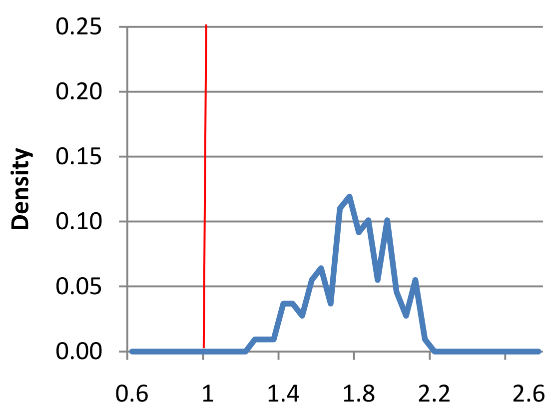


Figure 5.11: Productivity of (2) / Productivity of (1)

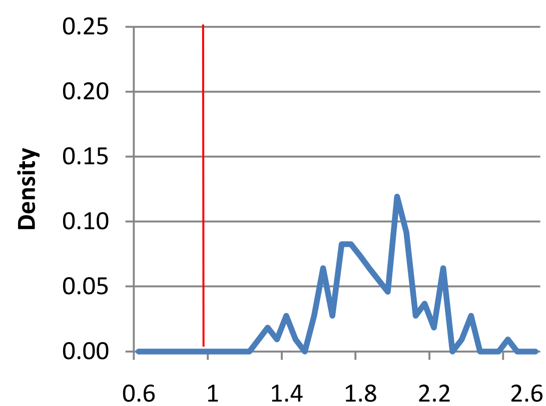


Figure 5.12: Productivity of (4)/ Productivity of (1)

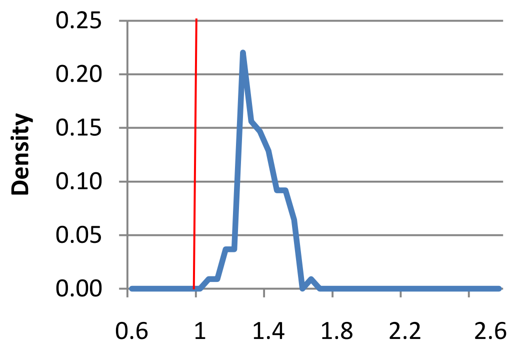


Figure 5.13: Productivity of (3) / Productivity of (1)

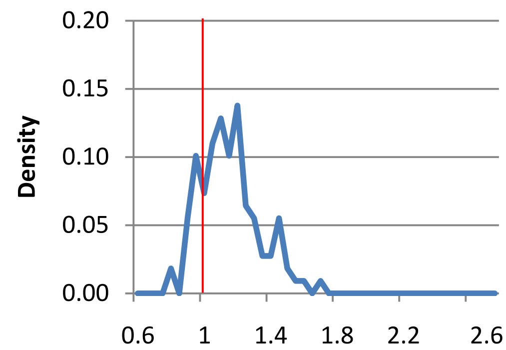


Figure 5.14: Productivity of (4) /Productivity of (2)

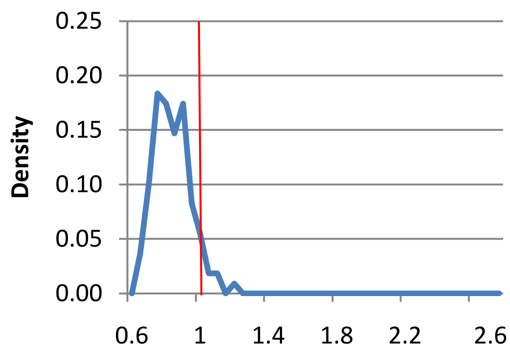


Figure 5.15: Productivity of (3) / Productivity of (2)

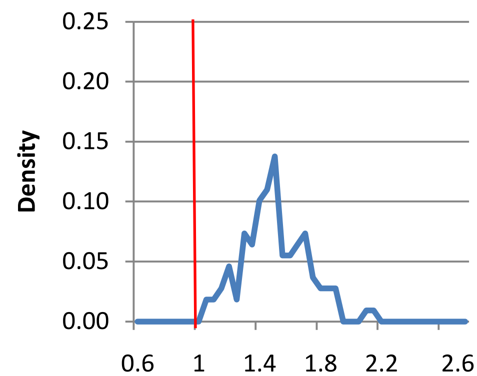


Figure 5.15: Productivity of (4) / Productivity of (3)

From Figures 5.11 and 5.12, it is clear that the curve is completely to the right of 1. This indicates that the productivity of scenarios 2 and 4 are always greater than that achieved when the lighting condition provided is scenario 1. In Figures 5.13 and 5.15, there is a small area under the curve that is to the left and right of unity respectively. This shows that there is a small chance that the productivity achieved with scenario 1 could be greater than that achieved with scenario 3 and that the productivity achieved with scenario 3 could be greater than that achieved with scenario 2. Figure 5.14 shows that a substantial area segment of the curve is located on either side of 1, which indicates that there is not much of a difference between the productivity achieved with scenarios 4 and 2. Table 5.10 provides the results of the pairwise comparison of the different lighting scenarios along with the conclusions that can be drawn from the analysis.

Table 5.10:Results of pairwise comparison of different lighting scenarios

Productivity of Lighting Scenario (i)/ Productivity of Lighting Scenario (j)	**Probability of (i) providing better productivity than (j)**	**Probability of (j) providing better productivity than (i)**	**Conclusion**
(2) / (1)	1	0	There is always a higher productivity in the presence of roadway lighting than when no general lighting is present.
(3) / (1)	1	0	There is always a higher productivity in the presence of trailer lighting than when no general lighting is present.
(4) / (1)	1	0	There is always a higher productivity in the presence of roadway and trailer lighting than when no general lighting is present.
(3) / (2)	0.02	0.98	98% of the time, the productivity achieved in the presence of roadway lighting is greater than that achieved in the presence of trailer lighting.
(4) / (2)	0.66	0.34	There is a 66% chance that the productivity achieved with roadway and trailer lighting is higher than that achieved with just roadway lighting.
(4) / (3)	0.99	0.01	99% of the time, the productivity achieved in the presence of roadway and trailer mounted lighting is greater than that achieved in the presence of trailer lighting.

The analysis performed above provides a comparison of the productivity achieved by the different lighting scenarios when compared in pairs. It is clear from the results of the analysis that scenario 4 provides the highest operation productivity level, followed by scenario 2.

5.2.4.3 Implications of the results

This section discusses the implications of the analysis performed and the possible methods which could be used to interpret and implement the results obtained. After the synchronized simulation runs were performed for the different lighting strategies that were tested, histograms of the ratio of expected productivities achieved by two different lighting scenarios were obtained (Figures 5.11 to 5.16). These histograms are of interest to a decision maker as it allows for the comparison of different lighting strategies from the perspective of the resulting change in productivity that can be obtained from the respective lighting scenario.

The results obtained could be considered to be valid and the methodology to be robust, if an individual with the power to make decisions regarding work zone lighting, would use these results as the basis for making a particular decision regarding lighting on the work zone. Such an individual would be interested in knowing if the extra expenditure spent on changing the current lighting strategy would be offset by a significant improvement in the productivity and subsequently the profitability of the operation. There are two methods which could be used to serve as a logical basis for making the above decision in the light of the results obtained.

The first method uses the expected profit as the basis for making a decision on whether to change from a lighting scenario to another. If a cost component can be associated with both the expenditure incurred during the change in lighting strategy and with the change in productivity, the expected value of profit can be computed from the histogram. This parameter could help in the decision making process regarding the selection of lighting strategy.

A decision that is based solely on the expected profit does not factor in the risk involved with the strategy. For example, while the expected productivity operation increases by seven percent (7%) when a change is made from scenario (2) to scenario (4), an observation of the variation in the data reveals that the there is a 34% chance that the productivity achieved with scenario (2) is higher. The variation in the data which can be observed in the histograms gives an idea of the risk involved in the decision making process.

The second method factors the risk attitudes of the decision maker in the decision making process (Howard 1976). Given two distributions with equal means, where the spread of one is substantially greater than the other, a risk averse person would choose the option with lesser spread as opposed to a risk seeker, as there is a greater certainty associated with the former option. Here the personal risk attitudes of the decision maker could be obtained as a utility function of the profitability associated with the productivity that can be obtained under different lighting scenarios. expressed in terms of its utility to the decision maker (Benjamin and Cornell 1970). Since the histograms enable the calculation of the probability of obtaining different productivities, it could be combined with the utility curve of the decision maker to calculate the expected utility of various alternatives in order to make an informed decision.

The above two processes could be performed using the results obtained from the proposed framework to analyze the impact of different lighting scenarios on operation productivity. Using the methods described above, a decision maker can make an informed choice regarding the lighting strategy to be followed on the work zone from the perspective of improving the opaeration productivity. The main limitation of the proposed methodology is that it assumes the relationship between the lighting provided and the duration of the activity to be defined only by the multivariate regression model that was developed based on the survey responses. A better understanding of this relationship, by considering the characteristics of the activity and of the equipment used to perform activity etc. would enable the modeling of the effect of lighting on the duration of the activity more accurately than the regression model. This would improve the reliability of the results and improve the credibility of the proposed methodology as a decision making tool.

5.3 Chapter Summary

This chapter described the methodology proposed to quantify the impact of different lighting scenarios on the productivity of nighttime operations by considering a case study. The regression analysis performed on the lighting and productivity data that were obtained from nighttime practitioners was described in the first section of the chapter along with the development of the Lighting Duration Factors (LDFs) for the different activities, depending on the type of lighting that was used. The next section described the methodology for the collection and analysis of data for the discrete event simulation model that was developed using STROBOSCOPE. The results of the simulation were discussed and the incorporation of the LDFs into the simulation model to obtain the productivity was explained. The analysis was used to compare the change in productivity obtained while considering different lighting scenarios. The implications of the data analysis was also discussed along with the importance of the histograms obtained as a decision making tool.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

This thesis analyzed the impact of lighting on the safety and productivity of workers in nighttime highway construction operations. The data collection process consisted of interviews with project managers, site foremen, and site workers, as well as a literature review of the commonly used construction lighting strategies and site visits. This process was used to develop a simulation model and a visualization of the work zone, which could be used to calculate the productivity of the operation according to the various lighting plans tested. Surveys which aimed to understand the perceptions of nighttime workers regarding the lighting of work zones were administered to contractors in Indiana and Illinois and the responses were analyzed statistically and econometrically. These surveys helped to identify important aspects of lighting in highway construction operations and to understand how it is possible to improve the safety and productivity of workers in nighttime highway construction work zones with regard to lighting.

6.1 Summary of the Research Process

The objective of the research was to study the effect of lighting in the work zone on the workers' perceptions of safety and productivity and to develop a methodology to incorporate the effect of lighting in the calculation of operation productivity of nighttime highway construction operations. In order to understand the perceptions of workers, a questionnaire was developed and administered to the workers who had worked both during the day and at night on highway construction projects. The results were then subjected to a statistical and econometric analysis to understand the perceptions of the workers. An ordered probit model was used to model the perceptions of the workers regarding the effectiveness of current lighting practices in making them feel safe on the work site and allowing them to be as productive at night as during the day.

To develop a framework to incorporate the effect of lighting in the calculation of operation productivity and in order to study the productivity of nighttime construction operations, several visits were made to nighttime highway construction work zones and a paving operation that was conducted at night was studied and modeled. The work breakdown structure of the operation, the duration of various activities, the resources used, and the lighting equipment used for the operation was noted from the visits to the site. Interviews were conducted with the operators of the equipment to gauge the effect that the illumination of the work zone had on the time it takes to complete a certain activity.

6.2 Research Conclusions

The literature review as well as interactions with nighttime workers indicated that lighting in a work zone is very important and it affects the safety and productivity of workers, which in turn affects the overall productivity and the cost of the operation. The research sought to understand the impact of the various aspects of lighting on the perceptions of safety and productivity of the workers in nighttime highway construction work zones.

In a paving operation, the most commonly used type of lighting fixture is equipment-mounted lighting. This is due to the fact that the area where a particular activity is being done keeps changing with time and is required to be lit up uniformly. Hence, it is most convenient to have the balloon lighting fixtures mounted on the equipment, so that the required illumination is provided in the area where the equipment is working. Apart from the equipment-mounted lighting fixtures, light from the ground-mounted or trailer-mounted lighting towers could also be used to illuminate the work zone. Therefore, while calculating the illumination at different areas on the site, it was required to take into account the dynamic nature of the site lighting due to the equipment-mounted lighting fixtures which move along the length of the road that is being paved. Statistical and econometric analysis of the data received from the surveys indicated that the balloon lights had a very positive impact on both the perceptions of safety and productivity of the nighttime workers. Unlike conventional lighting towers, balloon lights diffuse the light uniformly in the work zone and do not cause glare to the workers and to the traveling public. Glare causes visual discomfort and affects the productivity of the operation negatively.

It was found during the econometric analysis of the data that the absence of general lighting affects the perception of safety in the work zone negatively. The absence of general lighting affects the awareness of workers to their immediate surroundings and this negatively affects their feeling of safety. In the case of productivity, task lighting is more important than general lighting. The presence of roadway lighting, for instance, did not affect the productivity of the workers positively. The presence of balloon lights, on the other hand, greatly affected the perceptions of safety and productivity. Based on interactions with the workers on the site, it was found that improved lighting enabled them to finish their task more quickly by enabling them to see the work they were doing more clearly and by being more aware of the surroundings. This was particularly true for the milling and paving activity, where the operator of the machines had to ensure that the new lane that was being milled or paved was in alignment with the previously paved lane. This was in agreement with the results of the econometric analysis for productivity, which showed that the intensity and illumination provided for the task area was very important in determining the perception of the effectiveness of lighting with respect to productivity.

Four different lighting scenarios were tested using the framework developed during the research and the respective productivities obtained were compared. It was found that the productivity of the operation was the higest when there was both trailer mounted and roadway lighting available for the general illumination of the work zone. The other scenarios for which the operation productivity was estimated were the rpresence of only roadway lighting, the presence of only trailer mounted lighting and the absence of any general lighting on the work zone.

6.3 Limitations of the Research

The thesis intended to study and understand the impact of the lighting used on the safety and productivity of nighttime highway construction operations. However, the research is limited in the following aspects:

- Only the paving operation was considered in developing the simulation model. Other operations that are of a similar continuous nature are painting markings on the pavement, concrete paving etc. Inclusion of these operations in the simulation model could broaden the scope of the thesis to include other highway construction operations typically performed at night.

- The effect of the motorists traveling through the site was not modeled. The lighting plan to be used on the site will have to take into consideration the glare that is caused to the motorists by the lighting fixtures used. The volume of traffic through the site could affect the productivity of the operation, however, the effect of traffic was not incorporated into the model as it was not related to the lighting of the work zone.
- The sample size for the surveys collected is low and this affected the econometric models used to analyze the perceptions of safety and productivity and the regression analysis used to determine the impact of different lighting strategies on the productivity of the operation. A larger sample size for the surveys could provide a more robust analysis of the perceptions of nighttime workers and more accurate parameter estimates for the regression model, which could lead to a better estimation of the productivity levels under different lighting conditions.
- The ordered probit model was used because of the ordinal nature of the responses that were collected. Other methods of data collection could be used to gauge the perceptions of the workers such as the selection of multiple options from a list of possible answers regarding the worker's perceptions about work zone lighting and the use of unordered alternatives. This would allow for the use of different econometric models, such as multinomial logit model and nested logit model etc. to model the relationship between the independent and dependent variables.
- The sample size for the multivariate regression analysis was small and hence the regression model may not be reliable in terms of explaining the effect of different lighting sources on the productivity achieved during the night. However, the data from the surveys was used in order to illustrate the proposed methodology for the incorporation of the lighting conditions in the calculation of operation productivity.
- The framework for incorporating the effects of lighting on the operation productivity could not be validated as it would have required the paving operation to be performed under different lighting conditions.

6.4 Contributions of the Research

The research studied the aspects of lighting with respect to the safety and productivity of nighttime highway construction projects and developed a framework to analyze the impact of the lighting conditions in a work zone on the productivity of a nighttime paving operation. Commonly used lighting equipment and factors related to lighting, such as the presence of shadows and the visibility of the workers, were considered while determining the effectiveness of the lighting used in construction work zones with regard to the safety and productivity of the workers. This section enumerates the contributions made by the research to the body of knowledge and the body of practice.

6.4.1 Contributions to the Body of Knowledge

The research builds upon previous work done in the area of construction work zone lighting that involved the development of methodologies to optimize lighting plans, calculating the illuminance required for a particular operation, calculate the illuminance, uniformity ratio, and veiling luminance ratio of different lighting plans. Previous studies in the area of lighting, safety, and productivity of nighttime construction projects have not attempted to link these three aspects of nighttime construction and have dealt with them separately. There have been studies that have linked lighting and productivity in office and industrial settings, but not in an outdoor construction work zone setting. This research aims to qualitatively link the aspects of lighting with the workers' perceptions of safety and productivity. Since a significant percentage, 40% of the highway construction and maintenance work is being done increasingly at night (FHWA 2008), an understanding of the dependence of safety and productivity of the operation on the lighting that is used on the site could help to significantly improve the implementation of lighting in nighttime work zones so as to minimize the difference between working during the day and night, with regard to the safety and productivity of the operation.

A framework that can be used to incorporate the effect of lighting conditions on the work zone to the calculation of productivity using a multivariate regression model and a discrete event simulation model has been proposed. This framework could be used to develop a robust methodology that could be used to predict the productivity of nighttime operations when different types of lighting equipment are available. The robustness of the methodology could be tested by applying it to different construction operations that are performed at night like concrete patching and earthwork removal etc. This framework could even be adapted to be tested in other industries like manufacturing etc, to calculate the productivity of an assembly line in a warehouse under different lighting conditions etc.

6.4.2 Contributions to the Body of Practice

The study has contributed to the body of practice by identifying areas of construction work zone lighting that have a significant impact on the perceptions of safety and productivity of the nighttime workers. By understanding these factors, practitioners of nighttime construction can develop sound lighting plans that can minimize the differences between working at night, in the absence of natural light, with regard to the lighting of the work zone.

An understanding of the effect that lighting has on the safety and productivity of the operation can also be used by the manufacturers of construction equipment while designing lights specifically to be used in nighttime work zones, either on trailer-mounted lighting towers or as lighting fixtures mounted on the equipment.

The framework developed to incorporate the effects of lighting conditions on the site could be developed into a tool that can be used by contractors to compare the effect and different lighting equipment on the productivity, thus enabling the contractor to optimize the use of available lighting equipment.

6.5 Recommendations for Future Research

This research studied the link between lighting and the safety and productivity of nighttime construction operations, and a lighting visualization tool and the simulation and animation of a commonly performed nighttime highway operation were developed. While this research looks at the qualitative impact of lighting on the safety and productivity of workers, a methodology that calculates the effect of lighting on the productivity of the operation could be developed by studying the performance of workers under different lighting conditions and developing simulation models under those different conditions. The following recommendations address the limitations of the research that were enumerated earlier in this chapter.

- The methodology developed can be used to incorporate the effect of the lighting scenario used to predict the productivity of the operation. Distributions of productivity are obtained for different lighting scenarios. If the cost component of the lighting could be obtained and incorporated into the framework, it would be possible to use this analysis to calculate the trade-offs between the expenditure incurred on extra lighting with the improvement in the productivity of the operation, which leads to profitability for the contractor. The histograms obtained from the analysis could help in calculating the expected value and expected cost of various lighting strategies and thus help in making decisions regarding work zone lighting from the view of increased profitability.
- The framework that is proposed in this research could be built upon and validated by future researchers. This can be possible by having a larger sample size (the sample size required for the analysis of Indiana construction workers' perceptions at a 95% confidence level was estimated to be 96) of respondents and by collecting data from a group of workers who perform the same task under different lighting conditions.
- As discussed in Section 6.3, further research should use data collected for the same activity under different lighting conditions. Collecting such data under controlled simulated work environments where the lighting can be changed is a possible way to collect the data. This data could be used to generate conditional probabilistic distributions for the duration of the activity. These distributions can be incorporated into the framework and could be more reliable than the use of Lighting Duration Factors.
- The scope of the tool can be expanded to include more operations that are performed at night, like painting of stripes and markers and concrete paving, etc. The methodology followed would be the same, consisting of collecting data about the work breakdown structure and activity duration as well as the illumination requirements of different activities.
- The perceptions of nighttime workers regarding the effect of other factors, such as the density of traffic through the work zone, could be studied and related to the lighting provided on the site. This could help with issues such as improving the

visibility of workers and obstacles to the drivers, therefore increasing the workers' awareness of through traffic.

