PREDICTING PRODUCTION RATES IN THE WISCONSIN HIGHWAY CONSTRUCTION INDUSTRY USING COMPUTER TOOLS

by

Brent Tyler Flaten

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ABSTRACT

Poor estimates of project contract completion time can produce dire consequences. Awarding too much time to complete a project creates conditions where contractors may be encouraged to perform work less aggressively, while awarding too little time can increase prices and decrease the amount of bids received. Traditionally, the Wisconsin Department of Transportation's (WisDOT) methods for determining contract completion time have relied upon production rates published in their decades old Facilities Design Manual (FDM). However, the FDM has not been updated to reflect advancements in technology, and the use of its production rates has fallen out of favor with WisDOT staff. This study improved upon the prototype version of a productivity estimation tool (PET) created to provide WisDOT estimators with more reliable productivity information.

WisDOT's PET uses models created using stepwise linear regression to identify significant project specific factors in order to estimate productivity on future projects. The prototype of WisDOT's PET suffered from limited data and omitted several miscellaneous highway construction activities. This study improved upon the PET by gathering additional data, including 26 new miscellaneous activities, enhancing the visual means of displaying productivity information, identifying additional factors for estimators to consider when determining contract time, and creating a web domain to gather productivity data from WisDOT field engineers in the future. Applying the PET and incorporating new data into its models as projects are completed will allow WisDOT estimates of contract time to improve over time.

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As I said earlier, research and statistics were daunting and intimidating subjects for me to think about two years ago. Thankfully, many individuals from around campus gladly offered their help. Laura Schmidli, an information services librarian at Wendt Library, greatly improved my effectiveness as a researcher. Her can-do attitude and expertise helped me greatly in understanding where to look for current and pertinent information. The course of my research required me to create a web domain to enable WisDOT field engineers to easily provide productivity data. Creating a website for the PET could not have been an easier process without Joyce Tikalsky's help from Engineering External Relations. My research required a thorough understanding and application of multiple linear regression. Dr. Murray Clayton, my statistics professor, and Hoayang Fan, a Ph.D. candidate at the time, offered their help numerous times to ensure sound statistical analysis methods were being applied. Creating the models for the PET involved a great deal of time using the statistical analysis software program R and Microsoft Excel. Hala Nassereddine, a fellow graduate student and peer, was always willing to provide her own tips and tricks for using these two programs to help accomplish my statistical analysis more efficiently.

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CHAPTER ONE
INTRODUCTION

1.1 Background

The United States of America possesses a rapidly aging infrastructure as it progresses into the 21st century. The American Society of Civil Engineers (ASCE), addressed this predicament in a very candid and self-critical manner in a 2013 report on America's infrastructure. In this report, ASCE graded the country's roadway system and bridges at grades of "D" and "C+" respectively. ASCE notes that these poor grades are warranted for reasons such as 42% of America's major urban highways being congested, one in nine bridges being structurally deficient, and the average age of the nation's bridges being 42 years old. These problems will undoubtedly be addressed as the country's economy so heavily relies upon a dependable transportation infrastructure. As issues with aging infrastructure are corrected, ASCE estimates that $20.5 billion for the nation's bridges and $170 billion for the nation's roadways would need to be invested *annually.*

While the ASCE investigated transportation infrastructure on a national level, in 2014 Hartgen et al. ranked roadways on a state by state basis. Hartgen et al. found that a wide disparity existed between states in terms of both the quality of their roadways and the cost-effectiveness of their state highway systems. Highlighting the extremes in cost effectiveness were South Carolina and West Virginia which spent $39,000 per mile of road compared to New Jersey which spent $2 million per mile. Encouragingly, Hartgen et al. ranked Wisconsin's highway system at 15th nationally noting that Wisconsin was among three states which saw the greatest improvement in roadway conditions between 2011 and 2012. Ranking well above average is certainly not an accident, and the transportation professionals working at WisDOT perform well on a national level. However, maintaining this status and improving Wisconsin's standing requires continuous inward investigation into opportunities for improvement. Of the various avenues of approach to improving WisDOT operations, this research study intends to focus on the role that productivity data and improved contract time determination can play.

Contract time is the maximum amount of time a contractor is allowed to complete a given project. Varying methods for determining contract time exist among state DOT's, but productivity data is at the root of the methods employed by the majority of DOT's examined by this study. In its simplest form, productivity can be described as the rate of time which a given construction activity can be completed. Successful organizations, both public and private, continuously capture productivity data for historical databases as work is completed. Productivity data is then used to determine activity durations while building a schedule that covers the duration of a construction project. In the private sector, poor productivity data can be the difference between a firm entering a winning bid and a firm losing a job to another qualified lower bidder. Additionally, poor productivity data can create situations where a contractor submits a winning bid, and is later unable to meet contractual obligations. From WisDOT's perspective, poor productivity data leads to poor estimates of contract time which causes an assortment of issues. If a contract time estimate is too large, contractors may be encouraged to perform work less aggressively which inconveniences and exposes the public to roadway safety concerns for longer than necessary (Hildreth, 2005). If a contract time estimate is too small, the public is at risk of increased transportation construction costs because contractors are more likely to submit claims to recoup added costs and competitiveness is lost in the bidding process as a reduced number of bids are received (FHWA, 2015; Hildreth, 2005). Ultimately, the combination of immense public spending and the consequences to the public caused by poor estimates of contract time rooted in inaccurate productivity data create a necessity for WisDOT to use accurate historical data.

WisDOT's method of determining contract time is currently in an exploratory and transitionary phase. This research is funded and motivated by helping to improve WisDOT operations, which had grown outdated in terms of ascertaining productivity rates. Traditionally, WisDOT staff would obtain production rates from their Facilities Design Manual (FDM) to find activity durations to build an estimate for contract time. In 2013, Aoun found that this information was greatly outdated and many WisDOT estimators instead relied upon experience and historical data that was gathered personally. The FDM has lost relevance with WisDOT staff because FDM has not been updated to reflect advancements in technology. Additionally, activities listed in the FDM are reported with ranges of values where maximum values can be found to be as large as several hundred percent of the minimum value. Without guidance as to how to select a single value from such a large range of values, choosing production rates from the FDM can become an arbitrary process that doesn't consider a given project's unique site conditions. Aoun's research culminated in a prototype version of the PET, which can be used to predict productivity on future projects based on a number of project specific factors. However, the prototype PET suffered greatly from limited data, did not include many pertinent miscellaneous roadway construction activities, and did not offer guidance to estimators for applying their experience when considering factors other than productivity which can impact contract time. Expanding upon initial phases of this research strives to give WisDOT staff a more complete and useful estimation tool.

1.2 Scope of Research

This research strived to improve and expand upon the prototype version of WisDOT's PET. Major items in the scope of this research include gathering additional data, update the prototype PET's productivity models, creating additional productivity models, incorporate new miscellaneous activities, update the PET's visual output, identify additional factors that affect productivity, and establish a web-based data collection system. Productivity data for asphalt pavement, bridges, concrete pavement, and earthwork construction activities were initially gathered in 2013 to update the decades old rates listed in WisDOT's Facilities Development Manual (FDM). In 2014, additional miscellaneous activities were included to this project's data collection survey before being used to gather additional data from WisDOT project engineers throughout the state. After adding new data to the existing productivity database, models were analyzed using stepwise linear regression in R to identify significant project factors their respective coefficients. The output in the PET was changed from a format that used tables of confidence intervals to a visual output system that relies upon box-and-whisker diagrams. The revised tool was then made available to WisDOT transportation designers on a new web-based platform that also includes data collection surveys for field engineering staff to provide new data in the future. The list of additional factors that affect productivity identified by the literature review were added to the PET to help guide designers as they used their personal experience and judgement to ultimately determine contract time. Finally, user manuals were created to guide WisDOT employees in using and updating the tool.

1.3 Organization of Thesis

The following chapters serve as a comprehensive exploration of the thought processes and actions undertaken throughout this research. The following chapter, Chapter 2, explores current literature in order to align this research both with efforts undertaken by previous studies and with transportation agencies across the United States. The role of reliable productivity estimates in the success of transportation projects is discussed before considering what knowledge other DOT's offer than can be incorporated into the PET. Chapter 3 explains the research methodology that was used while improving and making additions to the original version of the PET. Various statistical analysis methods were applied to make this project come to fruition, and the concepts that make this research unique will be explained in detail. Chapter 4 will present the data analysis and results that were conducted to create the models that were incorporated into the PET. Five major sections separated by type of construction comprise this chapter where the relationships between project factors and construction activities are explored. Key findings and the results from cross validation are presented to conclude this chapter. Chapter 5 details the changes that were made to the PET throughout 2015 before providing a short yet comprehensive user guide. Chapter 6 discusses how to update the estimation tool, a new data collection system that has been developed, and current limitations of the tool. Finally, Chapter 6 concludes with a set of conclusions and recommendations that can be made for further development of the PET.

CHAPTER TWO
LITERATURE REVIEW

Conducting a literature review while in the process of this research was necessary to orientate the research with the findings of previous studies. Productivity has been a frequently studied subject not just within construction, but across all industries as well. Each industry possesses its own nuances and ideas in regards to productivity. The intricacies involved in construction labor undoubtedly make accuracy and diligence in data collection paramount to the success of any attempt to rely upon historical data. Furthermore, successfully using historical data to project future productivity is complicated by the incredible amount of factors that influence productivity. A study by Teicholz in 2001 went as far to claim that construction productivity is the most difficult to understand in the U.S economy because there are so many factors that could affect productivity. However, this complexity should be seen as a challenge and an opportunity for innovation rather than an insurmountable barrier. Organizations working within the highway construction industry have attempted to predict productivity to better estimate contract time in the past and can offer varying insight. The skills, techniques, and thought processes employed by various entities with an interest in highway construction productivity has the potential to lead this research to greater findings.

The goals of the literature review are as follows:

1. Understand the importance of productivity in determining the success of a highway construction project
2. Investigate techniques and rates used by other DOT's
3. Identify factors to consider when determining contract time other than productivity that can be incorporated into the productivity estimation tool

2.1 Productivity's Role in Project Success

Several factors that arise throughout the project lifecycle such as quality plans, accurate takeoff, effective management, owner involvement, and safety principles can become deciding factors in ultimately determining project success. However, the focus of this research entails productivity's role in delivering a successful project. More specifically the goal is to better understand the impact productivity data has on the accuracy of the total duration of Critical Path Method (CPM) schedules. A construction scheduler relies heavily upon accurate productivity data to generate quality CPM schedules. Kim et al. (2014) explained that poor productivity data affects the accuracy of activity durations, and inaccurate activity duration makes it impossible to produce a reliable construction schedule. In larger organizations, productivity is often tracked continuously to evaluate performance and prepare for future biddings (Ghanem et al., 2006). From WisDOT's perspective, productivity data is required to accurately determine contract. Burton (1991) expressed that productivity data is essential to estimators and those involved in contract negotiations. Without reliable data it becomes impossible for WisDOT's engineers, estimators, and schedulers to envision realistic activity durations that ultimately lead to accurate contract durations.

Risk in its numerous forms is inherent to any undertaking involving the construction industry. Mitigating these risks is a paramount concern of project management professionals striving to deliver a successful project. While the conventional project cost components are material, labor, and equipment, the most risk is generally associated with labor (Hanna et al., 2005). In the mechanical and electrical fields where labor is more intensive, labor can grow to become 33-50% of a projects total budget (Hanna, 2001). When looking at labor in highway construction it is apparent that advancements in equipment drastically changed labor's percentage of total project expenditures. In 1961, Kutscher et al. found that between 1947 and 1958 onsite labor requirements decreased by 47% due to the increasing use and efficiency of roadbuilding equipment. Kutscher et al. additionally reported that labor accounted for 23.9% of project expenditures on federally aided highway construction in 1958. Surprisingly, in 2004 the Construction Labor Research Council reported that labor constitutes approximately 20% of total project costs on large highway construction projects indicating that only minimal improvements have been made after the initial implementation of highway construction equipment. The uncertainty involved with productivity generally affects contractors who fail to meet the productivity levels assumed by estimators when preparing a bid. However, governmental agencies can be effected by this uncertainty as well when issuing unrealistic amounts of time for contract completion.

Contract time is the maximum amount of time a contractor is allowed to complete a given project. The amount of time awarded to complete a contract is a direct function of the productivity data used to calculate activity durations. Concerns with inaccurate contract time are created when either more time than necessary or an insufficient amount of time is awarded to complete a project. When too much time is allotted the public is inconvenienced by roadway projects for more time than necessary. Contractors who have been awarded too much time can tend to conduct their work less aggressively. The Missouri DOT notes that excessive contract time exposes the public to prolonged safety concerns, encourages contractors to bid more work than can be completed in a timely manner, and discourages contractors from employing innovative management and/or construction techniques (Hildreth, 2005). Weather, concrete curing, and late material delivery can all lead to a project sitting dormant, however often times the cause can be traced to excessive time being awarded by the scheduling engineer to complete a project (Florida Department of Transportation, 2010). When insufficient amounts of time are awarded contractor's become likely to submit claims to recoup added cost and time to the contract (Federal Highway Administration, 2015). Short contract times can encourage excessive bid prices and reduce the number of bids submitted (Hildreth, 2005). Reducing the number of bids received is an especially undesirable proposition because the lack of competitors vying for a project removes competitiveness from the bidding process and can ultimately increase the project's cost to the public. Effective productivity data is at the root of the aforementioned concerns involving contract time. Ultimately, obtaining accurate productivity data can avoid the issues created by awarding inaccurate contract time by providing schedulers with reliable inputs to generate reliable activity durations.

2.2 Methods Used by Other DOT's

Investigating techniques currently used by DOT's other than WisDOT provides an opportunity to gain insight into potential methods to deploy in the future and legitimize practices which are currently in place at WisDOT. Additionally, gathering productivity data from other states can temporarily fill gaps where data collection challenges experienced by this study have resulted in a lack of viable production rates. Obtaining this information in the private sector would undoubtedly be a challenge because private entities often do not want to run the risk of losing their competitive advantage. However, this information is readily available from governmental agencies, and there is little incentive for one transportation agency to outperform another. Consequently, production rates and methods for determining contract time have been gathered from other states.

2.2.1 Determining Contract Time

All DOT's investigated reiterated the importance of establishing an accurate database of historical productivity data in order to better estimate contract time. A common method found involved dividing the total quantity of work for a particular activity by the total amount of time used to complete the activity. The Florida Department of Transportation (FDOT) emphasized that this method was not recommended because it often gives rise to lower production rates because they often include time spent in startup, cleanup, and interruptions (Florida Department of Transportation, 2010). Instead FDOT preferred data collected on site or from project records such as field diaries while capturing information regarding the contractor's crew make up to gauge the contractor's level of work effort. Additionally, FDOT maintains a productivity database spanning three to five years of historical data. Published production rate guides were noted as a resource, but their use is cautioned as it is difficult to apply these rates to actual highway projects. In 2013, Taylor et al. explained that the tools and methods used by DOTs in contract time determination systems can be categorized into three categories:

- **Archived Production Rates:** Historical production rate information is continually captured in a database for future use. Critical activities are identified and durations are determined from production rate databases. Archived production rates appear in the methods of nearly all DOTs, but DOTs classified by this system typically did not use additional methods to determine contract time. 28% of DOTs were found to utilize archived production rates.
- **Pre-determined Logic:** Predetermined schedules are created for various types of roadway projects (bridge replacement, bridge rehabilitation, new route, resurfacing, etc.) to be used at a later date. Production rates are tracked separately for each type of roadway project to be

used in determining activity durations. Contract time is developed by 17% of DOTs via predetermined logic systems.

- **Integrated Scheduling:** A software based system is generally developed specifically for a DOT. Integrated production rate and schedule logic is based upon bid item quantities. A system considered to be in this category uses both archived production rates and pre-determined logic. These types of systems constituted 48% of DOTs. The remaining 7% of DOTs could not be categorized by the aforementioned categories.

The Kentucky Contract Time Determination System (KY-CTDS) was implemented on February 9, 2000 with the intention of providing a tool to assist in estimating contract time on KY-DOT projects (Kentucky Transportation Cabinet, 2013). Kentucky's method uses a regression based system, but is divided into separate categories for projects both over and under $1 million. Initially, Kentucky found that regression based modeling was more accurate for determining contract time on larger projects. Smaller projects were estimated with a separate process using activities, production rates, and activity logic. After the process used on smaller projects was deemed to be too time intensive, separate similar models were created for Kentucky's smaller roadway projects. Models were created for four different types of projects (limited access, open access, bridge replacement, and bridge rehabilitation) that use the engineer's estimate and activity quantities as parameters. Ultimately, Kentucky recognized that the percent deviations for these models were between 53-162% and did not recommend using the system further for determining contract time. To reiterate, Kentucky chose not to use historical rates to determine activity durations for building a total contract time because it was deemed to be too time intensive. However, their results suggest that determining contract time should be performed by breaking a project into smaller components (activities) when building a project schedule.

2.2.2 Production Rates Used by Other DOT's

The necessity of obtaining production rates used by other DOT's is rooted in the data collection challenges experienced by this study. The research team was unable to gather any data for nine of the construction activities included in this study (more information regarding activities with an absence of data can be found in Chapter Four). Consequently, rates used by other states were incorporated into the PET until more data can be collected from WisDOT projects and substituted into the tool. Productivity data for many of the DOT's investigated is readily available on their websites as a tool for engineers to use in determining contract time. As previously discussed, the sophistication of the methods used ranges from simple lists of production rates to computer software that organizes, displays, and allows engineers to modify the data based on project conditions. In 2013, Aoun gathered rates used by Illinois, Indiana, Iowa, Oklahoma, Minnesota, Texas, and Washington. Additionally, this literature review gathered rates from Florida, Michigan, and Virginia to supplement Aoun's findings that can be found in Appendix B. Data from neighboring states was used first when available before using information from more geographically distant states. In the future, the goal is for all of the productivity information incorporated into the PET to be data gathered from WisDOT projects.

2. 3 Other Factors to Consider When Determining Contract Time

Thus far obtaining accurate productivity data to determine a reliable contract time has been the focus of this literature review. In 2013, Aoun identified 21 project specific factors which impact productivity that were previously incorporated into an earlier phase of this research. A complete listing and description of these 21 factors can be found in Chapter Three's "Data Collection" section. However, Aoun's factors were identified with the purpose of determining how productivity was specifically affected by varying project conditions. Additionally, this research study determined that there were possibly other activities not directly related to productivity that should be considered by WisDOT engineers when determining contract time. Identifying these factors and incorporating them into the PET will give WisDOT engineers a list of considerations to evaluate projects with when applying their experience and personal judgement.

The Federal Highway Administration (2015) proposed a list of factors in addition to production rates that should be considered when determining contract time:

1. Effects of maintenance of traffic requirements on scheduling and the sequence of operations;
2. Curing time and waiting periods between successive paving courses or between placement operations, as well as specified embankment settlement periods;
3. Seasonal limitations for certain items when determining both the number of days the contractor will be able to work as well as production rates;
4. Conflicting operations of adjacent projects, both public and private;
5. Time for reviewing false-work plans, shop drawings, post-tensioning plans, mix designs, etc.;
6. Time for fabrication of structural steel and other specialty items;
7. Coordination with utilities;

8. Time to obtain necessary permits;
9. Restrictions for nighttime and weekend operations;
10. Additional time for obtaining specialty items or materials with long-lead requirements;
11. Non-traditional contracting methods such as Bonuses and Incentive/Disincentive specifications for early completion;
12. Instances where business closures may become necessary;
13. Geographic location;
14. Other pertinent items as determined by the scheduling engineer.

The aforementioned factors generally represent blocks of time where work is either hindered or stopped altogether. Items such as concrete curing, embankment settlement, obtaining necessary permits, seasonal limitations, conflicting operations with adjacent projects, and time for fabricating or procuring specialty items have the potential to stop certain work activities, if not all. Allowing adequate time for concrete curing and embankment settlement ensures the structural integrity of components of a project is not compromised. Proceeding with work before adequate time has passed raises the potential for failure in a component resulting in the added time involved with rework. Without the necessary environmental permits, work may not be able to begin until the impact on the existing environment has been considered and deemed acceptable. Seasonal limitations can prevent paving activities from occurring due to temperature requirements that cannot be overcome in a highway construction setting. Without providing adequate lead time the absence of necessary specialty items can make work impossible especially in bridge construction where unique precast concrete or steel girders cannot be produced on site. The scenario can be avoided by specifying a completion date several months after the notice to proceed and limiting the amount of time the contractor may spend on site. This may be accomplished by including a "conditional notice to proceed" clause in the contract which allows a specified amount of time to acquire materials followed by issuing a final work order after the procurement period has ended (Florida Department of Transportation, 2010). The common theme connecting these issues is that schedulers must possess the necessary experience to make assumptions and decisions that align scheduling more closely with an art than a science.

The factors outlined by the Federal Highway Administration above are public information available to all states across the United States. While researching other DOT's for production rates and the methods used to establish them accurately, the Federal Highway Administration guidelines were found to be utilized both in their entirety and by focusing on key factors in the states of California, Florida, Ohio, Virginia, and Washington. In 2005, Hildreth arrived at the same conclusion that the format recommended by the FWHA has been widely adopted after examining 23 state DOT's. The Washington Department of Transportation (WSDOT) went on to concur with the FHWA's proposal that determining an accurate contract time is important due to continually increasing traffic volumes and the ability to optimize construction engineering costs (Washington Department of Transportation, 2013). WSDOT emphasized that written procedures should be used in order to ensure that production rates and other considerations are applied uniformly throughout the state. A reasonable contract time was also advised as bid prices, contractor claims, and time overruns are likely to be more prevalent in the absence of adequate contract time. Seasonal effects were noted while determining working days per month with an emphasis that bridge construction projects should be assigned the greatest number of working days when presented with a range to choose from. WSDOT further added to the FWHA's guidelines by including working hour restrictions, noise restrictions, time of year of the contract letting, special local area events (such as parades, festivals, athletics, fairs, and races), and the occurrence of Canadian and neighboring states' holidays.

CHAPTER THREE
RESEARCH METHODOLOGY

This investigation into highway construction productivity in Wisconsin was an expansion of the initial research conducted by Diane Aoun (Phase I) at the University of Wisconsin-Madison while working to attain her Master of Science. In the following chapter, a brief history of the methodology used during Phase I and the methods used as the research continued (Phase II) will be described.

3. 1 History of Phase I's Methodology

Phase I began with a literature review that strived to find project factors that affect productivity in highway construction, identify techniques to predict productivity, and gather production rates from other agencies (Aoun, 2013). Various components of Phase I's literature review were unable to be found via previously published research. Consequently, interviews were conducted with contractors to fill in the gaps of missing information. A final list of project factors was then incorporated into Microsoft Excel (MS Excel) based data collection tools. Four data collection tools were created for asphalt paving, bridge construction, concrete paving, and earthwork construction activities. The tools were then distributed to construction contractors and WisDOT project engineers to obtain their input. Survey responses were then compiled into a four separate databases to be used during statistical analysis.

Similar statistical analysis methods were used during Phase I and Phase II because one goal was to update the PET by gathering more data. For example, sequential regression was again utilized in Phase II, and will therefore be discussed later in this chapter with Phase II's research methods. However, a major change was made to the database during Phase II because more data became available. During Phase I, data was limited and the research team opted to impute the average value of a particular construction activity's observed values in the empty cells of the MS Excel database (Aoun, 2013). As discussed in Chapter Four, Phase II's research team was able to increase the productivity database considerably, and imputing mean values was no longer required.

Phase I then developed the first version of the PET, which was considerably different than the versions created during Phase II. During Phase I, the PET reported production rates in a tabular form as shown in Figure 1. In this version, production rates were predicted and reported as 80%, 90%, and 95% confidence intervals as desired by the user of the tool. In instances where rates could not be predicted, values were derived from a combination of information gathered from contractors and other DOT's. Once the first version of the PET was finalized, it was validated using five-fold cross validation and by showcasing the tool to transportation engineering professionals from WisDOT.

	Productivity Rates			
Activity	**Min**	**Average**	**Max**	**Unit**
HMA Placement: Lower Layer	54	150	246	Tons/Hour
HMA Placement: Surface Layer	20	30	137	Tons/Hour
Hand Placement of Asphalt Pavement	3	22	50	Tons/Hour
Base Course Placement	2,489	3,197	3,904	Tons/Day

Figure 1: Phase I's Productivity Estimation Tool Output

3.2 Data Collection

Many aspects of the data collection methods utilized during Phase II remained the same as those used during Phase I. Determining the target population was relatively simple considering the scope of this research. Since the PET was developed for the WisDOT to predict productivity in highway construction in Wisconsin, only WisDOT projects were considered. The data collection tool used was nearly identical to those used in Phase I. However, the four original tools were combined with a new miscellaneous activities survey into a single MS Excel file. Surveys were again delivered to WisDOT field engineers via email.

The data collection tool consists of two sections. The first section allows respondents to describe their project based upon various project factors specific to each category of construction. This section provides a scale based upon the impact a project specific factor would have on a project ranging from one to three. The second section collects the production rates that were achieved. A list containing all of the project factors included in this study along with the descriptions given to aid respondents in rating their projects is given by Tables 1 and 2.

Table 1: Data Collection Tool Project Factors 1 of 2

Factor	Description
Asphalt Thickness	1 = Thick pavement structure (≥ 4'') 2 = Thin pavement structure (between 2'' and 4'') 3 = Very thin pavement structure (≤ 2'')
Difficulty	1 = Normal 2 = Difficult 3 = Very Difficult
Expedited Project Schedule	1 = 40 hours week, 8 hours per day, normal (optimum) crew size, no work on holidays 2 = 50 hours per week, larger than normal or constantly changing crew sizes, work on some holidays 3 = Working beyond 50 weekly hours (overtime), larger crew sizes (overmanning), holidays
Night Time Paving	1 = Daytime paving 3 = Nighttime paving
Numerous Typical Section Transitions	1 = Continuous pavement width 2 = Some incidental pavement (intersections, ramp tapers) 3 = Many incidental pavement areas (roundabouts, ramps)
Paving Width	1 = Wide paving width (>14’) 2 = Medium paving width (<14’) 3 = Narrow paving width (shoulders only)
Permit Restrictions	1 = Having approved environmental documents, no noise constraints, no vibration constraints 2 = Need to account for noise restrictions and/or vibration constraints during operating time 3 = Permits needed for erosion control, dust, storm water, hazardous material, underground fuel tanks, contaminated soils
Presence of Ride Specification	1 = No ride specification 3 = Presence of ride specifications
Project Constraints	1 = No site constraints (few utilities, intersections, driveways, gaps, roundabouts) 2 = Moderate site constraints (some utilities, ramps, limited space for equipment, adjacent buildings) 3 = Difficult site constraints (presence of significant utilities, conflict with other operations)
Project Duration	1 = Short (≤ 15 calendar weeks) 2 = Mid-range (15-30 calendar weeks) 3 = Long (≥ 30 calendar weeks)

Table 2: Data Collection Tool Project Factors 2 of 2

Factor	Description
Project Length	1 = Short total project length 2 = Medium total project length 3 = Long total project length
Project Size	1 = Small (≤ 10,000 total tons) 2 = Medium (10,000 - 50,000 total tons) 3 = Large (≥ 50,000 total cubic tons)
Season	1 = Summer, air temperature above 60 °F, some rainfall 2 = Spring or fall, air temperature between 35 and 60 °F, moderate level of rainfall 3 = Winter, air temperature below 35 °F, extreme rainfall and snow
Size and Proximity of Storage and Staging Areas	1 = Adequate storage and staging, on site 2 = Limited size of storage and staging 3 = Insufficient storage and staging, in the general area of the project
Soil Moisture Condition	1 = Soil near optimum moisture 2 = Wet soil that must be dried 3 = Very wet soil
Soil Type	1 = Soil is mainly sand 2 = Soil is granular and sandy with some silt and clay 3 = Soil is mainly wet silt, clay or silty clay
Staged Construction	1 = Single phase 2 = Two phases, structure done half at a time 3 = Three or more phases, portions of roadway done in different stages and multiple mobilizations
Traffic Conditions	1 = Low traffic, road closed 2 = Moderate traffic, working adjacent to existing traffic 3 = High traffic, open to traffic, lane restrictions, limited work area
Type and Amount of Milling	1 = No correction required 2 = Some correction and asphalt paving removal required 3 = Significant correction required
Type of work	1 = New construction project 2 = Reconstruction, resurfacing or maintenance project 3 = Rehabilitation project (structure currently used for transportation)
Urban Project	1 = Rural area no traffic 2 = Rural area under traffic 3 = Urban area with city streets, nearby residents, commercial buildings, urban cross-sections

It is important to note that the project factors involving the time of day during which work was conducted and the presence of a ride specification only have two possible entries as opposed to three. This is due to the binomial nature of daylight and nighttime hours and the presence versus absence of a ride specification possibly affecting productivity. Additionally, not every project factor was investigated for all categories of construction. The project factors used for each type of construction can be found below in Table 3.

Table 3: Project Factors Used by Construction Activity Type

Project Factor	Asphalt Paving	Bridge Construction	Concrete Paving	Earthwork	Miscellaneous Activities
Asphalt Thickness	x				
Expedited Project Schedule	x	x	x	x	x
Materials Delivery			x	x	x
Night Time Construction	x	x	x	x	x
Numerous Typical Section Transitions	x		x		x
Paving Width	x				
Permit Restrictions		x			x
Presence of Ride Specification	x				x
Project Complexity	x	x	x	x	x
Project Constraints		x	x	x	x
Project Duration		x		x	x
Project Length	x		x	x	
Project Size	x	x	x	x	
Season	x	x	x	x	x
Size and Proximity of Storage and Staging Areas	x		x		x
Soil Moisture Condition				x	x
Soil Type				x	x
Staged Construction	x	x	x	x	x
Traffic Conditions		x	x		x
Type and Amount of Milling	x				x
Type of Construction	x	x		x	x
Urban Project	x	x	x	x	x

After completing the project factor section of the survey, contractors were then asked to enter the productivity rates that were actually achieved on their projects as shown below in Figure 2. Contractors were provided with a list of construction activities, the units with which each activity is tracked, and an empty cell for entering the productivity rates achieved. While contractors are asked for an array of construction activities, most projects only conducted a small portion of the activities listed. Further information portraying the number of observations collected for each activity can be found in Chapter 4.

Activity	Productivity Rates	Unit
Adjust Frames & Grates		Each
Catch Basins		Each
Manholes		Each
Pipe Underdrains		Ft
Riprap Light/Medium		S.Y

Figure 2: Data Collection Tool Miscellaneous Activity Productivity Rates Achieved

3.3 Statistical analysis methods

After collecting data, various statistical analysis methods and software packages were utilized to organize the data and formulate models that could be used for estimating productivity. MS Excel was used to organize the data into a format that was compatible with the statistical analysis software package employed. Next, R was used to conduct the necessarily statistical calculations including outlier detection, model selection, and checking the assumptions of linear regression.

3.3.1 Model Selection

Numerous types of models and selection methods exist within the broader field of linear regression. Simple linear regression refers to cases where models are created using a single dependent variable and a single independent (explanatory) variable. However, the goal of this research was to determine if multiple project factors existed that could be used to explain and predict productivity. Consequently, multiple linear regression was required to incorporate several independent variables into models that predict productivity for a single dependent variable as seen below.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \dots. + \beta_k X_k + \varepsilon$$

As applied to this research, Y corresponds to construction activities, β_0 signifies a model's intercept, and the $\beta_k X_k$ terms refer to the regression coefficients calculated for project factors and the project factor rating given to a project respectively. However, it was suspected that not all project factors would be significant to every construction activity investigated. The standard multiple regression method forces a model to use all possible independent variables at once, but was not deemed useful because it lacks the capability of identifying which, if any, project factors are significant to productivity.

The problem of including project factors that are insignificant can be solved by applying various model selection methods and criteria. Sequential model selection allows for adding and/or removing independent variables from a model in a manner that considers each variable's significance in a step-by-step algorithm (Clayton, 2015). This approach creates logical and well-calculated sequence when determining which independent variables to either include or remove. Sequential model selection is sometimes, perhaps inaccurately, referred to as stepwise regression. However, further distinction can be made between different types of model selection within sequential model selection such as backward elimination, forward selection, and stepwise selection.

Backward elimination uses an algorithm based on a particular sequence of steps to arrive at a final model consisting of the best combination of independent variables (Clayton, 2015). First, a full model is fitted that includes all of the possible independent variables. Then an independent variable is chosen based on a given criterion as a candidate for removal from the model. The independent variable chosen offers the greatest improvement to the model considering the selection criterion used. Next, it is determined if the candidate independent variable should be removed or if it should be allowed to remain in the model. If the candidate variable will improve the model by being removed, it is removed from the model. The model is then refitted and another candidate variable is chosen to repeat the process. This process continues until a candidate variable cannot be found that will improve the model by being removed. Backward elimination was ultimately not chosen because it requires first fitting a full model with all possible parameters before selecting candidate variables. The number of observations required to fit a full model must be at least the number of independent variables plus two to account for the model's intercept and bring the degrees of freedom for error above zero. Any number of observations less than this value creates a situation where a model has zero degrees of freedom or less. R simply returned an error message concerning an insufficient amount of degrees of freedom to fit a full model when attempts were made to utilize backwards elimination for the majority of activities investigated.

Forward selection is in a sense a process which operates opposite from backward elimination. Instead of beginning with a full model, as in backward elimination, forward selection begins with a model that only includes the intercept. A candidate independent variable is then chosen that makes the greatest improvement to the model when added. If the candidate variable improves the model, it is added, the model is refitted, and another candidate variable is chosen. If a candidate variable cannot improve the model by being added, the process stops (Clayton, 2015). A single selection criterion is again used to determine candidate variables and the most improved model. Forward selection was preferred over backward elimination because it allowed an analysis to be conducted on activities with less observations, whereas backward elimination was not possible.