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APPENDICES

Appendix A: Surveys distributed to nighttime workers

Questionnaire- Focus on the Perspectives of Nighttime Construction Workers

Introduction:
Purdue University is conducting a study investigating the importance and impact of the lighting conditions on the site of nighttime highway construction projects on the productivity and safety of the project. This survey tries to gauge the perceptions of workers regarding the impact of lighting on their safety and productivity on the work site.
We are requesting you to complete this survey which includes general questions about lighting on the worksite and its impact of the work environment and worker productivity and safety.
The questionnaire will take about 10 minutes of you time to complete. The information collected will be kept confidential and it will only be used for academic purposes. Your participation in this survey is completely voluntary. It is the goal of this research to develop a tool that can assess the productivity of a nighttime construction operation under different lighting conditions. This research also aims to assist planners of nighttime construction projects to choose better lighting confgurations that will help to improve worker safety and productivity at night. For this reason, your cooperation is vital to the success of this research.
Questions in this questionnaire will fall into one of the following categories:

A) General Information
B) Comparison between nighttime and daytime work
C) Duties performed on Projects
D) Information about lighting used
E) Demographic Information (Optional)
F) Additional Comments and Suggestions

Please return the completed survey to the following address:

Joseph Louis
c/o Dr. Dulcy Abraham
Purdue University
School of Civil Engineering
550 Stadium Mall Drive
West Lafayette, IN 47907-2051
Telephone: 765 586 5298

A) General Information:

Company: ____

Location: ____

Years of Experience ____

B) Daytime and Nighttime Work:

Please check the most appropriate answer:

1) Have you worked on highway construction projects during the day?
   - ☐ Yes
   - ☐ No

2) Have you worked on highway construction projects at night?
   - ☐ Yes
   - ☐ No

3) Select the type of projects that you mostly work on ☐ Construction ☐ Maintenance

4) Please rate the following issues based on your perception of their importance and impact on productivity while working at night when compared to working during the day:

Issue	Scale of Importance / Impact on Productivity				
	Not at all	Not very	No opinion	Somewhat	Very
Traffic					
Lighting Conditions					
Alertness/ Awareness of Hazards					
Temperature					
Visibility in the worksite					

C) Duties Performed on Site:

1) Please describe the task(s) that you perform most often on the work site below:

____

2) If you are an equipment operator, please enter the name and model of the equipment that you operate:
   - Type of Equipment/ Vehicle : ________________________________
   - Manufacturer's Name: _____________________________________
   - Model Name: ____

3) While performing the activity that you perform most often, what is the approximate rate at which the work is done under the following conditions:

   Activity that you perform:
   ____

DAY/ NIGHT	**Favorable Conditions**[1]	**Normal Conditions**[2]	**Adverse Conditions**[3]
DAY SHIFT			
NIGHT SHIFT			

The above rate has been expressed in the __________ / __________.
(Eg: Square foot/ minute, tons/hour etc)

[1]"*Very Favorable Conditions*" refers to the conditions on the worksite that are conducive to the speedy and proper execution of the operation. It could include, but is not limited to the following conditions: a) light traffic, b) warm weather, c) work-zone lighting (for nighttime construction) etc.
[2]"*Normal Conditions*" refers to the conditions of weather, traffic and lighting etc, that can be assumed to prevail on most days or nights on the worksite, when the operation is being performed.
[3]"*Adverse Conditions*" refers to the conditions of weather, traffic and lighting etc that prevail on the worksite, which hinders the speedy and proper execution of the operation. Examples of *Adverse Conditions* could include bad lighting, very cold weather, heavy traffic through the work zone etc.

D) Information about the Lighting Used

1) While working at night, please select the type of lighting that is available on the worksite to provide general lighting. Do not include lighting equipment that is fixed on specific equipment. (Select all that apply)

☐ Roadway lighting.
☐ Light from surrounding buildings etc.
☐ Trailer-mounted lighting towers.
☐ Sometimes there is no lighting, other than lights mounted on equipment.
☐ Other (Please Specify):
____

2) Please select the lighting equipment that is available to provide lighting for the activity that you perform from the following list: (Check all that apply)
Activity that you perform: ______________________________

☐ Balloon lights fixed on construction equipment:
- How many such balloon lights are provided? ________________
- What is the power of the lamp used?
  - o 500 Watts
  - o 1000 Watts
  - o 2000 Watts
  - o Other (Please specify):_________________________

☐ Lights fixed on the equipment by the manufacturer
☐ Other (Please Specify): ______________________________

3) Do you feel that lighting that is provided (for the illumination of the worksite and the activity) is adequate in terms of the following aspects:

Issue	Strongly Disagree	Disagree	No opinion	Agree	Strongly Agree
Makes you feel safe					
Does not affect the quality of the work					
Keeps you alert and aware of the surrounding area					
Allows you to achieve the same productivity as during the day					
Prevents you from making mistakes/ errors in the activity					

4) Please rate the following issues that may be faced with regard to visibility/ lighting on the work site, based on how often you encounter them and how much it adversely affects your safety and productivity on the work site at night.

Issue	Scale of Importance				
	Not at all	Not very	No opinion	Somewhat	Very
Shadows on work zone make it hard to see the target objects clearly.					
It is hardly to visually communicate with fellow workers at night.					
The intensity / brightness of light is not adequate to see the details of the work that is performed.					
There is a glare produced by incoming traffic and/or improper positioning of lighting fixtures that affects the productivity and quality of work performed.					

5) In the space provided below, please enter any other problems that you may encounter with respect to lighting on the work zone.

____

____

____

____

E) Demographic Information (Voluntary)

Age:	
Gender:	
Years of experience in construction:	
Number of nighttime projects worked on:	
How frequently do you work night shifts?	

F) Additional Comments and Suggestions

In the space provided below, please write down any suggestions or comments that you may have regarding the improvement of lighting conditions on the site of highway construction operations.

Your help is greatly appreciated!

Appendix B: Responses from workers' surveys

Table 0.1 Responses obtained from worker surveys

Survey Question	1	2	3	4	5
Question #	Number of years of experience	Age	Gender	Have you worked on highway construction projects during the day?	Have you worked on highway construction projects during the night?
Possible Answers			m/f	1- Yes, 0 - No	1- Yes, 0 - No
1	15	44	m	1	1
2	14	36	m	1	1
3	24	46	m	1	1
4	10	32	m	1	1
5	8	31	m	1	1
6	18	34	m	1	1
7	23	50	m	1	1
8	20	50	m	1	1
9	42	63	m	1	1
10	18	41	m	1	1
11	4	27	m	1	1
12	25	44	m	1	1
13	7	28	m	1	1
14	22	42	m	1	1
15	16	46	m	1	1
16	15	40	f	1	1
17	23	39	m	1	1
18	6	45	m	1	1
19	28	54	m	1	1
20	25	52	m	1	1
21	10	30	m	1	1
22	18	38	m	1	1
23	3	26	m	1	1
24	5	25	m	1	1
25	10	32	m	1	1
26	20	44	m	1	1

Survey Question	1	2	3	4	5
Question #	Number of years of experience	Age	Gender	Have you worked on highway construction projects during the day?	Have you worked on highway construction projects during the night?
Possible Answers			m/f	1- Yes, 0 - No	1- Yes, 0 - No
27	15	38	m	1	1
28	27	48	m	1	1
29	11	29	m	1	1
30	5	28	m	1	1
31	2	23	m	1	1
32	40	62	m	1	1
33	10	35	m	1	1
34	20	42	m	1	1
35	6	36	m	1	1
36	23	45	m	1	1
37	41	60	m	1	1
38	37	59	m	1	1
39	21	49	m	1	1
40	16	40	m	1	1
41	20	37	f	1	1
42	12	38	m	1	1

Survey Question	6	7	8	9	10	11
Question #	Please rate the following issues based on your perception of their importance and impact on productivity while working at night when compared to working during the day:					Please describe the task(s) that you perform most often on the work site below:
	Traffic	Lighting Conditions	Awareness of Hazards	Temperat ure	Visibility in the worksite	
Possible Answers	1 - Not at all, 2 - Not very, 3 - No opinion, 4 - Somewhat, 5 - Very					1- Laborer, 2- Supervisor, 3- Operator
1	3	4	3	4	4	1
2	5	5	5	4	5	2
3	5	5	4	4	4	2
4	4	4	4	4	4	3
5	4	5	4	2	4	3
6	4	5	5	4	5	2
7	5	5	5	5	5	2
8	4	3	5	4	4	3
9	4	4	5	4	4	3
10	5	5	5	1	5	2
11	5	5	5	5	5	3
12	5	5	5	2	5	3
13	4	5	4	3	5	3
14	4	4	5	4	4	3
15	5	5	3	2	5	3
16	5	5	5	4	5	1
17	5	4	5	4	5	2
18	4	5	4	2	5	2
19	5	5	5	4	5	3
20	5	5	5	4	5	2
21	4	4	4	4	5	3
22	5	5	4	4	4	2
23	5	4	5	2	5	1
24	5	4	4	4	5	3
25	5	5	4	4	5	1
26	5	5	5	4	5	1

Survey Question	6	7	8	9	10	11
Question #	Please rate the following issues based on your perception of their importance and impact on productivity while working at night when compared to working during the day:					Please describe the task(s) that you perform most often on the work site below:
	Traffic	Lighting Conditions	Awareness of Hazards	Temperature	Visibility in the worksite	
Possible Answers	1 - Not at all, 2 - Not very, 3 - No opinion, 4 - Somewhat, 5 - Very					1- Laborer, 2- Supervisor, 3- Operator
27	5	5	5	4	5	2
28	4	5	5	5	5	3
29	5	5	4	4	5	3
30	4	4	4	5	4	1
31	4	4	5	4	3	3
32	5	5	5	5	5	2
33	5	5	5	5	5	3
34	5	5	5	4	5	2
35	4	5	5	4	5	3
36	5	5	5	4	5	3
37	5	4	5	3	5	2
38	4	4	5	2	4	1
39	3	5	4	3	5	1
40	5	5	5	4	5	3
41	5	5	5	4	5	2
42	4	4	3	2	5	1

Survey Question	12	13	14	15	16	17	18
Question #	Please select the lighting equipment that is available to provide lighting for the activity that you perform:		While working at night, please select the type of lighting that is available on the worksite to provide general lighting.				
	Balloon lights fixed	Manufacturer affixed lights	Roadway Lighting	Light from buildings	Trailer mounted lighting towers	Sometimes there is no lighting	Other
Possible Answers	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No
1	0	1	1	0	1	1	0
2	0	0	0	0	0	1	0
3	0	1	1	0	0	1	0
4	1	1	0	0	0	1	0
5	1	1	1	0	1	1	0
6	0	1	0	0	0	1	0
7	0	1	0	0	1	0	0
8	0	1	0	0	1	0	0
9	1	1	0	0	1	1	0
10	1		1	0	1	1	0
11	1	1	0	0	1	0	1
12	1	1	1	1	1	1	0
13	1	1	1	0	0	1	0
14	0	1	0	0	0	1	0
15	1	0	1	0	0	1	0
16	1	1	0	0	1	0	0
17	1	1	1	1	1	0	0
18	1	1	0	0	1	0	0
19	0	0	1	1	1	0	1
20	0	0	1	0	1	1	0
21	0	1	0	0	0	1	0
22	0	1	1	0	0	1	0
23	1	1	1	0	1	0	0
24	0	1	0	0	1	0	0
25	1	1	0	0	1	0	0
26	1	1	1	1	1	1	1

Survey Question	12	13	14	15	16	17	18
Question #	Please select the lighting equipment that is available to provide lighting for the activity that you perform from the following list:		While working at night, please select the type of lighting that is available on the worksite to provide general lighting.				
	Balloon lights fixed	Manufacturer affixed lights	Roadway Lighting	Light from buildings	Trailer mounted lighting towers	Sometimes there is no lighting	Other
Possible Answers	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No	1- Yes, 0 - No
27	1	1	1	0	1	1	0
28	1	1	1	0	0	0	0
29	1	0	0	0	1	0	0
30	1	0	0	0	0	1	0
31		1	1	0	0	1	0
32	1	1	0	0	0	0	0
33	1	0	0	1	0	1	1
34	1	1	0	0	0	0	0
35	0	1	0	0	0	1	0
36	1	1	1	1	1	0	0
37	1	0	1	1	1	0	0
38	0	0	0	1	0	1	0
39	0	0	1	0	0	1	0
40	1	1	1	1	1	1	0
41	1	0	1	0	1	0	0
42	0	0	0	0	0	1	0

Survey Question	19	20	21	22	23	24
Question #	Frequency of nighttime projects	Do you feel that lighting that is provided (for the illumination of the worksite and the activity) is adequate in terms of the following aspects				
		Makes you feel safe	Does not affect the quality of the work	Keeps you aware of surrounding area	Allows you to achieve same productivity as during the day	Prevents you from making errors in the activity
Possible Answers	1 - Often, 2 - Not often, 3- Very often	1 - Strongly Disagree, 2 - Disagree, 3 - No opinion, 4 - Agree, 5 - Strongly Agree				
1	1	4	2	4	3	3
2	1	2	1	2	2	2
3	1	5	1	4	1	4
4	1	5	2	4	2	4
5	1	4	1	4	4	5
6	2	4	1	4	4	4
7	2	4	2	4	2	2
8	2	4	4	4	4	4
9	2	4	2	4	2	2
10	2	4	2	4	4	2
11	1	4	1	4	5	1
12	2	4	2	4	2	2
13	1	4	3	4	3	2
14	1	4	2	4	3	4
15	1	3	1	4	3	3
16	2	2	1	1	4	2
17	2	4	2	4	2	2
18	2	4	2	4	4	2
19	2	4	1	4	2	4
20	1	2	2	3	2	2
21	2	4	4	5	4	5
22	3	5	2	5	2	4
23	1	4	4	4	3	3
24	1	3	4	3	2	1
25	1	1	2	2	1	2
26	2	3	2	4	4	4

Survey Question	19	20	21	22	23	24
Question #	Frequency of nighttime projects	Do you feel that lighting that is provided (for the illumination of the worksite and the activity) is adequate in terms of the following aspects				
		Makes you feel safe	Does not affect the quality of the work	Keeps you alert and aware of the surrounding area	Allows you to achieve the same productivity as during the day	Prevents you from making mistakes/ errors in the activity
Possible Answers	1 - Often, 2 - Not often, 3- Very often	1 - Strongly Disagree, 2 - Disagree, 3 - No opinion, 4 - Agree, 5 - Strongly Agree				
27	1	4	2	4	4	4
28	1	4	4	4	4	4
29	1	4	4	3	3	2
30	3	4	4	5	3	3
31	1	4	1	4	2	4
32	2	4	5	5	4	4
33	1	1	2	4	2	4
34	3	5	2	5	4	4
35	3	4	2	2	4	2
36	3	5	1	5	5	3
37	1	5	1	4	3	2
38	1	3	2	4	4	3
39	1	2	3	3	3	2
40	1	5	2	5	2	3
41	1	4	2	4	1	2
42	1	2	4	4	3	3

Survey Question	25	26	27	28
Question #	Please rate the following issues that may be faced with regard to visibility/ lighting on the work site, based on how often you encounter them and how much it adversely affects your safety and productivity on the work site at night.			
	Shadows on work zone make it hard to see the target objects clearly.	It is hardly to visually communicate with fellow workers at night.	The intensity / brightness of light is not adequate to see the details of the work that is performed.	There is a glare produced by incoming traffic and/or improper positioning of lighting fixtures.
Possible Answers	1 - Strongly Disagree, 2 - Disagree, 3 - No opinion, 4 - Agree, 5 - Strongly Agree			
1	2	2	2	4
2	3	4	5	4
3	5	4	5	1
4	4	4	5	2
5	4	2	1	3
6	4	4	4	4
7	5	5	5	5
8	2	1	2	2
9	4	1	4	4
10	4	4	4	4
11	4	4	2	4
12	4	4	2	4
13	5	4	3	4
14	4	4	5	2
15	4	3	4	4
16	4	5	1	4
17	4	5	5	4
18	4	4	2	4
19	5	4	4	4
20	4	4	4	5
21	4	5	5	1
22	4	4	5	2
23	4	4	4	4
24	2	2	2	3
25	5	4	4	5
26	4	5	5	5

Survey Question	25	26	27	28
Question #	Please rate the following issues that may be faced with regard to visibility/ lighting on the work site, based on how often you encounter them and how much it adversely affects your safety and productivity on the work site at night.			
	Shadows on work zone make it hard to see the target objects clearly.	It is hardly to visually communicate with fellow workers at night.	The intensity / brightness of light is not adequate to see the details of the work that is performed.	There is a glare produced by incoming traffic and/or improper positioning of lighting fixtures.
Possible Answers	1 - Strongly Disagree, 2 - Disagree, 3 - No opinion, 4 - Agree, 5 - Strongly Agree			
27	5	5	4	4
28	4	4	4	4
29	2	4	3	4
30	4	5	4	4
31	4	4	5	4
32	4	4	2	2
33	5	4	5	3
34	4	4	5	4
35	5	4	4	5
36	4	2	5	4
37	3	4	3	4
38	5	4	5	4
39	5	4	3	5
40	5	5	4	4
41	5	5	5	5
42	5	5	3	4

Appendix C: Ordered probit models

```
read;nvar=28;nobs=42;file=C:\Users\Joseph\Desktop\survey2.txt$
create;if(role=2)Superv=1$
ordered;lhs=EfSaf;rhs=one,LtRoad,LtBal,Superv;marginal effects$
ordered;lhs=EfPdy;rhs=one,LtOth,LtBal,LtNon,Int;marginal effects$

+-----------------------------------------------------------------------+
| Dependent variable is binary, y=0 or y not equal 0                    |
| Ordinary    least squares regression    Weighting variable = none     |
| Dep. var. = Y=0/Not0 Mean=   .9523809524    , S.D.=   .2155402687     |
| Model size: Observations =       42, Parameters =   4, Deg.Fr.=    38 |
| Residuals:  Sum of squares= .1674898319D+03, Std.Dev.=        2.09943 |
| Fit:        R-squared=*********, Adjusted R-squared =       -93.87417 |
| Diagnostic: Log-L =    -88.6437, Restricted(b=0) Log-L =       5.3641 |
|             LogAmemiyaPrCrt.=    1.574, Akaike Info. Crt.=      4.412 |
+-----------------------------------------------------------------------+
+---------+--------------+----------------+--------+---------+----------+
|Variable | Coefficient  | Standard Error |b/St.Er.|P[|Z|>z] | Mean of X|
+---------+--------------+----------------+--------+---------+----------+
 Constant  .8671682144      .81563663        1.063   .2877
 X13       .3608792759E-01  .67331492         .054   .9573   .59523810
 X16       .5348536499E-01  .71002008         .075   .9400   .69047619
 SUPERV    .8040437287E-01  .69676127         .115   .9081   .33333333

Normal exit from iterations. Exit status=0.
              +---------------------------------------------+
              | Ordered Probit Model                        |
              | Maximum Likelihood Estimates                |
              | Dependent variable               EfSaf      |
              | Weighting variable                 ONE      |
              | Number of observations              42      |
              | Iterations completed                11      |
              | Log likelihood function      -54.38028      |
              | Restricted log likelihood    -59.42219      |
              | Chi-squared                   10.08382      |
              | Degrees of freedom                   3      |
              | Significance level            .1786690E-01 |
              |    Cell frequencies for outcomes            |
              |  Y Count Freq  Y Count Freq  Y Count Freq   |
              |  0      2 .047  1      6 .142  2      7 .166   |
              |  3     18 .428  4      9 .214               |
              +---------------------------------------------+
+---------+--------------+----------------+--------+---------+----------+
|Variable | Coefficient  | Standard Error |b/St.Er.|P[|Z|>z] | Mean of X|
+---------+--------------+----------------+--------+---------+----------+
          Index function for probability
 Constant   1.311008343      .48296324       2.715   .0066
 LTROAD    -.3948255971      .35854224      -1.101   .2708   .59523810
 LTBAL      .9090360235      .42982076       2.115   .0344   .69047619
 SUPERV     .5844245321      .43345827       1.348   .1776   .33333333
          Threshold parameters for index
 Mu( 1)    .8741942158      .33915341        2.578   .0099
 Mu( 2)    1.471438286      .37663830        3.907   .0001
 Mu( 3)    2.818709812      .44457032        6.340   .0000
```

Matrix LastOutp

[7,4]

Marginal Effects for OrdProbt				
Variable	EfSaf=0	EfSaf =1	EfSaf =2	EfSaf =3
ONE	-.0863	-.2233	-.1679	.1350
LTROAD	.0260	.0672	.0506	-.0406
LTBAL	-.0598	-.1548	-.1164	.0936
SUPERV	-.0385	-.0995	-.0749	.0602

Frequencies of actual & predicted outcomes
Predicted outcome has maximum probability.

	Predicted					
Actual	0	1	2	3	4	Total
0	0	1	0	1	0	2
1	0	2	0	4	0	6
2	0	2	0	5	0	7
3	0	1	0	14	3	18
4	0	0	0	7	2	9
Total	0	6	0	31	5	42

```
+-----------------------------------------------------------------------+
| Dependent variable is binary, y=0 or y not equal 0                    |
| Ordinary    least squares regression    Weighting variable = none     |
| Dep. var. = Y=0/Not0 Mean=   .9523809524    , S.D.=   .2155402687     |
| Model size: Observations =      42, Parameters =   6, Deg.Fr.=     36 |
| Residuals:  Sum of squares= .9048222023D+02, Std.Dev.=        1.58537 |
| Fit:        R-squared=*********, Adjusted R-squared =       -53.10083 |
| Diagnostic: Log-L =    -75.7126, Restricted(b=0) Log-L =       5.3641 |
|             LogAmemiyaPrCrt.=    1.055, Akaike Info. Crt.=      3.891 |
+-----------------------------------------------------------------------+
```

Variable	Coefficient	Standard Error	b/St.Er.	P[|Z|>z]	Mean of X
Constant	.9268039391	.68413157	1.355	.1755	
LTNON	-.9378692927E-01	.49091537	-.191	.8485	.50000000
LTBAL	.2435094002E-01	.54828582	.044	.9646	.69047619
LTOTH	.1109758281	.85029302	.131	.8962	.95238E-01
INT	.1409489705	.51581426	.273	.7847	.64285714

```
Line search does not improve fn. Exit iterations. Status=3
Abnormal exit from iterations. If current results are shown
check convergence values shown below. This may not be a
solution value (especially if initial iterations stopped).
Gradient value: Tolerance= .1000D-05, current value= .3666D-05
Function chg. : Tolerance= .0000D+00, current value= .1421D-13
Parameters chg: Tolerance= .0000D+00, current value= .1818D-05
Smallest abs. parameter change from start value = .3346D+00
```

```
+--------------------------------------------+
| Ordered Probit Model                       |
| Maximum Likelihood Estimates               |
| Dependent variable                EfPdy    |
| Weighting variable                  ONE    |
| Number of observations               42    |
| Iterations completed                 14    |
| Log likelihood function       -50.80930    |
| Restricted log likelihood     -57.21859    |
| Chi-squared                    12.81858    |
| Degrees of freedom                    5    |
| Significance level          .2513946E-01 |
|    Cell frequencies for outcomes           |
|  Y Count Freq  Y Count Freq  Y Count Freq  |
|  0     2 .047  1    13 .309  2    10 .238  |
|  3    15 .357  4     2 .047                |
+--------------------------------------------+
+---------+--------------+----------------+--------+---------+----------+
|Variable | Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]| Mean of X|
+---------+--------------+----------------+--------+---------+----------+
          Index function for probability
 Constant  1.467736155      .91762229       1.599   .1097
 LTROAD     -.5764726817      .38120210      -1.512    .1305   .50000000
 LTBAL      .6155652674      .46258876       1.331    .1833   .69047619
 LTOTH      .8057423793      .66272055       1.216    .2241   .95238E-01
 INT        .8381287394      .40928309       2.048    .0406   .64285714

          Threshold parameters for index
 Mu( 1)    1.637685883      .62247147       2.631   .0085
 Mu( 2)    2.330997957      .64268729       3.627   .0003
 Mu( 3)    3.981007780      .74753505       5.326   .0000
```

Matrix LastOutp [9,4]

```
+----------------------------------------------------------+
| Marginal Effects for OrdProbt                            |
+----------+----------+----------+----------+----------+
| Variable | EfPdy=0  |EfPdy=1   | EfPdy=2  | EfPdy=3  |
+----------+----------+----------+----------+----------+
| ONE      |   -.0723 |   -.4666 |   -.0232 |    .4722 |
| LTROAD   |    .0284 |    .1833 |    .0091 |   -.1855 |
| LTBAL    |   -.0303 |   -.1957 |   -.0097 |    .1980 |
| LTOTH    |   -.0397 |   -.2561 |   -.0127 |    .2592 |
| INT      |   -.0413 |   -.2664 |   -.0132 |    .2696 |
+----------+----------+----------+----------+----------+
```

```
Frequencies of actual & predicted outcomes
Predicted outcome has maximum probability.

            Predicted
------  -------------------------  +  -----
Actual      0    1    2    3    4  |  Total
------  -------------------------  +  -----
  0         0    2    0    0    0  |      2
  1         0    9    0    4    0  |     13
  2         0    5    0    5    0  |     10
  3         0    3    0   12    0  |     15
  4         0    1    0    1    0  |      2
------  -------------------------  +  -----
Total       0   20    0   22    0  |     42
```

Appendix D: Data collected on site for milling and paving activity

Table 0.2 Duration data collected for simulation model

Date of site visit: 7/6/2009						
Start Time	Time recorded	Feet Milled	Absolute Time	Time (seconds)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
10:37 AM	0:01:07	100	10:38:07	67	67	102
	0:01:04	200	10:39:11	64	64	119
	0:00:58	300	10:40:10	58	58	298
	0:01:07	400	10:41:17	67	67	106
	0:01:11	500	10:42:28	71	71	158
	0:01:08	600	10:43:37	68	68	120
	0:01:01	700	10:44:38	61	61	172
	0:00:59	800	10:45:37	59	59	144
	0:01:03	900	10:46:39	63	63	196
	0:01:02	1000	10:47:42	62	62	297
	0:01:02	1100	10:48:44	62	62	116
	0:01:02	1200	10:49:46	62	62	118
	0:00:38	1300	10:50:24	58	58	238
	0:01:42	Break	10:52:06	102	64	114
	0:01:04	1400	10:53:10	64	60	124
	0:01:00	1500	10:54:10	60	61	80
	0:01:01	1600	10:55:11	61	58	150
	0:00:58	1700	10:56:09	58	65	174
	0:01:05	1800	10:57:14	65	63	121
	0:01:03	1900	10:58:17	63	57	122
	0:00:57	2000	10:59:14	57	55	112
	0:00:55	2100	11:00:09	55	58	99
	0:00:58	2200	11:01:07	58	61	99
	0:01:01	2300	11:02:08	61	68	200
	0:01:08	2400	11:03:16	68	52	189
	0:00:50	2500	11:04:06	52	56	
	0:01:59	Break	11:06:05	119	58	
	0:00:56	2600	11:07:01	56	61	
	0:00:58	2700	11:07:58	58	60	
	0:01:01	2800	11:09:00	61	62	
	0:01:00	2900	11:10:00	60	59	

Start Time	Time recorded	Feet Milled	Absolute Time	Time (seconds)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
	0:01:02	3000	11:11:02	62	57	
	0:00:59	3100	11:12:00	59	60	
	0:04:58		11:16:58	298	65	
	0:00:57	3200	11:17:55	57	66	
	0:01:00	3300	11:18:56	60	58	
	0:01:05	3400	11:20:01	65	59	
	0:01:06	3500	11:21:07	66	62	
	0:01:46	3600	11:22:53	106	66	
	0:01:59	Break	11:24:52	158	61	
	0:00:58	3700	11:25:50	58	63	
	0:00:59	3800	11:26:49	59	62	
	0:01:02	3900	11:27:51	62	62	
	0:01:06	4000	11:28:57	66	66	
	0:01:01	4100	11:29:58	61	66	
	0:01:03	4200	11:31:00	63	63	
	0:01:02	4300	11:32:03	62	65	
	0:01:02	4400	11:33:04	62	65	
	0:01:06	4500	11:34:10	66	63	
	0:01:06	4600	11:35:16	66	50	
	0:01:03	4700	11:36:20	63	58	
	0:01:05	4800	11:37:24	65	66	
	0:01:05	4900	11:38:30	65	61	
	0:01:03	5000	11:39:33	63	63	
	0:00:50	5100	11:40:23	53	63	
	0:02:00	Break	11:42:23	120	65	
	0:00:58	5200	11:43:21	58	65	
	0:01:06	5300	11:44:27	66	58	
	0:01:01	5400	11:45:28	61	58	
	0:01:03	5500	11:46:31	63	56	
	0:01:03	5600	11:47:34	63	65	
	0:01:05	5700	11:48:39	65	80	
	0:01:05	5800	11:49:44	65	58	
	0:00:58	5900	11:50:42	58	57	
	0:00:58	6000	11:51:40	58	65	

Start Time	Time recorded	Feet Milled	Absolute Time	Time (seconds)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
	0:00:56	6100	11:52:36	56	64	
	0:01:05	6200	11:53:41	65	64	
	0:01:20	6300	11:55:01	80	64	
	0:01:58	Break	11:56:59	172	67	
	0:00:58	6400	11:57:57	58	59	
	0:00:57	6500	11:58:54	57	66	
	0:01:05	6600	11:59:58	65	63	
	0:01:04	6700	12:01:02	64	58	
	0:01:04	6800	12:02:06	64	55	
	0:01:04	6900	12:03:10	64	55	
	0:01:07	7000	12:04:17	67	56	
	0:00:59	7100	12:05:16	59	56	
	0:01:56	7200	12:07:12	144	58	
	0:03:16	Break	12:10:28	196	53	
	0:01:06	7300	12:11:34	66	54	
	0:01:03	7400	12:12:38	63	57	
	0:00:58	7500	12:13:36	58	52	
	0:00:55	7600	12:14:31	55	55	
	0:00:55	7700	12:15:25	55	59	
	0:00:56	7800	12:16:21	56	61	
	0:00:56	7900	12:17:17	56	56	
	0:00:58	8000	12:18:15	58	60	
	0:00:53	8100	12:19:08	53	60	
	0:00:54	8200	12:20:02	54	56	
	0:00:57	8300	12:20:59	57	60	
	0:00:52	8400	12:21:51	52	60	
	0:00:55	8500	12:22:46	55	58	
	0:04:57	8600	12:27:44	297	57	
					66	
					58	
Day 2 Start						
11:23:32	0:00:59	100	11:24:31	61	59	
	0:01:01	200	11:25:33	56	61	
	0:00:56	300	11:26:29	60	70	
	0:01:00	400	11:27:29	60	66	

Start Time	Time recorded	Feet Milled	Absolute Time	Time (seconds)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
	0:01:00	500	11:28:29	56	58	
	0:00:56	600	11:29:25	60	58	
	0:01:00	700	11:30:25	60	55	
	0:01:00	800	11:31:25	58	53	
	0:00:58	900	11:32:23	57	57	
	0:00:57	1000	11:33:20	66	55	
	0:01:06	1100	11:34:26	116	58	
	0:01:56	Break	11:36:21	58	56	
10:36:16	0:00:58	1200	11:37:19	57	59	
	0:00:57	1300	11:38:16	59	56	
	0:00:59	1400	11:39:15	61	55	
	0:01:01	1500	11:40:16	70	61	
	0:01:10	1600	11:41:25	66	55	
	0:01:06	1700	11:42:31	58	58	
	0:00:58	1800	11:43:29	58	55	
	0:00:58	1900	11:44:28	55	56	
	0:00:55	2000	11:45:23	53	58	
	0:00:53	2100	11:46:16	57	63	
	0:00:57	2200	11:47:13	118	58	
	0:01:58	2300	11:49:11	238	61	
	0:03:58	Break	11:53:10	55	57	
10:58:06	0:00:55	2400	11:54:05	58	62	
	0:00:58	2500	11:55:03	56	59	
	0:00:56	2600	11:55:59	59	56	
	0:00:59	2700	11:56:58	56	59	
	0:00:56	2800	11:57:54	55	59	
	0:00:55	2900	11:58:49	61	71	
	0:01:01	3000	11:59:50	55	60	
	0:00:55	3100	12:00:45	58	58	
	0:00:58	3200	12:01:43	55	62	
	0:00:55	3300	12:02:38	56	57	
	0:00:56	3400	12:03:34	58	67	
	0:00:58	3500	12:04:33	63	57	
	0:01:03	3600	12:05:36	114	58	
	0:01:54	3700	12:07:30	124	59	

Start Time	Time recorded	Feet Milled	Absolute Time	Time (seconds)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
	0:02:04	Break	12:09:34	58	59	
12:14:30	0:00:58	3800	12:10:33	61	59	
	0:01:01	3900	12:11:34	57	61	
	0:00:57	4000	12:12:31	62	64	
	0:01:02	4100	12:13:33	59	62	
	0:00:59	4200	12:14:32	56	58	
	0:00:56	4300	12:15:28	59	61	
	0:00:59	4400	12:16:27	59	59	
	0:00:59	4500	12:17:27	71	56	
	0:01:11	4600	12:18:37	80	54	
	0:01:20	4700	12:19:57	150	54	
	0:02:30	Break	12:22:27	60	60	
00:26:43	0:01:00	4800	12:23:27	58	58	
	0:00:58	4900	12:24:25	62	64	
	0:01:02	5000	12:25:27	57	57	
	0:00:57	5100	12:26:25	67	60	
	0:01:07	5200	12:27:32	57	59	
	0:00:57	5300	12:28:29	174	60	
	0:04:57	Water Refill	12:33:26	58	72	
	0:00:58	5400	12:34:24	59	68	
	0:00:59	5500	12:35:23	59	57	
	0:00:59	5600	12:36:22	59	58	
	0:00:59	5700	12:37:21	61	60	
	0:01:01	5800	12:38:22	121	67	
	0:02:01	Break	12:40:22	64	64	
11:42:40	0:01:04	5900	12:41:26	62	62	
	0:01:02	6000	12:42:28	58	60	
	0:00:58	6100	12:43:26	61	58	
	0:01:01	6200	12:44:28	59	61	
	0:00:59	6300	12:45:26	56	69	
	0:00:56	6400	12:46:23	54	66	
	0:00:54	6500	12:47:16	54	58	
	0:00:54	6600	12:48:10	60	56	
	0:01:00	6700	12:49:10	58	57	
	0:00:58	6800	12:50:09	122	60	

Start Time	Time recorded	Feet Milled	Absolute Time	Time (seconds)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
	0:02:02	6900	12:52:11	112	56	
	0:01:52	Break	12:54:03	64	56	
11:58:29	0:01:04	7000	12:55:07	57	71	
	0:00:57	7100	12:56:05	60	68	
	0:01:00	7200	12:57:05	59	58	
	0:00:59	7300	12:58:04	60	61	
	0:01:00	7400	12:59:04	72	61	
	0:01:12	7500	13:00:16	68	59	
	0:01:08	7600	13:01:24	57	62	
	0:00:57	7700	13:02:21	58	62	
	0:00:58	7800	13:03:19	60	58	
	0:01:00	7900	13:04:19	67	56	
	0:01:07	8000	13:05:27	64	61	
	0:01:04	8100	13:06:30	62	59	
	0:01:02	8200	13:07:32	99	62	
	0:01:39	8300	13:09:11	99	62	
	0:01:39	Break	13:10:50	60	58	
12:18:56	0:01:00	8400	13:11:50	58	56	
	0:00:58	8500	13:12:47	61		
	0:01:01	8600	13:13:48	69		
	0:01:09	8700	13:14:57	66		
	0:01:06	8800	13:16:03	58		
	0:00:58	8900	13:17:01	56		
	0:00:56	9000	13:17:57	57		
	0:00:57	9100	13:18:54	60		
	0:01:00	9200	13:19:54	56		
	0:00:56	9300	13:20:50	56		
	0:00:56	9400	13:21:47	71		
	0:01:11	9500	13:22:57	200		
	0:03:20	Break	13:26:17	68		
12:37:04	0:01:08	9600	13:27:25	58		
	0:00:58	9700	13:28:23	61		
	0:01:01	9800	13:29:24	61		
	0:01:01	9900	13:30:25	59		
	0:00:59	10000	13:31:24	62		

Start Time	Time recorded	Feet Milled	Absolute Time	Time (second s)	Time to mill 100 feet under normal conditions (secs)	Time to mill 100 feet under break conditions (secs)
	0:01:02	10100	13:32:26	62		
	0:01:02	10200	13:33:28	58		
	0:00:58	10300	13:34:26	56		
	0:00:56	10400	13:35:22	189		
	0:03:09	10500	13:38:32			

Table 0.3 Paving data collected for simulation model

	Time Measured	Distance Paved	Comments	Time for 100' (mins)	Time for 100' (secs)
11:27:00	0:00:00		Truck Arrival		
	0:00:39		Truck Concrete Pour		
	0:02:42	0	Start 0 ft		
	0:03:00		Truck Leave		
	0:04:56	100	100 feet	0:02:14	134.0
	0:07:09		Truck Arrival		
	0:07:18	200	200 feet paverstop	0:02:22	142.0
	0:08:50		Truck Arrival		
	0:09:50		paverstop		
	0:10:02		Truck Departure		
	0:11:05		Truck Arrival		
	0:12:01	300	300 feet	0:02:11	131.0
	0:13:00		Truck Departure		
	0:14:13	400	400 feet	0:02:12	132.0
	0:15:18		Truck Arrival		
	0:16:40	500	500 feet	0:02:27	147.0
	0:17:00		Truck Departure		
	0:18:40	600	600 feet, Truck Arrival	0:02:00	120.0
	0:20:22		Truck Departure		
	0:00:00		Restart Timing		
	0:00:08	600	0 feet		
	0:00:57		Pour Ready		
	0:01:49	700	Finish 100 feet	0:01:41	101.0
	0:03:33	800	Finish 200 feet	0:01:44	104.0
	0:03:50		Truck Arrival		
	0:05:11	900	Finish 300 feet	0:01:38	98.0
	0:05:51		Truck Departure		
	0:06:50	1000	Finish 400 feet	0:01:39	99.0
	0:08:31	1100	Finish 500 feet	0:01:41	101.0
	0:10:13	1200	Finish 600 feet	0:01:42	102.0
	0:11:43		Truck Arrival		
	0:11:51	1300	Finish 700 feet	0:01:38	98.0
	0:12:29		Truck Pour Ready		