Stepwise selection is a combination of forward selection and backward elimination. In forward selection and backward elimination, an independent variable can no longer become a candidate variable once it is added or removed from a model. If an independent variable is added using forward selection, then it permanently becomes a part of the model even if it becomes insignificant. If an independent variable is removed using backward elimination, it can no longer be added back into a model even if it becomes significant (Clayton, 2015). Stepwise selection instead reconsiders all possible independent variables at every step regardless of their presence in or absence from a model. In R, it is possible to run both a “backward/forward” and a “forward/backward” stepwise approach. The “backward/forward” approach was not possible for most activities because it again required fitting a full model with all possible independent variables before selecting candidate variables. An illustration of the stepwise forward/backward process in

R for the activity “HandAP” using AIC as the selection criterion can be seen below in Figures 3 and 4. AIC is just one of several selection criteria which will be discussed in further detail later.

First, in Figure 3, a model is generated using the model’s intercept as the only parameter, which results in an AIC score of 127.05. Then AIC scores are calculated for all of the possible candidate variables (project factors). The optimal AIC score of 122.86 results by adding the project factor “ProjectLength” to the existing model. The model is then refitted to include the intercept and “ProjectLenth.” The process is then again repeated by calculating AIC scores for all candidate variables in the lower half of Figure 3. In this step, the optimal AIC score becomes 117.56 by adding the project factor “Difficulty” to the model.

```
Start:  AIC=127.05
HandAP ~ 1

                      Df Sum of Sq   RSS    AIC
+ ProjectLength        1    5795.0 12023 122.86
+ NightPaving          1    4546.6 13271 124.64
+ TypicalTransitions   1    4511.4 13307 124.68
+ ProjectWidth         1    3612.5 14206 125.86
<none>                             17818 127.05
+ ExpediatedSchedule   1    2136.9 15681 127.64
+ TypeWork             1    2034.0 15784 127.76
+ ProjectSize          1    1863.2 15955 127.95
+ TypeAmountMiling     1    1678.3 16140 128.16
+ StorageStaging       1    1242.6 16575 128.64
+ StagedConstruction   1    1226.5 16592 128.65
+ RideSpecification    1    1222.6 16595 128.66
+ Difficulty           1     250.6 17567 129.68
+ UrbanProject         1      64.4 17754 129.87
+ AsphaltThickness     1      22.2 17796 129.91
+ Season               1      22.0 17796 129.91

Step:  AIC=122.86
HandAP ~ ProjectLength

                      Df Sum of Sq     RSS    AIC
+ Difficulty           1    4394.7  7628.4 117.56
+ ProjectWidth         1    3277.7  8745.3 120.02
<none>                             12023.0 122.86
+ TypeAmountMiling     1    1508.0 10515.0 123.33
+ ExpediatedSchedule   1    1473.2 10549.8 123.39
+ NightPaving          1    1417.2 10605.8 123.49
+ TypicalTransitions   1     805.9 11217.2 124.50
+ StorageStaging       1     637.5 11385.6 124.77
+ AsphaltThickness     1     380.6 11642.5 125.17
+ TypeWork             1     308.1 11714.9 125.28
+ UrbanProject         1     196.4 11826.6 125.45
+ Season               1      67.8 11955.3 125.64
+ StagedConstruction   1      39.8 11983.3 125.69
+ RideSpecification    1       2.3 12020.7 125.74
+ ProjectSize          1       1.1 12022.0 125.75
- ProjectLength        1    5795.0 17818.0 127.05
```

Figure 3: Stepwise Selection Using Forward/Backward 1 of 2

This process can repeat numerous times while adding and removing candidate variables until the optimal value of AIC is found as shown in Figure 4. In the upper portion of Figure 4, the process identifies the best improvement to the model as actually removing a project factor that has already been added to the model. In this case, removing “ProjectLength” improves AIC from a value of 109.88 to 109.27. The ability to reconsider the entire set of project factors at every step illustrates why forward/backward stepwise regression was ultimately chosen over forward selection. The final step occurs in the lower half of Figure 4 during which the option “<none>” of making no changes to the model leads to the best possible AIC score.

```
Step:  AIC=109.88
HandAP ~ ProjectLength + Difficulty + StagedConstruction
+ ExpediatedSchedule + ProjectSize + Season + StorageStaging

                      Df Sum of Sq    RSS    AIC
- ProjectLength        1     301.2 2532.6 109.27
+ TypeWork             1     355.9 1875.5 109.65
<none>                             2231.4 109.88
- StorageStaging       1     452.4 2683.8 110.32
+ TypicalTransitions   1     186.7 2044.7 111.20
+ UrbanProject         1     181.8 2049.6 111.24
+ AsphaltThickness     1     138.5 2092.9 111.62
+ ProjectWidth         1     100.8 2130.6 111.94
+ TypeAmountMiling     1      33.9 2197.5 112.50
+ RideSpecification    1      28.7 2202.7 112.54
+ NightPaving          1      16.3 2215.1 112.64
- Season               1    1102.1 3333.5 114.22
- ProjectSize          1    1739.8 3971.2 117.37
- ExpediatedSchedule   1    3104.2 5335.6 122.69
- StagedConstruction   1    4030.4 6261.8 125.57
- Difficulty           1    4543.0 6774.4 126.98

Step:  AIC=109.27
HandAP ~ Difficulty + StagedConstruction + ExpediatedSchedule
+ ProjectSize + Season + StorageStaging

                      Df Sum of Sq     RSS    AIC
<none>                              2532.6 109.27
+ TypicalTransitions   1     374.3  2158.3 109.28
+ ProjectLength        1     301.2  2231.4 109.88
- StorageStaging       1     588.1  3120.7 110.14
+ TypeWork             1     231.8  2300.8 110.44
+ ProjectWidth         1     224.7  2307.9 110.49
+ AsphaltThickness     1     209.1  2323.5 110.61
+ UrbanProject         1     138.9  2393.7 111.15
+ NightPaving          1      82.3  2450.3 111.57
+ TypeAmountMiling     1      18.9  2513.7 112.03
+ RideSpecification    1       2.2  2530.4 112.15
- Season               1    1554.6  4087.2 115.00
- ProjectSize          1    4048.4  6581.0 123.57
- Difficulty           1    4253.5  6786.1 124.12
- ExpediatedSchedule   1    6886.5  9419.1 130.03
- StagedConstruction   1    7479.4 10012.0 131.12
```

Figure 4: Stepwise Selection Using Forward/Backward 2 of 2

Any discussion of stepwise multiple linear regression cannot end without further explanation of the criteria used to judge a model's quality. A common criterion used in simple linear regression is the coefficient of determination, R^2. However, this method is a poor indicator of model quality when applied to this research's multiple linear regression technique because R^2 will always increase when more independent variables are added to a model. In the context of this research, the R^2 value for a construction activity's model will always increase by adding more project factors, even in instances where a project factor is not significant to an activity's productivity. Using R^2 to evaluate model quality simply will not direct stepwise regression to select a best model in line with the goals of this research.

To overcome the issue created by applying R^2 to model selection in the context of this research, adjusted R^2, Akaike's information criterion (AIC) and Schwarz's Bayensian information criterion (BIC) were investigated. All three of these criteria attempt to address the issue created by R^2 by using a penalty term to account for sample size and/or the number of independent variables included in a model. While utilizing adjusted R^2 is an improvement upon R^2, AIC and BIC offer additional scrutiny in model selection. AIC can be expressed by

$$n \ln\left(\frac{SSError}{n}\right) + 2p$$

where *n* is the number of observations collected for a particular activity, and *p* is the number of factors included in the model. A regression model of higher quality will generally have a smaller value for SSError. Therefore, when SSError becomes smaller AIC will also become smaller, and a model with a smaller AIC value is preferred to a model with a larger value of AIC (Clayton, 2015). AIC is not always a positive value, and the model with an AIC value closest to negative infinity is considered the highest quality of all possible models. Next, BIC can be expressed by

$$n\ln\left(\frac{\text{SSError}}{n}\right) + p\ln(n)$$

with *p* and *n* again having the same meaning as in AIC, and the optimal model having a value of BIC closest to negative infinity. The difference between the AIC and BIC criteria is that BIC has a larger penalty term when the number of observations becomes larger than seven, as is the case with the construction activities that were able to be modeled. The larger penalty term in BIC allows stepwise regression to generate models with less project factors, whereas AIC tends to include more project factors that may not always be as significant (Clayton, 2015). Therefore, BIC was chosen over AIC to be used when fitting models with forward/backward stepwise selection.

3.3.2 Bonferroni Outlier Test

A Bonferroni outlier test was conducted in R for each construction activity's productivity model prior to incorporating the regression coefficients into the PET. First, a suspected outlier (project) is removed from the dataset, and then regression coefficients are recomputed for the project factors previously identified. Next, the new model is used to predict a production rate with the project factor information that was taken out. Then a t-test is conducted to determine if there is a significant difference between the value actually observed and what the reduced dataset's model would predict. Finally, a Bonferroni adjustment is made to the p-value from the aforementioned t-test by multiplying the p-value times twice the number of observations. The adjustment factor in this method is critical because the underlying method implies that 5% of the observations would be outliers by chance alone (Jacoby, 2005). In total, 11 observations out of the 1,182 collected were identified, recorded, and removed from the dataset.

3.3.3 Checking the Assumptions of Linear Regression

When performing linear regression four assumptions are made: linearity, independence of errors, normality of the error terms, and equal variance. First, linearity implies that the underlying relationship between dependent and independent variables is linear. Second, independence of errors implies that the error terms (difference between the observed and predicted value) do not influence one another. Third, normality of the error terms implies that the error terms are normally distributed. Finally, equal variance implies that the probability distribution of the errors has constant variance (Mullins, 2013). To aid in checking these assumptions, residual and QQ plots were developed for each activity to ensure constant variance and normality respectively. Examples of the residual plot and QQ plot produced for the activity "Excelsior Blanket" are provided in Figures 5 and 6.

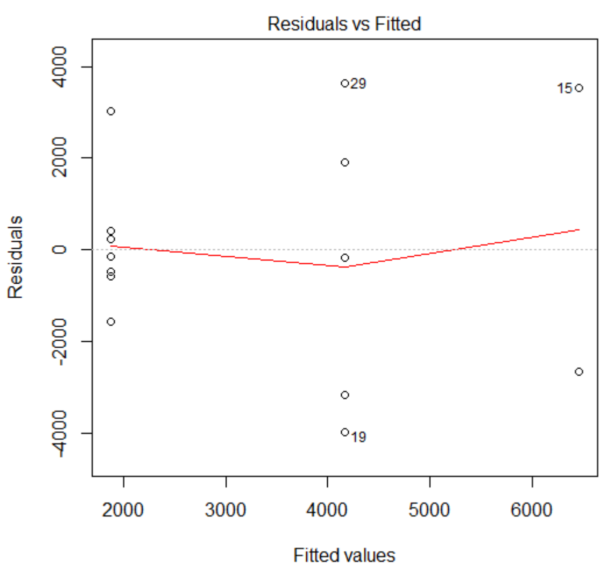


Figure 5: Excelsior Blanket Residual Plot

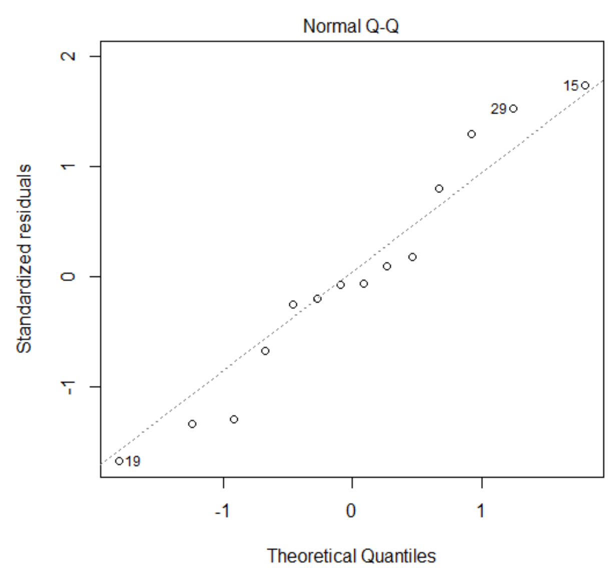


Figure 6: Excelsior Blanket QQ Plot

CHAPTER FOUR
DATA ANALYSIS AND RESULTS

Each of the five major areas of highway construction investigated possess a unique dataset and were analyzed independently from one another. Consequently, separate sections of this chapter discuss asphalt paving, bridge construction, concrete paving, earthwork, and miscellaneous construction activities. Within each section, information regarding sample sizes, characteristics of the projects from which data was collected, the effect project factors were found to have on productivity, the models generated for predicting productivity, and the productivity rates observed for activities that couldn't be modeled can be found. Finally, the validations results can be found for those activities which were modeled.

Asphalt Paving

4.1.1 Sample Size and Response Rate

After collecting data throughout the summer of 2014, 74 projects had responded to the asphalt paving productivity survey. Information regarding the quantity of data collected for each activity is given below by Table 4. The "% Responding to Activity" column refers to the portion of the 74 the projects responding to the survey. In other words, the number of projects that received the data collection tool without responding was neither tracked nor considered. With this information, certain activities become possible candidates for removing from the PET and further data collection efforts. For example, with only one observation gathered for "Profile Milling" it is likely that either project engineers do not track productivity for this activity or the activity rarely occurs on WisDOT projects. Additionally, certain activities are likely to never be used by WisDOT designers and estimators to produce the amount of time to award for contract completion.

Table 4: Asphalt Paving Sample Sizes

Activity Name	Number of Observations	% Responding to Activity
Base Course	23	31.1
Grooved Epoxy Marking: Grinding Only	4	5.4
Grooved Epoxy Marking: Marking Only	3	4.1
Hand Placement of Asphalt	18	24.3
Hot Mix Asphalt: Lower Layer	51	68.9
Hot Mix Asphalt: Surface Layer	63	85.1
Profile Milling	1	1.4
QMP Density	12	16.2
QMP Profiling	9	12.2
Rumble Strip Center	12	16.2
Rumble Strip Shoulder	13	17.6
Thick Milling	20	27.0
Thin Milling	12	16.2

4.1.2 Data Characteristics

Data gathered by the asphalt paving collection tool categorized construction projects based on 15 project specific factors and recorded productivity rates achieved on the job site for 13 construction activities. Each project factor has been combined into a single graph showing the composition of responses for each factor in Figure 7. Note that the "Night Paving" and "Ride Specification" project factors only include two values for work conducted either during the daylight or nighttime hours and the presence versus absence of a ride specification respectively. Analyzing the composition of responses to the project factor information portion of the asphalt productivity survey identifies areas where the dataset may be improved. The current productivity database contains the least amount of information on projects with various attributes: very difficult, rehabilitation work, larger than 50,000 total cubic tons, work more than 50 hours a week, working at night, narrow paving width (shoulders only), insufficient storage and staging, working during winter, less than 2” paving thickness, and those requiring a significant amount of milling to make corrections. With this information, future research will be able to focus data collection efforts on the types of projects that make up a smaller portion of the dataset to get a clearer understanding of the effect of each project factor.

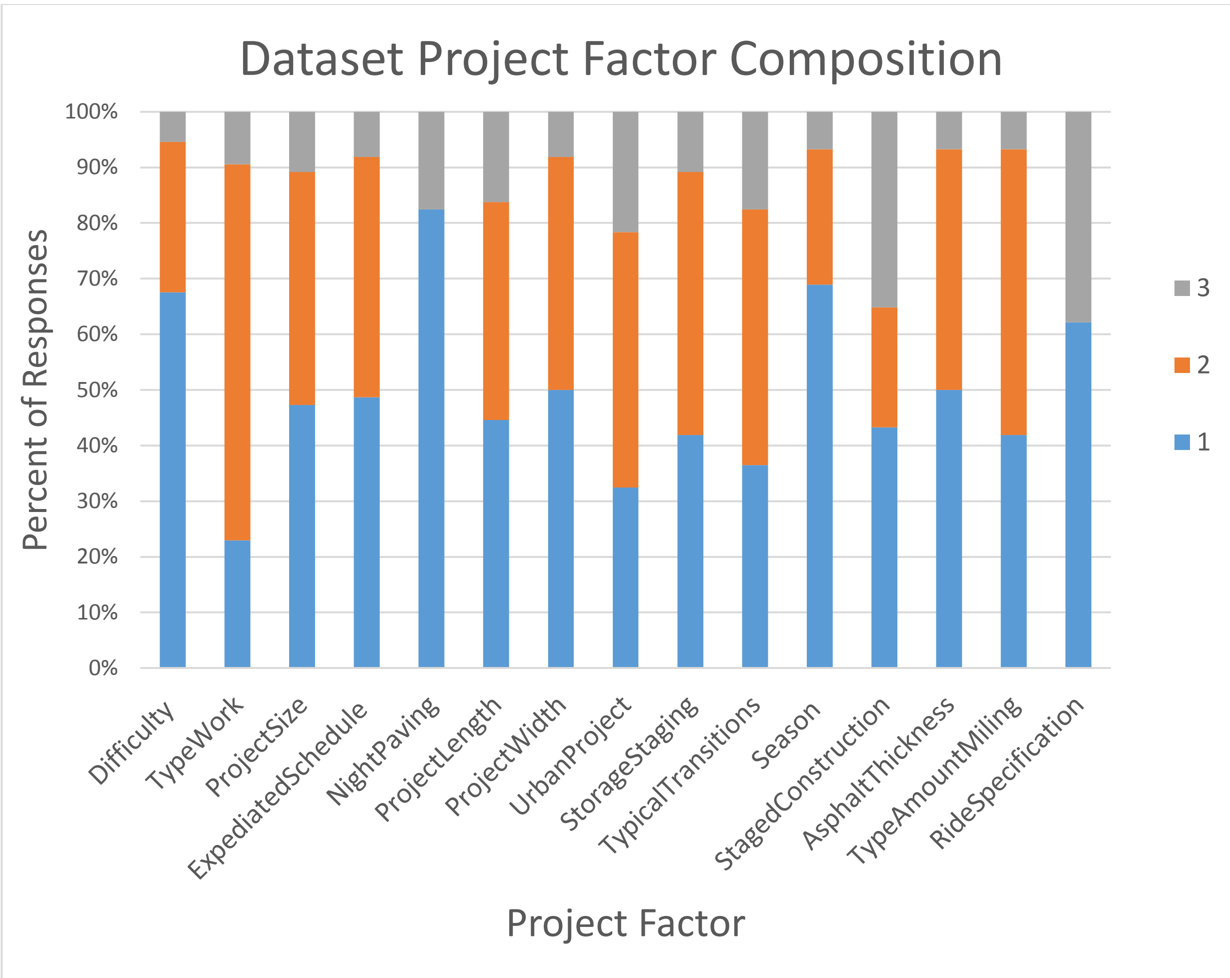


Figure 7: Asphalt Paving Dataset Project Factor Composition

4.1.3 Effect of Project Factors on Asphalt Paving Productivity

Although the survey conducted elicited responses for 13 different asphalt paving activities, it was only possible to create eight models due to insufficient sample sizes for the activities of profile milling, thin milling, QMP Profiling, GEMGO, and GEMMO. The stepwise selection results are organized below in Table 5 by construction activity, project factors selected, p-value for each factor selected, and adjusted multiple R^2 value for each model created. The eight models generated each possess a unique set of project factors. The project factors selected all possess p-values less than 0.05. Adjusted R^2 values range from excellent values such as 0.98 for Rumble Strip Center to values as low as 0.11 for Hot Mix Asphalt Lower Layer (HMALL). The model for HMALL was included in spite of its adjusted R^2 values due to the fact that project size has been found with strong evidence (p=0.01) to be significant to HMALL productivity. In other words, the evidence strongly suggests that the coefficient for "Project Size" in the model used to predict "HMALL" productivity is not equal to 0. If a coefficient is not equal to zero, there is therefore a relationship between the given project factor and construction activity that can be used for prediction purposes.

Table 5: Effect of Project Factors on Asphalt Paving

Activity	Factor Selected	P-Value	Adjusted R^2
HMALL	Project Size	0.01	0.1098
HMASL	Project Size	0.0005	0.1705
Hand Placement of Asphalt	Project Length	0.008	0.9753
	Difficulty	0.005	
	Staged Construction	0.016	
	Expedited Schedule	0.021	
	Project Size	0.019	
	Season	0.009	
	Storage and Staging	0.043	
	Type of Work	0.015	
	Type Amount of Milling	0.006	
	Typical Transitions	0.012	
	Night Paving	0.014	
	Ride Specification	0.017	
	Urban Project	0.024	
	Asphalt Thickness	0.024	
Thick Milling	Project Length	0.008	0.2927
Base Course	Difficulty	0.003	0.3035
	Storage and Staging	0.028	
QMP Density	Type Amount of Milling	0.011	0.6609
	Staged Construction	0.003	
Rumble Strip Center	Presence of Ride Specification	0.078	0.9893
	Numerous Typical Section Transitions	0.00002	
	Project Size	0.00009	
	Asphalt Thickness	0.00192	
	Storage and Staging	0.009	
	Project Length	0.029	
	Project Width	0.031	
Rumble Strip Shoulder	Presence of Ride Specification	0.0003	0.7735
	Type Amount of Milling	0.0017	
	Project Width	0.023	

4.1.4 Productivity Rates for Asphalt Paving Activities

The models generated for asphalt paving activities consist of the best combination of project factors that can be used to make predictions about their respective productivity rates.

Regression coefficients are assigned to each project factor to be used for prediction purposes. The project factors selected for each activity along with their respective regression coefficients and each model's intercept are summarized below in Table 6. The remaining five activities that were not able to be modeled are reported via their minimum value observed, average, and maximum value observed in Table 7.

Table 6: Asphalt Paving Linear Models

Activity	Units	Factor Selected	Coefficient	Intercept	Minimum	Maximum
HMALL	Tons/Hour	Project Size	45.7	108.4	20	350
HMASL	Tons/Hour	Project Size	57.6	82.1	25	350
Hand Placement of Asphalt	Tons/Hour	Project Length	96.9	-332.6	4	150
		Difficulty	-98.4			
		Staged Construction	94.3			
		Expedited Schedule	-23.7			
		Project Size	81.6			
		Season	71.8			
		Storage and Staging	39.2			
		Type of Work	170.1			
		Type Amount of Milling	-52.4			
		Typical Transitions	86.1			
		Night Paving	-90.7			
		Ride Specification	75.6			
		Urban Project	-143			
		Asphalt Thickness	-104.1			
Thick Milling	S.Y./Day	Project Length	4,794	1638	1467	20,500
Base Course	Tons/Day	Difficulty	866.5	1,199.2	60	3,400
		Storage and Staging	-709.9			
QMP Density	S.Y./Day	Type Amount of Milling	-9,140	47,443	2,000	40,000
		Staged Construction	-8,472			
Rumble Strip Center	Feet/Day	Presence of Ride Specification	5,635	47,221	650	125,000
		Numerous Typical Section Transitions	-105,228			
		Project Size	105,453			
		Asphalt Thickness	12,680			
		Storage and Staging	-16,872			
		Project Length	-13,854			
		Project Width	-12,905			
Rumble Strip Shoulder	Feet/Day	Presence of Ride Specification	36,910	-150,645	1,250	125,000
		Type Amount of Milling	47,590			
		Project Width	30,549			

Table 7: Production Rates for Non-Modeled Asphalt Paving Activities

Activity	Units	Minimum	Average	Maximum
QMP Profiling	S.Y./Day	9,100	105,116	469,300
Profile Milling	S.Y./Day	14,000	14,000	14,000
Thin Milling (0 – 2”)	S.Y./Day	287	19,816	45,000
GEMGO	Feet/Day	500	33,121	66,800
GEMMO	Feet/Day	500	34,433	126,000

Bridge Construction Activities

4.2.1 Sample Size and Response Rate

At the conclusion of the 2014 summer highway construction season, 32 projects had responded to the bridge construction productivity survey. A summary of the quantity of data collected for each activity is given below by Table 8. As a whole, bridge construction was the type of construction activities studied that garnered the least amount of data. Furthermore, zero observations were collected for ten of the structures activities studied. Consequently, the least amount of models were generated for structures compared to other types of construction even though this category of construction had the most activities included in the survey. In total, models were created for four of the 32 structures activities studied. The lack of sufficient data to create linear models for predicting bridge construction productivity is a major challenge of this research study. However, this shortcoming can be viewed as an opportunity to guide future research efforts and will be discussed in further detail later in Chapter Six.

Table 8: Bridge Construction Sample Sizes

Activity	Number of Observations	% Responding to Activity
Bridge Deck Grooving	1	3.1
Bridge Overlay with <25% Deck Prep	3	9.4
Bridge Overlay with ≥25% Deck Prep	2	6.3
Bridge Overlay with Joint Repair	0	0.0
Bridge Overlay without Joint Repair	2	6.3
Caissons	2	6.3
Cofferdam	2	6.3
Concrete Masonry, Culverts *	0	0
Concrete Masonry, Substructure *	18	56.3
Deck Placement, Girder Bridge*	20	62.5
Deck Placement, Slab Bridge*	0	0.0
Deck Removal, Full Depth	14	43.8
Deck Removal, Partial Depth	0	0.0
Deck Slab Repair	0	0.0
Driving Piles (All Types)	19	59.4
Form + Pour Diaphragms *	8	25.0
Full Containment Painting (Clean + Paint)	3	9.4
Maintenance Painting (Clean + Paint)	0	0.0
Moment Slab on MSE walls*	3	9.4
Noise Walls	0	0.0
Parapet (Architectural)	0	0.0
Parapet (Straight Back)	12	37.5
Parapet (with Liner)	4	12.5
Precast Concrete Girder Erection	15	46.9
Retaining Walls: Cast in Place*	2	6.3
Retaining Walls: Mechanically Stabilized	2	6.3
Retaining Walls: Precast (with footing)	1	3.1
Spread Footings *	1	3.1
Steel Girder Erection	0	0.0
Temporary Sheet Piling (height<15’)	0	0.0
Temporary Sheet Piling (height≥15’)	13	40.6
* denotes form, pour, and strip		

4.2.2 Data Characteristics

Data gathered by the bridge construction data collection tool categorized highway construction projects with 12 project specific factors. The composition of responses for each project factor are shown by Figure 8. The "Permit Restriction" project factor had three possible responses in actuality, but zero respondents reported projects that needed to account for noise and vibration restrictions. The current productivity database could be improved by gaining information from various types of projects: very difficult, over 40,000 square feet of bridge deck, difficult site constraints, working at night, and working during the winter. Making an effort to obtain information on the aforementioned types of projects allows future research to better understand the effects of certain project factors.

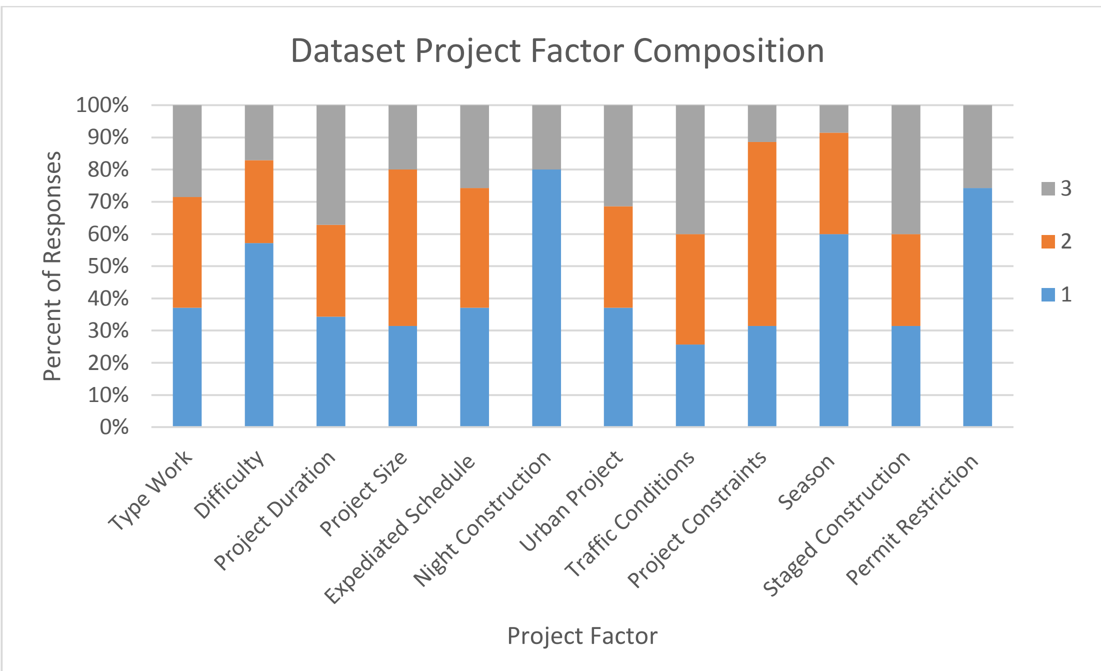


Figure 8: Bridge Construction Dataset Project Factor Composition

4.2.3 Effect of Project Factors on Bridge Construction Productivity

In spite of the data collection tool being designed to collect information on 31 bridging activities, it was only possible to create linear models for four of the activities. The results from stepwise selection are organized below in Table 9 by construction activity, project factors selected, p-value for each project factor selected, and the adjusted multiple R^2 value for each model created.

Table 9: Effect of Project Factors on Bridge Construction

Activity	Factor Selected	P-value	Adjusted R2
Concrete Masonry, Substructure	Staged Construction	0.0008	0.4765
	Project Constraints	0.0445	
Sheet Piling (height>=15')	Season	0.0003	0.7631
	Project Size	0.0099	
	Permit Restriction	0.0218	
Parapet Straight	Project Duration	0.0125	0.4284
Deck Placement, Girder bridge	Staged Construction	0.0002	0.523

4.2.4 Productivity Rates for Bridge Construction Activities

The models generated for bridge construction activities consist of the best combination of project factors that could be used to make predictions about their respective production rates. Each factor identified has been given a coefficient to be used in estimating a particular activity's production rate. The project factors selected for each activity along with their respective regression coefficients and each model's intercept are summarized below in Table 10. The remaining 27 bridge construction activities were unable to be modeled, and the minimum value observed, average, and maximum value observed are given below in Table 11.

Table 10: Bridge Construction Linear Models

Activity	Units/Day	Factors Selected	Coefficient	Intercept	Minimum	Maximum
Concrete Masonry, Substructure	Pours	Staged Construction	-1.03	2.52	0.2	4
		Project Constraints	0.76			
Sheet Piling (height >= 15')	S.F.	Season	1,111.50	-1,068.30	115	2,000
		Project Size	343.20			
		Permit Restriction	-363.20			
Parapet Straight	Feet	Project Duration	49.75	1	16	200
Deck Placement, Girder bridge	S.F.	Staged Construction	-338.63	1,396.04	120	1,499

Table 11: Production Rates for Non-Modeled Bridge Construction Activities

Construction Activity	Unit/Day	Minimum	Average	Maximum
Bridge Deck Grooving	FT	7,800	7,800	7,800
Bridge Overlay with <25% Deck Prep	S.F.	700	2,000	4,400
Bridge Overlay with ≥25% Deck Prep	S.Y.	20	190	360
Bridge Overlay with Joint Repair	FT	600	1300	2000
Bridge Overlay without Joint Repair	FT	125	146	168
Caissons	FT	60	74	88
Cofferdam	FT	250	265	280
Concrete Masonry, Culverts *	Panels	0.7	1.3	1.8
Deck Placement, Slab Bridge*	Panels	263	383	500
Deck Removal, Full Depth	S.F.	2,577	5,383	8,189
Deck Removal, Partial Depth	S.F.	197	3,444	20,000
Deck Slab Repair	S.F.	90	270	450
Driving Piles (All Types)	S.Y.	50	350	1,000
Form + Pour Diaphragms *	FT	0.5	2.7	6
Full Containment Painting (Clean + Paint)	Each	550	7,180	19,400
Maintenance Painting (Clean + Paint)	S.F.	100	200	300
Moment Slab on MSE walls*	S.F.	28	176	350
Noise Walls	FT	300	650	1,000
Parapet (Architectural)	S.F.	69	110	150
Parapet (with Liner)	FT	33	74	150
Precast Concrete Girder Erection	Each	2.5	5.8	9
Retaining Walls: Cast in Place*	Panels	273	286	300
Retaining Walls: Mechanically Stabilized	S.F.	165	1,080	2,000
Retaining Walls: Precast (including footing)	S.F.	350	350	350
Spread Footings *	Pours	0.25	0.25	0.25
Steel Girder Erection	Each	4.0	7.5	11.0
Temporary Sheet Piling (height<15’)	S.F.	433	783	1,133
*** Signifies a forming, pouring, and stripping of a concrete activity**				

Concrete Paving Activities

4.3.1 Sample Size and Response Rate

Upon completion of data collection, the concrete paving portion of the productivity database contained 44 projects. A summary of the quantity of data collected for each activity is given below by Table 12. The amount of information gathered for concrete paving activities is considerably larger than that of bridging activities. However, zero observations for "Grinding" and only five for "Patching" have been gathered after multiple data collection iterations. The amount of data collected for the remaining activities is encouraging because they all possessed a dataset large enough to support the creation of linear models.

Table 12: Concrete Paving Sample Sizes

Activity	Number of Observations	% Responding to Activity
Barrier Wall	9	20.5
Base Course	18	40.9
Curb Gutter	34	77.3
Grinding	0	0.0
Hand Placement of Concrete	31	70.5
Patching	5	11.4
Sidewalks	26	59.1
Thick Paving	13	29.5
Thin Paving	22	50.0

4.3.2 Data Characteristics

Data gathered by the concrete paving collection tool categorized construction projects based on 13 project specific factors and recorded productivity rates achieved on the job site for nine highway construction concrete paving activities. The composition of responses for each project factor are shown in Figure 9. Analyzing Figure 9 suggests future research can improve the dataset by focusing on projects with certain characteristics: larger than 100,000 square yards, work occurring at night, rural projects, moderate traffic, very difficult to deliver materials, insufficient storage and staging areas, work occurring during winter, and work occurring in a single phase. Gathering more data on these types of projects has the potential to provide a better understanding of the effect of an assortment of factors.