	Time Measured	Distance Paved	Comments	Time for 100' (mins)	Time for 100' (secs)
	0:13:52		Truck Departure		
	0:00:00		Truck Pour Ready		
	0:03:32		Truck Departure		
	0:04:04		paver start stopped		
	0:04:32		Truck Pour Ready		
	0:07:00		Truck Departure		
	0:07:08		paver start stopped		
	0:10:43		paver start stopped		
	0:11:58		Truck Arrival		
	0:13:07	1400	Finish 100 feet	0:02:24	144.0
	0:13:55		Truck Departure		
	0:15:09	1500	Finish 200 feet	0:02:02	122.0
	0:15:20		Truck Pour Ready		
	0:17:13	1600	Finish 300 feet	0:02:04	124.0
	0:17:39		Truck Departure		
	0:19:18	1700	Finish 400 feet	0:02:05	125.0
	0:21:23	1800	Finish 500 feet	0:02:05	125.0
	0:23:18	1900	Finish 600 feet	0:01:55	115.0
	0:25:18	2000	Finish 700 feet	0:02:00	120.0
	0:25:35		Truck Arrival		
	0:27:55	2100	Finish 800 feet	0:02:37	157.0
	0:28:44		Truck Arrival		
	0:29:09		Truck Pour Ready		
	0:29:36	2200	Finish 900 feet	0:01:41	101.0
	0:31:15	2300	Finish 1000 feet	0:01:39	99.0
	0:31:19		Truck Departure		
	0:00:00		Restart Timing		
	0:02:12	2400	Finish 100 feet	0:02:12	132.0
	0:02:34		Truck Arrival		
	0:02:40		Truck Arrival		
	0:04:02		Truck Pour Ready		
	0:04:35	2500	Finish 200 feet	0:02:23	143.0
	Time Measured	Distance Paved	Comments	Time for 100' (mins)	Time for 100' (secs)
	0:05:41		Truck Departure		
	0:06:35		Truck Pour Ready		
	0:06:51	2600	Finish 300 feet	0:02:16	136.0
	0:07:43		Truck Arrival		
	0:08:44		Truck Departure		

	0:09:04	2700	Finish 400 feet	0:02:13	133.0
	0:09:20		Truck Pour Ready		
	0:10:54	2800	Finish 500 feet	0:01:50	110.0
	0:11:35		Truck Departure		
	0:12:44	2900	Finish 600 feet	0:01:50	110.0
	0:14:33	3000	Finish 700 feet	0:01:49	109.0
	0:16:19	3100	Finish 800 feet	0:01:46	106.0
	0:16:30		paver stopped		

Table 0.4: Data used for Paving

S.No	**X(i)**	**X(i+1)-X(i)**
1	134.0	-8.0
2	142.0	11.0
3	131.0	-1.0
4	132.0	-15.0
5	147.0	27.0
6	120.0	19.0
7	101.0	-3.0
8	104.0	6.0
9	98.0	-1.0
10	99.0	-2.0
11	101.0	-1.0
12	102.0	4.0
13	98.0	-46.0
14	144.0	22.0
15	122.0	-2.0
16	124.0	-1.0
17	125.0	0.0
18	125.0	10.0
19	115.0	-5.0
20	120.0	-37.0
21	157.0	56.0
22	101.0	2.0
23	99.0	-33.0
24	132.0	-11.0
25	143.0	7.0
26	136.0	3.0
27	133.0	23.0
28	110.0	0.0
29	110.0	1.0
30	109.0	3.0
31	106.0	