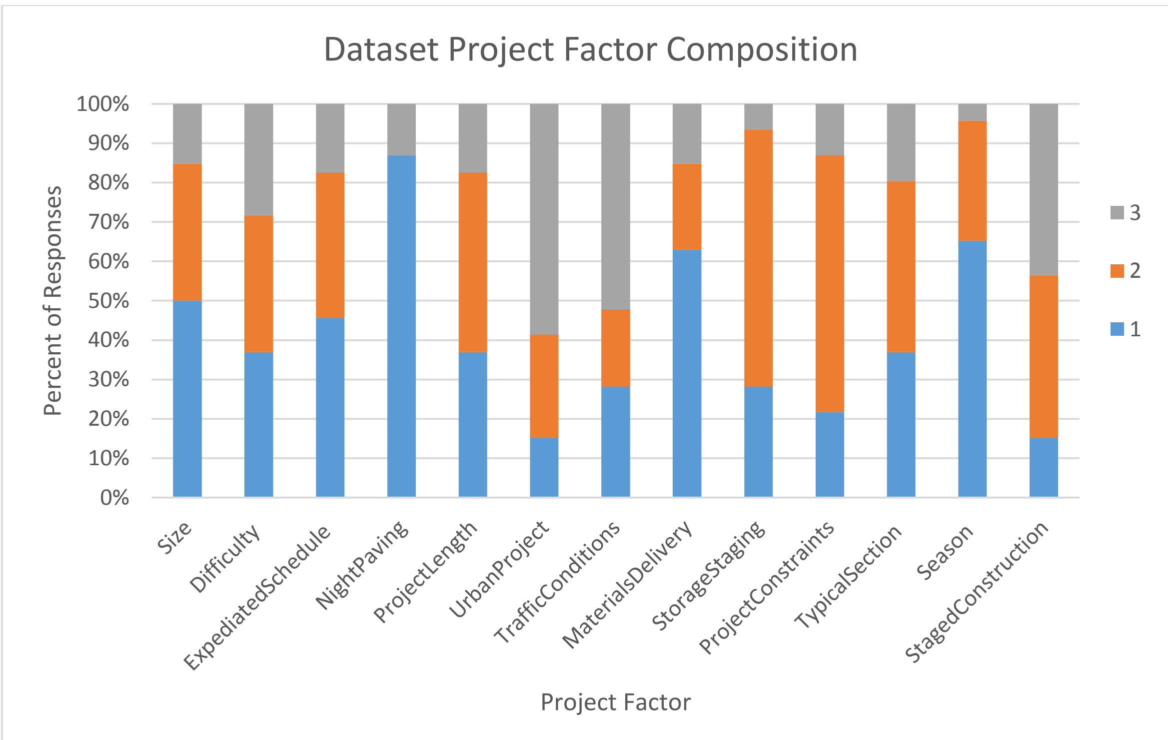


Figure 9: Concrete Paving Dataset Project Factor Composition

4.3.3 Effect of Project Factors on Concrete Paving Productivity

The amount of data collected for concrete paving activities allows for a more encouraging analysis than bridging activities. Linear models were generated for six of the eight activities studied. The extent to which the project factors identified affect each individual construction activity is organized below in Table 13 by the activity, factors selected, p-value for each factor selected, and adjusted multiple R^2 value.

Table 13: Effect of Project Factors on Concrete Paving

Activity	Factor Selected	P-Value	Adjusted R^2
Concrete Paving (thickness > 10")	Size	0.0004	0.989
	Season	0.0006	
	Traffic Conditions	0.0005	
	Night Paving	0.0006	
	Typical Section	0.004	
	Staged Construction	0.027	
	Storage Staging	0.003	
	Project Constraints	0.003	
	Materials Delivery	0.014	
Concrete Paving (thickness < 10")	Expedited Schedule	0.002	0.389
	Night Paving	0.027	
	Difficulty	0.050	
Base Course	Traffic Conditions	0.000154	0.8512
	Difficulty	0.003	
	Project Length	0.001	
	Night Paving	0.008	
	Expedited Schedule	0.013	
	Project Constraints	0.027	
	Materials Delivery	0.058	
Placement of Sidewalks	Traffic Conditions	0.0009	0.3403
	Storage Staging	0.0322	
Hand Placement of Concrete	Size	0.0216	0.1403
Curb and Gutter	Staged Construction	0.0121	0.1556

4.3.4 Productivity Rates for Concrete Paving Activities

The models that were generated in R consist of the best combination of project factors that could be used to maximize each model's BIC value. Each factor has been given a coefficient to be used in estimating a particular activity's production rate. For the six concrete paving activities that were able to be modeled the project factors selected for each activity, regression coefficients, intercepts, minimum value observed, and maximum value observed are summarized below in Table 14. The remaining three concrete paving activities were unable to be modeled, and their minimum value observed, average value, and maximum value observed are given below in Table 15.

Table 14: Concrete Paving Linear Models

Activity	Units/Day	Factor Selected	Coefficient	Intercept	Minimum	Maximum
Concrete Paving (thickness > 10")	S.Y.	Size	5,779.1	852.3	173	12,000
		Season	-5,166.5			
		Traffic Conditions	2,643.8			
		Night Paving	3,728.3			
		Typical Section	-2,231.2			
		Staged Construction	-1,644.4			
		Storage Staging	4,199.9			
		Project Constraints	-5,000.6			
		Materials Delivery	-1,694.5			
Concrete Paving (thickness < 10")	S.Y.	Expedited Schedule	-2,662	2,565	300	14,000
		Night Paving	2,899			
		Difficulty	1,519			
Base Course	Tons	Traffic Conditions	-1,156.7	1,247.8	21	3,940
		Difficulty	484.2			
		Project Length	664			
		Night Paving	1,011.8			
		Expedited Schedule	424.8			
		Project Constraints	-436.7			
		Materials Delivery	-378.9			
Placement of Sidewalks	S.F.	Traffic Conditions	-1,999.4	3,393.6	350	10,000
		Storage Staging	2,305.2			
Hand Placement of Concrete	S.Y.	Size	167.66	172.12	57	1,300
Curb and Gutter	S.Y.	Staged Construction	-546	2,642.5	300	4,112

Table 15: Productivity Rates for Non-Modeled Concrete Paving Activities

Activity	Units/Day	Minimum	Average	Maximum
Barrier Wall	Feet	44	1032	2000
Grinding	S.Y.	NA	NA	NA
Patching	S.Y.	70	285	725

Earthwork Activities

4.4.1 Sample Size and Response Rate

After the conclusion of the latest round of data collection, the number of projects included in the earthwork productivity database grew to include 61 projects. The number of observations collected for each activity is shown individually by Table 16. As with the concrete construction activities included in this study, most earthwork activities possess enough observations to support stepwise selection. However, a few activities still remain which would benefit from further data collection efforts.

Table 16: Earthwork Sample Sizes

Activity	Number of Observations	% Responding to Activity
Base Course Roadway	49	80.3
Base Course Shoulders	31	50.8
Breaker Run	36	59.0
Clearing and Grubbing	27	44.3
Excavation Articulated	15	24.6
Excavation Below Subgrade	24	39.3
Excavation Scraper	22	36.1
Excavation Truck	33	54.1
Hard Rock Excavation	4	6.6
Marsh <8' Deep	3	4.9
Marsh >8' Deep	9	14.8
Shallow Excavation	17	27.9
Soft Rock Excavation	3	4.9
Topsoil Placement	32	52.5

4.4.2 Data Characteristics

Data gathered by the earthwork construction data collection tool categorized construction projects based on 14 project specific factors and recorded productivity rates achieved on the job site for 14 earthwork construction activities. The composition of responses for each project factor are shown in Figure 10. The potential to improve the earthwork productivity database exists through collecting data from projects with various characteristics: between 135,000 and 300,000 cubic yards, very difficult, rehabilitation, more than 50 hour workweeks, work occurring at night, and work occurring during the winter.

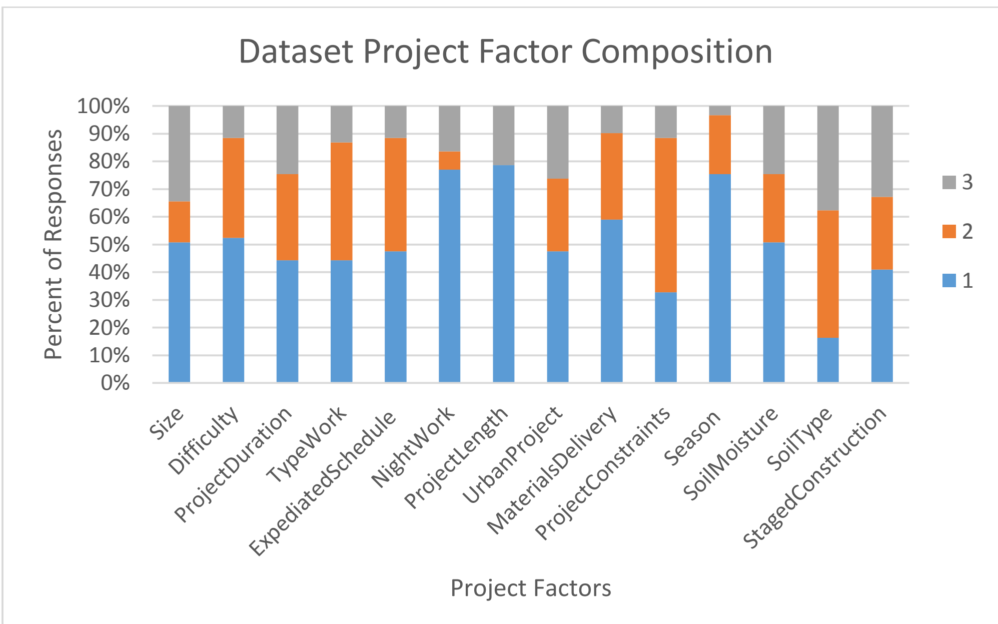


Figure 10: Earthwork Dataset Project Factor Composition

4.4.3 Effect of Project Factors on Earthwork Activity Productivity

Linear models were generated for nine of the 14 earthwork activities studied. As can be expected, four activities had sample sizes below ten and consequently did not return any significant results from stepwise selection. The project factors selected for each activity can be found in Table 17 along with the p-values and adjusted multiple R^2 values corresponding to each model. The project factor "Size" was selected for every earthwork activity that was modeled suggesting a profound importance to not just any individual activity, but rather the entire earthwork industry as a whole.

Table 17: Effect of Project Factors on Earthwork Construction Activities

Name	Factor Selected	P-Value	Adjusted R^2
Excavation: Truck	Size	0.0001	0.4419
Excavation: Scraper	Size	0.002	0.5303
	Materials Delivery	0.023	
Excavation: Articulated	Size	0.0002	0.7254
	Expedited Schedule	0.0207	
	Season	0.0943	
Base Course Roadway	Size	0.0001	0.4355
	Night Work	0.021	
Base Course Shoulders	Size	0.0002	0.4794
	Type of Work	0.0075	
Breaker Run	Size	0.0006	0.633
	Soil Moisture	0.0087	
	Difficulty	0.0246	
Shallow Excavation	Size	0.0087	0.7983
	Type of Work	0.0017	
	Project Duration	0.0001	
	Night Work	0.0003	
Excavation Below Subgrade	Size	0.0002	0.5017
	Night Work	0.0073	
	Type of Work	0.0276	
Clearing and Grubbing	Size	0.0004	0.3695
	Expedited Schedule	0.0245	

4.4.4 Productivity Rates for Earthwork Activities

The models generated for earthwork activities consists of the best combination of project factors that could be used to maximize each BIC value. Each factor has been given a coefficient to be used in estimating a particular activity's production rate. For the nine earthwork that were modeled, the project factors selected for each activity, regression coefficients, intercepts, minimum value observed, and maximum value observed are summarized in Table 18. The remaining five earthwork activities were unable to be modeled, and their minimum value observed, average value, and maximum value observed are given in Table 19.

Table 18: Earthwork Construction Linear Models

Name	Unit/Day	Factor Selected	Coefficient	Intercept	Minimum	Maximum
Excavation: Truck	C.Y.	Size	967.8	-141.5	40	5000
Excavation: Scraper	C.Y.	Size	3,344.40	1,528.50	190	17000
		Materials Delivery	-2,792.90			
Excavation: Articulated	C.Y.	Size	2,203.20	2,199.80	250	8000
		Expedited Schedule	-1,377.90			
		Season	-1,694.70			
Base Course Roadway	Tons	Size	1,243.30	385.1	40	7000
		Night Work	-612.3			
Base Course Shoulders	Tons	Size	382.5	-477.6	30	2500
		Type of Work	332.7			
Breaker Run	C.Y.	Size	1,122.40	-582.6	25	4115
		Soil Moisture	494.5			
		Difficulty	-588.7			
Shallow Excavation	C.Y.	Size	405.8	350.3	75	4000
		Type of Work	-622.8			
		Project Duration	1,181.30			
		Night Work	-832.1			
Excavation Below Subgrade	C.Y.	Size	715.4	-422.7	15	3000
		Night Work	-549.4			
		Type of Work	507.6			
Clearing and Grubbing	Stations	Size	6.8	6	1	30
		Expedited Schedule	-5.2			

Table 19: Productivity Rates for Non-Modeled Earthwork Activities

Name	Unit/Day	Minimum	Average	Maximum
Soft Rock Excavation	C.Y.	1000	1300	1800
Hard Rock Excavation	C.Y.	176	806	1200
Topsoil Placement	C.Y.	20	1100	8223
Marsh Excavation (depth ≤ 8')	C.Y.	458	3486	5000
Marsh Excavation (depth > 8')	C.Y.	1200	2139	4600

Miscellaneous Construction Activities

4.5.1 Sample Size and Response Rate

During the summer of 2014, 26 miscellaneous highway construction activities were added to the data collection tool. These miscellaneous activities do not fall under one of the major construction previously mentioned: earthwork, concrete paving, asphalt paving or bridging. However, the various miscellaneous activities were deemed to be found on WisDOT projects frequently enough to justify their inclusion as they impact the project schedule. Over the course of one summer, 44 separate projects responded to the miscellaneous activity section of the data collection tool. A detail of each miscellaneous construction activity that shows its corresponding number of observations can be found in Table 20.

Table 20: Miscellaneous Activities Sample Sizes

Activity	Number of Observations	% Responding to Activity
Adjust Frames & Grates	15	34.1
Catch Basins	20	45.5
Culvert Pipe	16	36.4
Electrical Conduit In Trench	10	22.7
Electrical Wire Pulling Lighting	8	18.2
Electrical Wire Pulling Signals	4	9.1
Excelsior Blanket	14	31.8
Geotextiles	12	27.3
Guardrails	6	13.6
Install Chain Link Fence	6	13.6
Install Concrete Barrier	11	25.0
Install Steel Plate Beam Guardrail	21	47.7
Manholes	15	34.1
Paint Pavement Marking	25	56.8
Pipe Underdrains	15	34.1
Remove Curb & Gutter	11	25.0
Remove Pavement	14	31.8
Remove Sidewalk	8	18.2
Remove Steel Plate Beam Guardrail	25	56.8
Riprap Heavy & Extra Heavy	9	20.5
Riprap Light & Medium	13	29.5
Seal Coat	0	0.0
Seeding	13	29.5
Silt Fence	26	59.1
Sodding	5	11.4
Straw Mulch	10	22.7

4.5.2 Data Characteristics

Data gathered by the miscellaneous activities data collection tool categorized construction projects based on 18 project specific factors. The composition of responses for each project factor are shown in Figure 11. The “Night Paving” and “Ride Specification” project factors only include two values for work conducted either during the day or the night and requiring versus not requiring a ride specification. A variety of project characteristics were less common in the dataset:

rehabilitation, workweeks greater than 50 hours, work occurring at night, significant amounts of milling required, very difficult in complexity, very difficult to deliver materials and equipment to the project site, and very wet soil present on site.

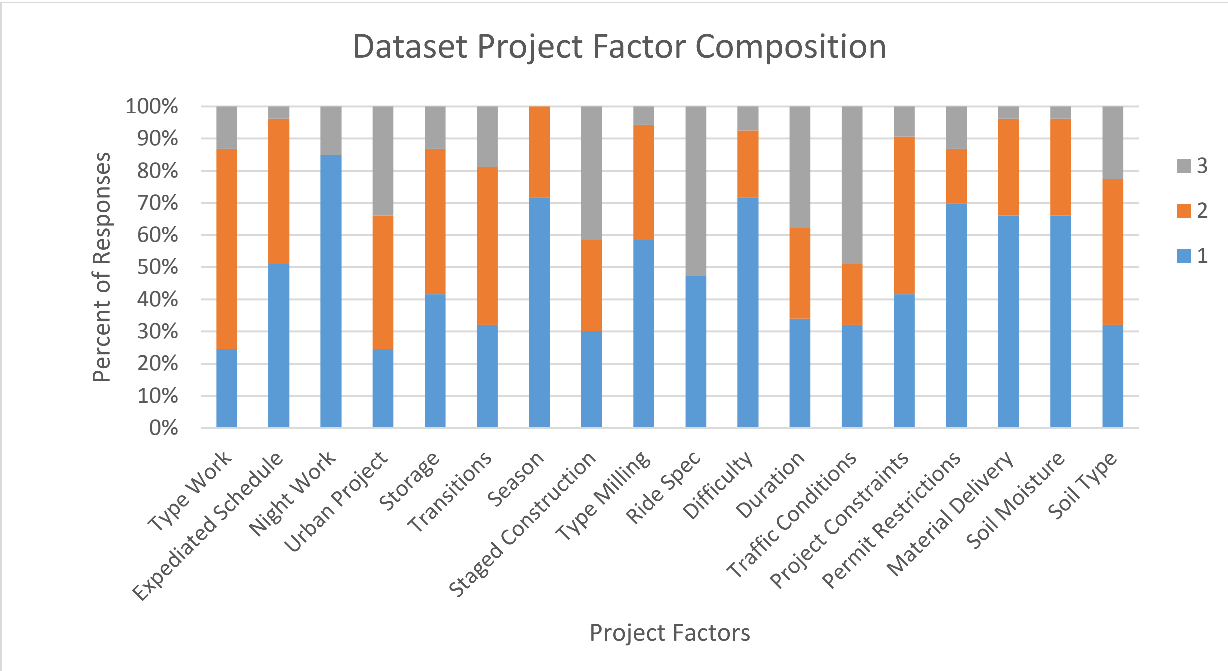


Figure 11: Miscellaneous Activity Dataset Project Factor Composition

4.5.3 Effect of Project Factors on Miscellaneous Activity Productivity

While analyzing the miscellaneous activity dataset linear models were created for 11 of the 26 activities. The results are organized below in Table 21 by the activity, factors selected, p-value for each factor selected, and adjusted multiple R^2 value. In general, factors selected have a p-value below 0.05 suggesting a significant relationship between the factors selected its corresponding miscellaneous activity.

Table 21: Effect of Project Factors on Miscellaneous Construction Activities

Activity	Factors Selected	P-value	Adjusted R^2
Adjust Frames & Grates	Duration	0.004	0.4511
Pipe Underdrains	Night Work	0.0002	0.7613
	Soil Moisture	0.0006	
	Material Delivery	0.0089	
Riprap Light/Medium	Soil Moisture	0.0417	0.2643
Riprap Heavy/Extra Heavy	Duration	0.019	0.7814
	Season	0.011	
	Staged Construction	0.032	
Concrete Barrier	Material Delivery	0.02	0.4294
	Duration	0.05	
Paint Pavement Marking(Truck)	Project Constraints	0.0163	0.1924
Excelsior Blanket	Soil Moisture	0.023	0.2804
Seeding	Expedited Schedule	0.0451	0.2549
Straw Mulch	Night Work	0.000003	0.9965
	Soil Moisture	0.00003	
	Material Delivery	0.00002	
	Soil Type	0.001	
	Project Constraints	0.00002	
Remove Pavement(concrete)	Night Work	0.00735	0.4189
Geotextiles	Duration	0.0024	0.6395
	Expedited Schedule	0.0155	
	Difficulty	0.0177	

4.5.4 Productivity Rates for Miscellaneous Activities

The models generated for miscellaneous construction activities are comprised of the best combination of project factors that could be used to optimize the BIC selection criterion for each activity. Each factor has been given a coefficient to be used in estimating a particular activity's production rate. For the eleven miscellaneous construction activities that were modeled, the project factors selected for each activity, regression coefficients, intercepts, minimum value observed, and maximum value observed are summarized below in Table 22. No significant relationships between project factors and the remaining miscellaneous construction activities were found, and their minimum value observed, average value, and maximum value observed are given in Table 23.

Table 22: Miscellaneous Construction Linear Models

Activity	Units/Day	Factors Selected	Coefficient	Intercept	Minimum	Maximum
Adjust Frames & Grates	Each	Duration	-21.9	71.2	1	74
Pipe Underdrains	Feet	Night Work	1,628.10	-1,712.00	110	4349
		Soil Moisture	1,343.70			
		Material Delivery	-918.2			
Riprap Light/Medium	S.Y.	Soil Moisture	58.4	6.3	20	216
Riprap Heavy/Extra Heavy	S.Y.	Duration	-238.3	1,167.20	49	1100
		Season	-583.9			
		Staged Construction	266.4			
Concrete Barrier	Feet	Material Delivery	1,309.90	925.9	44	3280
		Duration	-767.3			
Paint Pavement Marking (Truck)	Feet	Project Constraints	-9,756.00	33,394.00	1117	48971
Excelsior Blanket	S.Y.	Soil Moisture	2,289.00	-410.4	190	10000
Seeding	Acres	Expedited Schedule	0.9	-0.1	0.25	4
Straw Mulch	Tons	Night Work	32,847.20	-34,981.90	500	25000
		Soil Moisture	15,942.90			
		Material Delivery	-6,929.60			
		Soil Type	-4,839.00			
		Project Constraints	3,360.40			
Remove Pavement(concrete)	S.Y.	Night Work	20,388.00	-16,777.00	150	24000
Geotextiles	S.Y.	Duration	-587.4	2,043.60	12	1204
		Expedited Schedule	-449.2			
		Difficulty	421.2			

Table 23: Productivity Rates for Non-Modeled Miscellaneous Construction Activities

Activity	Unit/Day	Minimum	Average	Maximum
Catch Basins	Each	2	6	23
Chain Link Fence	Feet	349	741	2,000
Culvert Pipe	Feet	40	179	589
Electrical Conduit in Trench	Feet	350	1,057	2,500
Electrical Wire Pulling (Lighting)	Feet	1,000	7,362	16,300
Electrical Wire Pulling (Signals)	Feet	1,000	2,748	5,593
Manholes	Each	0.5	3.5	12
Remove Curb & Gutter	Feet	200	2,260	10,300
Remove Sidewalk	S.Y.	100	1,371	7,850
Seal Coat	Feet	15,840	26,400	52,800
Silt Fence	Feet	110	2,005	10,000
Sodding	S.Y.	321	3,054	10,850
Steel Plate Beam Guardrail	Feet	25	618	1,829
Steel Plate Beam Guardrail Removal	Feet	97	854	1,900

In some instances, the link between project factors and construction activities is intuitive. For example, placing electrical conduit in a trench requires excavation and stepwise regression has selected soil moisture and soil type as significant factors. Alternatively, project factors such as season and difficulty that may be expected to impact the majority construction activities were sparsely found to be significant to any activities. The absence of these two factors is likely explained by a lack of data because the miscellaneous activities dataset simply lacks projects that were categorized as working during the winter and very difficult. Future phases of research should focus on gathering data from projects that either complete work during the winter or are rated as very difficult by their project management team to ascertain whether these factors impact productivity.

4.6 Cross Validation

After generating the aforementioned linear models, cross validation was used to assess accuracy, reliability, and credibility of the models incorporated into the PET. The ideal manner of testing the models is gathering more new data and comparing the model's predictions against new observations. However, limited data has been collected since the creation of linear models, and other methods that rely upon previously collected data became necessary as well. Five-fold cross validation was selected because it partitions the existing dataset into training and test sets. As explained by Steinberg in 2014, it is impossible to access data from the future before it occurs, but it is possible to reserve some of the currently available data and treat it as if it were data from the future. With this approach, the datasets were randomly partitioned five separate times with each of the iterations containing 80% of the data as the training set and the remaining 20% as the test set. The training set data was used to regenerate regression models, and the test set data was used to gauge model strength by comparing the values actually observed versus the values that were predicted. The results of five-fold cross validation can be found for each activity below in Table 24 with values reported in the units of production of each specific activity.

Table 24: Five Fold Cross Validation Results

Activity	Units	Deviation		
		Min	Max	Average
ASPHALT PAVING ACTIVITIES				
Hot Mix Asphalt: Lower Layer	Tons/hr	-129.42	201.27	0.90
Hot Mix Asphalt: Surface Layer	Tons/hr	-121.22	228.57	-1.66
Hand Placement of Asphalt	Tons/hr	-71.82	56.00	-1.31
Thick Milling	S.Y./day	-10075.83	12138.07	-81.87
Base Course	Tons/day	-1506.25	1515.10	79.89
QMP Density	S.Y./day	-12684.41	12684.41	-27.51
Rumble Strip Center	Feet/day	-25903.29	25903.29	-2316.30
Rumble Strip Shoulder	Feet/day	-44708.88	52343.09	-2751.11

BRIDING ACTIVITIES				
Concrete Masonry (Substructure)	Pours/day	-1.92	2.25	0.07
Sheet Piling (height >= 15')	S.F./day	-530.54	1032.33	78.32
Parapet Straight	Feet/day	-66.21	126.09	1.77
Deck Placement, Girder Bridge	S.F./day	-588.66	676.89	7.28
CONCRETE PAVING ACTIVITIES				
Concrete Paving(thickness > 10")	S.Y./day	-7138.00	5327.00	-936.85
Concrete Paving (thickness < 10"	S.Y./day	-11000.00	8503.50	-555.53
Base Course	Tons/day	-1311.89	2529.30	130.46
Placement of Sidewalks	S.F./day	-5355.16	4758.54	-79.19
Hand Placement of Concrete	S.Y./day	-618.60	531.40	-2.60
Curb and Gutter	S.Y./day	-1783.00	2265.81	-57.32
EARTHWORK ACTIVITIES				
Excavation (Truck)	C.Y./day	-2086.93	2489.15	-48.04
Excavation (Scraper)	C.Y./day	-4135.63	8442.49	-217.79
Excavation (Articulated)	C.Y./day	-2230.79	2269.21	-150.57
Base Course Roadway	Tons/day	-2703.78	3673.13	-19.61
Base Course Shoulders	Tons/day	-973.88	1085.26	-0.65
Breaker Run	C.Y./day	-2292.87	1438.39	-23.35
Shallow Excavation	C.Y./day	-998.03	1310.47	22.41
Excavation Below Subgrade	C.Y./day	-867.10	1520.42	-37.19
Clearing and Grubbing	Stations/day	-8.12	14.93	-0.08
MISCELLANEOUS ACTIVITIES				
Adjust Frames & Grates	Each/day	-31.61	43.67	-0.06
Pipe Underdrains	Feet/day	-1300.64	1954.00	93.18
Riprap Light/Medium	S.Y./day	-113.80	102.52	-0.05
Riprap Heavy/Extra Heavy	S.Y./day	-749.16	293.75	-125.62
Concrete Barrier	Feet/day	-1177.02	1363.98	35.13
Paint Pavement Marking (Truck)	Feet/day	-20854.32	324238.30	12316.15
Excelsior Blanket	S.Y./day	-4123.73	4416.28	54.41
Seeding	Acres/day	-1.07	2.37	-0.01
Straw Mulch	Tons/day	-1612.79	24500.00	2671.84
Remove Concrete Pavement	S.Y./day	-4414.20	21560.80	1894.82
Geotextiles	S.Y./day	-421.28	512.09	26.38

At first glance, cross validation did not return particularly encouraging results. Only two of the 38 activities modeled, Sheet Piling >= 15' and Straw Mulch, have an average deviation of less than 20%. In fact, 61% of the activities modeled possessed an average deviation larger than 100%. In general, each activity contained a few observations with maximum deviations that were extremely large that consequently skewed average deviation. Additionally, the extreme observations were previously deemed to not be outliers. However, on an individual basis, several projects tested saw success predicting the actual rate. For example, 60% of the projects tested for placing straw mulch had an average deviation less than $\pm$ 15% as seen in Table 25. The cross validation results for the remaining activities can be found in Appendix C.

Table 25: Straw Mulch Validation Results

Straw Mulch			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
10.00	570.63	5400.00	-89.43
5.00	7694.88	7000.00	9.93
Second 20%			
7.00	698.62	500.00	39.72
1.00	7820.12	8800.00	-11.14
Third 20%			
2.00	500.00	25000.00	-98.00
3.00	2347.79	735.00	219.43
Fourth 20%			
6.00	15683.75	15000.00	4.56
9.00	12298.37	11417.00	7.72
Fifth 20%			
8.00	500.00	476.00	5.04
4.00	500.00	510.00	-1.96

Overall, the results of the comprehensive statistical analysis conducted offer an encouraging look towards the future as more data is collected. Data limitations have restrained the ambitions of this research project from conception as 45 of the 83 activities studied were unable to be modeled due to insufficient data. However, 38 construction activities were able to be modeled that all found significant relationships with various project factors. In the future, collecting more data should enable models to be created for the 45 activities without regression models. Collecting more data points would also help improve estimates of the underlying linear relationship (Wu, 2008). To illustrate this, Figure 12 shows that an increase in sample size coincides with a decrease in average percent deviation. Ultimately, as more data is collected additional activities will be able to be modeled and the models created can be expected to be more reliable.

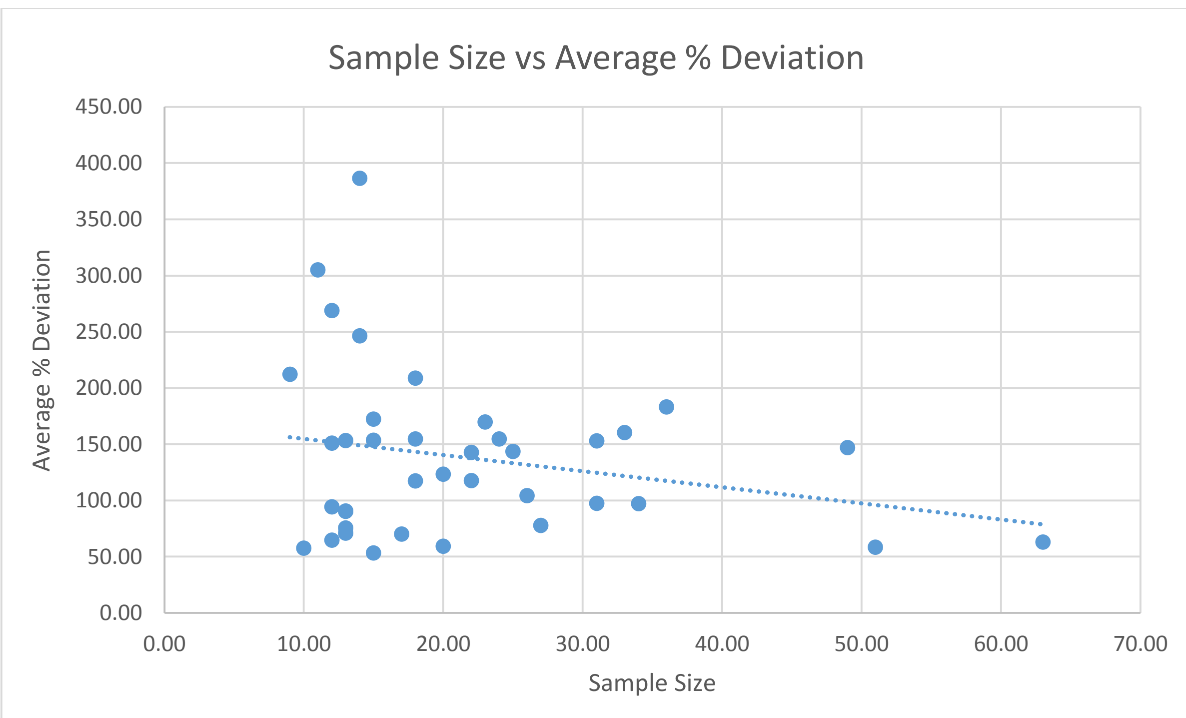


Figure 12: Sample Size vs Average % Deviation

4.7 Validation Using New Data

As previously mentioned, only a limited amount of additional data has been collected since models were generated using stepwise linear regression. However, five additional projects have submitted data, which was used to gain an initial understanding of the models' ability to make predictions. The results of the validation conducted using new data can be found below in Table 26 wherein "Validation Sample Size" corresponds to the number of new observations gathered for a particular activity. Four activities returned encouraging results of an average percent deviation of less than plus or minus ten percent. At the same time, nine activities provided the much less encouraging results of average percent deviations larger than plus or minus 100 percent. However, it must be noted that that validation sample sizes used are much too small to gain meaningful conclusions.

Table 26: Validation Results Using New Data

Activity	Average % Deviation	Model Sample Size	Validation Sample Size
Base Course Roadway (earthwork)	1.6	49	2
Hot Mix Asphalt Surface Layer	3.2	63	2
Excelsior Blanket	-6.1	14	2
Hot Mix Asphalt Lower Layer	-8.6	51	3
Concrete Paving (thickness < 10")	21.7	22	2
Curb and Gutter	-24.6	34	2
Parapet (straight back)	-36.9	12	1
Excavation (truck)	-38.1	33	2
Paint Pavement Marking (truck)	-50.6	25	1
Base Course (concrete)	51	18	2
Base Course (asphalt)	69.5	23	1
Geotextiles	-70	12	1
Excavation (articulated truck)	-75	15	1
Temp Sheet Piling (height >= 15')	-75.3	13	1
Hand Placement of Concrete	77.5	31	2
Hand Placement of Asphalt	-80	18	1
Shallow Excavation	-81.3	17	1
Clearing and Grubbing	-85.7	27	1
Deck Placement (girder bridge)	-92.8	20	1
Breaker Run	111.8	36	2
Excavation Below Subgrade	153	24	1
Sidewalks	204	26	2
Adjust Frames and Grates	216.7	15	2
Concrete Masonry (substructure)	278	18	2
Seeding	406	13	1
Remove Pavement (concrete)	411	14	5
Install Concrete Barrier	2838	11	1

CHAPTER FIVE
PRODUCTIVITY ESTIMATION TOOL

5.1 Introduction to Tool

The culmination of this research project was the creation of the Productivity Estimation Tool (PET). The PET is a user-friendly tool which was designed to help WisDOT's transportation engineers and designers estimate highway construction productivity rates for future projects. The PET is comprised of various types of sections, or tabs in Microsoft Excel (MS Excel), to include: introduction, main menu, five project information user input tabs, five hidden tabs for creating linear regression models, and five output tabs. With this tool, designers are able to estimate production rates for various activities by inputting project factor information corresponding to projects occurring in the future. The tool then takes the user's project information input into consideration when providing productivity rate estimates. Ultimately, WisDOT will be able to utilize this tool to improve estimates of contract time awarded to contractors working on WisDOT highway construction projects.