Appendix E: Source Code for the STROBOSCOPE Model

```
/**********************************************************************************
/* Stroboscope source file generated from Visio drawing
C:\Users\Joseph\Desktop\OP_3Sw_2Ml.vsd
/**********************************************************************************
/**********************************************************************************/*
General section for problem parameters
VARIABLE PageX 81;
VARIABLE PageY 15.9749;
VARIABLE scale 9;
VARIABLE nTotLenFeet 12000;
VARIABLE nMTruck 5;
VARIABLE nATruck 5;
VARIABLE MillUnusualSpeed Uniform[50,60];
VARIABLE PaveUnusualSpeed Uniform[50,60];
VARIABLE SpeedTruck 3960; /fpmin = 45 mph
VARIABLE TimeMillPow Normal[4.0943,0.29511];
VARIABLE TimeMill 2.7182^Normal[4.0943,0.02951]/60;
VARIABLE SpeedSweeper Uniform[60,70];
VARIABLE SpeedTacker 100;
VARIABLE TimePavePow Normal[4.7538,0.02876];
VARIABLE TimePave 2.7182^TimeMillPow/60;
VARIABLE SpeedPaver 100/((2.7182^Normal[4.7538,0.02876])/60);
VARIABLE SpeedDumper 50;
VARIABLE SpeedRoller 50;
VARIABLE MinSweepLength 100;
VARIABLE MinTackLength 100;
VARIABLE MinRollLength 100;
VARIABLE MinPaveLength 100;
VARIABLE LaneWidthFt 5;
VARIABLE MillDepthFt 1.5/12;
VARIABLE MillTruckCapCuFt 620;
VARIABLE AsphaltTruckCapCuFt 600;
VARIABLE LenMillPerCycle 100;
VARIABLE millercost 650/60;
VARIABLE sweepercost 75/60;
VARIABLE tackercost 75/60;
VARIABLE mtvcost 110/60;
VARIABLE pavercost 145/60;
VARIABLE rollercost 80/60;
VARIABLE lightcost 75/60;
VARIABLE ncrew 13;
VARIABLE crewcost 62.5/60;
VARIABLE aspcost 50;
VARIABLE truckcost 80/60;
VARIABLE aspdensity 220; /lb/cft
VARIABLE diaMreturnpathlength 1448.91; / app 12 miles in real world
VARIABLE diaMhaulpathlength 1465.84; / app 12 miles in real world
VARIABLE diaAhaulpathlength 1447.46; / app 12 miles in real world
VARIABLE diaAreturnpathlength 1412.14; /app 12 miles in real world
VARIABLE actreturnpathlength 63360; /12 miles in real
```

```
VARIABLE acthaulpathlength 63360; /12 miles in real
VARIABLE diaSpeedTruck diaAreturnpathlength/(actreturnpathlength/SpeedTruck);
VARIABLE diaMretspeed diaMreturnpathlength/(actreturnpathlength/SpeedTruck);
VARIABLE diaMhaulspeed diaMhaulpathlength/(acthaulpathlength/SpeedTruck);
VARIABLE diaAhaulspeed diaAhaulpathlength/(acthaulpathlength/SpeedTruck);
VARIABLE diaseg1 278*scale;
VARIABLE diaseg2 391.09*scale;
VARIABLE diaseg3 669.09*scale;
VARIABLE diaseg4 725.63*scale;
VARIABLE diaseg5 1003.63*scale;
VARIABLE diaseg6 1116.72*scale;
VARIABLE diaseg7 1394.72*scale;
VARIABLE mretdist1 69.5*scale;
VARIABLE mretdist2 139*scale;
VARIABLE mretdist3 208.5*scale;
VARIABLE mretdist4 278*scale;
VARIABLE mretdist5 502.62*scale;
VARIABLE mretdist6 572.12*scale;
VARIABLE mretdist7 641.62*scale;
VARIABLE mretdist8 711.12*scale;
VARIABLE mretdist9 780.62*scale;
VARIABLE mretdist10 895.29*scale;
VARIABLE mretdist11 964.79*scale;
VARIABLE mretdist12 1034.29*scale;
VARIABLE mretdist13 1103.79*scale;
VARIABLE mretdist14 1173.29*scale;
VARIABLE mretdist15 1397.91*scale;
VARIABLE mretdist16 1467.41*scale;
VARIABLE mretdist17 1536.91*scale;
VARIABLE mretdist18 1606.41*scale;
VARIABLE mretdist19 1675.91*scale;
VARIABLE aretdist1 69.5*scale;
VARIABLE aretdist2 139*scale;
VARIABLE aretdist3 208.5*scale;
VARIABLE aretdist4 278*scale;
VARIABLE aretdist5 502.62*scale;
VARIABLE aretdist6 572.12*scale;
VARIABLE aretdist7 641.62*scale;
VARIABLE aretdist8 711.12*scale;
VARIABLE aretdist9 780.62*scale;
VARIABLE aretdist10 964.79*scale;
VARIABLE aretdist11 1034.29*scale;
VARIABLE aretdist12 1103.79*scale;
VARIABLE aretdist13 1173.29*scale;
VARIABLE aretdist14 1397.91*scale;
VARIABLE aretdist15 1467.41*scale;
VARIABLE aretdist16 1536.91*scale;
VARIABLE aretdist17 1606.41*scale;
VARIABLE aretdist18 1675.91*scale;
VARIABLE PI 3.141592654;
VARIABLE degrad PI/180;
/*******************************************************************************
```

```
/* Definition of resource types
GENTYPE          Amount; /AM
COMPTYPE    ATruck; /AT
COMPTYPE    chk; /CH
GENTYPE          chk1; /CH
GENTYPE          Length; /LE
COMPTYPE    Loader; /LO
COMPTYPE    Mdumper; /MD
COMPTYPE    MillMach; /MI
COMPTYPE    MTruck; /MT
COMPTYPE    MTV; /MT
GENTYPE          overq; /OV
GENTYPE          PaveMach; /PA
COMPTYPE    RollMach; /RO
GENTYPE          Space; /SP
GENTYPE          statis; /ST
COMPTYPE    SweepMach; /SW
COMPTYPE    TackMach; /TA
/*******************************************************************************/*
Definition of network nodes
QUEUE                  ToMill Length;
COMBI            Mill;
QUEUE                  Miller MillMach;
QUEUE                  MillInTruck Amount;
COMBI            MTHaul;
QUEUE                  MTPos MTruck;
COMBI            MTPosition;
QUEUE                  MTWait MTruck;
QUEUE                  Milled Amount;
COMBI            Sweep;
QUEUE                  SweepDone2 Length;
COMBI            Tack;
QUEUE                  TackDone Length;
COMBI            Pave;
QUEUE                  PaveDone2 Length;
COMBI            Roll;
QUEUE                  RollDone Length;
QUEUE                  Sweeper SweepMach;
QUEUE                  Tacker TackMach;
QUEUE                  Paver PaveMach;
QUEUE                  Roller RollMach;
QUEUE                  AsphaltHopper Amount;
COMBI            AsphaltDump;
QUEUE                  Transfer MTV;
QUEUE                  ATPos ATruck;
COMBI            ATPosition;
QUEUE                  ATWait ATruck;
COMBI            ATReturn;
NORMAL                 ATHaul1;
CONSOLIDATOR     MillDone1;
QUEUE                  MillDone2 Length;
CONSOLIDATOR     SweepDone1;
```

```
QUEUE                       AsphaltTruck Amount;
NORMAL                      MTReturn2;
NORMAL                      ATHaul2;
QUEUE                       ATWaitPlant ATruck;
COMBI               ATLoad;
CONSOLIDATOR        TackDone1;
QUEUE                       SweeperPark SweepMach;
QUEUE                       TackerPark TackMach;
QUEUE                       PaverPark PaveMach;
QUEUE                       MTVPark MTV;
QUEUE                       RollerPark RollMach;
COMBI               RollOver;
QUEUE                       stats statis;
COMBI               calculate;
FORK                MillBreakRep MillMach;
COMBI               MillBreak;
QUEUE                       MillB MillMach;
FORK                PaveBrk PaveMach;
QUEUE                       PaverB PaveMach;
COMBI               PaveBreak;
COMBI               Mtrucks;
QUEUE                       MTPark MTruck;
QUEUE                       MTChk chk;
QUEUE                       ATPark ATruck;
COMBI               Atrucks;
QUEUE                       ATChk chk;
QUEUE               ATChk1 chk;
COMBI               Atrucks1;
QUEUE               ATEmpty Space;
QUEUE               MTWaitDump MTruck;
COMBI               MTDump;
QUEUE               AMWaitDump Amount;
QUEUE                       MTDumper Mdumper;
NORMAL                      Over;
CONSOLIDATOR        PaveDone1;
NORMAL                      MTReturn1;
COMBI               TackOver;
NORMAL                      Sweep2;
FORK                MlDur Length;
COMBI               MillDecide;
QUEUE                       Mill1a Length;
QUEUE                       Mill1b Length;
COMBI               MillUnusual;
NORMAL                      SweeperTravel;
COMBI               PaveDecide;
FORK                PaveDur Length;
COMBI               PaveUnusual;
QUEUE                       Pave1a Length;
QUEUE                       Pave1b Length;
/*****************************************************************************
/* Definition of network Links
LINK                MV5 Transfer RollOver;
```

```
LINK        MI1 Miller Mill;
LINK        MI2 Mill MillBreakRep;
LINK        AM2 MillInTruck MTHaul;
LINK        MT1 MTPosition MTPos;
LINK        MT3 MTHaul MTWaitDump;
LINK        MT5 MTWait MTPosition;
LINK        AM4 MTDump Milled;
LINK        LE3 MillDone1 MillDone2;
LINK        LE4 Sweep Sweep2 Length;
LINK        LE5 SweepDone2 Tack;
LINK        LE6 Tack TackDone1 Length;
LINK        LE7 TackDone PaveDecide;
LINK        LE10 Roll RollDone;
LINK        SW1 Sweeper Sweep;
LINK        PA1 Pave PaveBrk;
LINK        MV1 Transfer AsphaltDump;
LINK        MV2 AsphaltDump Transfer;
LINK        AT1 ATWait ATPosition;
LINK        AT5 ATHaul2 ATWait;
LINK        AM8 ATPosition AsphaltTruck;
LINK        MT4d MTReturn1 MTReturn2 MTruck;
LINK        AT4b ATLoad ATHaul1 ATruck;
LINK        AT4c ATHaul1 ATHaul2 ATruck;
LINK        MT4f MTReturn2 MTWait;
LINK        TA5 Tacker TackOver;
LINK        MV6 RollOver MTVPark;
LINK        TA6 TackOver TackerPark;
LINK        MT11 MTPark Mtrucks;
LINK        MT12 Mtrucks MTWait;
LINK        ST2 calculate stats;
LINK        LE1 ToMill MillDecide;
LINK        AM1 Mill MillInTruck;
LINK        MT2 MTPos MTHaul;
LINK        AM3 MTHaul AMWaitDump;
LINK        MT6 MTPos MTPosition;
LINK        MT4a MTDump MTReturn1 MTruck;
LINK        TA1 Tacker Tack;
LINK        TA2 Tack Tacker;
LINK        RO2 Roll Roller;
LINK        AM5 AsphaltHopper Pave;
LINK        AM6 AsphaltDump AsphaltHopper;
LINK        AM7 AsphaltHopper AsphaltDump;
LINK        AT2 ATPosition ATPos;
LINK        AT7 ATPos ATPosition;
LINK        LE3a MillDone2 Sweep;
LINK        LE8a Pave PaveDone1 Length;
LINK        RO5 Roller RollOver;
LINK        SW5 Sweeper TackOver;
LINK        RO6 RollOver RollerPark;
LINK        SW6 TackOver SweeperPark;
LINK        ch1 Mtrucks MTChk;
LINK        ch2 MTChk Mtrucks;
```

```
LINK    ch4 ATHaul1 ATChk;
LINK    LE1c Mill1a Mill;
LINK    LE2 Mill MillDone1 Length;
LINK    AT3 ATPos ATReturn;
LINK    AM9 AsphaltTruck AsphaltDump;
LINK    PA5 Paver RollOver;
LINK    PA6 RollOver PaverPark;
LINK    SP1 AsphaltDump ATEmpty;
LINK    o1 RollOver Over overq;
LINK    PA2u Paver PaveUnusual;
LINK    LE9 PaveDone2 Roll;
LINK    RO1 Roller Roll;
LINK    PA2 Paver Pave;
LINK    AT4 ATReturn ATWaitPlant;
LINK    LE4a SweepDone1 SweepDone2;
LINK    AT4a ATWaitPlant ATLoad;
LINK    LE6a TackDone1 TackDone;
LINK    MI2a MillBreakRep Miller;
LINK    MI2b MillBreakRep MillB;
LINK    MI2c MillB MillBreak;
LINK    MI2d MillBreak Miller;
LINK    PA2a PaveBrk Paver;
LINK    PA2b PaveBrk PaverB;
LINK    PA2c PaverB PaveBreak;
LINK    PA2d PaveBreak Paver;
LINK    AT11 ATPark Atrucks;
LINK    AT12 Atrucks ATWaitPlant;
LINK    ch3 ATChk Atrucks;
LINK    ch5 Atrucks ATChk1;
LINK    ch6 ATChk1 ATLoad;
LINK    ch7 ATLoad ATHaul1 chk;
LINK    AT21 ATWaitPlant Atrucks1;
LINK    AT22 Atrucks1 ATPark;
LINK    SP2 ATEmpty ATReturn;
LINK    ST1 stats calculate;
LINK    MT3a MTWaitDump MTDump;
LINK    AM3a AMWaitDump MTDump;
LINK    MD1 MTDumper MTDump;
LINK    MD2 MTDump MTDumper;
LINK    LE8b PaveDone1 PaveDone2;
LINK    SW1a Sweep Sweep2 SweepMach;
LINK    SW1b Sweep2 SweeperTravel SweepMach;
LINK    LE4b Sweep2 SweepDone1 Length;
LINK    LE1b MlDur Mill1a;
LINK    LE1a MillDecide MlDur;
LINK    LE1d MlDur Mill1b;
LINK    LE1e Mill1b MillUnusual;
LINK    AM1a MillUnusual MillInTruck;
LINK    LE2a MillUnusual MillDone1 Length;
LINK    MI1a Miller MillUnusual;
LINK    MI2e MillUnusual MillBreakRep;
LINK    SW1c SweeperTravel Sweeper;
```

```
LINK            LE7a PaveDecide PaveDur;
LINK            LE7b PaveDur Pave1a;
LINK            LE7c PaveDur Pave1b;
LINK            LE7d Pave1a Pave;
LINK            LE7e Pave1b PaveUnusual;
LINK            AM5a AsphaltHopper PaveUnusual;
LINK            PA8c PaveUnusual PaveDone1 Length;
LINK            PA1u PaveUnusual PaveBrk;
/*********************************************************************************
/* Definition of global variables and programing objects
OUTFILE V2D "C:\Users\Joseph\Desktop\trace.vtf2d";
SAVEVALUE millcost 0;
SAVEVALUE sweepcost 0;
SAVEVALUE tackcost 0;
SAVEVALUE pavecost 0;
SAVEVALUE mtrcost 0;
SAVEVALUE rollcost 0;
SAVEVALUE mlightcost 0;
SAVEVALUE plightcost 0;
SAVEVALUE crwcost 0;
SAVEVALUE milltcost 0;
SAVEVALUE asptcost 0;
SAVEVALUE asphaltcost 0;
SAVEVALUE pavingcost 0;
SAVEVALUE mrpn 1;
SAVEVALUE mrdist diaseg1;
SAVEVALUE arpn 1;
SAVEVALUE ardist diaseg1;
SAVEVALUE umiller 0;
SAVEVALUE usweeper 0;
SAVEVALUE utacker 0;
SAVEVALUE upaver 0;
SAVEVALUE uroller 0;
SAVEVALUE umilltruck 0;
SAVEVALUE uasphalttruck 0;
SAVEVALUE umtv 0;
/* Statements to assist in the definition of attributes of Mill and its related links
SAVEVALUE millerst 0;
SAVEVALUE milleren 0;
SAVEVALUE millingst 0;
SAVEVALUE millingen 0;
SAVEVALUE segment 1;
SAVEVALUE Xmilledstart 0;
SAVEVALUE Xmilledend 0;
SAVEVALUE angleline -1;
MVAVGCOLLECTOR millcoll 10;
/*********************************************************************************/*
Startup of Mill
SEMAPHORE       Mill 'MTPos.CurCount>0';
DRAWAMT                 LE1c 'Mill1a.CurCount';
//ONFLOW , ONDRAW , ONRELEASE Code Here
DURATION        Mill 'TimeMill';
```

```
ONSTART Mill ASSIGN millerst milleren;
ONSTART Mill ASSIGN milleren milleren+Mill.Length.Count;
ONSTART Mill PRINT V2D "DYNUPDATECELL statmill User.Row_1 %.7f FROM %.3f TO
%.3f\n" Mill.Duration millerst milleren;
ONSTART Mill COLLECT millcoll Mill.Length.Count/(Mill.Duration);
ONSTART Mill PRINT V2D "SETOBJCELL information User.um
%.1f\n"Mill.TotInst*Mill.AveDur/SimTime*100;
ONSTART Mill PRINT V2D "MOVE mtruck%.0f mhaulpath %.3f STARTING AT
%.3f\n"MTPos.MTruck.ResNum (diaMreturnpathlength-
milleren/scale)*Mill.Duration*scale/Mill.Length.Count milleren/scale+22;
ONSTART Mill PRINT V2D "SETOBJCELL miller1 PinX road!Geometry1.X9+Pages[Page-
1]!ThePage!XGridOrigin\n";
ONSTART Mill PRINT V2D "SETOBJCELL miller1 PinY road!Geometry1.Y9+Pages[Page-
1]!ThePage!YGridOrigin\n";
ONSTART Mill PRINT V2D "SETOBJCELL miller1 Angle road!Scratch.B7\n";

/Milling in Truck
ONSTART Mill ASSIGN millingst millingen;
ONSTART Mill ASSIGN millingen millingen+Mill.Length.Count*LaneWidthFt*MillDepthFt;
ONSTART Mill PRINT V2D "DYNUPDATECELL milling%.0f Width %.3f FROM %.3f TO
%.3f\n"MTPos.MTruck.ResNum Mill.Duration millingst/MillTruckCapCuFt*6.9063
millingen/MillTruckCapCuFt*6.9063;
/PROGRESS
ONSTART Mill ASSIGN segment 'milleren<diaseg1 ? 1
                        :milleren<diaseg2 ? 2
                        :milleren<diaseg3 ? 3
                        :milleren<diaseg4 ? 4
                        :milleren<diaseg5 ? 5
                        :milleren<diaseg6 ? 6 : 7 ' ;

//////////////////////////////////////////////////////
/Segment 1 LINE
ONSTART Mill ASSIGN Xmilledstart 'segment==1 & angleline==-1 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==1 & angleline==-1 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==1 & angleline==-1 ? 1 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==1 & angleline==1 ? millerst/scale :
Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==1  & angleline==1 ? milleren/scale :
Xmilledend';
/Segment 3 LINE
ONSTART Mill ASSIGN Xmilledstart 'segment==3 & angleline==0 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==3 & angleline==0 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==3 & angleline==0 ? 1 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==3 & angleline==1? (278+(diaseg2-
millerst)/scale) : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==3 & angleline==1? (278+(diaseg2-
milleren)/scale) : Xmilledend';
/Segment 5 LINE
ONSTART Mill ASSIGN Xmilledstart 'segment==5 & angleline==0 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==5 & angleline==0 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==5 & angleline==0 ? 1 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==5 & angleline==1 ? (millerst-diaseg4)/scale :
```

```
Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==5 & angleline==1 ? (milleren-diaseg4)/scale :
Xmilledend';
/Segment 7 LINE
ONSTART Mill ASSIGN Xmilledstart 'segment==7 & angleline==0 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==7 & angleline==0 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==7 & angleline==0 ? 1 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==7 & angleline==1 ? (278+(diaseg6-
millerst)/scale) : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==7 & angleline==1 ? (278+(diaseg6-
milleren)/scale) : Xmilledend';
/Segment 2 ARC
ONSTART Mill ASSIGN Xmilledstart 'segment==2 & angleline==1 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==2 & angleline==1 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==2 & angleline==1 ? 0 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==2 & angleline==0 ? Xmilledend: Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==2 & angleline==0 ?
Xmilledend+Mill.Length.Count/(scale*36) : Xmilledend';
/Segment 4 ARC
ONSTART Mill ASSIGN Xmilledstart 'segment==4 & angleline==1 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==4 & angleline==1 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==4 & angleline==1 ? 0 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==4 & angleline==0? Xmilledend: Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==4 & angleline==0?
Xmilledend+Mill.Length.Count/(scale*18.25) : Xmilledend';
/Segment 6 ARC
ONSTART Mill ASSIGN Xmilledstart 'segment==6 & angleline==1 ? 0 : Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==6 & angleline==1 ? 0 : Xmilledend';
ONSTART Mill ASSIGN angleline 'segment==6 & angleline==1 ? 0 : angleline';
ONSTART Mill ASSIGN Xmilledstart 'segment==6 & angleline==0? Xmilledend: Xmilledstart';
ONSTART Mill ASSIGN Xmilledend 'segment==6 & angleline==0?
Xmilledend+Mill.Length.Count/(scale*36) : Xmilledend';
ONSTART Mill PRINT V2D "SETOBJCELL road Scratch.D%.0f 1\n" 10+segment;
ONSTART Mill PRINT V2D "DYNUPDATECELL road Scratch.C%.0f %.3f FROM %.5f to
%.5f\n" segment Mill.Duration Xmilledstart Xmilledend;
/* Termination of Mill
/BEFOREEND Mill PRINT V2D "REMOVEFROMPATH
mtruck%.0f\n"MTPos.MTruck.ResNum;
RELEASEAMT          AM1 'Mill.Length.Count*LaneWidthFt*MillDepthFt';
RELEASEAMT          LE2 'Mill.Length.Count';
/* Startup of MTHaul
ENOUGH                        AM2 'MillInTruck.CurCount>=MillTruckCapCuFt';
DRAWAMT                       AM2 'MillInTruck.CurCount';
DURATION            MTHaul '(actreturnpathlength-milleren)/SpeedTruck';
ONSTART MTHaul PRINT V2D "MOVE mtruck%.0f mhaulpath %.3f STARTING AT %.3f\n"
MTHaul.MTruck.ResNum MTHaul.Duration milleren/scale+22;
/* Entry of resources into MTPos
ONENTRY MTPos PRINT V2D "SETOBJCELL mtruck%.0f LocPinY Height/2\n"
MTPos.MTruck.ResNum;
ONENTRY MTPos PRINT V2D "SETOBJCELL milling%.0f LocPinY Height/2\n"
MTPos.MTruck.ResNum;
ONENTRY MTPos ASSIGN millingst 0;
```

```
ONENTRY MTPos ASSIGN millingen 0;
/* Startup of MTPosition
PRIORITY              MTPosition '1';
SEMAPHORE             MTPosition 'MTPosition.CurInst==0';
ENOUGH                          MT6 'MTPos.CurCount==0';
DURATION              MTPosition 'Pertpg[1,1.2,1.3]';
/* Statements to assist in the definition of attributes of Sweep and its related links
SAVEVALUE sweeper1st 0;
SAVEVALUE sweeper1en 0;
SAVEVALUE swsegment 1;
SAVEVALUE Xsweptstart 0;
SAVEVALUE Xsweptend 0;
SAVEVALUE swangleline -1;
MVAVGCOLLECTOR sweepcoll 10;
COLLECT sweepcoll 0.1;
/* Startup of Sweep
DRAWAMT                         LE3a 'MillDone2.CurCount';
DURATION              Sweep 'Sweep.Length.Count/SpeedSweeper';
ONSTART Sweep ASSIGN sweeper1st sweeper1en;
ONSTART Sweep ASSIGN sweeper1en sweeper1en+Sweep.Length.Count;
ONSTART Sweep PRINT V2D "SETOBJCELL sweeper1 PinX
swroad!Geometry1.X9+Pages[Page-1]!ThePage!XGridOrigin\n";
ONSTART Sweep PRINT V2D "SETOBJCELL sweeper1 PinY
swroad!Geometry1.Y9+Pages[Page-1]!ThePage!YGridOrigin\n";
ONSTART Sweep PRINT V2D "SETOBJCELL sweeper1 Angle swroad!Scratch.B7\n";
ONSTART Sweep COLLECT sweepcoll Sweep.Length.Count/(Sweep.Duration);
ONSTART Sweep PRINT V2D "SETOBJCELL information User.us
%.1f\n"Sweep.TotInst*Sweep.AveDur/SimTime*100;
ONSTART Sweep PRINT V2D "DYNUPDATECELL statsweep User.Row_1 %.7f FROM %.3f
TO %.3f\n" Sweep.Duration sweeper1st sweeper1en;
/PROGRESS
ONSTART Sweep ASSIGN swsegment 'sweeper1en-20<diaseg1 ? 1
                     :sweeper1en-20<diaseg2 ? 2
                      :sweeper1en-20<diaseg3 ? 3
                      :sweeper1en-20<diaseg4 ? 4
                      :sweeper1en-20<diaseg5 ? 5
                      :sweeper1en-20<diaseg6 ? 6 : 7 ' ;
/Swsegment 1 LINE
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==1 & swangleline==-1 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==1 & swangleline==-1 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==1 & swangleline==-1 ? 1 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==1 & swangleline==1 ? sweeper1st/scale :
Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==1  & swangleline==1 ? sweeper1en/scale :
Xsweptend';
/Swsegment 3 LINE
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==3 & swangleline==0 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==3 & swangleline==0 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==3 & swangleline==0 ? 1 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==3 & swangleline==1? (278+(diaseg2-
sweeper1st)/scale) : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==3 & swangleline==1? (278+(diaseg2-
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sweeper1en)/scale) : Xsweptend';
/Swsegment 5 LINE
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==5 & swangleline==0 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==5 & swangleline==0 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==5 & swangleline==0 ? 1 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==5 & swangleline==1 ? (sweeper1st-
diaseg4)/scale : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==5 & swangleline==1 ? (sweeper1en-
diaseg4)/scale : Xsweptend';
/Swsegment 7 LINE
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==7 & swangleline==0 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==7 & swangleline==0 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==7 & swangleline==0 ? 1 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==7 & swangleline==1 ? (278+(diaseg6-
sweeper1st)/scale) : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==7 & swangleline==1 ? (278+(diaseg6-
sweeper1en)/scale) : Xsweptend';
/Swsegment 2 ARC
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==2 & swangleline==1 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==2 & swangleline==1 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==2 & swangleline==1 ? 0 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==2 & swangleline==0 ? Xsweptend:
Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==2 & swangleline==0 ?
Xsweptend+(Sweep.Length.Count)/(scale*35.75) : Xsweptend';
/Swsegment 4 ARC
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==4 & swangleline==1 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==4 & swangleline==1 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==4 & swangleline==1 ? 0 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==4 & swangleline==0? Xsweptend:
Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==4 & swangleline==0?
Xsweptend+(Sweep.Length.Count)/(scale*18.25) : Xsweptend';
/Swsegment 6 ARC
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==6 & swangleline==1 ? 0 : Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==6 & swangleline==1 ? 0 : Xsweptend';
ONSTART Sweep ASSIGN swangleline 'swsegment==6 & swangleline==1 ? 0 : swangleline';
ONSTART Sweep ASSIGN Xsweptstart 'swsegment==6 & swangleline==0? Xsweptend:
Xsweptstart';
ONSTART Sweep ASSIGN Xsweptend 'swsegment==6 & swangleline==0?
Xsweptend+(Sweep.Length.Count)/(scale*35.75) : Xsweptend';
ONSTART Sweep PRINT V2D "SETOBJCELL swroad Scratch.D%.0f 1\n" 10+swsegment;
ONSTART Sweep PRINT V2D "DYNUPDATECELL swroad Scratch.C%.0f %.7f FROM %.5f
to %.5f\n" swsegment Sweep.Duration Xsweptstart Xsweptend;
/* Statements to assist in the definition of attributes of Tack and its related links
SAVEVALUE tacker1st 0;
SAVEVALUE tacker1en 0;
SAVEVALUE tasegment 1;
SAVEVALUE Xtackedstart 0;
SAVEVALUE Xtackedend 0;
SAVEVALUE taangleline -1;
MVAVGCOLLECTOR tackcoll 10;
```

```
COLLECT tackcoll 0.1;
/* Startup of Tack
DRAWAMT                LE5 '10';
DURATION          Tack 'Tack.Length.Count/SpeedTacker';
ONSTART Tack ASSIGN tacker1st tacker1en;
ONSTART Tack ASSIGN tacker1en tacker1en+Tack.Length.Count;
ONSTART Tack PRINT V2D "SETOBJCELL tacker1 PinX taroad!Geometry1.X9+Pages[Page-
1]!ThePage!XGridOrigin\n";
ONSTART Tack PRINT V2D "SETOBJCELL tacker1 PinY taroad!Geometry1.Y9+Pages[Page-
1]!ThePage!YGridOrigin\n";
ONSTART Tack PRINT V2D "SETOBJCELL tacker1 Angle taroad!Scratch.B7\n";
ONSTART Tack COLLECT tackcoll Tack.Length.Count/(Tack.Duration);
ONSTART Tack PRINT V2D "SETOBJCELL information User.ut
%.1f\n"Tack.TotInst*Tack.AveDur/SimTime*100;
ONSTART Tack PRINT V2D "DYNUPDATECELL stattack User.Row_1 %.7f FROM %.3f TO
%.3f\n" Tack.Duration tacker1st tacker1en;
/PROGRESS
ONSTART Tack ASSIGN tasegment 'tacker1en<diaseg1 ? 1
                    :tacker1en<diaseg2 ? 2
                   :tacker1en<diaseg3 ? 3
                    :tacker1en<diaseg4 ? 4
                    :tacker1en<diaseg5 ? 5
                    :tacker1en<diaseg6 ? 6 : 7 ' ;
/Tasegment 1 LINE
ONSTART Tack ASSIGN Xtackedstart 'tasegment==1 & taangleline==-1 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==1 & taangleline==-1 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==1 & taangleline==-1 ? 1 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==1 & taangleline==1 ? tacker1st/scale :
Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==1  & taangleline==1 ? tacker1en/scale :
Xtackedend';
/Tasegment 3 LINE
ONSTART Tack ASSIGN Xtackedstart 'tasegment==3 & taangleline==0 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==3 & taangleline==0 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==3 & taangleline==0 ? 1 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==3 & taangleline==1? (278+(diaseg2-
tacker1st)/scale) : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==3 & taangleline==1? (278+(diaseg2-
tacker1en)/scale) : Xtackedend';
/Tasegment 5 LINE
ONSTART Tack ASSIGN Xtackedstart 'tasegment==5 & taangleline==0 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==5 & taangleline==0 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==5 & taangleline==0 ? 1 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==5 & taangleline==1 ? (tacker1st-
diaseg4)/scale : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==5 & taangleline==1 ? (tacker1en-
diaseg4)/scale : Xtackedend';
/Tasegment 7 LINE
ONSTART Tack ASSIGN Xtackedstart 'tasegment==7 & taangleline==0 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==7 & taangleline==0 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==7 & taangleline==0 ? 1 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==7 & taangleline==1 ? (278+(diaseg6-
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tacker1st)/scale) : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==7 & taangleline==1 ? (278+(diaseg6-
tacker1en)/scale) : Xtackedend';
/Tasegment 2 ARC
ONSTART Tack ASSIGN Xtackedstart 'tasegment==2 & taangleline==1 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==2 & taangleline==1 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==2 & taangleline==1 ? 0 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==2 & taangleline==0 ? Xtackedend:
Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==2 & taangleline==0 ?
Xtackedend+Tack.Length.Count/(scale*35.75) : Xtackedend';
/Tasegment 4 ARC
ONSTART Tack ASSIGN Xtackedstart 'tasegment==4 & taangleline==1 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==4 & taangleline==1 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==4 & taangleline==1 ? 0 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==4 & taangleline==0? Xtackedend:
Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==4 & taangleline==0?
Xtackedend+Tack.Length.Count/(scale*18.25) : Xtackedend';
/Tasegment 6 ARC
ONSTART Tack ASSIGN Xtackedstart 'tasegment==6 & taangleline==1 ? 0 : Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==6 & taangleline==1 ? 0 : Xtackedend';
ONSTART Tack ASSIGN taangleline 'tasegment==6 & taangleline==1 ? 0 : taangleline';
ONSTART Tack ASSIGN Xtackedstart 'tasegment==6 & taangleline==0? Xtackedend:
Xtackedstart';
ONSTART Tack ASSIGN Xtackedend 'tasegment==6 & taangleline==0?
Xtackedend+Tack.Length.Count/(scale*35.75) : Xtackedend';
ONSTART Tack PRINT V2D "SETOBJCELL taroad Scratch.D%.0f 1\n" 10+tasegment;
ONSTART Tack PRINT V2D "DYNUPDATECELL taroad Scratch.C%.0f %.7f FROM %.5f to
%.5f\n" tasegment Tack.Duration Xtackedstart Xtackedend;
/* Statements to assist in the definition of attributes of Pave and its related links
SAVEVALUE paver1st 0;
SAVEVALUE paver1en 0;
SAVEVALUE pasegment 1;
SAVEVALUE Xpavedstart 0;
SAVEVALUE Xpavedend 0;
SAVEVALUE paangleline -1;
MVAVGCOLLECTOR pavecoll 10;
COLLECT pavecoll 0.1;
/* Startup of Pave
DRAWAMT                 AM5 'Pave.Length.Count*MillDepthFt*LaneWidthFt';
DRAWAMT                 LE7d 'Pave1a.CurCount';
DURATION            Pave 'Pave.Length.Count/SpeedPaver*paveillum[Pave.TotInst/10+1]';
ONSTART Pave ASSIGN paver1st paver1en;
ONSTART Pave ASSIGN paver1en paver1en+Pave.Length.Count;
ONSTART Pave PRINT V2D "DYNUPDATECELL statpave User.Row_1 %.7f FROM %.3f TO
%.3f\n" Pave.Duration paver1st paver1en;
ONSTART Pave COLLECT pavecoll Pave.Length.Count/(Pave.Duration);
ONSTART Pave PRINT V2D "SETOBJCELL information User.up
%.1f\n"Pave.TotInst*Pave.AveDur/SimTime*100;
ONSTART Pave PRINT V2D "SETOBJCELL information User.umtv
%.1f\n"Pave.TotInst*Pave.AveDur/SimTime*100;
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ONSTART Pave PRINT V2D "SETOBJCELL mtv1 PinX paroad!Geometry1.X9+Pages[Page-
1]!ThePage!XGridOrigin\n";
ONSTART Pave PRINT V2D "SETOBJCELL mtv1 PinY paroad!Geometry1.Y9+Pages[Page-
1]!ThePage!YGridOrigin\n";
ONSTART Pave PRINT V2D "SETOBJCELL mtv1 Angle paroad!Scratch.B7\n";
ONSTART Pave PRINT V2D "SETOBJCELL paver1 PinX paroad!Geometry1.X9+Pages[Page-
1]!ThePage!XGridOrigin\n";
ONSTART Pave PRINT V2D "SETOBJCELL paver1 PinY paroad!Geometry1.Y9+Pages[Page-
1]!ThePage!YGridOrigin\n";
ONSTART Pave PRINT V2D "SETOBJCELL paver1 Angle paroad!Scratch.B7\n";
/PROGRESS
ONSTART Pave ASSIGN pasegment 'paver1en<diaseg1 ? 1
                    :paver1en<diaseg2 ? 2
                    :paver1en<diaseg3 ? 3
                    :paver1en<diaseg4 ? 4
                    :paver1en<diaseg5 ? 5
                    :paver1en<diaseg6 ? 6 : 7 ' ;
ONSTART Pave ASSIGN Xpavedstart 'pasegment==1 & paangleline==-1 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==1 & paangleline==-1 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==1 & paangleline==-1 ? 1 : paangleline';
ONSTART Pave ASSIGN Xpavedstart 'pasegment==1 & paangleline==1 ? paver1st/scale :
Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==1  & paangleline==1 ? paver1en/scale :
Xpavedend';
/Tasegment 3 LINE
ONSTART Pave ASSIGN Xpavedstart 'pasegment==3 & paangleline==0 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==3 & paangleline==0 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==3 & paangleline==0 ? 1 : paangleline';
ONSTART Pave ASSIGN Xpavedstart 'pasegment==3 & paangleline==1? (278+(diaseg2-
paver1st)/scale) : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==3 & paangleline==1? (278+(diaseg2-
paver1en)/scale) : Xpavedend';
/Tasegment 5 LINE
ONSTART Pave ASSIGN Xpavedstart 'pasegment==5 & paangleline==0 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==5 & paangleline==0 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==5 & paangleline==0 ? 1 : paangleline';
ONSTART Pave ASSIGN Xpavedstart 'pasegment==5 & paangleline==1 ? (paver1st-
diaseg4)/scale : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==5 & paangleline==1 ? (paver1en-
diaseg4)/scale : Xpavedend';
/Tasegment 7 LINE
ONSTART Pave ASSIGN Xpavedstart 'pasegment==7 & paangleline==0 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==7 & paangleline==0 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==7 & paangleline==0 ? 1 : paangleline';
ONSTART Pave ASSIGN Xpavedstart 'pasegment==7 & paangleline==1 ? (278+(diaseg6-
paver1st)/scale) : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==7 & paangleline==1 ? (278+(diaseg6-
paver1en)/scale) : Xpavedend';
/Tasegment 2 ARC
ONSTART Pave ASSIGN Xpavedstart 'pasegment==2 & paangleline==1 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==2 & paangleline==1 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==2 & paangleline==1 ? 0 : paangleline';
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ONSTART Pave ASSIGN Xpavedstart 'pasegment==2 & paangleline==0 ? Xpavedend:
Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==2 & paangleline==0 ?
Xpavedend+Pave.Length.Count/(scale*35.75) : Xpavedend';
/Tasegment 4 ARC
ONSTART Pave ASSIGN Xpavedstart 'pasegment==4 & paangleline==1 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==4 & paangleline==1 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==4 & paangleline==1 ? 0 : paangleline';
ONSTART Pave ASSIGN Xpavedstart 'pasegment==4 & paangleline==0? Xpavedend:
Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==4 & paangleline==0?
Xpavedend+Pave.Length.Count/(scale*18.25) : Xpavedend';
/Tasegment 6 ARC
ONSTART Pave ASSIGN Xpavedstart 'pasegment==6 & paangleline==1 ? 0 : Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==6 & paangleline==1 ? 0 : Xpavedend';
ONSTART Pave ASSIGN paangleline 'pasegment==6 & paangleline==1 ? 0 : paangleline';
ONSTART Pave ASSIGN Xpavedstart 'pasegment==6 & paangleline==0? Xpavedend:
Xpavedstart';
ONSTART Pave ASSIGN Xpavedend 'pasegment==6 & paangleline==0?
Xpavedend+Pave.Length.Count/(scale*35.75) : Xpavedend';
ONSTART Pave PRINT V2D "SETOBJCELL paroad Scratch.D%.0f 1\n" 10+pasegment;
ONSTART Pave PRINT V2D "DYNUPDATECELL paroad Scratch.C%.0f %.8f FROM %.5f to
%.5f\n" pasegment Pave.Duration Xpavedstart Xpavedend;
/* Statements to assist in the definition of attributes of Roll and its related links
SAVEVALUE roller1st 0;
SAVEVALUE roller1en 0;
SAVEVALUE rosegment 1;
SAVEVALUE Xrolledstart 0;
SAVEVALUE Xrolledend 0;
SAVEVALUE roangleline -1;
MVAVGCOLLECTOR rollcoll 10;
COLLECT rollcoll 0.1;
/* Startup of Roll
DRAWAMT                         LE9 '10';
DURATION              Roll 'Roll.Length.Count/SpeedRoller';
ONSTART Roll ASSIGN roller1st roller1en;
ONSTART Roll ASSIGN roller1en roller1en+Roll.Length.Count;
ONSTART Roll PRINT V2D "SETOBJCELL roller1 PinX roroad!Geometry1.X9+Pages[Page-
1]!ThePage!XGridOrigin\n";
ONSTART Roll PRINT V2D "SETOBJCELL roller1 PinY roroad!Geometry1.Y9+Pages[Page-
1]!ThePage!YGridOrigin\n";
ONSTART Roll PRINT V2D "SETOBJCELL roller1 Angle roroad!Scratch.B7\n";
ONSTART Roll COLLECT rollcoll Roll.Length.Count/(Roll.Duration);
ONSTART Roll PRINT V2D "DYNUPDATECELL statroll User.Row_1 %.7f FROM %.3f TO
%.3f\n" Roll.Duration roller1st roller1en;
ONSTART Roll PRINT V2D "SETOBJCELL information User.ur
%.1f\n"Roll.TotInst*Roll.AveDur/SimTime*100;
/PROGRESS
ONSTART Roll ASSIGN rosegment 'roller1en<diaseg1 ? 1
                    :roller1en<diaseg2 ? 2
                    :roller1en<diaseg3 ? 3
                    :roller1en<diaseg4 ? 4
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                    :roller1en<diaseg5 ? 5
                    :roller1en<diaseg6 ? 6 : 7 ' ;
/Tasegment 1 LINE
ONSTART Roll ASSIGN Xrolledstart 'rosegment==1 & roangleline==-1 ? 0 : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==1 & roangleline==-1 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==1 & roangleline==-1 ? 1 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==1 & roangleline==1 ? roller1st/scale :
Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==1  & roangleline==1 ? roller1en/scale :
Xrolledend';
/Tasegment 3 LINE
ONSTART Roll ASSIGN Xrolledstart 'rosegment==3 & roangleline==0 ? 0 : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==3 & roangleline==0 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==3 & roangleline==0 ? 1 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==3 & roangleline==1? (278+(diaseg2-
roller1st)/scale) : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==3 & roangleline==1? (278+(diaseg2-
roller1en)/scale) : Xrolledend';
/Tasegment 5 LINE
ONSTART Roll ASSIGN Xrolledstart 'rosegment==5 & roangleline==0 ? 0 : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==5 & roangleline==0 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==5 & roangleline==0 ? 1 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==5 & roangleline==1 ? (roller1st-diaseg4)/scale
: Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==5 & roangleline==1 ? (roller1en-diaseg4)/scale
: Xrolledend';
/Tasegment 7 LINE
ONSTART Roll ASSIGN Xrolledstart 'rosegment==7 & roangleline==0 ? 0 : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==7 & roangleline==0 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==7 & roangleline==0 ? 1 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==7 & roangleline==1 ? (278+(diaseg6-
roller1st)/scale) : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==7 & roangleline==1 ? (278+(diaseg6-
roller1en)/scale) : Xrolledend';
/Tasegment 2 ARC
ONSTART Roll ASSIGN Xrolledstart 'rosegment==2 & roangleline==1 ? 0 : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==2 & roangleline==1 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==2 & roangleline==1 ? 0 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==2 & roangleline==0 ? Xrolledend:
Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==2 & roangleline==0 ?
Xrolledend+Roll.Length.Count/(scale*35.75) : Xrolledend';
/Tasegment 4 ARC
ONSTART Roll ASSIGN Xrolledstart 'rosegment==4 & roangleline==1 ? 0 : Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==4 & roangleline==1 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==4 & roangleline==1 ? 0 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==4 & roangleline==0? Xrolledend:
Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==4 & roangleline==0?
Xrolledend+Roll.Length.Count/(scale*18.25) : Xrolledend';
/Tasegment 6 ARC
ONSTART Roll ASSIGN Xrolledstart 'rosegment==6 & roangleline==1 ? 0 : Xrolledstart';
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ONSTART Roll ASSIGN Xrolledend 'rosegment==6 & roangleline==1 ? 0 : Xrolledend';
ONSTART Roll ASSIGN roangleline 'rosegment==6 & roangleline==1 ? 0 : roangleline';
ONSTART Roll ASSIGN Xrolledstart 'rosegment==6 & roangleline==0? Xrolledend:
Xrolledstart';
ONSTART Roll ASSIGN Xrolledend 'rosegment==6 & roangleline==0?
Xrolledend+Roll.Length.Count/(scale*35.75) : Xrolledend';
ONSTART Roll PRINT V2D "SETOBJCELL roroad Scratch.D%.0f 1\n" 10+rosegment;
ONSTART Roll PRINT V2D "DYNUPDATECELL roroad Scratch.C%.0f %.7f FROM %.5f to
%.5f\n" rosegment Roll.Duration Xrolledstart Xrolledend;
/* Statements to assist in the definition of attributes of AsphaltDump and its related links
SAVEVALUE asphaltst 0;
SAVEVALUE asphalten 0;
/* Startup of AsphaltDump
PRIORITY          AsphaltDump '10';
ENOUGH                  AM7 'AsphaltHopper.CurCount<100';
//ONFLOW , ONDRAW , ONRELEASE Code Here
DRAWAMT                 AM7 '0';
//ONFLOW , ONDRAW , ONRELEASE Code Here
DRAWAMT                 AM9 'AsphaltTruck.CurCount';
//ONFLOW , ONDRAW , ONRELEASE Code Here
//ONDRAW AM9 PRINT V2D "DYNUPDATECELL asphalt%.0f Width %.3f FROM %.3f TO
%.3f\n" ATPos.ATruck.ResNum Uniform[1.5,3] asphaltst/AsphaltTruckCapCuFt*6.9063
asphalten/AsphaltTruckCapCuFt*6.9063;
DURATION          AsphaltDump 'Uniform[1.5,3]';
ONSTART AsphaltDump PRINT V2D "SETOBJCELL atruck%.0f LocPinY Height/2-5.9069\n"
ATPos.ATruck.ResNum;
ONSTART AsphaltDump PRINT V2D "SETOBJCELL asphalt%.0f LocPinY Height/2-
5.9069\n" ATPos.ATruck.ResNum;
ONSTART AsphaltDump PRINT V2D "DYNUPDATECELL asphalt%.0f Width %.3f FROM
%.3f TO %.3f\n" ATPos.ATruck.ResNum AsphaltDump.Duration 6.9063 0.0;
/* Termination of AsphaltDump
RELEASEAMT        AM6 'AsphaltDump.Amount.Count';
RELEASEAMT        SP1 '1';
SAVEVALUE atposres 0;
ONENTRY ATPos ASSIGN asphaltst AsphaltTruckCapCuFt;
ONENTRY ATPos ASSIGN asphalten 0;
/* Startup of ATPosition
SEMAPHORE         ATPosition 'ATPosition.CurInst==0';
ENOUGH                  AT7 'ATPos.CurCount==0';
DURATION          ATPosition 'Pert[1,2,3]';
/* Termination of ATPosition
/* Startup of ATReturn
PRIORITY          ATReturn '1';
SEMAPHORE         ATReturn 'AsphaltDump.TotInst>=1';
DURATION          ATReturn '(actreturnpathlength-paver1en)/SpeedTruck';
ONSTART ATReturn PRINT V2D "MOVE atruck%.0f ahaulpath %.3f STARTING AT %.3f\n"
ATReturn.ATruck.ResNum ATReturn.Duration paver1en/scale;
ONSTART ATReturn PRINT V2D "SETOBJCELL atruck%.0f LocPinY
Height/2\n"ATReturn.ATruck.ResNum;
ONSTART ATReturn PRINT V2D "SETOBJCELL asphalt%.0f LocPinY
Height/2\n"ATReturn.ATruck.ResNum;
/* Startup of ATHaul1
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DURATION            ATHaul1 '(acthaulpathlength+paver1en)/2/SpeedTruck';
ONSTART ATHaul1 PRINT V2D "MOVE atruck%.0f areturnpath %.3f\n"
ATHaul1.ATruck.ResNum ATHaul1.Duration;
CONSOLIDATEWHEN        MillDone1 'MillDone1.Length.Count>=MinSweepLength';
//ONFLOW , ONDRAW , ONRELEASE Code Here
CONSOLIDATEWHEN        SweepDone1 'SweepDone1.Length.Count>=MinTackLength';
//ONFLOW , ONDRAW , ONRELEASE Code Here
DURATION            MTReturn2 '(acthaulpathlength+milleren)/2/SpeedTruck';
ONSTART MTReturn2 ASSIGN mrpn 'milleren<mretdist1 ? 1
                   :milleren<mretdist2 ? 2
                   :milleren<mretdist3 ? 3
                   :milleren<mretdist4 ? 4
                   :milleren<mretdist5 ? 5
                   :milleren<mretdist6 ? 6
                  :milleren<mretdist7 ? 7
                  :milleren<mretdist8 ? 8
                  :milleren<mretdist9? 9
                  :milleren<mretdist10? 10
                  :milleren<mretdist11? 11
                   :milleren<mretdist12 ? 12
                   :milleren<mretdist13 ? 13
                   :milleren<mretdist14 ? 14
                   :milleren<mretdist15 ? 15
                   :milleren<mretdist16 ? 16
                  :milleren<mretdist17 ? 17
                  :milleren<mretdist18 ? 18 : 19';

ONSTART MTReturn2 ASSIGN mrdist 'milleren<mretdist1 ? mretdist1
                   :milleren<mretdist2 ? mretdist2
                   :milleren<mretdist3 ? mretdist3
                   :milleren<mretdist4 ? mretdist4
                   :milleren<mretdist5 ? mretdist5
                   :milleren<mretdist6 ? mretdist6
                   :milleren<mretdist7 ? mretdist7
                   :milleren<mretdist8 ? mretdist8
                   :milleren<mretdist9 ? mretdist9
                   :milleren<mretdist10 ? mretdist10
                   :milleren<mretdist11 ? mretdist11
                   :milleren<mretdist12 ? mretdist12
                   :milleren<mretdist13 ? mretdist13
                   :milleren<mretdist14 ? mretdist14
                   :milleren<mretdist15 ? mretdist15
                   :milleren<mretdist16 ? mretdist16
                   :milleren<mretdist17 ? mretdist17
                   :milleren<mretdist18 ? mretdist18 : mretdist19';
ONSTART MTReturn2 ASSIGN mrdist mrdist+100;
ONSTART MTReturn2 PRINT V2D "SETOBJCELL mtruck%.0f LocPinY Height/2-5.9069\n"
MTReturn2.MTruck.ResNum;
ONSTART MTReturn2 PRINT V2D "SETOBJCELL milling%.0f LocPinY Height/2-5.9069\n"
MTReturn2.MTruck.ResNum;
ONSTART MTReturn2 PRINT V2D "MOVE mtruck%.0f mroadpath%.0f
%.3f\n"MTReturn2.MTruck.ResNum mrpn+5 MTReturn2.Duration;
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BEFOREEND MTReturn2 PRINT V2D "SETOBJCELL mtruck%.0f LocPinY Height/2-11.9069\n" MTReturn2.MTruck.ResNum;
BEFOREEND MTReturn2 PRINT V2D "SETOBJCELL milling%.0f LocPinY Height/2-11.9069\n" MTReturn2.MTruck.ResNum;
DURATION        ATHaul2 '(945*ATHaul2.TotInst/scale)/diaSpeedTruck';
ONSTART ATHaul2 PRINT V2D "MOVE atruck%.0f ahaulpath %.3f\n"ATHaul2.ATruck.ResNum 12000/scale/diaSpeedTruck;
BEFOREEND ATHaul2 PRINT V2D "REMOVEFROMPATH atruck%.0f\n"ATHaul2.ATruck.ResNum;
BEFOREEND ATHaul2 PRINT V2D "SETOBJCELL atruck%.0f LocPinY Height/2+6\n" ATHaul2.ATruck.ResNum;
BEFOREEND ATHaul2 PRINT V2D "SETOBJCELL asphalt%.0f LocPinY Height/2+6\n" ATHaul2.ATruck.ResNum;
SAVEVALUE asphaltusedst 0;
SAVEVALUE asphaltuseden 0;