The PET is a MS Excel based prototype tool that was originally created by Diane Aoun while completing her Master's degree under Dr. Awad Hanna at the University of Wisconsin-Madison. In its original form, the PET reported estimated productivity rates by using confidence intervals with a level of confidence as specified by the user. The original tool included four tabs in MS Excel for asphalt paving, bridge construction, concrete paving, and earthwork (Aoun, 2013). However, significant changes have been made to the PET since 2013 to include: recreation of existing linear models with additional data, addition of miscellaneous construction activities, and a complete overhaul of the method used to report production rates. A comprehensive PET user guide intended to be used to train WisDOT employees on the use of the PET can be found in Appendix E, and the following sections discuss the significant changes made to the tool since 2013 while providing an abridged explanation of the PET.

5.2 Recreation of Existing Models

Various asphalt paving, bridge construction, concrete paving, and earthwork construction activities were previously assigned linear models in the prototype version of the PET. However, limited data was available when the PET was first created, and efforts were made to enhance the reliability of the existing models by increasing the number of observations in the dataset from which the models were created. In total, the linear models are used by the PET for eight asphalt paving activities, four bridge construction activities, six concrete paving activities, and eight earthwork activities were recreated. Further explanation regarding precisely which activities' linear models were updated and their "goodness of fit" can be found in Chapter Four: Data Analysis and Results.

5.3 Updates to Remaining Activities

The sample sizes for an assortment of construction activities remained insufficient for creating linear models after the conclusion of the latest round of data collection efforts. However, in these instances the sample sizes increased allowing the research team to update the production rate ranges reported by the tool. These activities were reported with the following summary statistics: minimum, average, maximum, and sample size. Estimators are then able to apply personal experience to ascertain whether or not to apply production rates that deviate from the calculated average values. The number of construction activities assigned linear models versus reported with summary statistics for each category of highway construction activities can be found below in Table 27. Ultimately, five asphalt paving activities, 27 bridge construction activities, three concrete paving activities, and six earthwork activities were updated in this manner. More information conveying which construction activities were reported via summary statistics can be found in Chapter Four: Data Analysis and Results.

Table 27: Method of Reporting Production Rates

Category	Number of Activities	
	Linear Model	Summary Statistics
Asphalt Paving	8	5
Bridge Construction	4	27
Concrete Paving	6	3
Earthwork	8	6

5.4 Addition of Construction Activities

As a considerable amount of additional highway construction productivity data was collected, it became possible to greatly expand the variety of construction activities modeled and included in the PET. First, the number of observations collected for two previously included activities (centerline rumble strip production and shoulder rumble strip production) became large enough to allow for the creation of linear models. Previously, production rates for these activities were reported with ranges of values found by investigating DOT's from states other than Wisconsin and reviewing existing literature. Next, 25 entirely new miscellaneous activities were added to the research team's data collection efforts, and were incorporated into the PET as well. Of the 25 new miscellaneous activities, enough data was collected for 11 activities to create linear models. For the remaining 14 miscellaneous activities, sample sizes were insufficient to create linear models, and production rates were reported via the following summary statistics: minimum, average, and maximum. The miscellaneous activities added to the PET and the method used to report their individual production rates can be found below in Table 28.

Table 28: Method of Reporting Miscellaneous Activities

Activity	Linear Model	Summary Statistics
Adjust Frames and Grates	x	
Pipe Underdrains	x	
Riprap Light/Medium	x	
Riprap Heavy/Extra Heavy	x	
Concrete Barrier	x	
Paint Pavement Marking (Truck)	x	
Excelsior Blanket	x	
Seeding	x	
Straw Mulch	x	
Remove Concrete Pavement	x	
Geotextiles	x	
Catch Basins		x
Chain Link Fence		x
Culvert Pipe		x
Electrical Conduit In Trench		x
Electrical Wire Pulling (Lighting)		x
Electrical Wire Pulling (Signals)		x
Manholes		x
Remove Curb & Gutter		x
Remove Sidewalk		x
Seal Coat		x
Silt Fence		x
Sodding		x
Steel Plate Beam Guardrail		x
Steel Plate Beam Guardrail Removal		x

5.5 New Method for Reporting Production Rates

The output generated for each particular construction activity depends on whether or not a model was generated for that activity using stepwise linear regression in R. If a model's dataset would support the creation of a model, then an output as shown below in Figure 13 was generated.

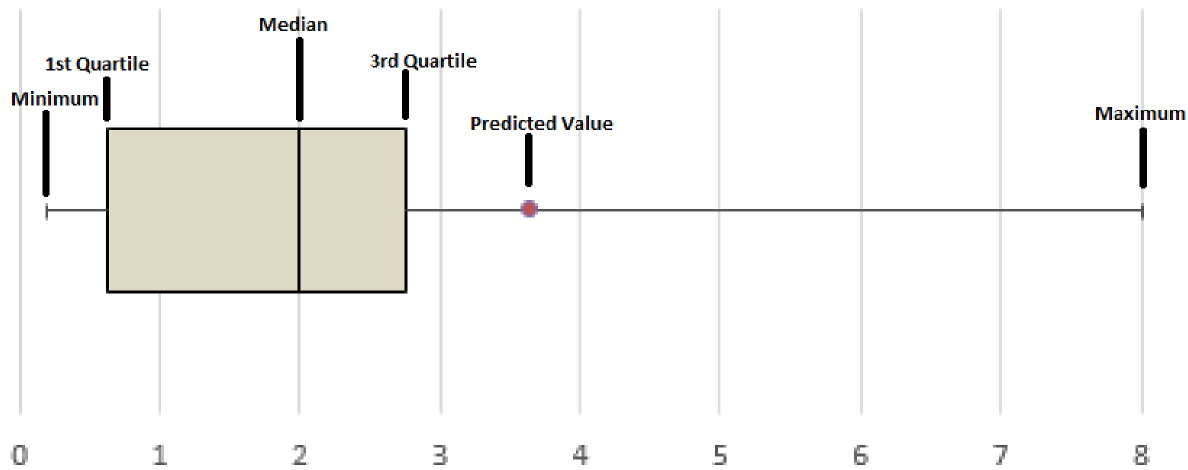


Figure 13: Output Display for Modeled Activities

In this type of output, the minimum and maximum values shown are the actual minimum and maximum values observed during the data collection phase. The first quartile is the value which is greater than 25% of the data observed, the median is the value greater than 50% of the data observed, and the third quartile is the value greater than 75% of the data observed. The predicted value, represented by a red circular marker on Figure 13, is the value generated by the linear model created using project factors as inputs. While the models generated may predict a value outside of the observed range of values in some instances, the PET automatically truncates these predictions to either the minimum or maximum value observed accordingly. If a particular construction activity did not have a large enough sample size to create a linear model, then the output is modified as shown below in Figure 14.

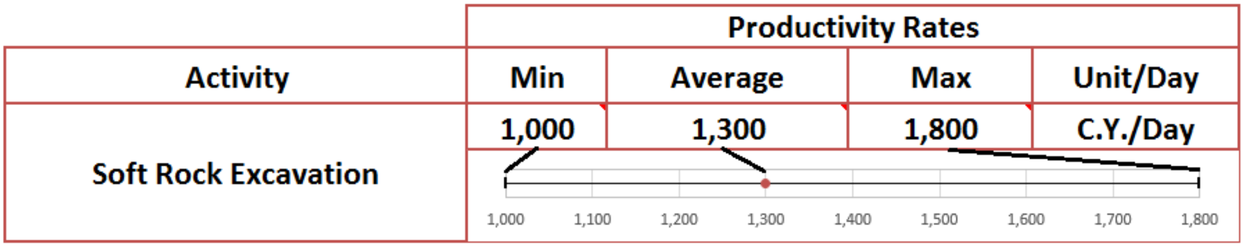


Figure 14: Output Display for Non-modeled Activities

In this type of output, the minimum value observed, average, maximum value observed, and unit of measurement are displayed for a particular construction activity. To communicate the reliability of the values reported to users of the PET, a message indicating the sample size collected for each activity is displayed when the mouse cursor is hovered over the cells containing either the minimum, average, or maximum values. An example of the sample size message can be seen below in Figure 15.

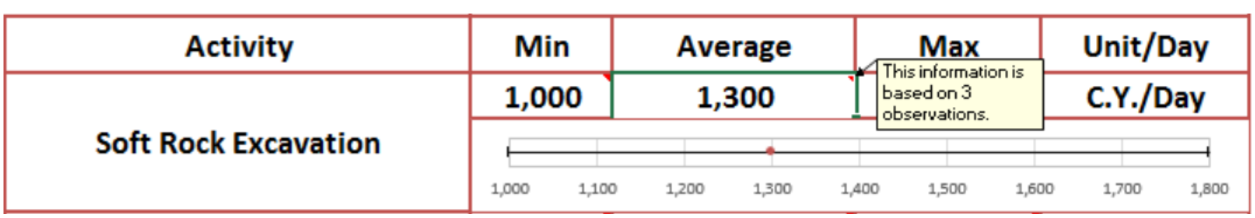


Figure 15: Sample Size Message

5.6 Using the Productivity Estimation Tool

The PET was designed to be a user-friendly and intuitive tool requiring minimal training that quickly allows estimators to obtain production rates to employ on future projects. When using the tool users mainly interact with one of the five user input tabs where they are prompted to rate their projects based on various project-specific factors. Portions of the asphalt paving user input tab are shown below in Figures 16 and 17.

Productivity Estimation Tool for
Asphalt Paving Projects

Project ID	
Project Location	
Date	
Description	
Name of Estimator	

RESET PAGE

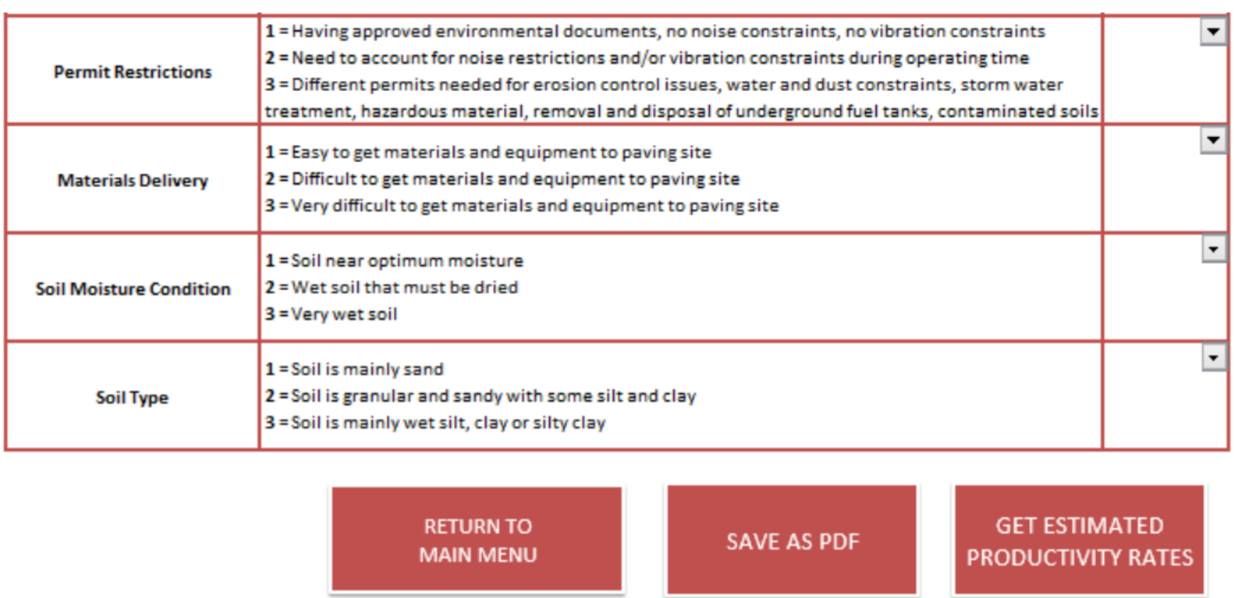
Step 1: Thinking of the project for which you want to estimate productivity rates, determine for each of these project factors whether 1, 2 or 3 would best desribe your project.

Factor	Description	Severity
Type of work	**1** = New construction project **2** = Reconstruction, resurfacing or maintenance project **3** = Rehabilitation project (structure currently used for transportation)	
Project Size	**1** = Small (≤ 10,000 total tons) **2** = Medium (10,000 - 50,000 total tons) **3** = Large (≥ 50,000 total cubic tons)	
Expedited Project Schedule	**1** = 40 hours week, 8 hours per day, normal (optimum) crew size, no work on holidays. **2** = 50 hours per week, larger than normal or constantly changing crew sizes, work on some holidays. **3** = Working beyond 50 weekly hours (overtime), much larger than normal crew sizes	

Figure 16: User Input Tab 1 of 2

Near the top left of Figure 16, project administrative information entered into the Main Menu page is automatically populated. The body of the user input tabs consists of questions for the user to rate the various project factors to be used in providing estimated productivity rates later in the output tab. Users can either type in 1, 2 or 3, or users can make their selection from dropdown menus located at the top right of each project factor's data entry cell. The "Data Validation" tool was used in MS Excel to ensure that users are restricted to entering the values specified by the project factor descriptions. The "Reset Page" icon clears all of the project information user data inputted.

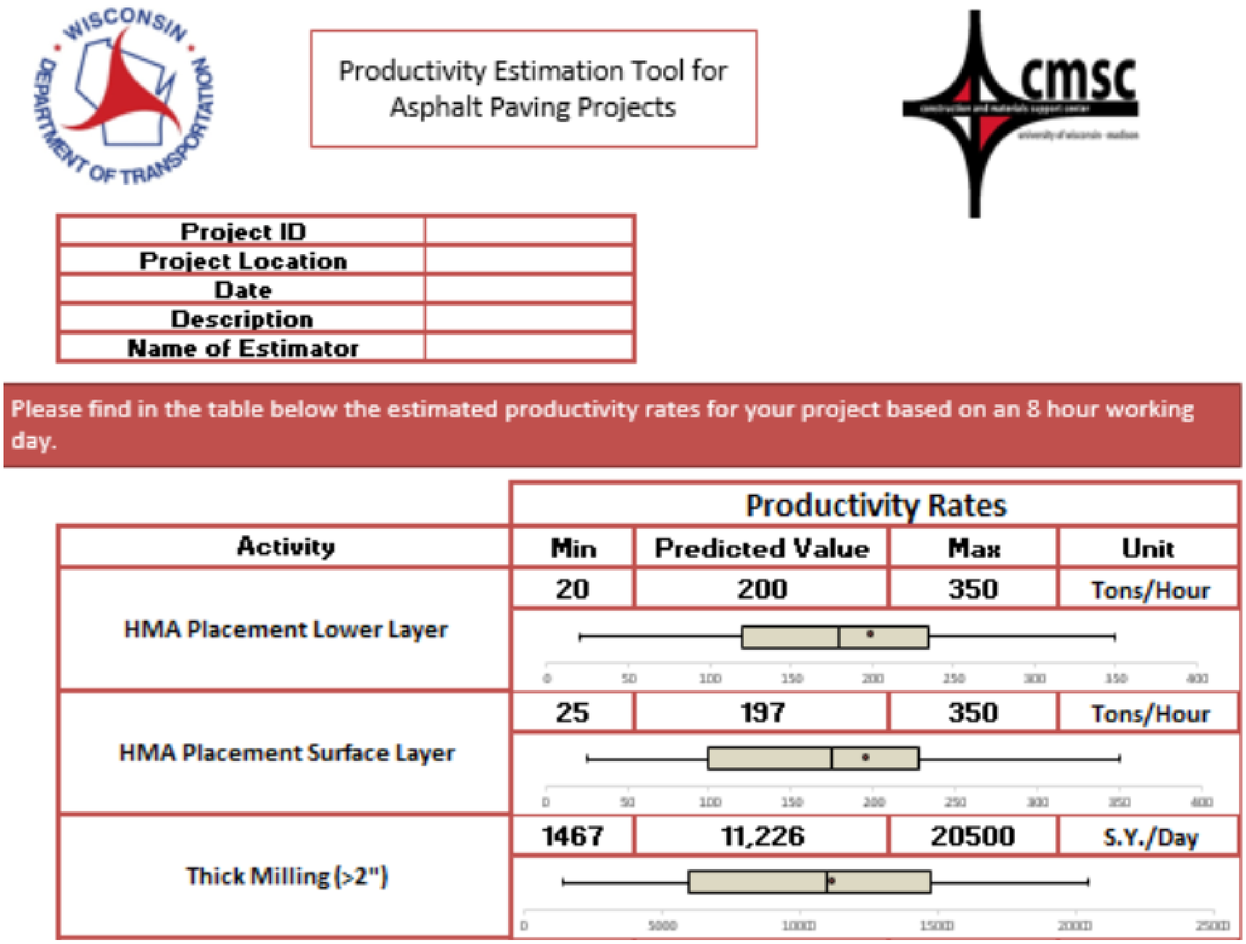
After completing an entry for each project factor, users then find three icons at the bottom of the user input page shown by Figure 17. The "Return to Main Menu" icon simply returns the user to the Main Menu page and hides all other tabs currently visible in MS Excel. The "Save as PDF" icon brings users to a windows navigation page where users can select precisely where they would like to save a copy of the user input page. Finally, the "Get Estimated Productivity Rates" icon sends users to the output tab.



Permit Restrictions	1 = Having approved environmental documents, no noise constraints, no vibration constraints 2 = Need to account for noise restrictions and/or vibration constraints during operating time 3 = Different permits needed for erosion control issues, water and dust constraints, storm water treatment, hazardous material, removal and disposal of underground fuel tanks, contaminated soils	
Materials Delivery	1 = Easy to get materials and equipment to paving site 2 = Difficult to get materials and equipment to paving site 3 = Very difficult to get materials and equipment to paving site	
Soil Moisture Condition	1 = Soil near optimum moisture 2 = Wet soil that must be dried 3 = Very wet soil	
Soil Type	1 = Soil is mainly sand 2 = Soil is granular and sandy with some silt and clay 3 = Soil is mainly wet silt, clay or silty clay	

Figure 17: User Input Tab 2 of 2

The output tabs of the PET are where the user ultimately acquires the information that this tool was designed to convey. Portions of the asphalt paving output tab can be found below in Figures 18 and 19. At the top left of the output tab, users will again find the project administrative information that was entered into the main menu tab. The user can then find productivity rates for each of the construction activities that were assigned linear models. For each activity, the minimum value observed, value predicted by the PET, maximum value observed, and unit of measurement are displayed both in text and graphically.



Productivity Estimation Tool for Asphalt Paving Projects

Project ID	
Project Location	
Date	
Description	
Name of Estimator	

Please find in the table below the estimated productivity rates for your project based on an 8 hour working day.

Activity	Productivity Rates			
	Min	Predicted Value	Max	Unit
HMA Placement Lower Layer	20	200	350	Tons/Hour
HMA Placement Surface Layer	25	197	350	Tons/Hour
Thick Milling (>2")	1467	11,226	20500	S.Y./Day

Figure 18: Output Tab 1 of 2

Construction activities reported with summary statistics are separated in the output tabs to show their appropriate display. As seen below in Figure 19, the minimum value observed, average value, maximum value observed, and unit of measurement are given for each construction activity. The red triangles in each of the "min, average, and max" cells indicate the sample size messages waiting to be discovered, if so desired by the user. At the bottom of the output tabs, users can select from three icons. The "Return to Main Menu" icon simply returns the user to the main menu and hides all other tabs in MS Excel. The "Return to Project Factors" icon returns users to the project factor user input tab and hides the output tab. Finally, the "Save as PDF" icon brings users to a windows navigation page to choose specifically where to save a copy of the output tab.

	Productivity Rates			
Activity	Min	Average	Max	Unit/Day
Catch Basins	2	6	23	Each
	1 6 11 16 21			
Chain Link Fence	349	741	2000	Ft
	340 540 740 940 1140 1340 1540 1740 1940			
Culvert Pipe	40	179	589	Ft
	35 135 235 335 435 535			

Figure 19: Output Tab 2 of 2

This concludes a brief tour of the PET created in MS Excel. The tool is designed to be intuitive and guide the user through the tool as it is being used, if even for the first time. There are many processes and computations that are hidden from the end user, and aesthetically pleasing displays allow designers to extract necessary information. The PET is part of a larger framework for improving estimates of contract time awarded for completion. The PET will require periodic updates as more data is collected, and future iterations of the framework put in place to update the PET will strive to improve its utility and accuracy.

CHAPTER SIX
LIMITATIONS, FUTURE WORK, AND RECOMMENDATIONS

The PET is inherently a work in progress. At this time, perhaps it is even most appropriate to consider the PET as a larger process or framework rather than simply as a tool. Various factors involving the advancement of technology and construction methods will lead to the current PET's gradual decline in accuracy and usefulness over time. However, future efforts can instead improve the current PET by collecting more data and refitting linear models with stepwise regression in R. In the following passages, limitations of the tool, a new data collection interface, the process of updating the tool, and recommendations for future research and use of the tool will be discussed.

6.1 Limitations of the Productivity Estimation Tool

First and foremost, the PET is a great starting point for designers to use when beginning to estimate the amount of time to award a contractor for contract completion. The tool makes predictions that are to be used to help guide estimates rather than be used as a final determining factor. Admittedly, the tool does not and cannot capture all of the variability involved with each construction activity. Depending on the construction activity, approximately 15 project factors were investigated to uncover a relationship that drives productivity. There are certainly other factors that have either gone undiscovered by the research team or were deemed too unrealistic to incorporate into the PET such as contractor specific factors.

The type of estimate that the PET produces should be greatly considered before relying on its results. The PET should be considered as capable of providing an engineering estimate rather than a contractor's estimate due to the project factors considered. When a designer is using the

PET to predict productivity, many important contractor specific factors remain unknown and are unable to be used to predict productivity. For example, the PET can never consider the crew composition or equipment being used on a project because a specific contractor has yet to be awarded the project. Crew composition and the type of equipment being used can impact productivity greatly, but omitting factors such as these was deemed acceptable considering where in the project timeline the PET will be utilized.

Issues with the quantity of data available to the PET is both the largest limitation and the greatest opportunity to improve the tool. As discussed in Chapter 4, the database grew significantly during the summer of 2014, however many construction activities still lack an adequate sample size for conducting stepwise linear regression with 15 independent variables (project factors). In fact, only 38 of the possible 92 highway construction activities that were investigated by this study have had linear models generated. Future data collection efforts will certainly increase the number of observations in the productivity database allowing the creation of linear models for more activities.

The final limitation of this tool deals with the efficiency of the PET. In its current version, the PET cannot update itself automatically as more data is collected. To be updated, the current PET requires considerable human effort to generate new models and update regression coefficients in the tabs hidden inside the tool. With the current state of technology and computing, it is with certainty you can say that it is possible to completely automate the PET, but this objective was not included in the scope of this research. One avenue to take when investigating the possibility of creating a fully automated PET is the software package “R Excel.” R Excel is an “Add-In” which can be integrated into any MS Excel spreadsheet. With this add-in, it is possible to run the R coding language from inside MS Excel without the need of the actual R software package. Once R Excel is able to generate models in MS Excel, it would become possible to write macros into the PET that update all of the models when prompted with an updated version of the database. This proposition is an ambitious goal, is made entirely in the hypothetical realm, and would require advanced MS Excel and R programming skills to accomplish. The time-savings tradeoff made by automating the PET would likely require a few years to reach its breakeven point. However, the alternative to automating the PET is requiring approximately 40 work hours when the PET's database grows after every construction season requiring the tool to be updated.

6.2 Future Web-Based Data Collection

The data collection method utilized while conducting this research involved emailing a MS Excel based data collection tool to contractors, and required manual data entry of each survey response into a database. In the future, data will be collected using the online survey application Google Form created as part of this research. The online surveys have been embedded into the Google Sites domain, http://wisdot-productivity.engr.wisc.edu/, to allow access to all five surveys from a single URL. Data collected will remain confidential, and is secured with username and password account information. Administrators can find productivity surveys for each of the five types of construction considered and five databases that automatically grow each time a survey respondent completes one of the surveys. A screenshot showing the format of the surveys is shown below for Asphalt Paving in Figure 20. Each survey contains mandatory questions for each project factor and questions that can remain unanswered for each of the construction activities tracked.

Once completed with the survey, respondents click the "submit" button, and their responses are automatically added to the productivity database for updating the PET at a later date.

Asphalt Paving Activities WisDOT Productivity Data Collection Tool

The WisDOT is in the process of updating production rates for various highway construction activities. The information provided in this form will be used to improve estimating time for contract completion.

Please contact Larry Jones if you have any questions regarding this survey.
Email: Larry.Jones@dot.wi.gov
Phone: (608) 267-7954

Please rate each project factor as either a 1, 2 or 3, and then provide productivity rates for the construction activities that were tracked on your project.

* Required

Project ID: *
Please enter your project's ID #

Project Location *
Please enter the location for your project

Date *
Please enter the date

Figure 20: Google Forms Data Collection Survey

6.3 Conclusion of Research

This research has improved WisDOT's PET and set the conditions that will enable more accurate predictions of productivity therefore providing more accurate estimations of contract completion time. The PET now benefits from a wealth of additional historical productivity data, 26 new miscellaneous activities, an enhanced visual means of displaying productivity information, additional factors for estimators to consider when determining contract time, and a web domain to gather productivity data from WisDOT field engineers in the future. Adding historical productivity data to the existing database provided for the creation of more reliable models to predict productivity. Including 26 new miscellaneous highway construction activities allows designers to estimate more activity durations than previously when determining contract completion time. Displaying productivity predictions in a visual manner with box-and-whisker plots makes the estimation tool more user-friendly. By gathering additional factors to consider when determining contract time, estimators now have guidance to follow when applying their own personal experience and judgement. The creation of a web-based productivity data collection tool provides field engineers a streamlined method of providing data in the future. The aforementioned improvements have truly transformed the PET. Finally, the system now in place will allow the PET's accuracy to improve year-by-year as more additional data is incorporated into the historical database.

6.4 Recommendations for Future Research

Great improvements have been made to the PET during the course of this research. However, continuing this research undoubtedly will make additional improvements to the effectiveness and accuracy of the estimation tool. First, additional historical productivity data should be collected to increase the accuracy of the models used by the tool. The current productivity database contains the least amount of information on projects with various attributes: very difficult, rehabilitation work, larger than 50,000 total cubic tons, working more than 50 hours a week, working at night, narrow paving width (shoulders only), insufficient storage and staging, working during winter, less than 2” paving thickness, and those requiring a significant amount of milling to make corrections. Furthermore, more data will allow for the creation of predictive models for activities where current data is insufficient. Creating additional models will allow estimators to predict productivity using project specific factors for more construction activities than the current tool is capable of.

While new data is collected, it is also recommended that a quality assurance program is implemented for the field engineers providing data. The old adage that “junk in equals junk out” absolutely applies to the models created for this tool. Field engineers should be trained on the expectations of them when providing data. Field engineers need to understand the importance of the data they provide. Gaining buy-in from field staff will encourage diligence when tracking productivity on the project site.

Finally, the activities in the estimation tool can be reevaluated for their relevance when determining contract time. Discussions with estimators should take place to ascertain which activities are critical when determining contract time. It is possible that both frivolous activities are included and pertinent activities have been left out. Identifying the critical tasks will allow future research to focus its efforts and improve the reliability of the tool.

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Appendix B – Productivity Rates Used by Other DOT's

Florida				
Activity	**Unit**	**Production Rate**		
		Low	**Average**	**High**
MOT				
MOBILIZE / MOT / EROSION CONTROL	WKS	1	2	3
ADVANCED WARNING PANELS	EA		15	
BARRICADES	EA		500	
REMOVABLE PAV'T MARKINGS	LF		18500	
TEMP IMPACT ATTENUATORS	EA		20	
TEMPORARY BARRIER WALLS	LF		450	3000
TEMPORARY CURB	LF		900	
TEMPORARY PAV'T	SY		440	750
TEMPORARY RPM'S	EA		500	
TEMPORARY STRIPING	MI		4	
VARIABLE MESSAGE SIGNS	EA		10	
WORK ZONE SIGNS	EA		30	
EROSION CONTROL				
FILTER FABRIC	SY		2,500	
FLOATING TUBIDITY BARRIER	LF			500
HAY BALES	TON		3	
ROCKBAGS/SAND BAGS	EA			400
SILT FENCE	LF	750	1,500	3,000
SOIL TRACKING DEVICE	EA			5
TURBIDITY BARRIER	LF			600
CLEARING & GRUBBING				
MAILBOXES	EA			25
REMOVE EXISTING CONCRETE PAV'T	SY			600
REMOVE SIDEWALK	SY	1,500	2,500	3,500
REWORK SHOULDERS	SY		20,000	
SHOULDER	Mi		1	
C & G	Ac	1		10
EARTHWORK				
BACKFILL AROUND STRUCT.	CY	50	100	200
EXCAVATION - TRUCK HAUL				
< 100,000	CY	900		
100,000 - 300,000	CY		3,800	
> 300,000	CY			7,500
SHOULDER GRADING	MI	0.5	1	2

DRAINAGE				
ADJUST MANHOLE	EA			6
CONCRETE BOX CULVERTS	CY	20	50	80
CONCRETE BOX CULVERTS (PRECAST)	LF	50	100	150
CONCRETE CLASS I (Culvert)	CY	5		10
CONCRETE CLASS I (Endwalls)	CY	5		10
CONCRETE ENDWALLS	CY			15
DESILT PIPE	LF		1,000	
DESILT, CLEAN & SEAL JNT	LF		30	
DITCH PAVING	SY		200	
DRAINCRETE	LF		1,500	
GUNITE	CF	65	130	
INLET	EA			6
JACK & BORE	LF	20		
JUNCTION BOX	EA			6
MANHOLES	EA			4
MISC. CONCRETE	CY			15
MITERED END SECTIONS	EA	8	13	
PARTIAL MANHOLE	EA			6
PIPE INSTALLATION < 5' deep	LF	200		400
PIPE INSTALLATION > 5' deep	LF	100		200
RIPRAP	TN		50	
STORM SEWERS, (Manholes & Inlet)	LF	100	300	400
TEMPORARY PIPE(Slope Drain)	LF			400
TRENCH DRAIN (Special)	LF	100		400
VALVE BOX, ADJUST	EA			8
WINGWALLS	SF	100	150	200
ROADWORK				
CONCRETE BARRIER WALL	LF	200	300	400
CONCRETE CURB & GUTTER	LF	400	600	800
CONCRETE PAVING	SY		5000	
DIAMOND GRINDING CONC	SY		2000	
MILLING	SY			8000
MILLING ASPHALT	SY		8000	
MISC ASPHALT PAVEMENT	TN		60	
RUBBLIZATION	SY		7000	
RUMBLE STRIP GRINDING	MI		5	
STABILIZE ROADBED	SY	1400	1500	
STABLIZATION	SY	1400	1600	1800
TEMPORARY PAV'T	SY			60
TEXTURED PAVEMENT	SY		150	

TRAFFIC SEPERATOR	LF		800	
TURNOUT CONSTRUCTION	SY		200	
REMOVE EXISTING GUARDRAIL	LF		2,000	
FURNISH & INSTALL GUARDRAIL	LF	200	1,000	1,500
END ANCHORS (GUARDRAIL)	EA		8	
HANDRAIL & BICYCLE RAILING	LF	100		400
FENCE < 10,000	LF	500		
FENCE > 10,000	LF		1,200	3,500
GATES	EA		10	
PAVEMENT MARKING				
DELINEATOR TUBULAR (Flexible)	EA	500	750	1,000
DIRECTIONAL ARROWS	EA	25		50
GUIDE LINES (Thermo)(White)	LF		2,000	
ISLAND NOSE PAINT	SY		55	
MESSAGES	EA		30	
MISC. STRIPE	LF		3,000	
PAINTED PAV'T MARKINGS (Final Surface)	NM		7	
REFLECTIVE PAINT (Island Nose)	SY		30	55
REMOVE EXIST THERMO (White/Black)(Other)	SF	2,000	2,400	4,800
REMOVE EXIST THERMO (White/Black)(Solid)	LF	2,000	4,800	9,600
REMOVE EXIST THERMO (White/Black/Blue)(Skip)	GM		7	
REMOVE EXIST THERMO (White/Black/Blue)(6")	NM		7	
REMOVE EXIST THERMO (Yellow)(Other)	SF	2,000	4,800	9,600
REMOVE EXIST THERMO (Yellow)(Skip)	LF	2,000	2,400	4,800
REMOVE EXIST THERMO (Yellow)(Solid)	LF	2,000	2,400	4,800
REMOVE EXISTING THERMO	SY		350	
RPM's (0 - 5,000)	EA	500	750	1,000
STRIPING SKIP	GM		7	
STRIPING SOLID	NM		7	
THERMOPLASTIC STRIPING	MI		6.7	
TRAFFIC STRIPE	MI		7	
TRAFFIC STRIPE SKIP (Thermo)(White/Black/Blue)	LF		2,000	
TRAFFIC STRIPE SKIP (Yellow)	LF		2,000	
TRAFFIC STRIPE SOLID (Paint)(White)(24")	LF		2,000	
TRAFFIC STRIPE SOLID (Paint)(White/Black)	LF		2,000	
TRAFFIC STRIPE SOLID (Two Component)(18")	LF		2,000	
TRAFFIC STRIPE SOLID (Yellow)(18")	LF		2,000	
TRAFFIC STRIPE SOLID (Yellow)(6")	NM		7	
TRAFFIC STRIPE SKIP (Standard)(White)(6")	GM		7	
TRAFFIC STRIPE SKIP (White)(6")	LF		2,000	
SIGNALIZATION				