SAVEVALUE atrucksignal 500;
/* Startup of ATLoad
SEMAPHORE       ATLoad
'ATLoad.TotInst<(LaneWidthFt*MillDepthFt*nTotLenFeet/AsphaltTruckCapCuFt+1)&PaveBreak.CurInst==0&ATHaul1.CurInst==0';
ENOUGH          ch6 'ATChk1.CurCount>=0';
DURATION        ATLoad 'Pertpg[1.5,1.7,2.0]';
ONSTART ATLoad ASSIGN asphaltusedst asphaltuseden;
ONSTART ATLoad ASSIGN asphaltuseden asphaltuseden+AsphaltTruckCapCuFt;
ONSTART ATLoad PRINT V2D "DYNUPDATECELL statasphalt User.Row_1 %.3f FROM %.3f TO %.3f\n" ATLoad.Duration asphaltusedst asphaltuseden;
ONSTART ATLoad PRINT V2D "DYNUPDATECELL asphalt%.0f Width %.3f FROM %.3f TO %.3f\n" ATLoad.ATruck.ResNum ATLoad.Duration 0.0 6.9063 ;
ONSTART ATLoad PRINT V2D "SETOBJCELL information User.uat %.0f\n"(1-(ATWait.TotCount*ATWait.AveWait+ATPos.TotCount*ATPos.AveWait+ATWaitPlant.TotCount*ATWaitPlant.AveWait)/(nATruck*SimTime))*100;
ONSTART ATLoad PRINT V2D "SETOBJCELL atruck%.0f LocPinY Height/2\n" ATLoad.ATruck.ResNum;
ONSTART ATLoad PRINT V2D "SETOBJCELL asphalt%.0f LocPinY Height/2\n" ATLoad.ATruck.ResNum;
CONSOLIDATEWHEN      TackDone1
'TackDone1.Length.Count>MinPaveLength|TackDone.TotCount>=nTotLenFeet-150';
PRIORITY        RollOver '1';
SEMAPHORE       RollOver 'RollDone.CurCount>=nTotLenFeet';
DURATION        RollOver '10';
ONSTART RollOver PRINT V2D "MOVE mtv1 eqendpath 8\n";
ONSTART RollOver PRINT V2D "MOVE paver1 eqendpath 8\n";
ONSTART RollOver PRINT V2D "MOVE roller1 eqendpath 8\n";
ONSTART RollOver ASSIGN pavecost SimTime*sweepercost;
ONSTART RollOver ASSIGN mtrcost SimTime*tackercost;
ONSTART RollOver ASSIGN rollcost SimTime*rollercost;
ONSTART RollOver ASSIGN plightcost SimTime*lightcost;
ONSTART RollOver ASSIGN crwcost SimTime*ncrew*crewcost;
/* Statements to assist in the definition of attributes of calculate and its related links
SAVEVALUE graphX 134+PageX;
SAVEVALUE graphY 193.5+PageY;
SAVEVALUE graphXscale 20;
```

```
SAVEVALUE graphYscale 20;
SAVEVALUE millstatX graphX;
SAVEVALUE millstatY1 graphY;
SAVEVALUE millstatY2 graphY;
SAVEVALUE millerprod 0;
SAVEVALUE sweepstatX graphX;
SAVEVALUE sweepstatY1 graphY;
SAVEVALUE sweepstatY2 graphY;
SAVEVALUE sweeperprod 0;
SAVEVALUE pavestatX graphX;
SAVEVALUE pavestatY1 graphY;
SAVEVALUE pavestatY2 graphY;
SAVEVALUE paverprod 0;
SAVEVALUE tackstatX graphX;
SAVEVALUE tackstatY1 graphY;
SAVEVALUE tackstatY2 graphY;
SAVEVALUE tackerprod 0;
SAVEVALUE rollstatX graphX;
SAVEVALUE rollstatY1 graphY;
SAVEVALUE rollstatY2 graphY;
SAVEVALUE rollerprod 0;
/* Startup of calculate
SEMAPHORE		calculate 'RollOver.TotInst==0& Mill.TotInst>1';
DRAWAMT				ST1 '1';
DURATION		calculate '10';
ONSTART calculate ASSIGN millerprod millcoll.AveVal;
ONSTART calculate ASSIGN millstatY2 graphY+millerprod*graphYscale;
ONSTART calculate PRINT V2D "CREATE millstat%.0f line %.0f %.0f\n"calculate.TotInst
millstatX millstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL millstat%.0f LineColor 2\n" calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL millstat%.0f PinX
(BeginX+EndX)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL millstat%.0f PinY
(BeginY+EndY)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL millstat%.0f BeginX %.3f\n"calculate.TotInst
millstatX;
ONSTART calculate PRINT V2D "SETOBJCELL millstat%.0f BeginY %.3f\n"calculate.TotInst
millstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL millergraph PinX
millstat%.0f!EndX\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL millergraph PinY
millstat%.0f!EndY\n"calculate.TotInst;
ONSTART calculate PRINT V2D "DYNUPDATECELL millstat%.0f EndX 10 FROM %.3f TO
%.3f\n"calculate.TotInst millstatX millstatX+2.5;
ONSTART calculate PRINT V2D "DYNUPDATECELL millstat%.0f EndY 10 FROM %.3f TO
%.3f\n"calculate.TotInst millstatY1 millstatY2;
ONSTART calculate ASSIGN millstatY1 millstatY2;
ONSTART calculate ASSIGN millstatX millstatX+2.5;
ONSTART calculate ASSIGN sweeperprod sweepcoll.AveVal;
ONSTART calculate ASSIGN sweepstatY2 graphY+sweeperprod*graphYscale;
ONSTART calculate PRINT V2D "CREATE sweepstat%.0f line %.0f %.0f\n"calculate.TotInst
sweepstatX sweepstatY1;
```

```
ONSTART calculate PRINT V2D "SETOBJCELL sweepstat%.0f LineColor 3\n"
calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL sweepstat%.0f PinX
(BeginX+EndX)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL sweepstat%.0f PinY
(BeginY+EndY)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL sweepstat%.0f BeginX
%.3f\n"calculate.TotInst sweepstatX;
ONSTART calculate PRINT V2D "SETOBJCELL sweepstat%.0f BeginY
%.3f\n"calculate.TotInst sweepstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL sweepergraph PinX
sweepstat%.0f!EndX\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL sweepergraph PinY
sweepstat%.0f!EndY\n"calculate.TotInst;
ONSTART calculate PRINT V2D "DYNUPDATECELL sweepstat%.0f EndX 10 FROM %.3f
TO %.3f\n"calculate.TotInst sweepstatX sweepstatX+2.5;
ONSTART calculate PRINT V2D "DYNUPDATECELL sweepstat%.0f EndY 10 FROM %.3f
TO %.3f\n"calculate.TotInst sweepstatY1 sweepstatY2;
ONSTART calculate ASSIGN sweepstatY1 sweepstatY2;
ONSTART calculate ASSIGN sweepstatX sweepstatX+2.5;
ONSTART calculate ASSIGN tackerprod tackcoll.AveVal;
ONSTART calculate ASSIGN tackstatY2 graphY+tackerprod*graphYscale;
ONSTART calculate PRINT V2D "CREATE tackstat%.0f line %.0f %.0f\n"calculate.TotInst
tackstatX tackstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL tackstat%.0f LineColor 5\n" calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL tackstat%.0f PinX
(BeginX+EndX)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL tackstat%.0f PinY
(BeginY+EndY)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL tackstat%.0f BeginX %.3f\n"calculate.TotInst
tackstatX;
ONSTART calculate PRINT V2D "SETOBJCELL tackstat%.0f BeginY %.3f\n"calculate.TotInst
tackstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL tackergraph PinX
tackstat%.0f!EndX\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL tackergraph PinY
tackstat%.0f!EndY\n"calculate.TotInst;
ONSTART calculate PRINT V2D "DYNUPDATECELL tackstat%.0f EndX 10 FROM %.3f TO
%.3f\n"calculate.TotInst tackstatX tackstatX+2.5;
ONSTART calculate PRINT V2D "DYNUPDATECELL tackstat%.0f EndY 10 FROM %.3f TO
%.3f\n"calculate.TotInst tackstatY1 tackstatY2;
ONSTART calculate ASSIGN tackstatY1 tackstatY2;
ONSTART calculate ASSIGN tackstatX tackstatX+2.5;
ONSTART calculate ASSIGN paverprod pavecoll.AveVal;
ONSTART calculate ASSIGN pavestatY2 graphY+paverprod*graphYscale;
ONSTART calculate PRINT V2D "CREATE pavestat%.0f line %.0f %.0f\n"calculate.TotInst
pavestatX pavestatY1;
ONSTART calculate PRINT V2D "SETOBJCELL pavestat%.0f LineColor 4\n" calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL pavestat%.0f PinX
(BeginX+EndX)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL pavestat%.0f PinY
(BeginY+EndY)/2\n"calculate.TotInst;
```

```
ONSTART calculate PRINT V2D "SETOBJCELL pavestat%.0f BeginX %.3f\n"calculate.TotInst pavestatX;
ONSTART calculate PRINT V2D "SETOBJCELL pavestat%.0f BeginY %.3f\n"calculate.TotInst pavestatY1;
ONSTART calculate PRINT V2D "SETOBJCELL pavergraph PinX pavestat%.0f!EndX\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL pavergraph PinY pavestat%.0f!EndY\n"calculate.TotInst;
ONSTART calculate PRINT V2D "DYNUPDATECELL pavestat%.0f EndX 10 FROM %.3f TO %.3f\n"calculate.TotInst pavestatX pavestatX+2.5;
ONSTART calculate PRINT V2D "DYNUPDATECELL pavestat%.0f EndY 10 FROM %.3f TO %.3f\n"calculate.TotInst pavestatY1 pavestatY2;
ONSTART calculate ASSIGN pavestatY1 pavestatY2;
ONSTART calculate ASSIGN pavestatX pavestatX+2.5;
ONSTART calculate ASSIGN rollerprod rollcoll.AveVal;
ONSTART calculate ASSIGN rollstatY2 graphY+rollerprod*graphYscale;
ONSTART calculate PRINT V2D "CREATE rollstat%.0f line %.0f %.0f\n"calculate.TotInst rollstatX rollstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL rollstat%.0f LineColor 6\n" calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL rollstat%.0f PinX (BeginX+EndX)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL rollstat%.0f PinY (BeginY+EndY)/2\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL rollstat%.0f BeginX %.3f\n"calculate.TotInst rollstatX;
ONSTART calculate PRINT V2D "SETOBJCELL rollstat%.0f BeginY %.3f\n"calculate.TotInst rollstatY1;
ONSTART calculate PRINT V2D "SETOBJCELL rollergraph PinX rollstat%.0f!EndX\n"calculate.TotInst;
ONSTART calculate PRINT V2D "SETOBJCELL rollergraph PinY rollstat%.0f!EndY\n"calculate.TotInst;
ONSTART calculate PRINT V2D "DYNUPDATECELL rollstat%.0f EndX 10 FROM %.3f TO %.3f\n"calculate.TotInst rollstatX rollstatX+2.5;
ONSTART calculate PRINT V2D "DYNUPDATECELL rollstat%.0f EndY 10 FROM %.3f TO %.3f\n"calculate.TotInst rollstatY1 rollstatY2;
ONSTART calculate ASSIGN rollstatY1 rollstatY2;
ONSTART calculate ASSIGN rollstatX rollstatX+2.5;
RELEASEAMT          ST2 '1';
/* Activation of successors and routing of resources through MillBreakRep
STRENGTH            MI2a '0.95';
STRENGTH            MI2b '0.05';
SAVEVALUE mbn 0;
/* Startup of MillBreak
DURATION            MillBreak 'Uniform[15,30]';
ONSTART MillBreak ASSIGN mbn mbn+1;
ONSTART MillBreak PRINT V2D "REMOVEFROMPATH mtruck%.0f\n"MTPos.MTruck.ResNum;
ONSTART MillBreak PRINT V2D "CREATE mbreak%.0f break 0 0\n" mbn;
ONSTART MillBreak PRINT V2D "SETOBJCELL mbreak%.0f PinX miller1!PinX\n" mbn;
ONSTART MillBreak PRINT V2D "SETOBJCELL mbreak%.0f PinY miller1!PinY\n" mbn;
ONSTART MillBreak PRINT V2D "SETOBJCELL mbreak%.0f Angle miller1!Angle\n" mbn;
BEFOREEND MillBreak PRINT V2D "DESTROY mbreak%.0f\n" mbn;
```

```
/* Activation of successors and routing of resources through PaveBrk
STRENGTH            PA2a '0.95';
STRENGTH            PA2b '0.05';
SAVEVALUE bn 0;
DURATION            PaveBreak 'Uniform[15,30]';
ONSTART PaveBreak ASSIGN bn bn+1;
ONSTART PaveBreak PRINT V2D "CREATE break%.0f break 0 0\n" bn;
ONSTART PaveBreak PRINT V2D "SETOBJCELL break%.0f PinX paver1!PinX\n" bn;
ONSTART PaveBreak PRINT V2D "SETOBJCELL break%.0f PinY paver1!PinY\n" bn;
ONSTART PaveBreak PRINT V2D "SETOBJCELL break%.0f Angle paver1!Angle\n" bn;
BEFOREEND PaveBreak PRINT V2D "DESTROY break%.0f\n" bn;
SAVEVALUE initialmrpn 0;
DURATION            Mtrucks '10';
ONSTART Mtrucks PRINT V2D "SETOBJCELL mtruck%.0f LocPinY Height/2-5\n"
Mtrucks.MTruck.ResNum;
ONSTART Mtrucks PRINT V2D "SETOBJCELL milling%.0f LocPinY Height/2-5\n"
Mtrucks.MTruck.ResNum;
ONSTART Mtrucks PRINT V2D "MOVE mtruck%.0f mroadpath%.0f %.3f\n"
Mtrucks.MTruck.ResNum Mtrucks.MTruck.ResNum+1 Mtrucks.Duration;
/* Termination of Mtrucks
BEFOREEND Mtrucks PRINT V2D "SETOBJCELL mtruck%.0f LocPinY Height/2-11.9069\n"
Mtrucks.MTruck.ResNum;
BEFOREEND Mtrucks PRINT V2D "SETOBJCELL milling%.0f LocPinY Height/2-11.9069\n"
Mtrucks.MTruck.ResNum;
/* Startup of Atrucks
SEMAPHORE           Atrucks 'milleren>500&Atrucks.TotInst<=nATruck';
DURATION            Atrucks '5';
SEMAPHORE           Atrucks1
'ATLoad.TotInst>LaneWidthFt*MillDepthFt*nTotLenFeet/AsphaltTruckCapCuFt';
DURATION            Atrucks1 '5';
SAVEVALUE dumpst 0;
SAVEVALUE dumpen 0;
DRAWAMT                     AM3a 'AMWaitDump.CurCount';
DURATION            MTDump 'Pertpg[1.5,1.7,2.0]';
ONSTART MTDump ASSIGN dumpst dumpen;
ONSTART MTDump ASSIGN dumpen dumpen+MTDump.Amount.Count;
ONSTART MTDump PRINT V2D "DYNUPDATECELL statmilling User.Row_1 %.3f FROM
%.3f TO %.3f\n" MTDump.Duration dumpst dumpen;
ONSTART MTDump PRINT V2D "DYNUPDATECELL milling%.0f Width %.3f FROM %.3f
TO %.3f\n" MTDump.MTruck.ResNum MTDump.Duration 6.9063 0.0;
ONSTART MTDump PRINT V2D "SETOBJCELL information User.umt %.0f\n"(1-
(MTPos.TotCount*MTPos.AveWait+MTWait.TotCount*MTWait.AveWait+MTWaitDump.TotCo
unt*MTWaitDump.AveWait)/(nMTruck*SimTime))*100;
DURATION            Over '1';
ONSTART Over PRINT V2D "END\n";
CONSOLIDATEWHEN             PaveDone1
'PaveDone1.Length.Count>=MinRollLength|PaveDone2.TotCount>=nTotLenFeet-150';
DURATION            MTReturn1 '(acthaulpathlength+milleren)/2/SpeedTruck';
ONSTART MTReturn1 PRINT V2D "MOVE mtruck%.0f mreturnpath %.3f\n"
MTReturn1.MTruck.ResNum MTReturn1.Duration;
PRIORITY            TackOver '10';
SEMAPHORE           TackOver 'tacker1en==nTotLenFeet';
```

```
DURATION             TackOver '5';
ONSTART TackOver PRINT V2D "MOVE tacker1 eqendpath 8\n";
ONSTART TackOver PRINT V2D "MOVE sweeper1 eqendpath 8\n";
ONSTART TackOver ASSIGN sweepcost SimTime*sweepercost;
ONSTART TackOver ASSIGN tackcost SimTime*tackercost;
DURATION             Sweep2 'Sweep2.Length.Count/SpeedSweeper';
STRENGTH             LE1b '80';
STRENGTH             LE1d '7';
SEMAPHORE            MillDecide 'MillDecide.TotInst-MillUnusual.TotInst-Mill.TotInst==1 |
MillDecide.TotInst==0';
DRAWAMT                      LE1 'LenMillPerCycle';
DURATION             MillDecide '0.0001';
RELEASEAMT           LE1a 'MillDecide.Length.Count';
SEMAPHORE            MillUnusual 'MTPos.CurCount>0';
DRAWAMT                      LE1e 'Mill1b.CurCount';
DURATION             MillUnusual '100/MillUnusualSpeed';
ONSTART MillUnusual ASSIGN millerst milleren;
ONSTART MillUnusual ASSIGN milleren milleren+MillUnusual.Length.Count;
ONSTART MillUnusual PRINT V2D "DYNUPDATECELL statmill User.Row_1 %.7f FROM
%.3f TO %.3f\n" MillUnusual.Duration millerst milleren;
ONSTART MillUnusual COLLECT millcoll MillUnusual.Length.Count/(MillUnusual.Duration);
RELEASEAMT           AM1a 'MillUnusual.Length.Count*LaneWidthFt*MillDepthFt';
RELEASEAMT           LE2a 'MillUnusual.Length.Count';
DURATION             SweeperTravel '100/80';
SEMAPHORE            PaveDecide 'PaveDecide.TotInst-PaveUnusual.TotInst-Pave.TotInst==1
| PaveDecide.TotInst==0';
DRAWAMT                      LE7 '10';
DURATION             PaveDecide '0.0001';
RELEASEAMT           LE7a 'PaveDecide.Length.Count';
STRENGTH             LE7b '80';
STRENGTH             LE7c '20';
DRAWAMT                      LE7e 'Pave1b.CurCount';
DRAWAMT                      AM5a 'PaveUnusual.Length.Count*MillDepthFt*LaneWidthFt';
DURATION             PaveUnusual 'PaveUnusual.Length.Count/PaveUnusualSpeed';
INIT ToMill nTotLenFeet;
INIT MTWait 1;
INIT MTPark nMTruck-1;
INIT MTChk 1;
INIT ATChk 1;
INIT ATPark nATruck;
INIT stats 1;
INIT MTDumper 1;
PRINT V2D "SETOBJCELL information User.um 0\n";
PRINT V2D "SETOBJCELL information User.us 0\n";
PRINT V2D "SETOBJCELL information User.ut 0\n";
PRINT V2D "SETOBJCELL information User.up 0\n";
PRINT V2D "SETOBJCELL information User.ur 0\n";
PRINT V2D "SETOBJCELL information User.umtv 0\n";
PRINT V2D "SETOBJCELL information User.umt 0\n";
PRINT V2D "SETOBJCELL information User.uat 0\n";
PRINT V2D "SETOBJCELL information User.nmt %.0f\n"nMTruck;
PRINT V2D "SETOBJCELL information User.nat %.0f\n"nATruck;
```

```
PRINT V2D "SETOBJCELL millergraph PinX %.0f\n"134+PageX;
PRINT V2D "SETOBJCELL millergraph PinY %.0f\n"193.5+PageY;
PRINT V2D "SETOBJCELL sweepergraph PinX %.0f\n"134+PageX;
PRINT V2D "SETOBJCELL sweepergraph PinY %.0f\n"193.5+PageY;
PRINT V2D "SETOBJCELL tackergraph PinX %.0f\n"134+PageX;
PRINT V2D "SETOBJCELL tackergraph PinY %.0f\n"193.5+PageY;
PRINT V2D "SETOBJCELL pavergraph PinX %.0f\n"134+PageX;
PRINT V2D "SETOBJCELL pavergraph PinY %.0f\n"193.5+PageY;
PRINT V2D "SETOBJCELL rollergraph PinX %.0f\n"134+PageX;
PRINT V2D "SETOBJCELL rollergraph PinY %.0f\n"193.5+PageY;
PRINT V2D "SETOBJCELL statmill User.Row_1 0\n";
PRINT V2D "SETOBJCELL statsweep User.Row_1 0\n";
PRINT V2D "SETOBJCELL stattack User.Row_1 0\n";
PRINT V2D "SETOBJCELL statpave User.Row_1 0\n";
PRINT V2D "SETOBJCELL statroll User.Row_1 0\n";
PRINT V2D "SETOBJCELL statmilling User.Row_1 0\n";
PRINT V2D "SETOBJCELL statasphalt User.Row_1 0\n";
SAVEVALUE i 1;
WHILE i<8;
PRINT V2D "SETOBJCELL road Scratch.C%.0f 0\n " i ;
PRINT V2D "SETOBJCELL swroad Scratch.C%.0f 0\n " i ;
PRINT V2D "SETOBJCELL taroad Scratch.C%.0f  0\n "i ;
PRINT V2D "SETOBJCELL paroad Scratch.C%.0f  0\n "i ;
PRINT V2D "SETOBJCELL roroad Scratch.C%.0f  0\n "i ;
PRINT V2D "SETOBJCELL road Scratch.D%.0f  0\n " i+10 ;
PRINT V2D "SETOBJCELL swroad Scratch.D%.0f  0\n " i+10 ;
PRINT V2D "SETOBJCELL taroad Scratch.D%.0f  0\n "i+10 ;
PRINT V2D "SETOBJCELL paroad Scratch.D%.0f  0\n "i+10 ;
PRINT V2D "SETOBJCELL roroad Scratch.D%.0f  0\n "i+10 ;
PRINT V2D "SETOBJCELL road BeginX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL road BeginY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL road EndX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL road EndY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL swroad BeginX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL swroad BeginY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL swroad EndX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL swroad EndY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL taroad BeginX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL taroad BeginY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL taroad EndX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL taroad EndY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL paroad BeginX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL paroad BeginY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL paroad EndX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL paroad EndY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL roroad BeginX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL roroad BeginY Pages[Page-1]!ThePage!YGridOrigin\n " ;
PRINT V2D "SETOBJCELL roroad EndX Pages[Page-1]!ThePage!XGridOrigin\n " ;
PRINT V2D "SETOBJCELL roroad EndY Pages[Page-1]!ThePage!YGridOrigin\n " ;
ASSIGN i i+1;
WEND;
ASSIGN i 1;
```

```
WHILE i<=nMTruck;
PRINT V2D "\nCREATE mtruck%.0f milltruck %.0f %.0f  \n"i PageX-96+14*i PageY+5.9069;
PRINT V2D "CREATE milling%.0f milling 0 0\n"i ;
PRINT V2D "SETOBJCELL milling%.0f PinX GUARD(mtruck%.0f!PinX)\n"i i;
PRINT V2D "SETOBJCELL milling%.0f PinY GUARD(mtruck%.0f!PinY)\n"i i;
PRINT V2D "SETOBJCELL milling%.0f Angle GUARD(mtruck%.0f!Angle)\n"i i;
PRINT V2D "SETOBJCELL milling%.0f Width 0 \n"i;
ASSIGN i i+1;
WEND;
ASSIGN i 1;
WHILE i<=nATruck;
PRINT V2D "\nCREATE atruck%.0f asphalttruck %.0f %.0f \n"i PageX-60 PageY+190.3251-6*i;
PRINT V2D "CREATE asphalt%.0f asphalt 0 0\n"i ;
PRINT V2D "SETOBJCELL asphalt%.0f PinX GUARD(atruck%.0f!PinX)\n"i i;
PRINT V2D "SETOBJCELL asphalt%.0f PinY GUARD(atruck%.0f!PinY)\n"i i;
PRINT V2D "SETOBJCELL asphalt%.0f Angle GUARD(atruck%.0f!Angle)\n"i i;
PRINT V2D "SETOBJCELL asphalt%.0f Width 0 \n"i;
ASSIGN i i+1;
WEND;
PRINT V2D "CREATE miller1 miller %.4f %.4f\n"PageX-0.75 PageY;
PRINT V2D "CREATE tacker1 tacker %.4f %.4f\n"PageX-8.5 PageY+0.7649;
PRINT V2D "CREATE sweeper1 sweeper %.4f %.4f\n"PageX-11.9105 PageY;
PRINT V2D "CREATE mtv1 mtv %.4f %.4f\n"PageX-39 PageY;PRINT V2D "CREATE paver1
paver %.4f %.4f\n"PageX-58.5312 PageY;
PRINT V2D "CREATE roller1 roller %.4f %.4f\n"PageX-72 PageY;
INIT Miller 1;
INIT Sweeper 1;
INIT Tacker 1;
INIT Paver 1;
INIT Roller 1;
INIT Transfer 1;
PRINT V2D "PATH mreturnpath RIGHTPASS +mrp3 +rp1 +mrp1\n";
PRINT V2D "PATH areturnpath RIGHTPASS +arp3 +rp1 +arp1\n";
PRINT V2D "PATH ahaulpath RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13 +app14 +app15 +app16 +app17 +app18
+arp2\n";
PRINT V2D "PATH mhaulpath RIGHTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19 +mrp2\n";
PRINT V2D "PATH mroadpath24 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19\n";
PRINT V2D "PATH mroadpath23 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19\n";
PRINT V2D "PATH mroadpath22 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19\n";
PRINT V2D "PATH mroadpath21 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19\n";
PRINT V2D "PATH mroadpath20 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
```

```
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19\n";
PRINT V2D "PATH mroadpath19 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18 +mpp19\n";
PRINT V2D "PATH mroadpath18 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16 +mpp17
+mpp18\n";
PRINT V2D "PATH mroadpath17 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16
+mpp17\n";
PRINT V2D "PATH mroadpath16 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15 +mpp16\n";
PRINT V2D "PATH mroadpath15 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14 +mpp15\n";
PRINT V2D "PATH mroadpath14 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13 +mpp14\n";
PRINT V2D "PATH mroadpath13 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12 +mpp13\n";
PRINT V2D "PATH mroadpath12 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11 +mpp12\n";
PRINT V2D "PATH mroadpath11 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10 +mpp11\n";
PRINT V2D "PATH mroadpath10 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9 +mpp10\n";
PRINT V2D "PATH mroadpath9 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8 +mpp9\n";
PRINT V2D "PATH mroadpath8 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7 +mpp8\n";
PRINT V2D "PATH mroadpath7 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5 +mpp6
+mpp7\n";
PRINT V2D "PATH mroadpath6 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5
+mpp6\n";
PRINT V2D "PATH mroadpath5 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4 +mpp5\n";
PRINT V2D "PATH mroadpath4 LEFTPASS +mpp1 +mpp2 +mpp3 +mpp4\n";
PRINT V2D "PATH mroadpath3 LEFTPASS +mpp1 +mpp2 +mpp3\n";
PRINT V2D "PATH mroadpath2 LEFTPASS +mpp1 +mpp2\n";
PRINT V2D "PATH mroadpath1 LEFTPASS +mpp1\n";
PRINT V2D "PATH aroadpath18 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13 +app14 +app15 +app16 +app17 +app18\n";
PRINT V2D "PATH aroadpath17 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13 +app14 +app15 +app16 +app17\n";
PRINT V2D "PATH aroadpath16 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13 +app14 +app15 +app16\n";
PRINT V2D "PATH aroadpath15 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13 +app14 +app15\n";
PRINT V2D "PATH aroadpath14 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13 +app14\n";
PRINT V2D "PATH aroadpath13 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12 +app13\n";
PRINT V2D "PATH aroadpath12 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11 +app12\n";
```

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PRINT V2D "PATH aroadpath11 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10 +app11\n";
PRINT V2D "PATH aroadpath10 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9 +app10\n";
PRINT V2D "PATH aroadpath9 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8 +app9\n";
PRINT V2D "PATH aroadpath8 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6 +app7
+app8\n";
PRINT V2D "PATH aroadpath7 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6
+app7\n";
PRINT V2D "PATH aroadpath6 RIGHTPASS +app1 +app2 +app3 +app4 +app5 +app6\n";
PRINT V2D "PATH aroadpath5 RIGHTPASS +app1 +app2 +app3 +app4 +app5\n";
PRINT V2D "PATH aroadpath4 RIGHTPASS +app1 +app2 +app3 +app4\n";
PRINT V2D "PATH aroadpath3 RIGHTPASS +app1 +app2 +app3\n";
PRINT V2D "PATH aroadpath2 RIGHTPASS +app1 +app2\n";
PRINT V2D "PATH aroadpath1 RIGHTPASS +app1\n";
PRINT V2D "PATH eqendpath +eqp\n";
PRINT V2D "PATH trendpath1 +trp1\n";
PRINT V2D "PATH trendpath2 +trp2\n";
AFTERTIMEADVANCE PRINT V2D "TIME %.7f\n" SimTime;
SIMULATE;
REPORT;
 DISPLAY "Productivity of Operation     = " nTotLenFeet/SimTime;
```

Appendix F: Results of Simulation Model

Table A.5: Results of Simulation Model

Lighting Scenario		None (1)	Roadway Lighting (2)	Trailer Lighting (3)	Roadway + Trailer Lighting (4)	Productivity of scenario i/ Productivity of scenario j					
Normalized LDF for Mill, Pave		1	0.67	0.86	0.61	i = 2	i = 3	i = 4	i = 3	i = 4	i = 4
Normalized LDF for Sweep, Tack and Roll		1	0.52	0.77	0.45	j = 1			j = 2		j = 3
Run	SEED	*Productivity (fpm)*				*Ratio (Pdy of Sc i /Pdy of Sc j)*					
1	1000000	28.71	47.91	33.49	42.80	1.67	1.17	1.49	0.70	0.89	1.28
2	1257484691	23.91	42.04	35.36	46.05	1.76	1.48	1.93	0.84	1.10	1.30
3	1808938221	26.25	43.89	35.89	47.66	1.67	1.37	1.82	0.82	1.09	1.33
4	492764792	24.00	46.19	32.20	47.31	1.92	1.34	1.97	0.70	1.02	1.47
5	1417192517	28.10	42.78	36.29	56.06	1.52	1.29	1.99	0.85	1.31	1.54
6	870158156	26.95	41.40	32.39	53.21	1.54	1.20	1.97	0.78	1.29	1.64
7	133208743	27.50	41.49	32.98	47.59	1.51	1.20	1.73	0.79	1.15	1.44
8	369347881	22.91	42.37	32.73	40.24	1.85	1.43	1.76	0.77	0.95	1.23
9	979615096	28.46	40.58	32.10	32.86	1.43	1.13	1.15	0.79	0.81	1.02
10	236284008	27.22	50.97	35.47	44.08	1.87	1.30	1.62	0.70	0.86	1.24
11	208087247	24.75	49.68	32.25	48.56	2.01	1.30	1.96	0.65	0.98	1.51
12	112702294	26.33	48.37	30.54	34.76	1.84	1.16	1.32	0.63	0.72	1.14
13	149877062	26.04	42.54	32.18	45.41	1.63	1.24	1.74	0.76	1.07	1.41
14	974135571	26.38	38.63	36.17	40.54	1.46	1.37	1.54	0.94	1.05	1.12
15	797257652	26.59	40.01	31.60	58.13	1.50	1.19	2.19	0.79	1.45	1.84
16	1945151146	26.56	49.85	32.59	48.12	1.88	1.23	1.81	0.65	0.97	1.48
17	1225227764	26.70	47.29	30.89	56.65	1.77	1.16	2.12	0.65	1.20	1.83
18	769775693	26.61	43.47	35.98	44.69	1.63	1.35	1.68	0.83	1.03	1.24
19	1681521256	24.97	50.26	37.42	41.34	2.01	1.50	1.66	0.74	0.82	1.10
20	1505560500	25.79	32.10	36.06	49.63	1.24	1.40	1.92	1.12	1.55	1.38
21	1701725203	29.13	34.63	34.13	48.30	1.19	1.17	1.66	0.99	1.39	1.42
22	23950127	26.75	46.34	34.07	47.39	1.73	1.27	1.77	0.74	1.02	1.39
23	86225410	25.63	43.09	32.83	45.02	1.68	1.28	1.76	0.76	1.04	1.37
24	1721397935	24.97	40.14	32.75	46.78	1.61	1.31	1.87	0.82	1.17	1.43
25	1068501463	27.01	35.88	32.05	35.19	1.33	1.19	1.30	0.89	0.98	1.10
26	140984101	25.14	39.79	33.69	40.80	1.58	1.34	1.62	0.85	1.03	1.21
27	110317795	26.25	48.76	35.18	53.99	1.86	1.34	2.06	0.72	1.11	1.53
28	55334393	28.65	46.33	37.08	46.02	1.62	1.29	1.61	0.80	0.99	1.24

Lighting Scenario		None (1)	Roadway Lighting (2)	Trailer Lighting (3)	Roadway + Trailer Lighting (4)	Productivity of scenario i/ Productivity of scenario j					
Normalized LDF for Mill, Pave		1	0.67	0.86	0.61	i = 2	i = 3	i = 4	i = 3	i = 4	i = 4
Normalized LDF for Sweep, Tack and Roll		1	0.52	0.77	0.45	j = 1			j = 2		j = 3
Run	SEED	***Productivity (fpm)***				***Ratio (Pdy of Sc i / Pdy of Sc j)***					
29	1894693743	23.75	41.39	28.61	45.96	1.74	1.20	1.93	0.69	1.11	1.61
30	1987636426	25.06	40.45	33.94	38.58	1.61	1.35	1.54	0.84	0.95	1.14
31	842810295	25.30	47.79	35.83	58.74	1.89	1.42	2.32	0.75	1.23	1.64
32	736579602	26.75	49.86	29.08	53.67	1.86	1.09	2.01	0.58	1.08	1.85
33	476043219	23.36	42.24	32.28	45.93	1.81	1.38	1.97	0.76	1.09	1.42
34	52364160	27.68	48.79	34.30	36.15	1.76	1.24	1.31	0.70	0.74	1.05
35	794524130	28.81	37.88	36.77	46.84	1.31	1.28	1.63	0.97	1.24	1.27
36	554482728	26.74	43.59	37.64	53.26	1.63	1.41	1.99	0.86	1.22	1.41
37	914394338	27.91	45.79	33.70	47.62	1.64	1.21	1.71	0.74	1.04	1.41
38	1458160114	27.39	35.59	33.47	46.95	1.30	1.22	1.71	0.94	1.32	1.40
39	1654042487	26.84	47.00	30.50	53.98	1.75	1.14	2.01	0.65	1.15	1.77
40	1789105025	24.00	47.93	35.61	46.46	2.00	1.48	1.94	0.74	0.97	1.30
41	1955251125	23.38	40.06	37.28	41.62	1.71	1.59	1.78	0.93	1.04	1.12
42	1365837047	25.51	52.00	34.11	58.80	2.04	1.34	2.30	0.66	1.13	1.72
43	1046469450	26.75	37.42	33.84	33.99	1.40	1.27	1.27	0.90	0.91	1.00
44	648178335	26.33	49.87	30.55	42.58	1.89	1.16	1.62	0.61	0.85	1.39
45	472035101	29.38	41.08	34.47	36.49	1.40	1.17	1.24	0.84	0.89	1.06
46	2145844278	28.96	50.03	34.34	44.09	1.73	1.19	1.52	0.69	0.88	1.28
47	1061726454	29.52	39.15	33.08	44.81	1.33	1.12	1.52	0.84	1.14	1.35
48	1094659222	24.37	49.79	29.99	48.13	2.04	1.23	1.98	0.60	0.97	1.60
49	1364966270	27.79	46.12	29.14	40.42	1.66	1.05	1.45	0.63	0.88	1.39
50	1687895178	24.33	46.89	31.85	52.71	1.93	1.31	2.17	0.68	1.12	1.65
51	127005134	25.28	43.80	30.13	40.24	1.73	1.19	1.59	0.69	0.92	1.34
52	2118429669	26.82	41.10	35.54	46.24	1.53	1.33	1.72	0.86	1.13	1.30
53	583106815	27.53	48.13	34.34	41.32	1.75	1.25	1.50	0.71	0.86	1.20
54	1569731017	30.57	47.17	37.51	53.63	1.54	1.23	1.75	0.80	1.14	1.43
55	1042472294	27.96	50.10	29.42	52.23	1.79	1.05	1.87	0.59	1.04	1.78
56	1498336138	26.40	46.95	33.28	46.85	1.78	1.26	1.77	0.71	1.00	1.41
57	1154706508	22.20	43.29	31.42	51.26	1.95	1.42	2.31	0.73	1.18	1.63
58	2142456920	27.32	50.61	33.76	45.63	1.85	1.24	1.67	0.67	0.90	1.35
59	43961105	26.11	47.45	30.48	50.93	1.82	1.17	1.95	0.64	1.07	1.67

Lighting Scenario		**None (1)**	**Roadway Lighting (2)**	**Trailer Lighting (3)**	**Roadway + Trailer Lighting (4)**	**Productivity of scenario i/ Productivity of scenario j**					
Normalized LDF for Mill, Pave		**1**	**0.67**	**0.86**	**0.61**	**i = 2**	**i = 3**	**i = 4**	**i = 3**	**i = 4**	**i = 4**
Normalized LDF for Sweep, Tack and Roll		**1**	**0.52**	**0.77**	**0.45**	**j = 1**			**j = 2**		**j = 3**
Run	SEED	***Productivity (fpm)***				***Ratio (Pdy of Sc i / Pdy of Sc j)***					
60	756740895	26.30	44.31	32.28	54.15	1.68	1.23	2.06	0.73	1.22	1.68
61	1937527919	26.67	49.62	35.39	44.74	1.86	1.33	1.68	0.71	0.90	1.26
62	2115487311	24.87	36.53	31.69	45.25	1.47	1.27	1.82	0.87	1.24	1.43
63	1016127867	28.05	45.14	29.59	61.69	1.61	1.05	2.20	0.66	1.37	2.08
64	1746879906	24.01	40.72	33.04	38.85	1.70	1.38	1.62	0.81	0.95	1.18
65	717622779	23.67	48.33	34.51	41.77	2.04	1.46	1.76	0.71	0.86	1.21
66	634581077	24.22	46.40	35.09	54.60	1.92	1.45	2.25	0.76	1.18	1.56
67	584213684	26.78	36.75	31.74	51.09	1.37	1.19	1.91	0.86	1.39	1.61
68	1389950900	24.50	39.51	33.44	53.84	1.61	1.37	2.20	0.85	1.36	1.61
69	1985661866	23.83	48.73	31.92	49.62	2.04	1.34	2.08	0.65	1.02	1.55
70	772915748	27.73	41.00	31.38	53.60	1.48	1.13	1.93	0.77	1.31	1.71
71	553623542	25.65	42.95	31.81	47.07	1.67	1.24	1.84	0.74	1.10	1.48
72	1144070675	27.60	48.74	32.48	50.57	1.77	1.18	1.83	0.67	1.04	1.56
73	2133458947	26.34	50.92	32.17	41.14	1.93	1.22	1.56	0.63	0.81	1.28
74	508458536	28.31	48.11	33.44	55.29	1.70	1.18	1.95	0.70	1.15	1.65
75	833994341	24.78	33.81	34.52	47.77	1.36	1.39	1.93	1.02	1.41	1.38
76	45250651	25.78	42.74	30.26	39.94	1.66	1.17	1.55	0.71	0.93	1.32
77	550520312	25.15	38.57	31.71	47.26	1.53	1.26	1.88	0.82	1.23	1.49
78	1745487687	28.47	46.85	35.44	45.61	1.65	1.24	1.60	0.76	0.97	1.29
79	1168973464	27.25	42.93	32.11	47.28	1.58	1.18	1.74	0.75	1.10	1.47
80	1193952986	25.61	43.14	37.09	49.89	1.68	1.45	1.95	0.86	1.16	1.35
81	2130237321	26.51	39.42	35.33	44.16	1.49	1.33	1.67	0.90	1.12	1.25
82	209778841	26.75	48.93	31.91	51.59	1.83	1.19	1.93	0.65	1.05	1.62
83	55259393	29.01	48.40	36.31	42.63	1.67	1.25	1.47	0.75	0.88	1.17
84	1746695300	26.99	47.71	35.87	51.05	1.77	1.33	1.89	0.75	1.07	1.42
85	187666233	26.62	39.51	32.79	49.82	1.48	1.23	1.87	0.83	1.26	1.52
86	1235349665	24.99	49.63	31.26	42.11	1.99	1.25	1.69	0.63	0.85	1.35
87	254480525	28.06	46.87	36.89	51.34	1.67	1.31	1.83	0.79	1.10	1.39
88	625529722	23.41	41.85	34.93	46.69	1.79	1.49	1.99	0.83	1.12	1.34
89	1491924966	23.31	37.26	32.65	50.79	1.60	1.40	2.18	0.88	1.36	1.56
90	176265036	25.19	42.74	37.01	49.00	1.70	1.47	1.95	0.87	1.15	1.32

Lighting Scenario		None (1)	Roadway Lighting (2)	Trailer Lighting (3)	Roadway + Trailer Lighting (4)	Productivity of scenario i/ Productivity of scenario j					
Normalized LDF for Mill, Pave		1	0.67	0.86	0.61	i = 2	i = 3	i = 4	i = 3	i = 4	i = 4
Normalized LDF for Sweep, Tack and Roll		1	0.52	0.77	0.45	j = 1			j = 2		j = 3
Run	SEED	*Productivity (fpm)*				*Ratio (Pdy of Sc i / Pdy of Sc j)*					
91	1769501784	25.98	45.30	36.40	49.72	1.74	1.40	1.91	0.80	1.10	1.37
92	467176308	25.21	46.24	32.57	43.94	1.83	1.29	1.74	0.70	0.95	1.35
93	1603614844	23.53	31.00	32.25	50.99	1.32	1.37	2.17	1.04	1.64	1.58
94	1967712362	26.17	38.50	31.12	55.04	1.47	1.19	2.10	0.81	1.43	1.77
95	1670490063	24.99	46.74	31.58	47.59	1.87	1.26	1.90	0.68	1.02	1.51
96	1828503866	23.83	49.75	28.27	41.02	2.09	1.19	1.72	0.57	0.82	1.45
97	661797629	25.34	43.95	27.14	55.31	1.73	1.07	2.18	0.62	1.26	2.04
98	578460567	27.23	47.28	31.80	43.88	1.74	1.17	1.61	0.67	0.93	1.38
99	341537888	29.83	41.96	35.60	48.48	1.41	1.19	1.62	0.85	1.16	1.36
100	1326982474	30.00	49.32	29.39	46.18	1.64	0.98	1.54	0.60	0.94	1.57
101	1160736725	25.76	45.66	37.28	53.36	1.77	1.45	2.07	0.82	1.17	1.43
102	2022551240	25.70	48.35	32.96	49.66	1.88	1.28	1.93	0.68	1.03	1.51
103	1342839470	28.57	49.20	33.34	48.17	1.72	1.17	1.69	0.68	0.98	1.44
104	1524231284	25.11	40.81	29.51	42.13	1.63	1.18	1.68	0.72	1.03	1.43
105	70815537	22.59	41.85	33.23	57.02	1.85	1.47	2.52	0.79	1.36	1.72
106	1876948480	25.83	40.04	37.08	36.03	1.55	1.44	1.39	0.93	0.90	0.97
107	1340359874	27.09	52.08	33.85	42.59	1.92	1.25	1.57	0.65	0.82	1.26
108	1055716828	25.16	44.43	32.27	50.85	1.77	1.28	2.02	0.73	1.14	1.58
109	219279903	28.99	41.02	37.09	35.77	1.41	1.28	1.23	0.90	0.87	0.96
Half Width		0.2262	0.661848	0.293333	0.836493	0.04	0.02	0.05	0.02	0.03	0.04
Mean		26.037	43.89657	33.43261	47.26025	1.69	1.27	1.8	0.76	1.07	1.42
Standard Deviation		1.8212	5.328559	2.361632	6.734634	0.21	0.11	0.26	0.11	0.18	0.22
Number of Runs = 109											

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For the degree of Master of Science in Civil Engineering

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