DIRECTIONAL BORE < 6"	LF	400		800
DIRECTIONAL BORE 6" to < 12" (3- 1 ¼ Innerduct)	LF	400		800
DIRECTIONAL BORE 6" to < 12" (4- 1 ¼ Innerduct)	LF	400		800
JACK & BORE CASING DIAMETER (<6")	LF	50		400
JACK & BORE CASING DIAMETER (6" to <12")	LF	50		400
CONDUIT ABOVE GROUND < 3"	LF	500		1000
CONDUIT F & I ABOVE GROUND 3"	LF	500		1000
CONDUIT UNDERGROUND 1 ¼ RGS"	LF	500		1000
CONDUIT UNDERGROUND 4" 3- 1¼" Innerduct)	LF	500		1000
CONDUIT UNDERGROUND 4- 1 ¼ "	LF	500		1000
CONDUIT UNDERGROUND 2"	LF	500		1000
CONDUIT (F & I UNDERGROUND)(PVC SCH 40)(2")	LF	500		1000
CONDUIT UNDERGROUND 3"	LF	500		1000
CONDUIT UNDERGROUND 4"	LF	500		1000
CONDUIT UNDERGROUND 4" RGS	LF	500		1000
CONDUIT UNDER PAV'T 2" HDPE	LF	500		1000
CONDUIT UNDER PAV'T (3- 1¼ Innerduct)	LF	500		1000
CONDUIT UNDER PAV'T (4- 1¼ Innerduct)	LF	500		1000
CONDUCTORS (F&I)(Insulated)(No. 6)	LF	500		2500
CABLE SIGNAL	PI		5	
SPAN WIRE ASSEMBLY	PI		5	
CABLE INTERCONNECT (1-25 PR)	LF	1000	2000	2500
PULL BOXES		10		20
PULL & JUNCTION BOXES	EA		8	
PULL & JUNCTION BOXES (Fiber Optic-Pull Box)	EA	10	15	20
PULL BOXES (Special)	EA	5		10
PULL BOXES (Roadside)	EA	10		20
SURGE PROTECTOR (Pole Base)	EA	10		20
LIGHTNING PROTECTION SYSTEM (F&I)(Surge)	EA	10		20
LIGHTNING PROTECTION SYSTEM (F&I)(Point)	EA	1		4
ELCTRICAL POWER SERVICE (Underground)	AS		2	
ELECTRICAL POWER SERVICE WIRE (F&I)	LF	500	1000	2500
ELECT PWR SRV WIRE DISCONNECT (POLE)(Cabinet)	EA		2	
PRESTRESSED CONC. POLES (Type N-11)(Dir. Burial)	EA		2	
STEEL STRAIN POLE (F&I)(NS-IX)(36')	EA	0.5		0.7
STEEL STRAIN POLE (F&I)(NS-IX)(38')	EA	0.5		0.7
MAST ARM (F&I/HL)(Single w/Luminare)	EA		0.5	
MAST ARM (F&I/Reduced Loading)	EA		0.5	
MAST ARM (F&I/Reduced Loading)	EA		0.5	

MAST ARM (F&I/Reduced Loading)	EA		0.5	
MAST ARM (F&I)(Double Arm)	EA		0.5	
SIGNAL TRAFFIC	AS	10		20
SIGNAL, POLE & DET (Pedestrian)(Complete)	AS	2	3	5
DETECTOR CABINET	EA	3		5
DETECTOR CABINET(Type II) (Pay Item 668-32)	EA	3		6
DETECTOR CABINET(Type III) (Pay Item 668-33)	EA	1		4
DETECTOR CABINET(Type V) (Pay Item 668-35)	EA	1		4
DETECTOR CABINET(Type VI) (Pay Item 668-36)	EA	0.2		0.5
SYSTEM COMM. (Multi-pair Cable)	LF	1000		5000
SYSTEM COMM. (Fiber Optic Cable SM)	LF	1000		10000
SYSTEM COMM. (FOC, 6-Count SM)	LF	1000		10000
SYSTEM COMM. (FOC, 24-Count SM)	LF	1000		10000
SYSTEM COMM. (FOC, 48-Count SM)	LF	1000		10000
SYSTEM COMM. (FOC, 72-Count SM)	LF	1000		10000
CCTV Equipt. (Install)(Camera Assembly)	EA	2		5
SIGN (Internal Illuminated)	EA	4		8
LUMINARE (F&I)(Roadway)(Special)	EA	0.5		2
TMS Vehicle Sensor (Class II)(Type I)	EA	4		12
TMS Vehicle Sensor (Class II)(Type I)(1/2 Ln)	EA	4		12
TMS Inductive Loop Assembly (2 Loops per Lane)	AS	4		12
TMS Cabinet (F&I)(Type III)(Pedestal)(2 Backplane)	EA	3		6
SIGNALS PER INTERSECTION	DAYS		15	
ELECTRICAL POWER SERVICE	AS		3	
SIGNAL HEADS	EA		10	
POLES	EA		10	
LIGHTING POLE (Complete)	EA		0.5	
REMOVE EXISTING SPAN WIRE	EA		20	
REMOVE EXISTING SIGNAL EQUIPT.	EA		8	
REMOVE EXISTING SIGNAL INTERCONNECT (Cable)	LF	1000		1500
MAST ARM (SINGLE)	EA		4	
MASTARM (DOUBLE)	EA		3	
TRAFFIC SIGNALS	AS		8	
PEDESTRIAN SIGNALS	AS		10	
CUT LOOP DETECTORS	AS		6	
LOOP ASSEMBLIES	AS	4	6	8
PEDESTRIAN DETECTORS	EA		8	
SIGN PANELS	EA		6	
LIGHTING				
CONDUCTORS	LF		750	
MISC. CONCRETE	CY		15	

UNDERGROUND CONDUIT	LF		750	
PULL & JUNCTION BOXES	EA		8	
POLES	EA		10	
HIGHWAY STANDARD	EA		5	
SIGNING				
DELINEATORS	EA		10	
DIRECTIONAL BORE	LF		600	
MILTIPOST REMOVAL	AS		15	
MULITPOST (F & I)	AS		10	
OBJECT MARKER	EA		10	
OVERHEAD SIGNS	SF	0.2		0.7
RELOCATE SIGN PANELS	EA		10	
REMOVE SIGN PANELS	EA		12	
SIGN PANELS	EA		15	
SIGN INSTALL (Existing Breakaway Supports)	AS	4		12
SINGLE POST SIGN	AS		15	
SINGLE POST SIGN RELOCATE	AS		10	
SINGLE POST SIGN REMOVAL	AS		30	
LARGE SIGNS	EA	0.2		0.7
SMALL SIGNS	EA	10	20	30
DRILLSHAFT BASE	EA		0.5	
CONCRETE				
ADA RAMPS	EA		0.5	
BARRIER WALL	LF		200	
BLOCK SOUND WALLS	SF		400	
BOX CULVERT	CY	20		80
BREAK, COMPACT PAVM'T	SY		5000	
CURB & GUTTER	LF	400	600	800
DITCH PAVEMENT	SY		200	
PAVING	SY		5000	
SIDEWALK	SY		300	
SLAB REPLACEMENT	SY		130	1192
LANDSCAPING				
PLANTS (Small)	EA		30	
PLANTS (Large)	EA		15	
SEEDLINGS (Trees & Shrubs)	EA		800	1,000
1 GAL	EA		400	
3 GAL	EA		200	500
7 GAL	EA		100	
SCRUB - 30 GAL	EA		30	
DIRECTIONAL BORE	LF		600	

FINISH SOIL LAYER (LANDSCAPING OPERATIONS)	CY	1,500		5,000
FENCING (Type B(5.1 -6.0) (With Vinyl Coating)	LF		500	
FENCING GATE (Type B (Double 6.1 -12.0') Opening	EA	2	3	5
ARTIFICIAL COVERING	SY	1,500		5,000
SODDING	SY	1,500		5,000
SEEDING	SY		23,500	
PERFORMANCE TURF	SY	1,500		23,500
PERFORMANCE SOD	SY	1,500		5,000
PLASTIC EROSION MAT,(TURF REINFORCED, TYPE 3)	SY	1,500		5,000
PATTERNED/TEXTURED PAVEMENT (Asphalt)	SY	150		250
PAVERS, Architectural (Roadway)	SY	150		200
GRASSING				
SEED & MULCH	SY		23,500	
SOD	SY		1,500	2,200
FINISH SOIL LAYER (TOPSOIL)	SY		15,000	
MISCELLANEOUS CONSTRUCTION				
PRESSURE GROUT FOR SINK HOLE	CY	20	65	90
DEMOBILIZE / PUNCHLIST / CLEAN-UP	WKS		1	
TREATED TIMBER STRUCTURAL	MB	20		30
BRIDGE CONSTRUCTION				
MOBILIZE MARINE - BARGE & CRANE	DAYS		60	
COFFERDAMS	SY	100	200	300
DEMOLITION				
BRIDGE	SF	270	375	600
FENDER SYSTEM	LF		50	
SAW CUT DECK - 1" DEEP	LF		550	
BRIDGE RAIL	LF		50	
DECK & HANDRAIL	SY	30	35	40
PARAPET	LF	60	115	180
TIMBER BRIDGE	SY	40	50	60
GRINDING				
River Gravel Agg.	SY		2,600	
Limestone Agg.	SY		4,000	
HYDRO BLAST BRIDGE DECK				
2.5" DEEP	SF		600	
3.5" DEEP	SF		215	
PILES				
TEST PILES 24" - 30"	EA		0.8	
PRODUCTION PILES	LF	200	300	400

PILE JACKETS 18" - 24"	LF		7	
SHEET PILING				
CONCRETE PILE - 5 ft x 20 ft	EA		15	
SHEET STEEL PILING	SF	640	2000	4000
SHEET STEEL PILING	SHTS/day	32	40	48
STEEL PILE LENGTH - 40 ft	LF		200	
SUBSTRUCTURE				
COLUMNS / CAPS / BENTS	CY	4	8	12
FOOTINGS	CY	10	20	30
SUPERSTRUCTURE				
BRIDGE DECK	CY	6	11	14
BARRIER WALL	LF	80	120	160
STEEL BEAMS	LF		150	
PRECAST BEAMS	LF	250	425	600
CLEAN & SEAL CONCRETE DECK				
Cleaning & Resealing Joints	LF	0	5,280	10,560
Cleaning & Resealing Joints	MI	0	1	2
Cleaning & Sealing Random Cracks	LF	0	1,478	1,478
Cleaning & Sealing Random Cracks	MI	0	0.14	0.28
Grinding Concrete Pavement	SY	555	1,500	2,700
Concrete Pav't Slab Replacement	CY	24	60	94
Concrete Paving Plain (9")	SY	0	500	
Bridge Approach Expansion Joint	LF	30	50	80
BEAM ERECTION				
STEEL	LF	150	200	250
PRECAST	LF	250		600
WALLS				
RETAINING	SF	100	150	200
BARRIER WALL	LF		200	
BARRIER WALL w/3 components	LF		55	
MSE WALL	SF	500	750	
NOISE BARRIER WALL	SF		2,000	
WINGWALLS	SF	100	150	200
PAINTING				
ANTI-GRAFFITI COAT	SF		2,500	
STEEL	TN		20	
BRIDGE PAINTING	SF		2,000	
CLASS 5 APPLICATION	SF		2,000	
SMALL BASCULE	per Leaf		20	
STEEL GIRDERS	SF		2,000	
STEEL GIRDERS	TN		9	

PAINT REMOVAL				
DRY BLASTING	SF		60	
POWER TOOLED	SF		28	
WATER BLASTING	SF		235	
SANDBLASTING	SF		1500	
STEEL GIRDER-SANDBLASTING	SF		1500	
RIP RAP				
DUMPED	TON		750	
PLACED	TON		185	
PLACED	CY		75	
SAND BAG	SY		120	
Gabion mats & baskets	SY	40	850	1300
Gabion mats & baskets	CY	20	45	80

VIRGINIA DOT

Base Rate Adjustment Factors			
Factors	**Adjustment for Noted Conditions**		
Location	Rural = 1.0	Small City = 0.85	Big City = .75
Traffic Conditions	Light = 1.0	Moderate = .88	High = .70
Complexity	Low = 1.0	Medium = .85	High = .70
Soil Conditions	Good = 1.0	Fair = .85	Poor = .65
Quantity of Work	Large = 1.0	Medium = .88	Small = .75

Activity	Unit	Base Rate
Grade Items		
Mobilization	Days	5
Clearing & Grubbing	Acres	2.625
Demo. Of Buildings	Each	1
Asbestos Rem.(Res./Small Commercial)	Days	4
Asbestos Rem.(Large Commercial)	Days	10
Demo. Of Asphalt Pave.	S.Y.	1500
Sawcut Pavement	L.F.	800
Remove Curb& Gutter	L.F.	600
Remove Exist. DI/Manhole & Assoc. Pipe	Each	6
Temporary Detour	Days	6
Roadway Excavation	C.Y.	2000
Excavation Small/Irregular Area Projects	C.Y.	850
Excavation - Large quantity projects	C.Y.	5000
Drainage Corrug.Metal 18"	L.F.	205
Drainage Concrete Pipe 15"	L.F.	168
Drainage Conc. Pipe 18"	L.F.	144
Drainage Conc. Pipe (24" to 54")	L.F.	72
Drainage Conc. Pipe (60 in. & greater)	L.F.	48
Inlets/Manholes	Each	1.5
Minor Excavation (Drainage Structures)	C.Y.	250
Box Culverts, Class A Conc.	C.Y.	20
Box Culverts, Cast in Place	L.F.	5
Box Culverts, Precast	L.F.	20
Retaining Walls, Cast in Place	L.F.	5
Major Retaining Walls	S.F.	210
Sub-grade Stabilization	S.Y.	8000

Aggregate Base	Tons	1360
Aggregate Base Small/Irregular Projects	Tons	680
Drainage Blanket	Tons	1200
Asphalt Base	Tons	1175
Asphalt Intermediate	Tons	750
Asphalt Surface	Tons	500
Milling/Flexible Pavement Planing (Max. 2")	S.Y.	3000
Curb & Gutter (Machine Placed)	L.F.	800
Curb & Gutter (Hand Placed)	L.F.	400
Curb& Gutter Radial (Hand Placed)	L.F.	150
Concrete Entrance	S.Y.	80
Sidewalk	S.F.	1550
Concrete Driveway	S.Y.	150
Entrance Pavement	S.Y.	100
Barrier Walls, Slip Form	L.F.	630
Concrete Repair	S.Y.	30
Concrete Paving	S.Y.	2500
Slurry Seal	S.Y.	8000
Seeding	Acres	2.5
Fencing	L.F.	1000
Fine Grading	S.Y.	2000
Lime Stabilization	S.Y.	6000
Shoulder Construction	L.F.	500
Slope Protection	C.Y.	100
Underdrain	L.F.	1500
Underdrain Outlet/Endwall	Each	8
Utility 12" Ductile Iron	L.F.	105
Utility 12" PVC	L.F.	320
Directional Drilling	L.F.	50
Traffic Items		
Initial Traffic Control	Days	2
Ordering Signal Equip.	Days	30
Major Traffic Signals	Days/Intersec.	40
Pavement Markings	L.F.	10000
Stop Bars, etc.	L.F.	500
Arrows/Letters	Each	50
Order Sign Material	Days	60
Order Overhead Sign Struct.	Days	80
Erecting Overhead Signs	Days	10
Erecting Signs	S.F.	1000
Ordering Lighting Material	Days	60

Erecting Lighting	Days/support	3
Guardrail	L.F.	1500
Guardrail Terminals	Each	2
Order Impact Attenuators	Days	30
Install Impact Attenuator	Each	3
Electrical Conduit	L.F.	400
Electrical Wire	L.F.	3500
Precast concrete barrier	L.F.	800
Lighting, Total Installation Lumin.	Each	2
Phasing Allowance	Days/Phase	3
Bridge Items		
Impact Attenuators	EA	2
Median Barrier - Install	LF	800
Removing Exst. Guardrail	LF	1500
Shoulder Improvements	LF	500
Signs, Install Small (Sheet)	EA	30
Temporary Detour Bridge - Install	Days	13
Traffic Control Setup	Days	2
Cofferdam	Days	15
Dismantle/Remove Exst. Concrete Deck	SY	275
Dismantle/Remove Exst. Structure	SY	50
Minor Excavation	CY	250
Sheet Piling - Drive	SF	500
Structure Excavation	CY	300
CBR30 Backfill/Compact Abutment	TON	100
Drilled Shafts	EA	0.3
Epoxy Injection Crack Repair	LF	80
Reinforcing Steel	TON	2.5
Retaining Walls (CIP)	SF	400
Riprap - Dumped	TON	700
Riprap - Grouted	TON	50
Riprap - Machine Placed	TON	250
Slope Protection - Concrete	SY	750
Steel Piles - Prebored	LF	250
Steel Piles - Driven	LF	400
Concrete Piles - 8" to 14"	LF	300
Concrete Piles - 24" to 30"	LF	325
Substructure Footings - Form and Place	CY	20
Substructure Neatwork - Form and Place	CY	10
Substructure Footing - Place Seal	CY	15
Approach Slabs	DAY	5

Beam Repairs - Concrete Beam End	EA	0.25
Beam Repairs (Steel) - Bolted	EA	0.5
Beam Repairs (Steel) - Welded	EA	1
Bridge Deck - Form & Place Reinf. Steel	SY	50
Bridge Deck - Overlay	SY	500
Bridge Deck - Pour New	SY	850
Bridge Deck Grooving	SY	550
Bridge Deck - Sidewalk/Raised Median	LF	80
CIP Conc. Slab Span - Install Falsework	SF	250
CIP Conc. Slab Span - Pour	CY	10
Concrete Diaphragms - Form & Pour	CY	11
Concrete Removal - Sub/Super Patch	SY	15
Concrete Removal - Type B Patch	SY	50
Concrete Removal - Type C Patch	SY	10
Concrete Surface Color Coating	SY	100
Expansion Dam	EA	4
Expansion Joint Reconstruction	LF	25
Expansion Joint Removal	LF	250
Expansion Joint Sealer	LF	450
Milling (Concrete - per 1/2" depth)	SY	1600
Parapet - Hand Formed	LF	50
Parapet - Slip Formed	LF	200
Metal Rail Parapet	LF	100
Kansas Corrall Parapet	LF	20
Pedestrian Fence	LF	7
Prestressed Conc. Beam Erection	LF	400
Shotcrete	SY	65
Struct. Steel Surface Prep. (Method 1)	SF	3000
Struct. Steel Surface Prep. (Method 2)	SF	240
Struct. Steel Surface Prep. (Method 3)	SF	600
Struct. Steel Surface Prep. (Method 4)	SF	200
Struct. Steel Surface Prep. (Method 5)	SF	1100
Struct. Steel Surface Prep. (Method 6)	SF	6000
Struct. Steel Surface Prep. (Method 7)	SF	7500
Structural Steel - Painting (per coat)	SF	2000
Structural Steel Erection	TON	10
Structural Steel Erection	LF	200
Timber Bridge Deck	SF	200
CIP Conc. Slab Span - Remove Falsework	SF	500
Median Barrier - Remove	LF	800
Sheet Piling - Pull	SF	500

Temporary Detour Bridge - Remove	Days	4
Traffic Control Teardown	Days	2
Concrete Curing		**Cure days/Pour**
LMC	POUR	5
HESLMC	POUR	3
VESLMC	POUR	1
Substructure Footings	POUR	2
Substructure Neatwork	POUR	5
Bridge Deck Concrete	POUR	7
Parapet	POUR	7

MICHIGAN DOT

Activity	Time	
Cross Culverts		
Rural Highway	40m/day	
Expressways	50m/day	
Large Headwalls	5 days/unit	
Slab or Box Culverts	5 days/pour	
Plowed in Edge Drain	4500m/day	
Open-Graded Underdrain	1200m/day	
Sewers		
0-5m (up to 1500mm)	40m/day	
0-5m (over 1500mm)	25m/day	
5m-over (up to 1500mm)	25m/day	
5m-over (over 1500mm)	20m/day	
Jacked-in-Place	13m/day	
including excavation pit and set up	min. 5 days	
Tunnels		
Hand Mining	8m/day	
Maching Mining	20m/day	
including excavation pit and set up	min. 5 days	
Manholes	3 units/day	
Catch Basins	4 units/day	
Water Main (up to 400mm)	100m/day	
Flushing, testing and chlorination	4 days	
Water Main (500mm-1050mm)	25m/day	
Flushing, testing and chlorination	5 days	
Order and deliver 600mm HP Water Main	50 days/order	
Gas Lines	100m/day	
Earthwork and Grading	**Metro Exp Time**	**Rural-Time**
Embankment(CIP)	1500 m3/day	5300 m3/day
Excavation and/or Embankment (Freeway)	1500 m3/day	9200 m3/day
Excavation and/or Embankment (Reconst)	750 m3/day	3800 m3/day
Embankment (Lightweight Fill)	300 m3/day	600 m3/day
Muck (Excavation Waste and Backfill)		1500 m3/day
Excavation (Widening)		600 m3/day
Grading (G and DS)		750 m3/day
Subbase and Selected Subbase (up to 7.4m)		600 m3/day
Subbase and Selected Subbase (over 7.4m)		450 m3/day
Subgrade Undercut and Backfill		1500 m3/day

Subbase and Open-Graded Drainage		450 m3/day
Concrete		
Pavement (7.3 m)	450 m2/day	
Including forming and curing	min. 7 days	
Pavement (7.3 m)	1200 m/day/course	
Concrete Ramps (4.9 m)	300 m/day	
Including forming and curing	min. 7 days	
Curb (1 side)	750 m/day	
Concrete Shoulder-Median	1200 m2/day	
Sidewalk (Patching)	65 m2/day	
Sidewalk	180 m2/day	
Sheeting (Shallow)	30 m/day	
General Excavation at Bridge Site	750 m3/day	
Excavation for Substructure (Footings)	1 unit/day	
Piles (12m)	15 piles/day	
Substructure (Piers and Abutments)	5 days/unit	
Order and Delivery of beams		
Plate Girders	100-120 days/order	
Rolled Beams	90-120 days/order	
Concrete Beams	50 days/order	
Erection of Structual Steel	3 days/span	
Bridge Decks		
Form and Place Reinforcement (60m Structure)	15 days	
Pour Deck Slab (1-1/5 days/pour)	2 says/span	
Cure	14 days	
Sidewalks and Parapets	5 days/span	
Slip Formed Barriers	2 days/span	
Clean up	10 days	
Pedestrian Fencing	1 week/bridge	
Riprap Replacement (Bucket Dumped)	385 m3/day	
Riprap Replacement (Bucket Dumped/Hand Finish)	131-523 m3/day	
Retaining Walls	1 panel/day (min 10 days)	
Railroads		
Grade temporary turn around	750 m3/day	
Ballast, tiles, and track	50 m/day	
Place deck plates	5 days/span	
Waterproof, shotcrete and mastic	5 days/span	
Railroad crossing reconstruction	10-15 workdays	
Order and deliver steel	55 days/order	
Erect steel	1 day/span	
Tiles and track	3 days/span	

Pump House	
Structure	30 days/m
Order/Deliver Mechanical and Electrical Equipment	90 days
Instal Electrical and Mechanical Equipment	30 days
Miscellaneous	
Removing old pavement	60 m/day
Removing old pavement for recycling (7.3 m)	450 m/day
Crushing old concrete for 6A or OGDC	1350 mtons/day
Removing Trees (urban)	15 units/day
Removing Trees (rural)	30 units/day
Removing concrete pavement	450 m2/day
Removing sidewalk	250 m2/day
Removing curb and gutter	450 m2/day
Removing bituminouos surface	1600 m2/day
Conditioning aggregate	900 m2/day
Bituminous base stabilizing	2500 m2/day
Ditching	600 m/day
Trenching for shoulders	750 m/day
Station grading	610 m/day
Clearing	8000 m2/day
Restoration (Topsoil, seeding, fertilizer, and mulch)	1650 m2/day
Sodding	2100 m2/day
Seeding	40,000 m2/day
Guardrail	230 m/day
Fence (woven wire)	360 m/day
Fence (chain link)	150 m/day
Clean up	600 m/day
Concrete median barrier	300 m/day
Reroute traffic (Add 4 days if 1st item)	1 day/move
Concrete glare screen	450 m/day
Light foundations	6 units/day
Light foundations (order and delivery)	6-8 weeks/order
Longitudinal joint repair	1600 m/day
Crack sealing	4800 m/day
Joint and crack sealing	500 m/day
Repairing pavement joints	200 m/day
Seal coat	6400 lane m/day
Diamond grinding	3300 m2/day
Raised pavement markers	300 ea/day
Attenuators	2 ea/day
Shoulder corrugations, ground or cut	8-9.7km/side/day

Aggregate base	2900 m2/day
Aggregate shoulders	350 m3/day
Freeway signing - 3# post type	50 signs/day
Structural Repair	
Bridge painting	90 m2/day
Pin and hanger replacement	3 beams/day
Joint removal (including cleanup)	4 m/day
Joint removal (forming and replacement)	3.5 m/day
Hydro-demolishing	300 m/day
Barrier removal	15 m/day
Barrier placement	45 m/day
Hand chipping (other than deck)	0.24 m3/person/day
Casting latex overlay	250 m/day
Thrie beam retrofit	30 m/day
Deck removal	235 m2/day
Metro-primary (<18,000 tons)	
Paving	540 mtons/day
Joints	150 m/day
Cold milling	3400 m2/day
Aggregate shoulders	900 mtons/day
Metro-primary (>18,000 tons)	
Paving	540 mtons/day
Joints	200 m/day
Cold milling	7500 m2/day
Metro-interstate (>18,000 mtons)	
Paving	1100 mtons/day
Joints	360 m/day
Aggregate shoulders	900 mtons/day
Urban-primary (<18,000 mtons)	
Paving	640 m/tons/day
Joints	100 m/day
Cold milling	1700 m2/day
Rubblizing	1700 m2/day
Aggregate shoulders	450 mtons/day
Urban-primary (>18,000 mtons)	
Paving	1000 mtons/day
Joints	120 m/day
Cold milling	1700 m2/day
Aggregate shoulders	500 mtons/day
Urban-interstate (>18,000 mtons)	
Paving	1200 mtons/day

Joints	220 m/day
Cold milling	1700 m2/day
Rubblizing	5800 m2/day
Aggregate shoulders	640 mtons/day
Rural primary (<18,000 mtons)	
Paving	640 mtons/day
Joints	120 m/day
Cold milling	590 mtons/day
Crush and shape	10,000 m2/day
Aggregate shoulders	640 mtons/day
Rural-primary (>18,000 mtons)	
Paving	1100 mtons/day
Joints	150 m/day
Cold milling	800 mtons/day
Crush and shape	10,000 m2/day
Rural-interstate (>18,000 mtons)	
Paving	1280 mtons/day
Joints	220 m/day

Appendix C – Cross Validation Results

Hot Mix Asphalt: Lower Layer			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
36.00	195.70	240.00	-18.46
41.00	162.00	90.00	80.00
17.00	162.00	60.00	170.00
40.00	195.70	119.00	64.46
27.00	195.70	261.00	-25.02
23.00	195.70	180.00	8.72
15.00	195.70	300.00	-34.77
10.00	195.70	200.00	-2.15
32.00	162.00	50.00	223.99
38.00	195.70	194.00	0.88
4.00	195.70	350.00	-44.09
Second 20%			
1.00	148.73	270.00	-44.91
25.00	148.73	130.00	14.41
45.00	202.20	180.00	12.33
22.00	202.20	186.00	8.71
43.00	148.73	43.30	243.49
7.00	202.20	170.00	18.94
9.00	255.67	310.00	-17.53
39.00	255.67	150.00	70.45
16.00	148.73	89.00	67.11
5.00	148.73	350.00	-57.51
Third 20%			
8.00	204.19	145.00	40.82
48.00	148.42	80.00	85.52
24.00	204.19	300.00	-31.94
46.00	259.97	225.00	15.54
30.00	204.19	195.00	4.71
18.00	148.42	172.00	-13.71
37.00	259.97	175.00	48.55
26.00	148.42	175.00	-15.19
6.00	148.42	280.00	-46.99
49.00	204.19	150.00	36.13
Fourth 20%			
35.00	198.24	275.00	-27.91
42.00	198.24	216.00	-8.22
50.00	198.24	180.00	10.13
34.00	237.27	185.00	28.25
21.00	159.22	81.00	96.56
47.00	198.24	200.00	-0.88
13.00	237.27	300.00	-20.91
29.00	198.24	230.00	-13.81
44.00	159.22	175.00	-9.02
20.00	159.22	60.00	165.36
Fifth 20%			
11.00	149.42	212.00	-29.52
33.00	149.42	97.20	53.72
51.00	149.42	120.00	24.51
12.00	149.42	150.00	-0.39
19.00	149.42	20.00	647.08
3.00	149.42	350.00	-57.31
14.00	149.42	350.00	-57.31
2.00	198.95	180.00	10.53
31.00	149.42	75.00	99.22
28.00	149.42	101.00	47.94

Hot Mix Asphalt: Surface Layer			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
44.00	199.59	250.00	-20.16
42.00	151.34	200.00	-24.33
58.00	199.59	200.00	-0.20
21.00	151.34	60.00	152.24
52.00	151.34	40.00	278.35
29.00	151.34	214.00	-29.28
49.00	151.34	81.40	85.92
62.00	151.34	100.00	51.34
51.00	199.59	223.00	-10.50
33.00	151.34	50.00	202.68
59.00	151.34	119.00	27.18
7.00	199.59	130.00	53.53
48.00	151.34	100.00	51.34

Second 20%			
14.00	260.03	250.00	4.01
50.00	140.46	131.00	7.22
34.00	140.46	87.40	60.71
23.00	200.24	181.00	10.63
47.00	260.03	218.00	19.28
16.00	200.24	310.00	-35.41
32.00	140.46	75.00	87.28
63.00	200.24	271.00	-26.11
43.00	200.24	215.00	-6.86
38.00	200.24	142.00	41.02
11.00	140.46	217.00	-35.27
39.00	200.24	112.00	78.79
55.00	200.24	140.00	43.03
Third 20%			
57.00	146.22	37.00	295.19
3.00	146.22	325.00	-55.01
22.00	146.22	81.00	80.52
40.00	146.22	224.00	-34.72
41.00	198.12	178.00	11.31
20.00	146.22	25.00	484.88
25.00	146.22	93.30	56.72
19.00	146.22	94.50	54.73
37.00	198.12	170.00	16.54
10.00	198.12	120.00	65.10
12.00	198.12	265.00	-25.24
36.00	198.12	280.00	-29.24
60.00	146.22	62.00	135.84
Fourth 20%			
61.00	201.93	135.00	49.58
8.00	201.93	134.00	50.70
4.00	201.93	300.00	-32.69
1.00	140.19	260.00	-46.08
28.00	140.19	175.00	-19.89
45.00	140.19	39.20	257.63
2.00	201.93	150.00	34.62
31.00	201.93	165.00	22.38
35.00	263.67	200.00	31.84
18.00	140.19	50.00	180.38
26.00	201.93	300.00	-32.69
24.00	201.93	140.00	44.24

Fifth 20%			
5.00	121.43	330.00	-63.20
54.00	187.87	220.00	-14.60
6.00	121.43	220.00	-44.80
27.00	121.43	118.00	2.91
15.00	121.43	350.00	-65.31
46.00	187.87	250.00	-24.85
30.00	187.87	230.00	-18.32
53.00	187.87	275.00	-31.68
13.00	121.43	200.00	-39.28
9.00	254.32	300.00	-15.23
17.00	121.43	88.90	36.59
56.00	254.32	225.00	13.03

Hand Placement of Asphalt			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
13.00	65.50	40.00	63.75
1.00	53.00	4.00	1225.00
9.00	65.50	40.00	63.75
8.00	4.00	17.00	-76.47
Second 20%			
18.00	4.92	35.00	-85.95
14.00	107.46	150.00	-28.36
11.00	4.00	21.00	-80.95
3.00	38.95	50.00	-22.11
Third 20%			
4.00	91.82	20.00	359.10
16.00	4.00	50.00	-92.00
10.00	4.00	25.00	-84.00
17.00	4.00	60.00	-93.33
Fourth 20%			
2.00	4.00	5.00	-20.00
6.00	32.67	40.00	-18.34
5.00	72.17	20.00	260.83
Fifth 20%			
12.00	43.30	42.00	3.09
7.00	27.41	15.00	82.71
15.00	83.74	50.00	67.48

Thick Milling			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
9.00	8778.60	2500.00	251.14
10.00	8778.60	1500.00	485.24
20.00	8778.60	1600.00	448.66
13.00	15590.13	13000.00	19.92
Second 20%			
3.00	11421.28	7000.00	63.16
16.00	16095.39	18000.00	-10.58
14.00	11421.28	12000.00	-4.82
6.00	11421.28	9100.00	25.51
Third 20%			
18.00	3791.94	15930.00	-76.20
17.00	3791.94	14414.00	-73.69
4.00	15953.23	20500.00	-22.18
11.00	9872.58	13500.00	-26.87
Fourth 20%			
2.00	6428.07	3000.00	114.27
5.00	15895.77	17500.00	-9.17
12.00	11163.42	9500.00	17.51
1.00	6428.07	11000.00	-41.56
Fifth 20%			
7.00	11542.83	11000.00	4.93
15.00	11542.83	1467.00	686.83
19.00	11542.83	19633.00	-41.21
8.00	11542.83	8000.00	44.29

Base Course			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
14.00	1436.14	325.00	341.89
22.00	1444.27	2550.00	-43.36
4.00	646.46	800.00	-19.19
1.00	144.27	1200.00	-87.98
11.00	2242.08	2500.00	-10.32
Second 20%			
21.00	1566.25	1200.00	30.52
19.00	1566.25	1352.00	15.85
9.00	1566.25	60.00	2510.42
13.00	766.63	200.00	283.32
7.00	742.04	1000.00	-25.80
Third 20%			
18.00	592.79	1039.00	-42.95
23.00	592.79	745.00	-20.43
17.00	1322.26	1352.00	-2.20
10.00	1790.84	1500.00	19.39
6.00	1556.55	1000.00	55.65
Fourth 20%			
16.00	1247.92	970.00	28.65
2.00	2275.00	1200.00	89.58
5.00	1247.92	2316.00	-46.12
12.00	1247.92	2500.00	-50.08
Fifth 20%			
20.00	2136.29	2500.00	-14.55
8.00	1884.91	3400.00	-44.56
15.00	1453.52	800.00	81.69
3.00	1202.14	2000.00	-39.89

QMP Density			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
1.00	27902.90	25000.00	11.61
3.00	27902.90	40000.00	-30.24
12.00	14474.34	4500.00	221.65
Second 20%			
5.00	11837.96	10000.00	18.38
11.00	2985.19	8000.00	-62.69
8.00	11222.21	12000.00	-6.48
Third 20%			
7.00	2991.29	11000.00	-72.81
6.00	16384.41	3700.00	342.82
Fourth 20%			
2.00	3509.24	11000.00	-68.10
10.00	13983.13	5363.00	160.73
Fifth 20%			
9.00	4399.75	2000.00	119.99
4.00	28299.81	33000.00	-14.24

Rumble Strip Center			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
12.00	30728.25	11700.00	162.63
10.00	125000.00	125000.00	0.00
11.00	33977.00	40900.00	-16.93
Second 20%			
9.00	34903.29	9000.00	287.81
4.00	810.71	2783.00	-70.87
3.00	29504.71	38400.00	-23.16
Third 20%			
5.00	42196.16	30739.00	37.27
1.00	650.00	9300.00	-93.01
Fourth 20%			
7.00	125000.00	125000.00	0.00
8.00	35805.00	46580.00	-23.13
Fifth 20%			
2.00	7749.30	650.00	1092.20
6.00	59610.12	58087.00	2.62

Rumble Strip Shoulder			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
11.00	51060.29	30000.00	70.20
1.00	60500.00	25000.00	142.00
7.00	26966.18	44000.00	-38.71
Second 20%			
13.00	1250.00	3500.00	-64.29
5.00	10417.81	24000.00	-56.59
10.00	49612.15	30250.00	64.01
Third 20%			
9.00	10531.27	15000.00	-29.79
12.00	55708.88	11000.00	406.44
6.00	125000.00	125000.00	0.00
Fourth 20%			
8.00	72656.91	125000.00	-41.87
3.00	11282.35	18550.00	-39.18
Fifth 20%			
4.00	14164.27	1250.00	1033.14
2.00	14164.27	15000.00	-5.57

Concrete Masonry (Substructure)			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
11.00	1.75	4.00	-56.24
1.00	1.75	1.30	34.46
16.00	2.50	3.00	-16.56
9.00	3.26	4.00	-18.60
Second 20%			
10.00	2.28	2.00	13.93
14.00	2.28	2.00	13.93
7.00	0.88	0.40	119.54
3.00	0.20	1.00	-80.00
Third 20%			
12.00	1.20	1.00	19.72
8.00	2.17	0.25	769.76
4.00	1.20	0.50	139.45
6.00	1.20	0.33	262.80
Fourth 20%			
18.00	1.00	1.00	0.17
5.00	1.71	2.00	-14.54
17.00	1.00	0.20	400.86
Fifth 20%			
13.00	0.67	2.00	-66.40
2.00	1.17	3.00	-61.08
15.00	2.49	2.00	24.58

Sheet Piling (height >= 15')			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
11.00	398.17	899.00	-55.71
8.00	304.22	260.00	17.01
4.00	967.67	2000.00	-51.62
Second 20%			
1.00	363.43	115.00	216.02
9.00	46.15	250.00	-81.54
3.00	882.08	435.00	102.78
Third 20%			
6.00	962.54	432.00	122.81

5.00	584.47	750.00	-22.07
12.00	115.00	225.00	-48.89
Fourth 20%			
10.00	569.43	1000.00	-43.06
13.00	411.33	200.00	105.67
Fifth 20%			
7.00	345.72	530.00	-34.77
2.00	809.61	682.00	18.71

Parapet Straight			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
3.00	61.00	40.00	52.50
2.00	140.30	200.00	-29.85
9.00	100.60	60.00	67.67
Second 20%			
1.00	18.91	145.00	-86.96
6.00	18.91	48.00	-60.61
10.00	154.27	166.00	-7.06
Third 20%			
5.00	104.60	60.00	74.33
1.00	104.60	100.00	4.60
Fourth 20%			
7.00	157.21	91.00	72.76
12.00	157.24	190.00	-17.24
Fifth 20%			
4.00	105.59	90.00	17.33
8.00	61.54	16.00	284.60

Deck Placement, Girder Bridge			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
19.00	990.00	1200.00	-17.50
5.00	708.66	120.00	490.55
18.00	427.33	270.00	58.27
12.00	990.00	1499.00	-33.96
Second 20%			
4.00	420.27	250.00	68.11
9.00	751.82	700.00	7.40
6.00	420.27	345.00	21.82
17.00	751.82	360.00	108.84
Third 20%			
20.00	373.42	260.00	43.62
11.00	1055.82	1113.00	-5.14
1.00	714.44	640.00	11.63
2.00	373.42	600.00	-37.76
Fourth 20%			
15.00	1040.98	985.00	5.68
14.00	317.11	994.00	-68.10
16.00	1040.98	1275.00	-18.35
7.00	317.11	350.00	-9.40
Fifth 20%			
13.00	359.40	190.00	89.16
3.00	359.40	375.00	-4.16
10.00	1103.77	800.00	37.97
8.00	359.40	695.00	-48.29

Concrete Paving(thickness > 10")			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
6.00	173.00	173.00	0.00
1.00	8051.00	3166.00	154.30
5.00	1633.00	3700.00	-55.86
Second 20%			
13.00	3375.00	1308.00	158.03
9.00	3351.11	2750.00	21.86
8.00	9825.33	12000.00	-18.12
Third 20%			
3.00	10932.16	7350.00	48.74
7.00	173.00	5500.00	-96.85
2.00	10932.16	7500.00	45.76
Fourth 20%			
10.00	8496.47	7500.00	13.29
12.00	3472.88	3500.00	-0.77
Fifth 20%			
4.00	8638.00	1500.00	475.87
11.00	173.00	1100.00	-84.27

Concrete Paving (thickness < 10"			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
5.00	4018.25	5500.00	-26.94
9.00	8111.11	5000.00	62.22
10.00	4018.25	5500.00	-26.94
1.00	300.00	3200.00	-90.63
2.00	4018.25	2500.00	60.73
Second 20%			
8.00	1903.20	3000.00	-36.56
4.00	1903.20	2000.00	-4.84
11.00	7901.46	5000.00	58.03
14.00	6219.86	5600.00	11.07
19.00	1539.14	1200.00	28.26
Third 20%			
13.00	5604.00	5600.00	0.07
12.00	14000.00	2900.00	382.76
22.00	4437.17	1400.00	216.94
6.00	12854.38	6500.00	97.76
Fourth 20%			
21.00	2314.77	2256.00	2.61
17.00	5304.57	7700.00	-31.11
7.00	6660.08	11264.00	-40.87
15.00	4487.43	765.00	486.59
Fifth 20%			
16.00	5496.50	14000.00	-60.74
20.00	1090.40	2000.00	-45.48
18.00	2588.40	300.00	762.80
3.00	1869.30	1233.00	51.61

Base Course			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
4.00	235.65	700.00	-66.34
14.00	637.37	21.00	2935.10
12.00	1036.36	1500.00	-30.91
9.00	1319.58	1000.00	31.96
Second 20%			
13.00	1260.48	2500.00	-49.58
10.00	1410.70	3940.00	-64.20
11.00	21.00	70.00	-70.00
5.00	947.76	2000.00	-52.61
Third 20%			
1.00	1399.48	1200.00	16.62
17.00	2506.93	2500.00	0.28
6.00	1727.31	2000.00	-13.63
8.00	1451.15	1000.00	45.12
Fourth 20%			
3.00	1787.51	1200.00	48.96
7.00	998.92	800.00	24.87
18.00	2511.89	1200.00	109.32
Fifth 20%			
16.00	1047.58	1200.00	-12.70
2.00	166.56	750.00	-77.79
15.00	1466.41	700.00	109.49

Placement of Sidewalks			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
2.00	2613.00	1000.00	161.30
13.00	2613.00	3000.00	-12.90
23.00	2613.00	850.00	207.41
9.00	5476.80	2763.00	98.22
16.00	2316.00	1240.00	86.77
22.00	2316.00	836.00	177.03
Second 20%			
5.00	1241.46	4000.00	-68.96
4.00	3586.44	7000.00	-48.77
10.00	1241.46	6000.00	-79.31
21.00	3806.97	3000.00	26.90
17.00	1241.46	3000.00	-58.62
Third 20%			
8.00	1774.40	1750.00	1.39
26.00	3947.69	3337.00	18.30
6.00	1774.40	1750.00	1.39
25.00	5818.88	7250.00	-19.74
20.00	2076.50	1630.00	27.39
Fourth 20%			

18.00	6215.16	860.00	622.69
14.00	2079.06	2500.00	-16.84
3.00	6215.16	10000.00	-37.85
7.00	3723.46	4000.00	-6.91
15.00	2079.06	350.00	494.02
Fifth 20%			
19.00	4083.17	1000.00	308.32
1.00	6006.24	6000.00	0.10
24.00	6006.24	7850.00	-23.49
11.00	2160.10	1500.00	44.01
12.00	3949.90	2450.00	61.22

30.00	294.81	500.00	-41.04
22.00	478.36	950.00	-49.65
7.00	478.36	250.00	91.34
18.00	294.81	200.00	47.41
Fifth 20%			
31.00	532.20	375.00	41.92
25.00	295.90	630.00	-53.03
21.00	295.90	350.00	-15.46
2.00	768.60	1300.00	-40.88
6.00	768.60	150.00	412.40
29.00	768.60	200.00	284.30

Hand Placement of Concrete			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
23.00	469.63	500.00	-6.07
12.00	602.80	1000.00	-39.72
1.00	469.63	400.00	17.41
16.00	469.63	600.00	-21.73
15.00	469.63	600.00	-21.73
14.00	469.63	620.00	-24.25
8.00	469.63	700.00	-32.91
Second 20%			
26.00	518.50	600.00	-13.58
28.00	375.90	315.00	19.33
24.00	375.90	250.00	50.36
4.00	375.90	400.00	-6.03
19.00	375.90	57.00	559.47
20.00	518.50	450.00	15.22
Third 20%			
5.00	543.67	250.00	117.47
11.00	384.72	300.00	28.24
13.00	543.67	140.00	288.34
10.00	702.62	1000.00	-29.74
27.00	384.72	70.00	449.60
17.00	702.62	335.00	109.74
Fourth 20%			
9.00	478.36	800.00	-40.21
3.00	294.81	600.00	-50.87

Curb and Gutter			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
25.00	1592.89	300.00	430.96
26.00	1598.89	2750.00	-41.86
23.00	1598.89	400.00	299.72
2.00	1598.89	1800.00	-11.17
17.00	1598.89	1720.00	-7.04
22.00	1021.19	1000.00	2.12
7.00	2164.58	2000.00	8.23
Second 20%			
8.00	1041.09	800.00	30.14
27.00	1443.64	1200.00	20.30
16.00	1041.09	3000.00	-65.30
18.00	1846.19	4112.00	-55.10
3.00	1041.09	500.00	108.22
29.00	1041.09	486.00	114.22
30.00	1041.09	600.00	73.52
Third 20%			
1.00	1472.37	2000.00	-26.38
32.00	1472.37	2800.00	-47.42
10.00	1010.19	1000.00	1.02
31.00	1472.37	2500.00	-41.11
6.00	1010.19	500.00	102.04
33.00	1010.19	850.00	18.85
15.00	1010.19	630.00	60.35
Fourth 20%			

12.00	2569.00	2000.00	28.45
19.00	2569.00	786.00	226.84
34.00	2569.00	2700.00	-4.85
28.00	974.60	800.00	21.83
20.00	1771.80	325.00	445.17
5.00	1771.80	1875.00	-5.50
4.00	2569.00	1300.00	97.62
Fifth 20%			
21.00	1565.72	300.00	421.91
24.00	944.50	2327.00	-59.41
14.00	944.50	1680.00	-43.78
13.00	944.50	350.00	169.86
9.00	944.50	1520.00	-37.86
11.00	944.50	350.00	169.86

Excavation (Truck)			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
18.00	842.67	200.00	321.34
9.00	3086.93	1000.00	208.69
1.00	1964.80	2500.00	-21.41
7.00	3086.93	2250.00	37.20
2.00	3086.93	1800.00	71.50
13.00	1964.80	1200.00	63.73
6.00	3086.93	3000.00	2.90
Second 20%			
10.00	2884.39	1800.00	60.24
5.00	1843.72	1350.00	36.57
17.00	2884.39	2200.00	31.11
12.00	2884.39	3800.00	-24.10
31.00	803.05	1250.00	-35.76
8.00	2884.39	2900.00	-0.54
16.00	2884.39	2350.00	22.74
Third 20%			
33.00	862.32	2000.00	-56.88
4.00	1686.59	2400.00	-29.73
11.00	2510.85	5000.00	-49.78
19.00	862.32	450.00	91.63
23.00	2510.85	3000.00	-16.30
26.00	862.32	385.00	123.98

14.00	862.32	40.00	2055.80
Fourth 20%			
30.00	718.55	2500.00	-71.26
29.00	2595.77	5000.00	-48.08
20.00	718.55	190.00	278.18
22.00	718.55	1500.00	-52.10
15.00	718.55	380.00	89.09
32.00	718.55	1050.00	-31.57
Fifth 20%			
27.00	902.48	1807.00	-50.06
21.00	1871.34	200.00	835.67
24.00	902.48	800.00	12.81
28.00	902.48	600.00	50.41
25.00	1871.34	1200.00	55.94
3.00	902.48	200.00	351.24

Excavation (Scraper)			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
9.00	3460.14	1000.00	246.01
18.00	2065.54	450.00	359.01
5.00	9193.56	8000.00	14.92
1.00	4854.74	1000.00	385.47
15.00	9193.56	6000.00	53.23
Second 20%			
11.00	8341.90	11000.00	-24.16
19.00	2660.47	190.00	1300.25
16.00	8341.90	12000.00	-30.48
20.00	190.00	258.00	-26.36
6.00	5501.19	5000.00	10.02
Third 20%			
17.00	9285.63	5150.00	80.30
21.00	2270.90	4500.00	-49.54
10.00	9285.63	7000.00	32.65
2.00	190.00	600.00	-68.33
Fourth 20%			
3.00	190.00	2500.00	-92.40
12.00	8557.51	17000.00	-49.66
14.00	8557.51	4500.00	90.17

22.00	8557.51	8000.00	6.97
Fifth 20%			
7.00	6207.26	2500.00	148.29
8.00	8511.47	9000.00	-5.43
4.00	8511.47	7000.00	21.59
13.00	8511.47	15000.00	-43.26

Excavation (Articulated)			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
1.00	3757.49	3000.00	25.25
10.00	6057.89	5000.00	21.16
12.00	4529.87	4000.00	13.25
Second 20%			
6.00	2967.49	3000.00	-1.08
8.00	5730.79	3500.00	63.74
7.00	5730.79	8000.00	-28.37
Third 20%			
3.00	3448.21	3800.00	-9.26
4.00	2043.93	2000.00	2.20
15.00	250.00	258.00	-3.10
Fourth 20%			
2.00	1339.07	250.00	435.63
14.00	250.00	450.00	-44.44
13.00	2212.62	2500.00	-11.50
Fifth 20%			
9.00	5442.75	7000.00	-22.25
5.00	4319.28	5000.00	-13.61
11.00	3781.88	1850.00	104.43

Base Course Roadway			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
41.00	988.69	600.00	64.78
33.00	988.69	800.00	23.59
24.00	2347.53	1500.00	56.50
13.00	3326.87	2600.00	27.96
45.00	988.69	2500.00	-60.45
26.00	499.02	636.00	-21.54
18.00	3326.87	7000.00	-52.47
49.00	988.69	550.00	79.76
36.00	988.69	750.00	31.83
17.00	3326.87	3500.00	-4.95
Second 20%			
40.00	40.00	480.00	-91.67
21.00	1033.72	500.00	106.74
30.00	2222.83	250.00	789.13
2.00	2141.81	2277.00	-5.94
23.00	1033.72	480.00	115.36
43.00	3411.94	5000.00	-31.76
39.00	2222.83	2900.00	-23.35
6.00	2222.83	4000.00	-44.43
32.00	3411.94	2000.00	70.60
15.00	3411.94	5000.00	-31.76
Third 20%			
4.00	2124.24	3500.00	-39.31
8.00	2204.39	2750.00	-19.84
48.00	910.40	1200.00	-24.13
7.00	3338.07	7000.00	-52.31
29.00	910.40	325.00	180.12
19.00	3338.07	2400.00	39.09
46.00	910.40	2750.00	-66.89
42.00	910.40	1025.00	-11.18
31.00	910.40	1200.00	-24.13
9.00	3338.07	2500.00	33.52
Fourth 20%			
27.00	1049.23	600.00	74.87
28.00	1049.23	200.00	424.61
34.00	1049.23	920.00	14.05
47.00	1049.23	1570.00	-33.17
38.00	40.00	1039.00	-96.15
16.00	3741.94	3500.00	6.91
20.00	2395.58	2000.00	19.78
14.00	2905.05	3500.00	-17.00
12.00	3741.94	1900.00	96.94
35.00	2395.58	971.00	146.71
Fifth 20%			
37.00	1067.73	1352.00	-21.03
3.00	1067.73	200.00	433.87

44.00	2701.31	1200.00	125.11
10.00	2386.99	600.00	297.83
1.00	2386.99	3000.00	-20.43
25.00	3706.26	3000.00	23.54
11.00	2701.31	2500.00	8.05
5.00	3203.78	500.00	540.76
22.00	1067.73	40.00	2569.33

Fifth 20%			
8.00	1189.71	1200.00	-0.86
31.00	623.72	175.00	256.41
9.00	305.30	150.00	103.53
23.00	623.72	167.00	273.49
27.00	800.44	1750.00	-54.26
7.00	1437.27	2500.00	-42.51

Base Course Shoulders			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
19.00	560.53	200.00	180.26
29.00	560.53	600.00	-6.58
18.00	560.53	857.00	-34.59
28.00	1188.85	300.00	296.28
14.00	1188.85	1000.00	18.88
22.00	560.53	600.00	-6.58
21.00	308.36	41.00	652.11
Second 20%			
1.00	1276.44	1800.00	-29.09
24.00	114.74	1200.00	-90.44
13.00	1707.16	1465.00	16.53
16.00	480.24	988.00	-51.39
26.00	482.24	470.00	2.60
30.00	114.74	280.00	-59.02
Third 20%			
3.00	261.33	100.00	161.33
6.00	1384.63	1500.00	-7.69
5.00	1384.63	825.00	67.83
11.00	261.33	30.00	771.11
20.00	1062.88	89.00	1094.25
17.00	662.11	465.00	42.39
Fourth 20%			
2.00	1411.32	800.00	76.41
15.00	510.24	988.00	-48.36
25.00	510.24	743.00	-31.33
4.00	1108.18	1000.00	10.82
12.00	207.10	67.00	209.10
10.00	510.24	988.00	-48.36

Breaker Run			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
34.00	426.98	1250.00	-65.84
17.00	971.64	25.00	3786.57
7.00	3155.78	3500.00	-9.83
26.00	1516.31	1580.00	-4.03
8.00	3155.78	2390.00	32.04
29.00	426.98	400.00	6.74
35.00	426.98	310.00	37.73
12.00	3155.78	3045.00	3.64
Second 20%			
10.00	2517.34	3290.00	-23.49
9.00	3069.57	2390.00	28.43
22.00	433.80	138.00	214.35
25.00	1538.27	535.00	187.53
5.00	3069.57	4000.00	-23.26
19.00	2086.69	1000.00	108.67
1.00	1967.01	3000.00	-34.43
Third 20%			
13.00	3224.42	2550.00	26.45
3.00	25.00	200.00	-87.50
30.00	1303.58	1000.00	30.36
2.00	1947.73	500.00	289.55
36.00	940.01	750.00	25.33
6.00	1936.11	3375.00	-42.63
24.00	167.19	1570.00	-89.35
Fourth 20%			
28.00	2182.67	3300.00	-33.86
11.00	2904.13	4115.00	-29.43
14.00	2904.13	4115.00	-29.43

18.00	697.58	131.00	432.50
4.00	3292.87	1000.00	229.29
21.00	697.58	150.00	365.05
32.00	1765.62	1200.00	47.13
Fifth 20%			
20.00	2460.57	3000.00	-17.98
15.00	3117.85	2385.00	30.73
31.00	286.34	447.00	-35.94
33.00	943.62	1000.00	-5.64
16.00	1591.29	2000.00	-20.44
27.00	943.62	455.00	107.39
23.00	286.34	600.00	-52.28

Shallow Excavation			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
12.00	640.63	631.00	1.53
17.00	2072.25	2000.00	3.61
8.00	392.77	175.00	124.44
4.00	75.00	1200.00	-93.75
Second 20%			
3.00	560.36	150.00	273.57
13.00	528.53	670.00	-21.11
1.00	636.01	1000.00	-36.40
16.00	2689.53	4000.00	-32.76
Third 20%			
6.00	2198.03	1200.00	83.17
10.00	525.67	360.00	46.02
7.00	1221.02	500.00	144.20
Fourth 20%			
11.00	893.45	525.00	70.18
15.00	629.79	400.00	57.45
14.00	422.79	524.00	-19.31
Fifth 20%			
2.00	163.63	75.00	118.17
5.00	582.43	1100.00	-47.05
9.00	512.07	615.00	-16.74

Excavation Below Subgrade			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
5.00	888.49	1300.00	-31.65
14.00	1530.52	950.00	61.11
24.00	257.47	540.00	-52.32
9.00	1519.51	1800.00	-15.58
19.00	818.91	200.00	309.45
Second 20%			
21.00	646.06	1000.00	-35.39
4.00	1479.58	3000.00	-50.68
17.00	15.00	401.00	-96.26
18.00	902.02	1000.00	-9.80
1.00	2057.15	1500.00	37.14
Third 20%			
20.00	1867.10	1000.00	86.71
11.00	1867.10	2000.00	-6.65
15.00	723.65	705.00	2.64
13.00	723.65	500.00	44.73
22.00	723.65	1050.00	-31.08
Fourth 20%			
23.00	816.12	300.00	172.04
12.00	816.12	315.00	159.09
6.00	924.27	1000.00	-7.57
8.00	1996.72	3000.00	-33.44
2.00	1198.59	500.00	139.72
Fifth 20%			
10.00	310.28	15.00	1968.55
16.00	310.28	365.00	-14.99
7.00	1281.01	550.00	132.91
3.00	310.28	100.00	210.28

Clearing and Grubbing			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
9.00	16.59	26.00	-36.19
24.00	12.27	6.00	104.50
5.00	12.27	10.00	22.70
19.00	9.97	9.00	10.78

7.00	7.67	4.00	91.75
22.00	16.59	10.00	65.90
Second 20%			
20.00	8.12	10.00	-18.80
27.00	2.09	6.00	-65.17
26.00	8.12	5.00	62.40
16.00	9.69	7.00	38.43
10.00	17.30	10.00	73.00
21.00	8.12	3.00	170.67
Third 20%			
11.00	7.59	2.00	279.50
8.00	3.39	1.00	239.00
17.00	7.59	12.00	-36.75
4.00	19.51	25.00	-21.96
23.00	3.39	5.00	-32.20
Fourth 20%			
18.00	1.70	8.00	-78.75
3.00	9.16	6.00	52.67
13.00	7.10	2.00	255.00
15.00	7.10	17.00	-58.24
6.00	11.20	10.00	12.00
Fifth 20%			
2.00	14.12	6.00	135.33
12.00	8.79	8.00	9.87
1.00	7.85	14.00	-43.93
25.00	7.85	6.00	30.83
14.00	15.07	30.00	-49.77

Adjust Frames & Grates			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
15.00	34.61	20.00	73.05
12.00	34.61	12.00	188.42
1.00	34.61	3.00	1053.67
Second 20%			
8.00	25.76	52.00	-50.46
9.00	4.56	10.00	-54.40
14.00	25.76	14.00	84.00
Third 20%			
6.00	8.00	16.00	-50.00

11.00	8.00	5.00	60.00
7.00	30.33	74.00	-59.01
Fourth 20%			
13.00	28.89	14.00	106.36
5.00	5.54	10.00	-44.60
2.00	5.54	4.00	38.50
Fifth 20%			
4.00	4.21	20.00	-78.95
10.00	4.21	3.00	40.33
3.00	4.21	1.00	321.00

Pipe Underdrains			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
5.00	2278.61	2000.00	13.93
7.00	221.91	600.00	-63.01
11.00	221.91	500.00	-55.62
Second 20%			
6.00	110.00	112.00	-1.79
14.00	357.97	174.00	105.73
3.00	1205.20	400.00	201.30
Third 20%			
12.00	1480.49	2700.00	-45.17
13.00	752.57	400.00	88.14
10.00	292.17	110.00	165.61
Fourth 20%			
9.00	1515.00	2175.00	-30.34
4.00	110.00	220.00	-50.00
1.00	2395.00	4349.00	-44.93
Fifth 20%			
15.00	484.95	176.00	175.54
8.00	2000.64	700.00	185.81
2.00	951.35	140.00	579.54

Riprap Light/Medium			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
6.00	169.17	200.00	-15.42

7.00	55.50	120.00	-53.75
11.00	112.33	150.00	-25.11
Second 20%			
3.00	65.12	90.00	-27.64
2.00	136.80	100.00	36.80
1.00	136.80	23.00	494.78
Third 20%			
10.00	120.95	180.00	-32.81
4.00	120.95	85.00	42.29
5.00	64.78	60.00	7.97
Fourth 20%			
12.00	76.69	20.00	283.45
13.00	130.74	70.00	86.77
Fifth 20%			
8.00	113.48	216.00	-47.46
9.00	63.39	52.00	21.90

Riprap Heavy/Extra Heavy			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
4.00	1088.33	570.00	90.94
1.00	1088.33	1100.00	-1.06
Second 20%			
9.00	798.16	49.00	1528.90
7.00	474.25	768.00	-38.25
Third 20%			
5.00	74.72	100.00	-25.28
6.00	183.87	82.00	124.23
Fourth 20%			
2.00	120.63	50.00	141.26
3.00	120.63	80.00	50.79
Fifth 20%			
8.00	125.63	145.00	-13.36

Concrete Barrier			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
10.00	807.33	215.00	275.50

7.00	1115.66	2000.00	-44.22
3.00	1115.66	1500.00	-25.62
Second 20%			
6.00	1299.48	890.00	46.01
2.00	2043.68	3280.00	-37.69
Third 20%			
5.00	2877.35	2125.00	35.40
9.00	1519.75	1210.00	25.60
Fourth 20%			
4.00	1247.61	800.00	55.95
11.00	44.00	250.00	-82.40
Fifth 20%			
8.00	1221.02	44.00	2675.05
1.00	1221.02	2585.00	-52.77

Paint Pavement Marking (Truck)			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
4.00	15130.79	9000.00	68.12
5.00	15130.79	12000.00	26.09
8.00	24001.32	25000.00	-3.99
12.00	15130.79	6250.00	142.09
10.00	15130.79	7250.00	108.70
Second 20%			
17.00	1117.00	8000.00	-86.04
12.00	26385.33	48971.00	-46.12
22.00	26385.33	13709.00	92.47
9.00	1117.00	16210.00	-93.11
3.00	26385.33	7708.00	242.31
Third 20%			
11.00	15038.29	3600.00	317.73
24.00	15038.29	1117.00	1246.31
13.00	25954.32	5100.00	408.91
1.00	15038.29	9950.00	51.14
14.00	15038.29	29310.00	-48.69
Fourth 20%			
18.00	13840.56	6160.00	124.68
19.00	13840.56	5785.00	139.25
7.00	13840.56	30000.00	-53.86

2.00	13840.56	8630.00	60.38
25.00	22214.02	37712.00	-41.10
Fifth 20%			
6.00	20761.70	30000.00	-30.79
16.00	20761.70	26000.00	-20.15
21.00	20761.70	345000.00	-93.98
20.00	13025.94	15377.00	-15.29
15.00	13025.94	18000.00	-27.63

Excelsior Blanket			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
13.00	7670.80	3800.00	101.86
14.00	1818.56	315.00	477.32
11.00	1818.56	2300.00	-20.93
Second 20%			
9.00	3383.72	6080.00	-44.35
2.00	1108.99	4900.00	-77.37
10.00	3383.72	7800.00	-56.62
Third 20%			
1.00	1877.06	1722.00	9.00
12.00	1877.06	2100.00	-10.62
4.00	4181.10	4000.00	4.53
Fourth 20%			
3.00	4313.76	995.00	333.54
5.00	6269.40	10000.00	-37.31
7.00	4313.73	190.00	2170.38
Fifth 20%			
6.00	2061.88	1400.00	47.28
8.00	2061.88	1300.00	58.61

Seeding			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
10.00	0.72	2.60	-72.36
4.00	0.72	0.80	-10.16
3.00	1.63	4.00	-59.22
Second 20%			

9.00	1.75	1.25	40.10
7.00	0.98	0.63	56.88
1.00	0.98	0.25	292.20
Third 20%			
12.00	0.83	1.00	-17.50
8.00	1.84	1.00	83.75
6.00	1.84	1.00	83.75
Fourth 20%			
13.00	1.87	0.80	133.89
11.00	1.87	1.00	87.11
Fifth 20%			
5.00	1.62	2.00	-19.15
2.00	0.75	1.00	-24.85

Straw Mulch			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
10.00	570.63	5400.00	-89.43
5.00	7694.88	7000.00	9.93
Second 20%			
7.00	698.62	500.00	39.72
1.00	7820.12	8800.00	-11.14
Third 20%			
2.00	500.00	25000.00	-98.00
3.00	2347.79	735.00	219.43
Fourth 20%			
6.00	15683.75	15000.00	4.56
9.00	12298.37	11417.00	7.72
Fifth 20%			
8.00	500.00	476.00	5.04
4.00	500.00	510.00	-1.96

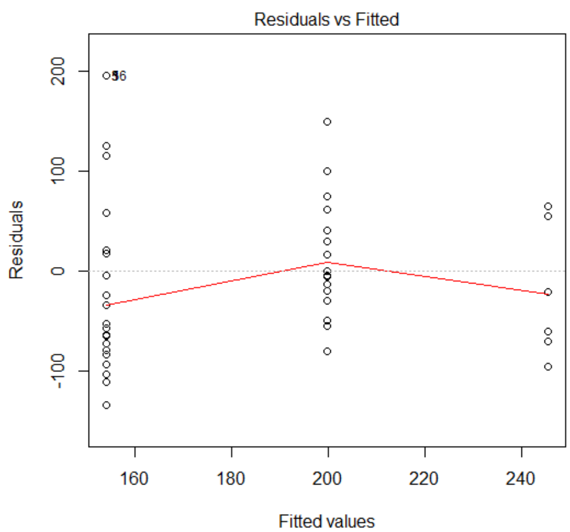
Remove Concrete Pavement			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
13.00	4564.20	580.00	686.93
14.00	4564.20	580.00	686.93
2.00	4564.20	150.00	2942.80

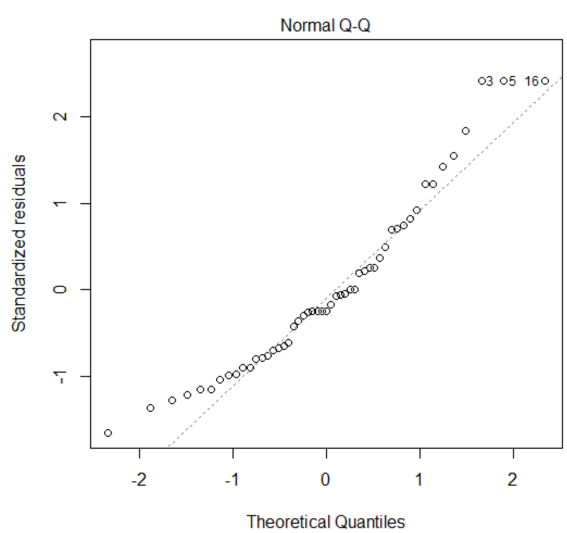
Second 20%			
3.00	3914.91	24000.00	-83.69
6.00	3914.91	1638.00	139.01
4.00	3914.91	2250.00	74.00
Third 20%			
11.00	4125.80	3600.00	14.61
1.00	4125.80	594.00	594.58
7.00	4125.80	1500.00	175.05
Fourth 20%			
12.00	2049.20	800.00	156.15
9.00	2049.20	23610.00	-91.32
5.00	2049.20	2500.00	-18.03
Fifth 20%			
8.00	3395.64	6000.00	-43.41
10.00	3395.64	3600.00	-5.68

Geotextiles			
No	**Predicted Rate**	**Actual Rate**	**Deviation (%)**
First 20%			
12.00	894.70	1064.00	-15.91
10.00	320.17	142.00	125.47
4.00	1146.50	1100.00	4.23
Second 20%			
2.00	446.37	168.00	165.70
5.00	271.39	12.00	2161.60
7.00	217.13	500.00	-56.57
Third 20%			
6.00	428.47	100.00	328.47
3.00	102.83	300.00	-65.72
Fourth 20%			
11.00	788.05	1204.00	-34.55
8.00	251.86	82.00	207.14
Fifth 20%			
9.00	317.91	830.00	-61.70
1.00	1200.00	1200.00	0.00

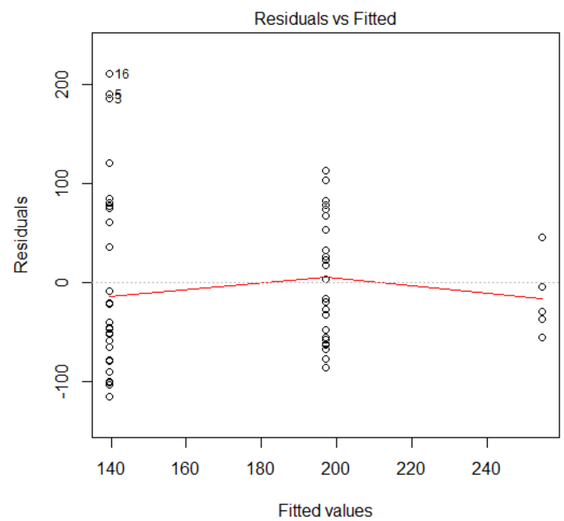
Appendix D – Residual Plots and QQ Plots

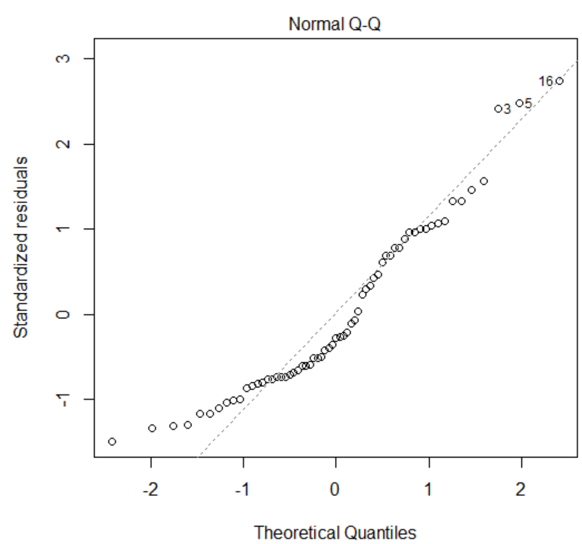
Hot Mix Asphalt – Lower Layer



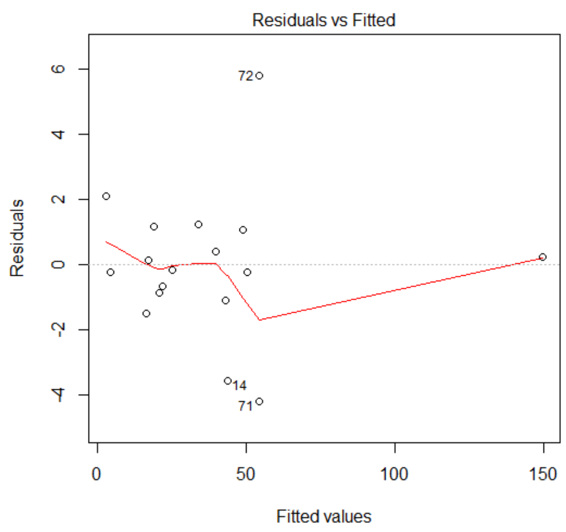


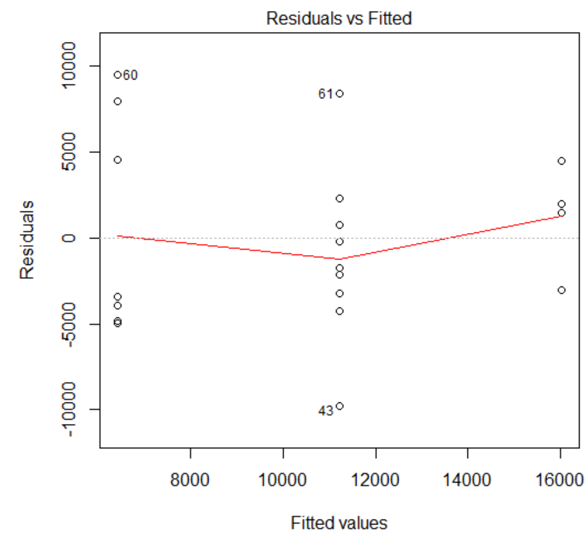
Hot Mix Asphalt – Surface Layer

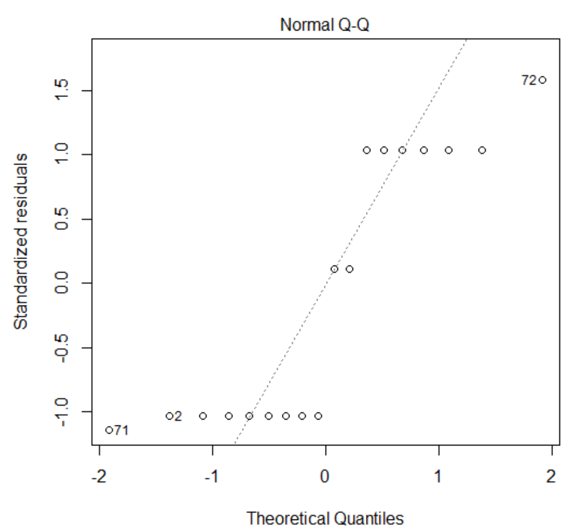


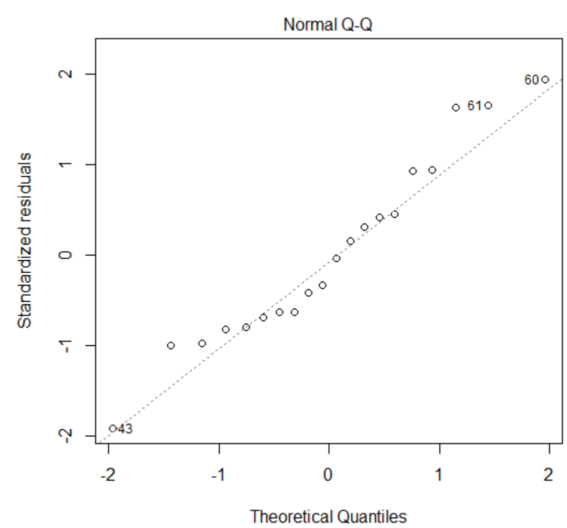


Hand Placement of Asphalt | **Thick Milling**

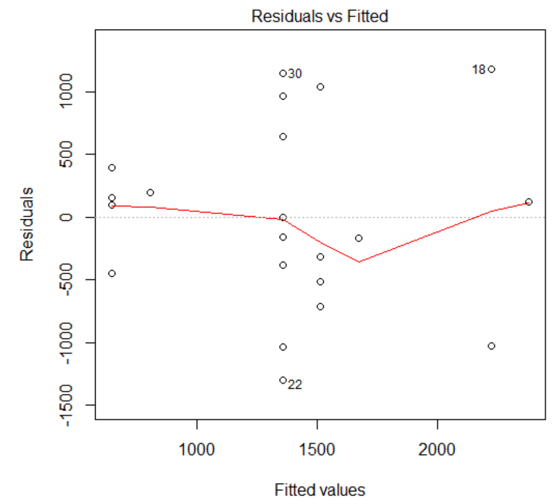


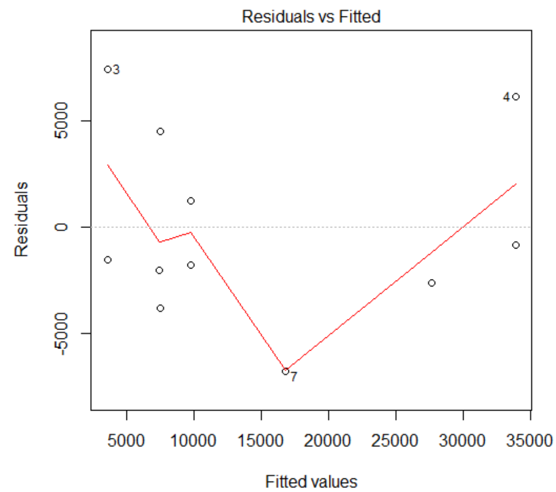


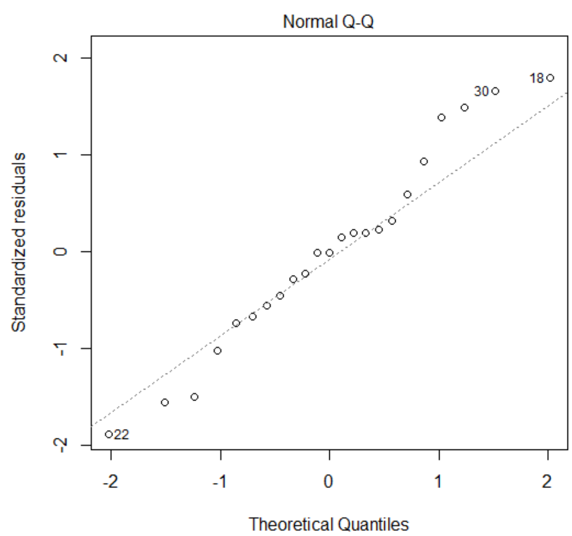


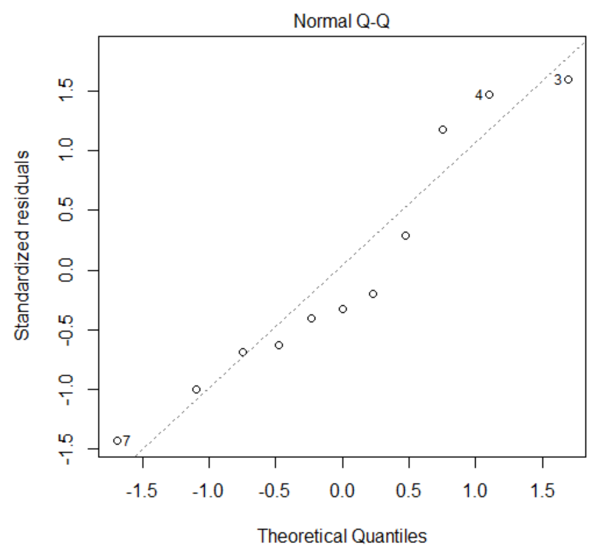


Base Course Placement **QMP Density**

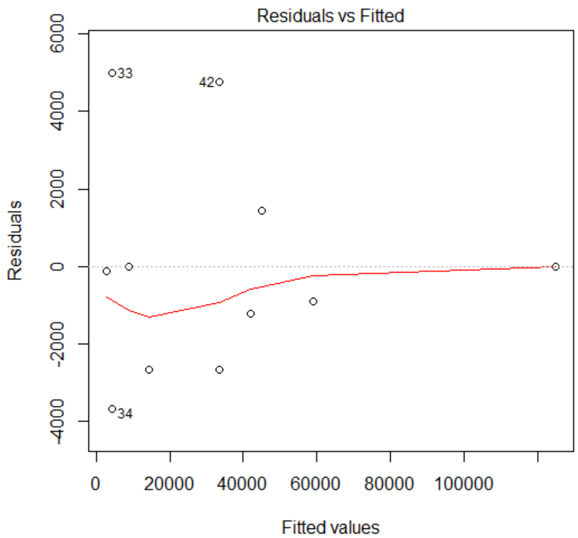


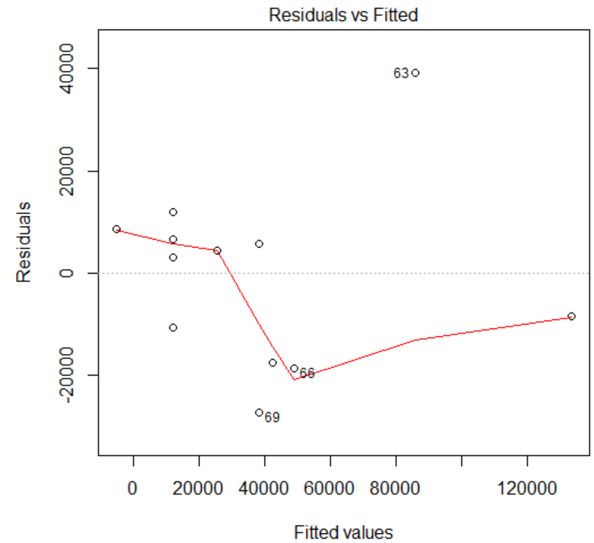


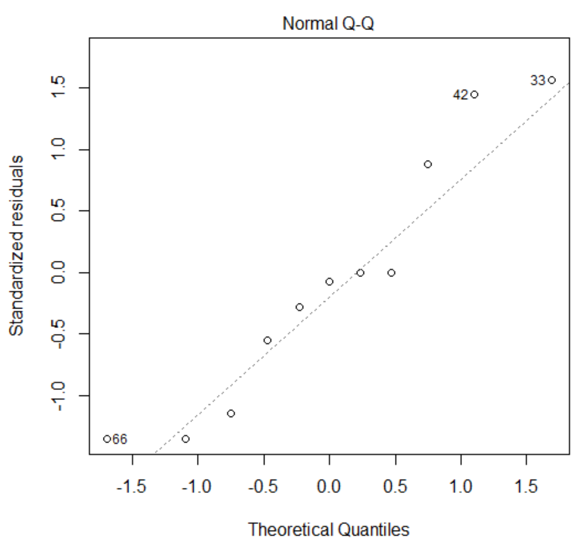


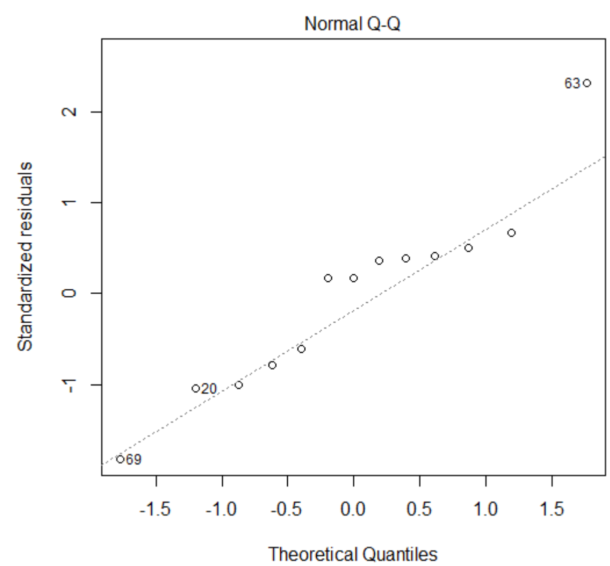


Rumble Strip Center | **Rumble Strip Shoulder**

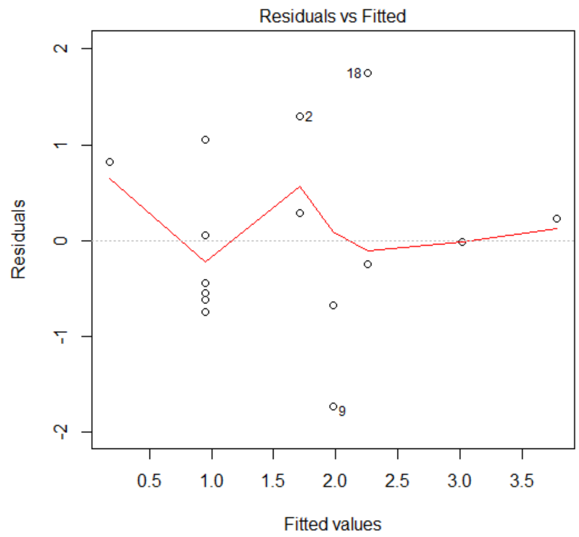


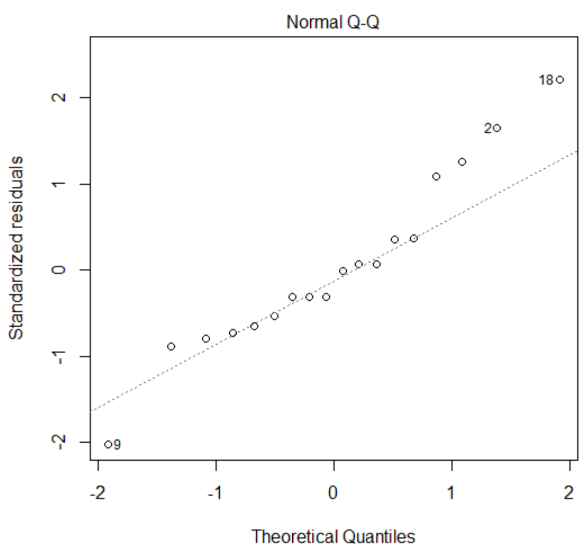




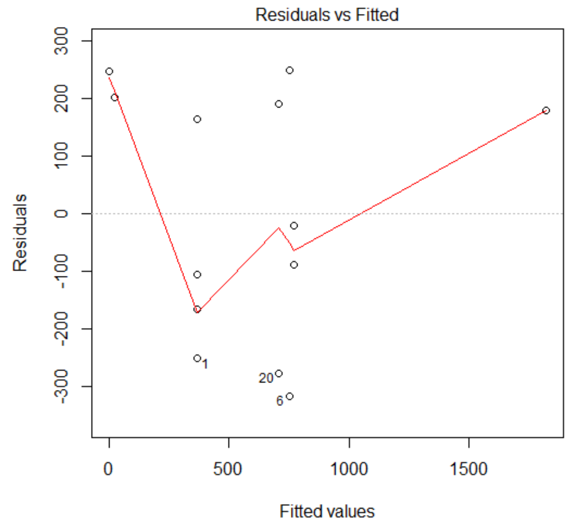


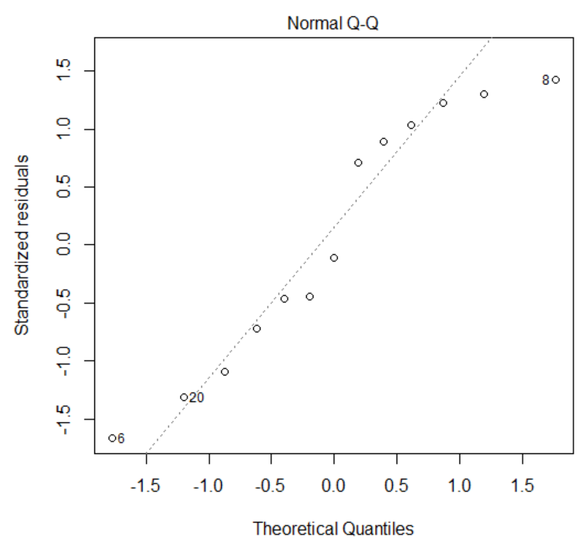
Concrete Masonry



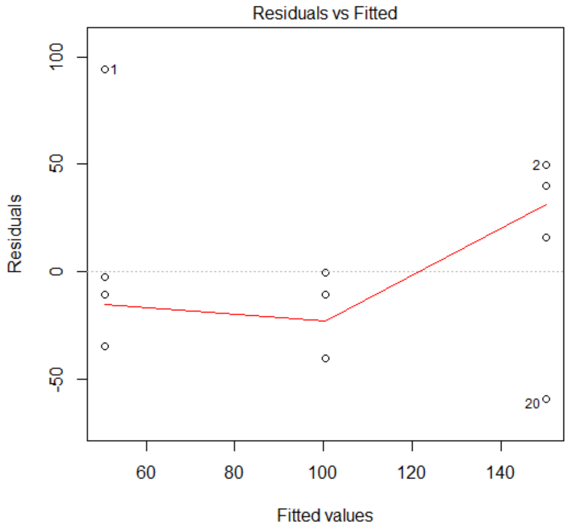


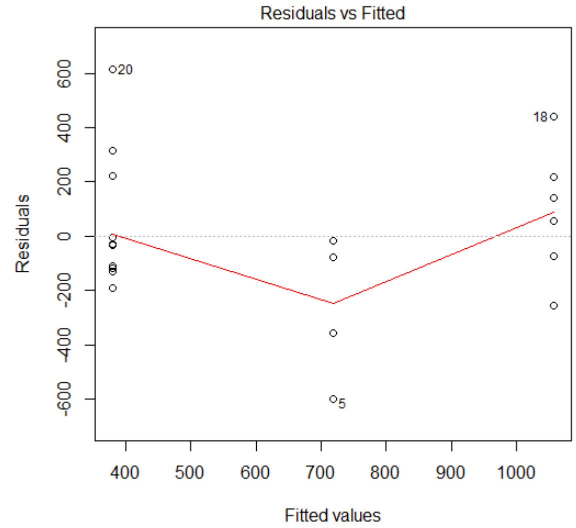
Sheet Piles

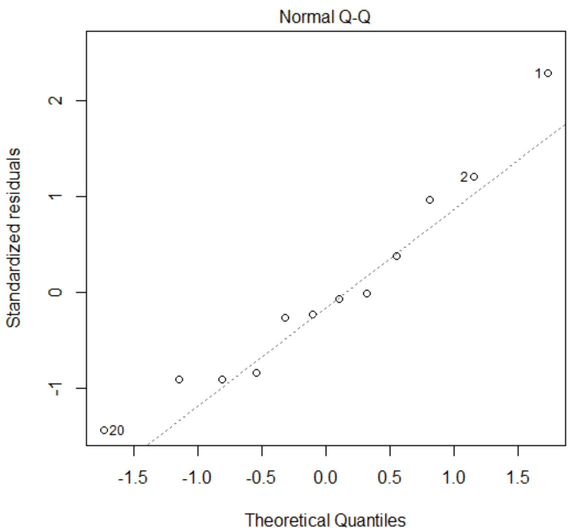


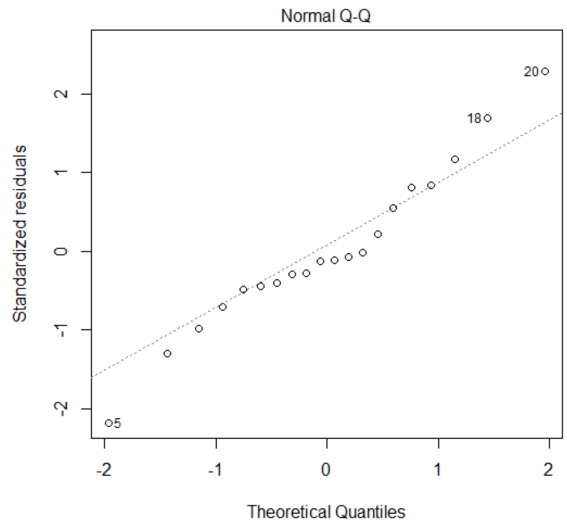


Parapet (Straight Back) **Deck Placement (Girder Bridge)**

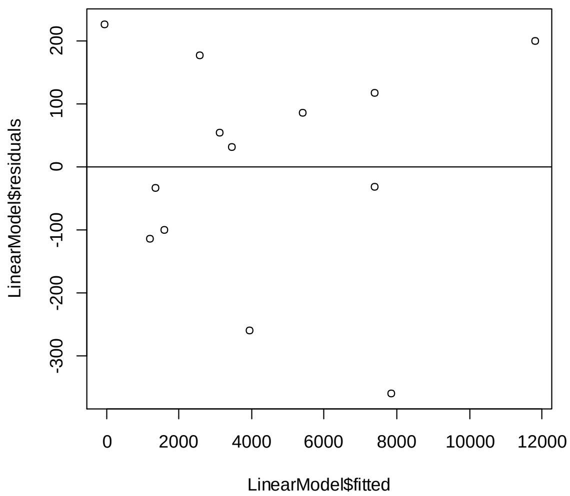


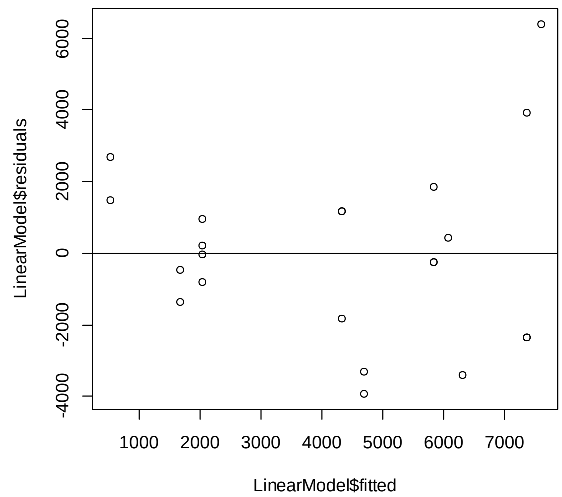


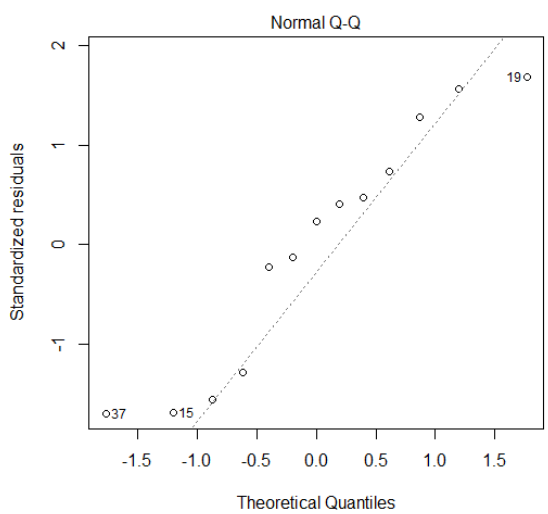


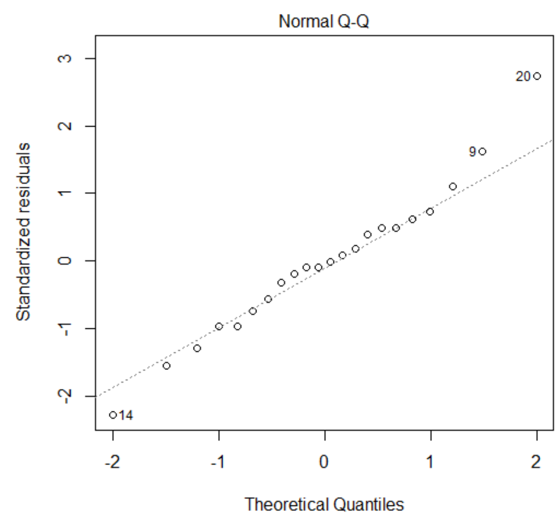


Thick Paving **Thin Paving**



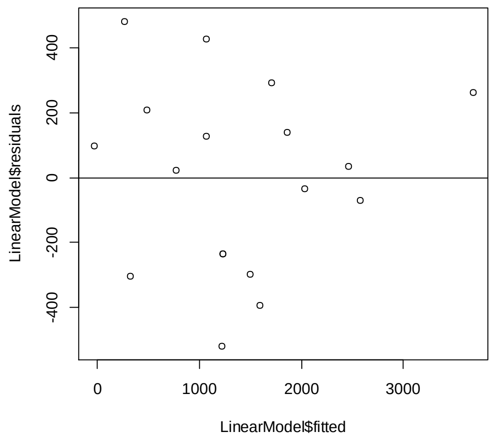


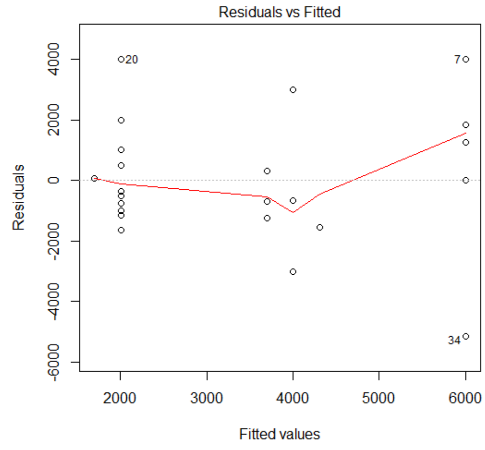


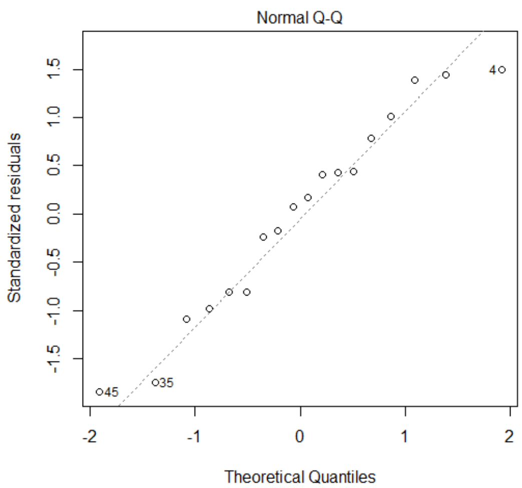


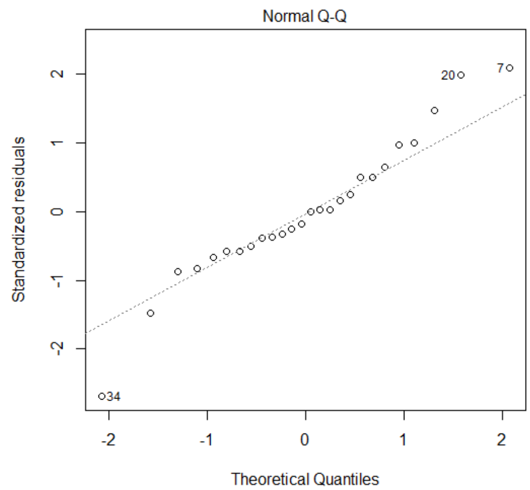
Base Course

Sidewalks

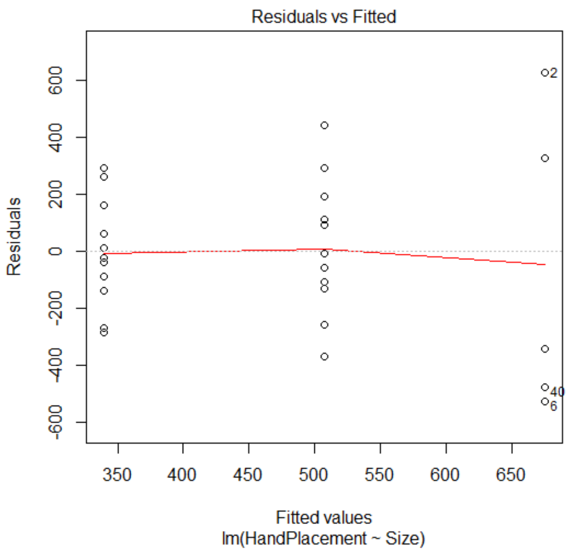


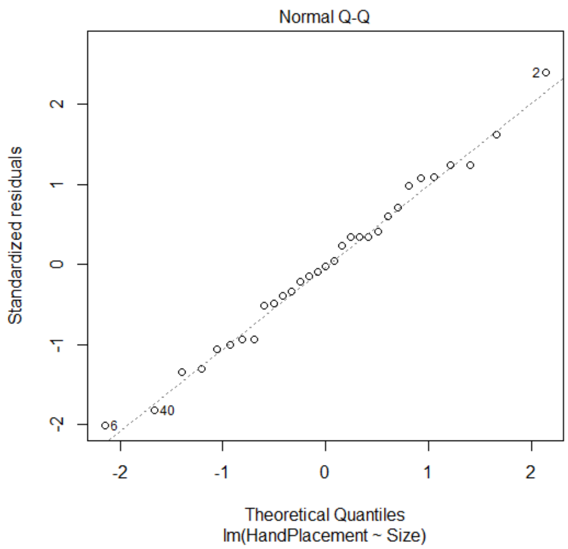




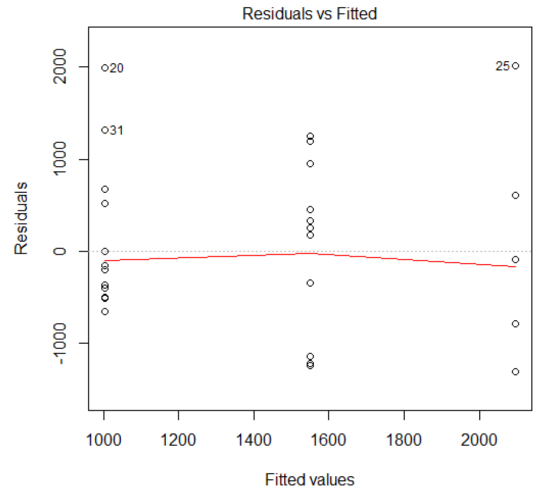


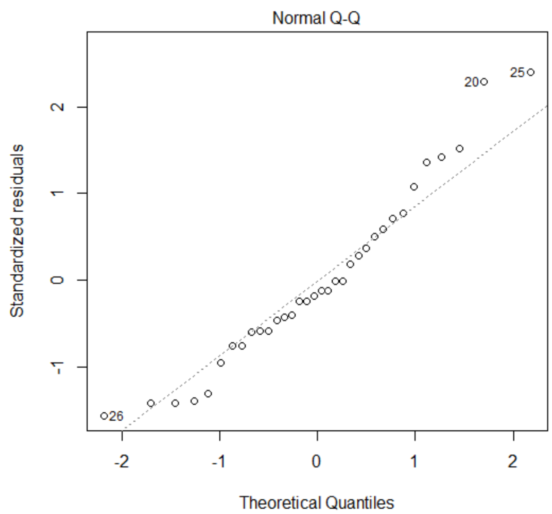
Hand Placement of Concrete



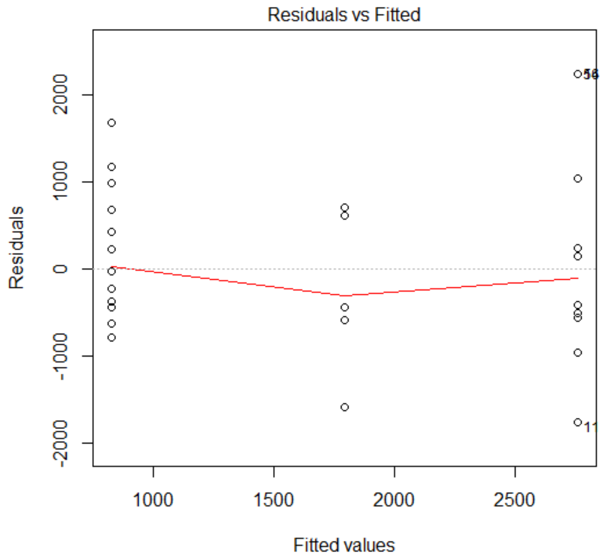


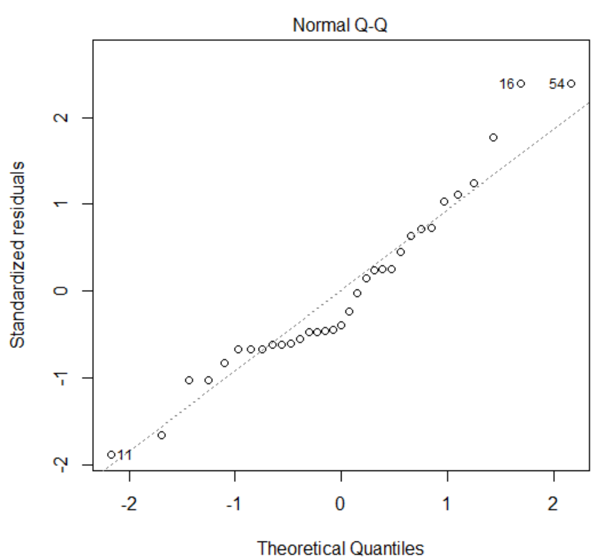
Curb and Gutter



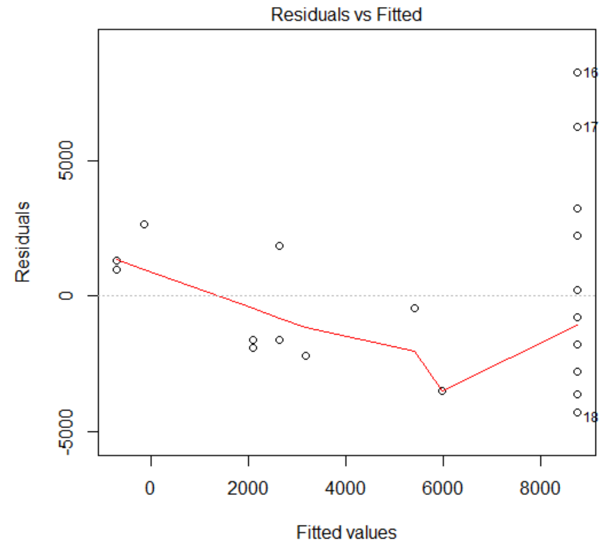


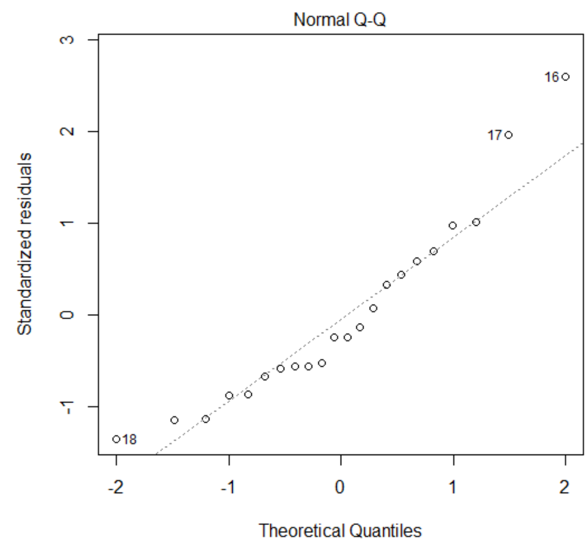
Excavation (Truck)



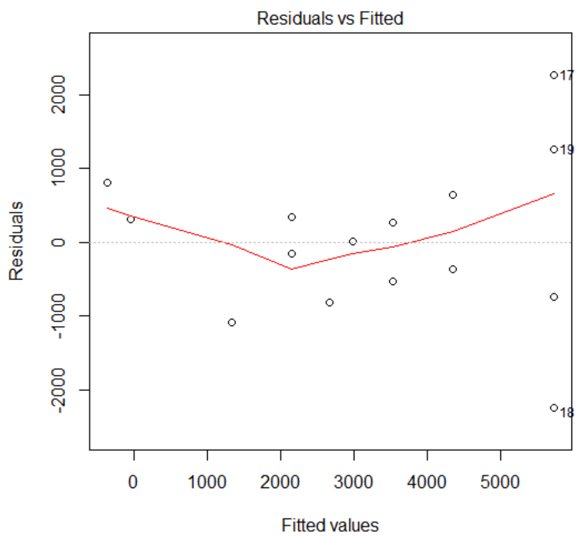


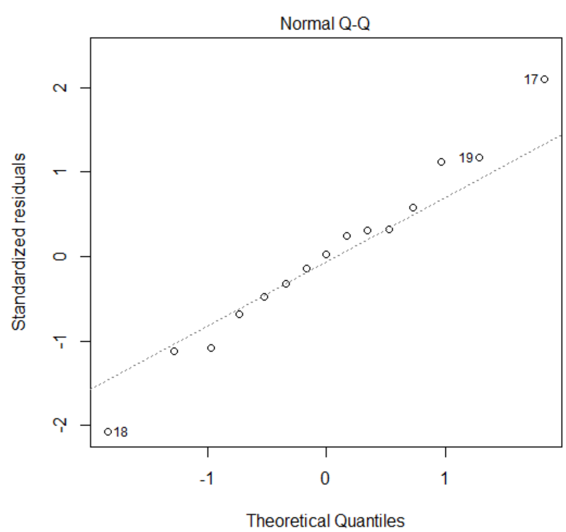
Excavation (Scraper)



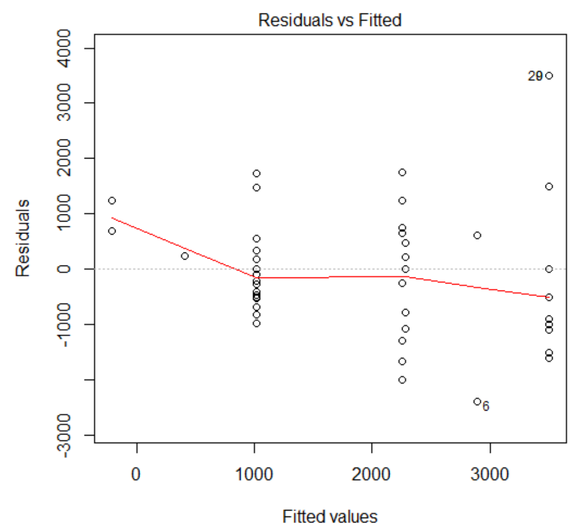


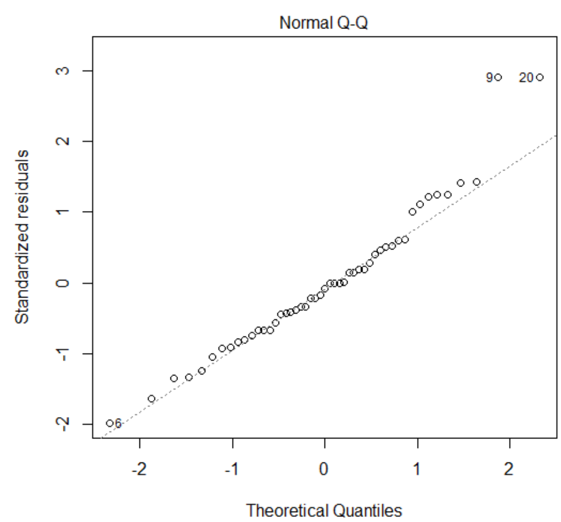
Excavation (Articulated Truck)



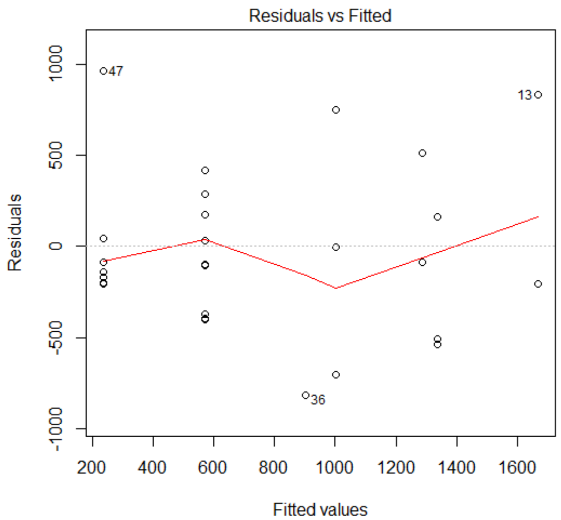


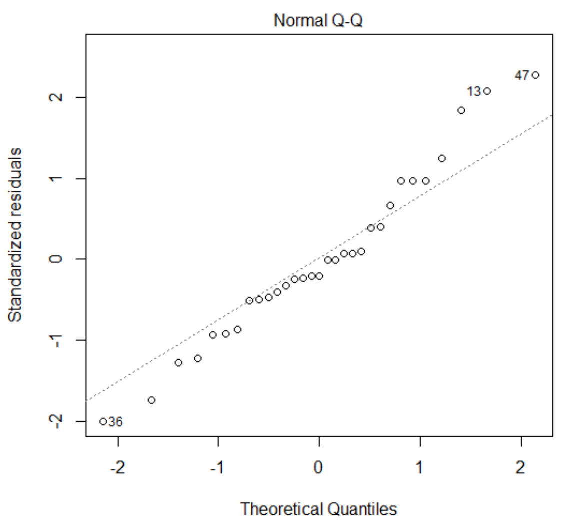
Base Course Roadway



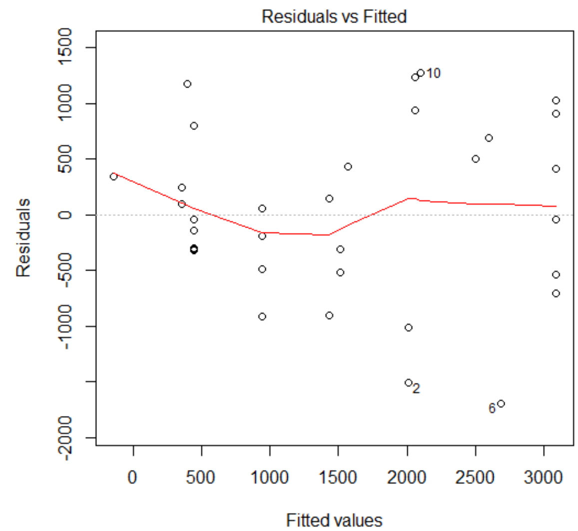


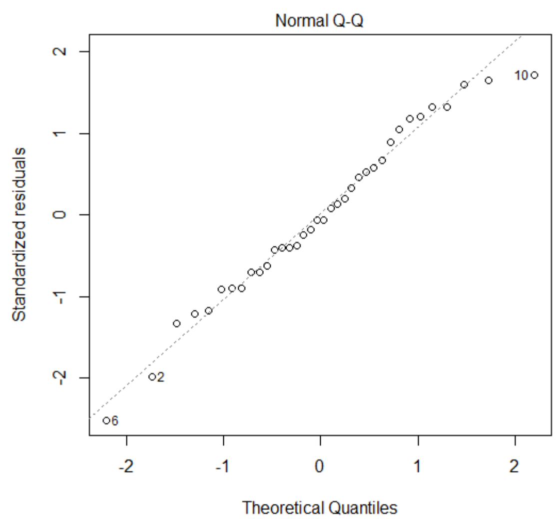
Base Course Shoulders





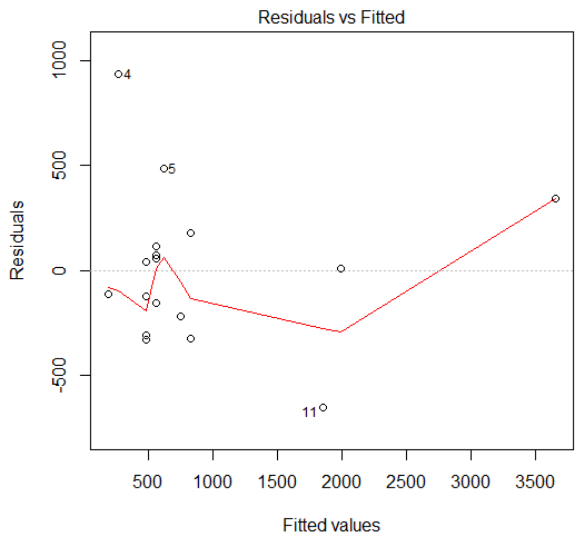
Breaker Run

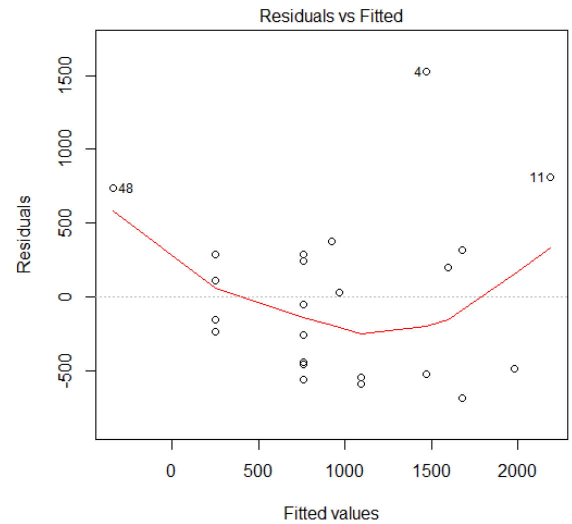


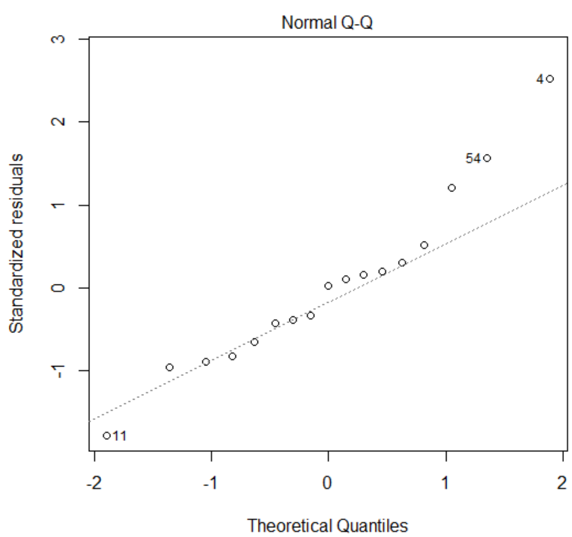


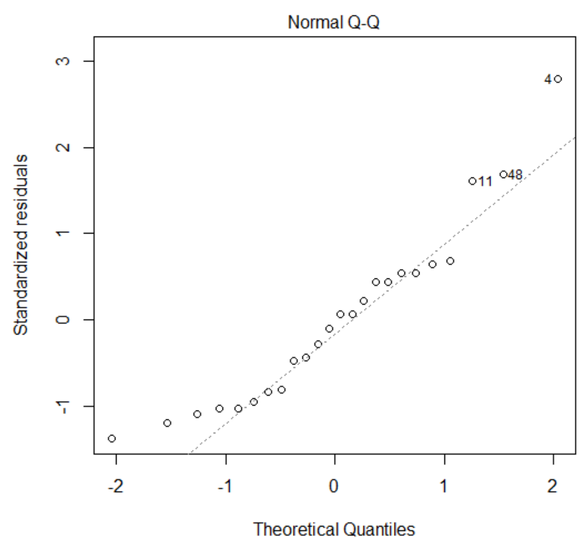
Shallow Excavation

Excavation Below Subgrade

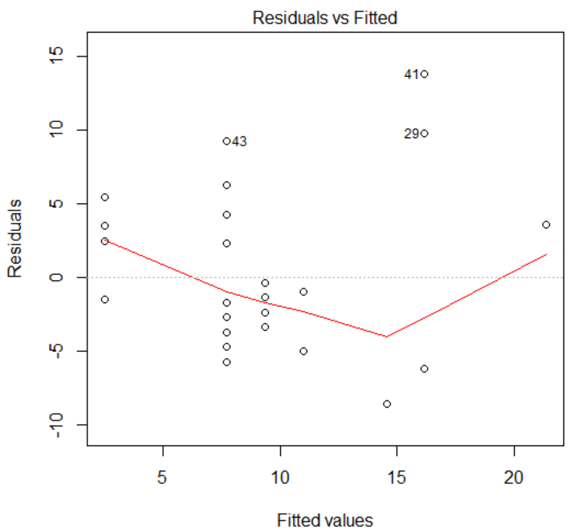


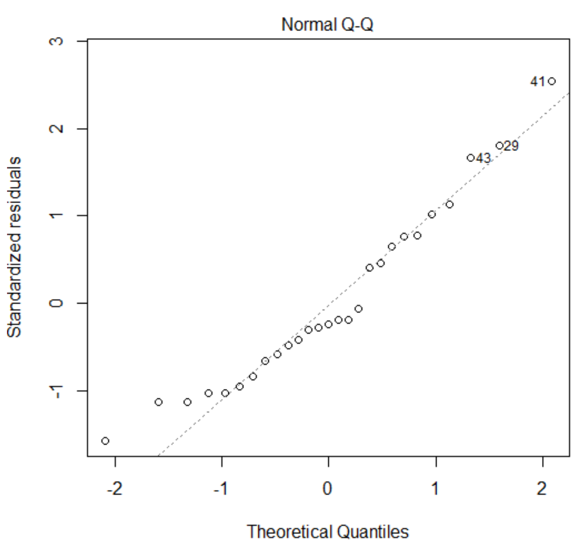




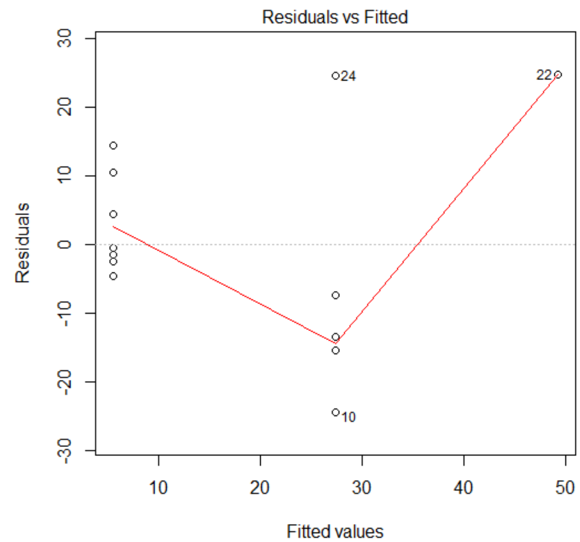


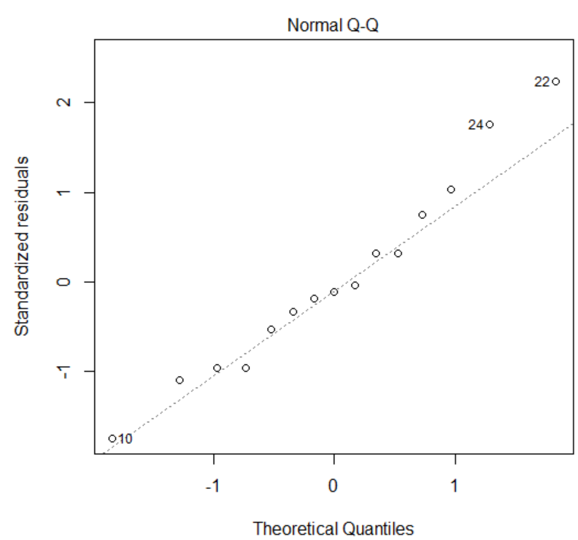
Clearing and Grubbing



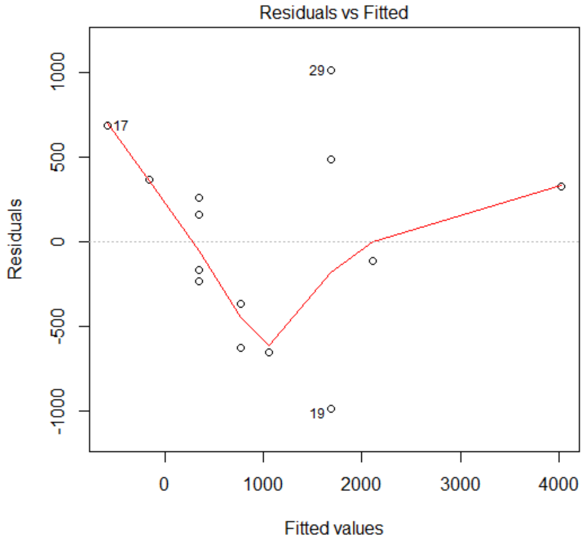


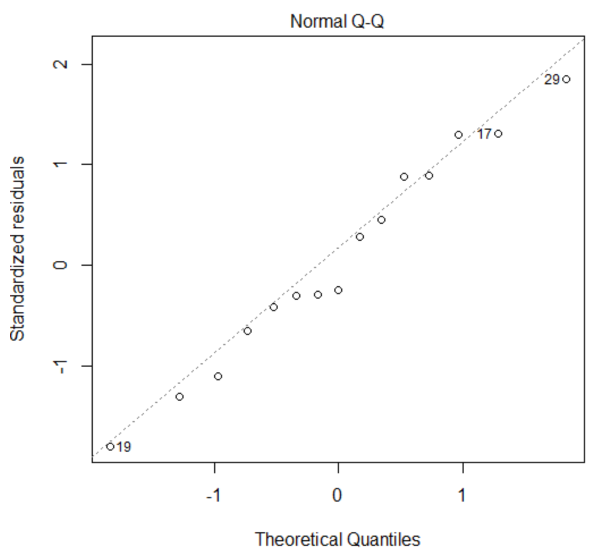
Frames and Grates



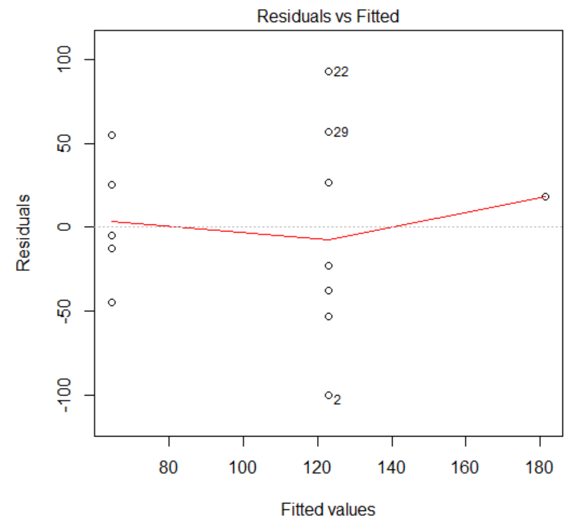


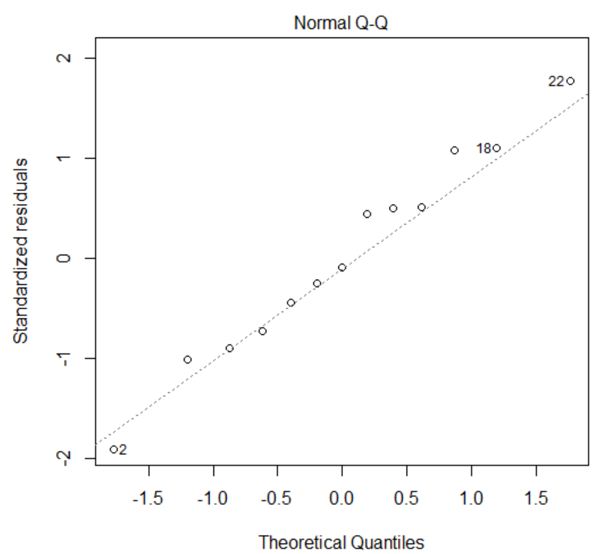
Pipe Underdrains



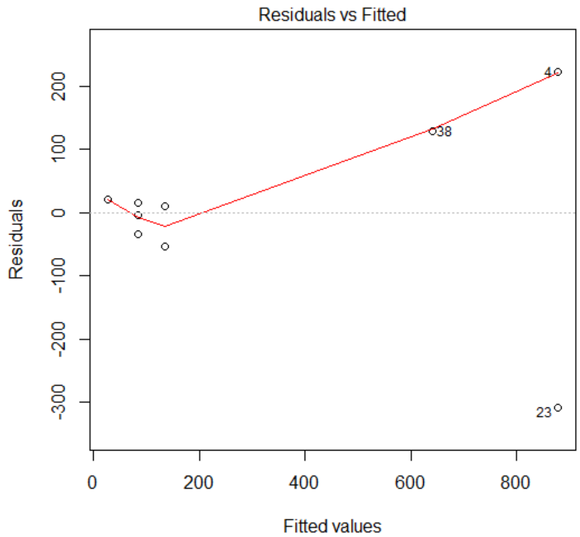


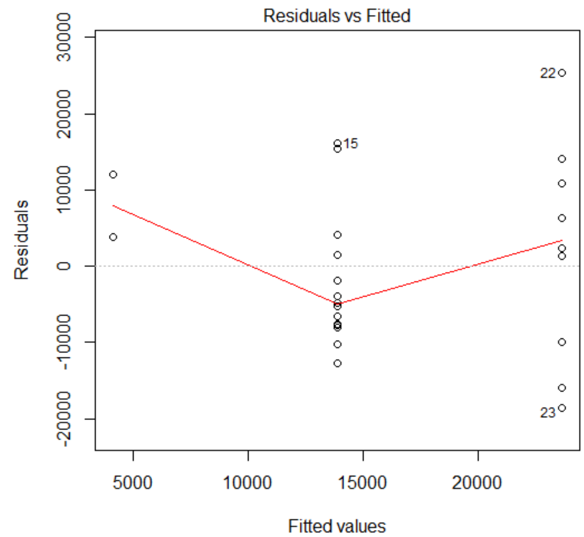
Riprap LM

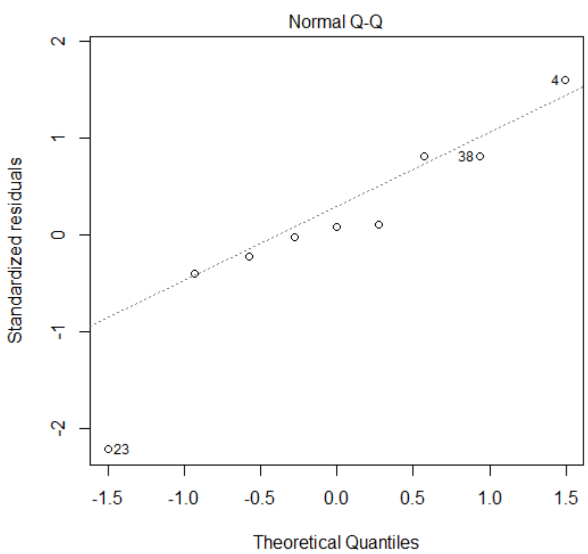


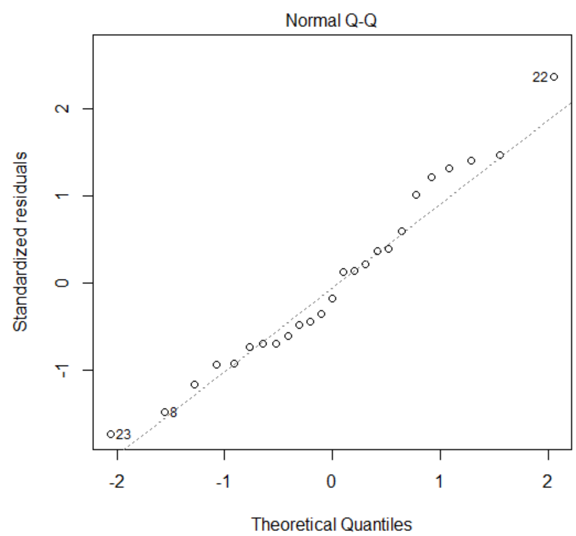


Riprap HEH **Paint Pavement Marking**

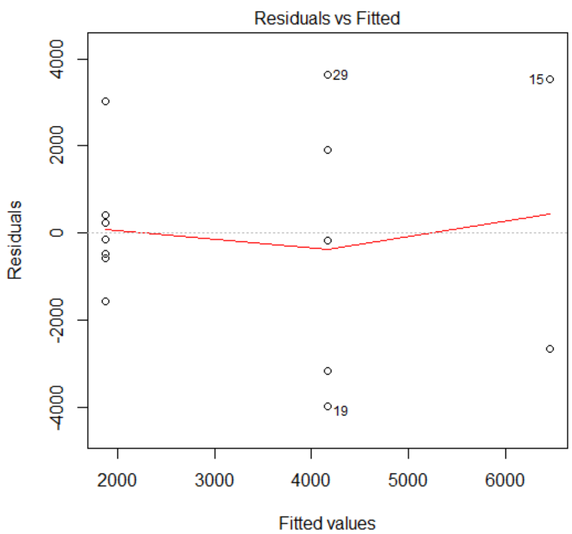


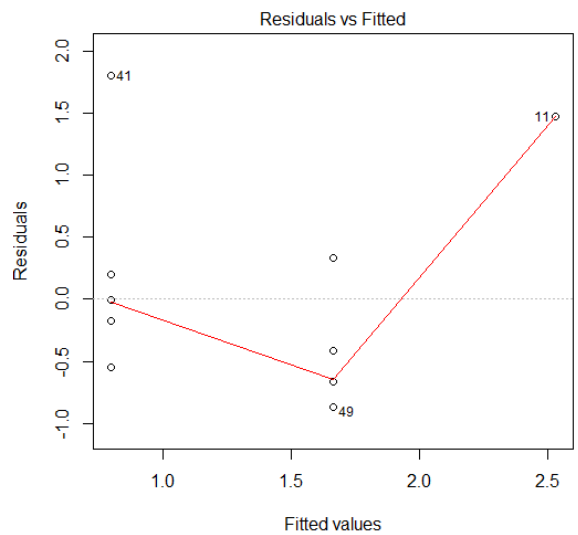


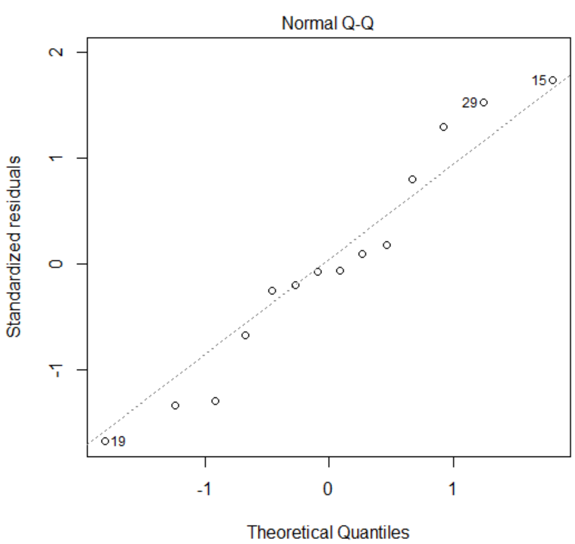


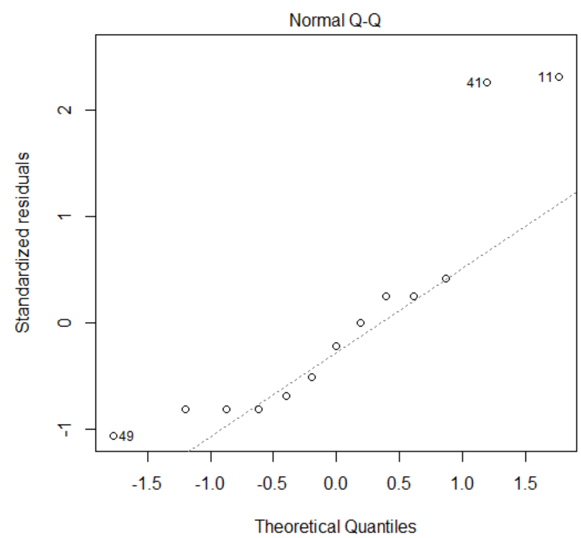


Excelsior Blanket **Seeding**

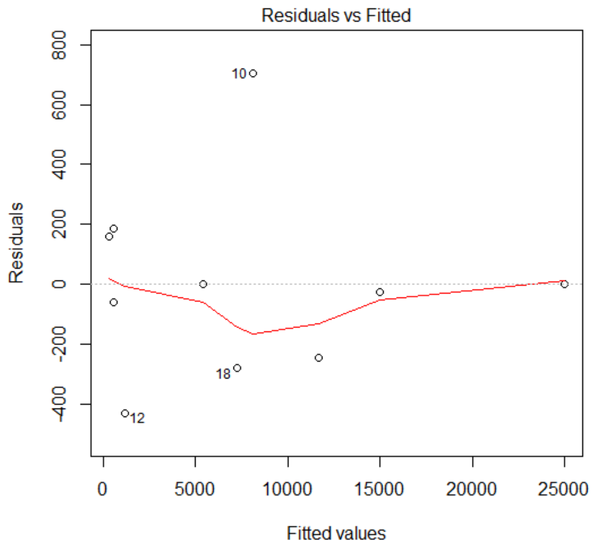


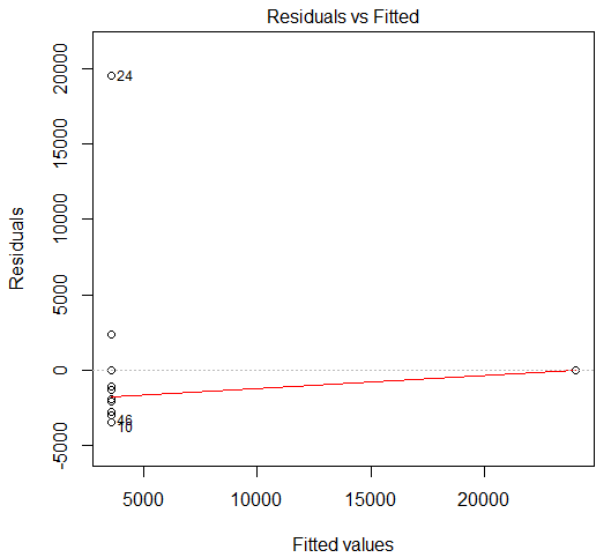


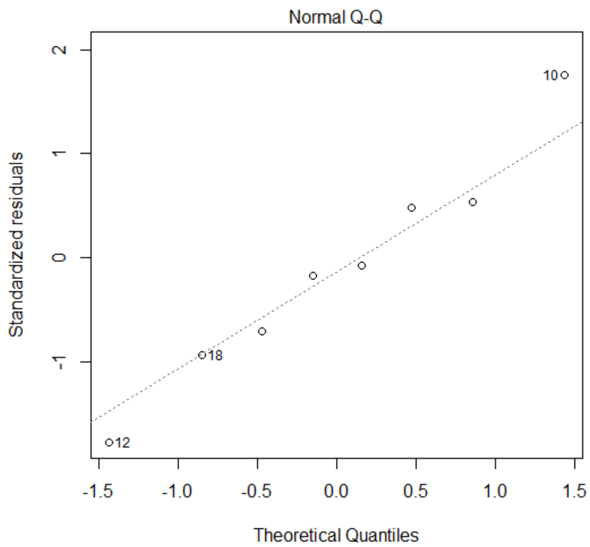


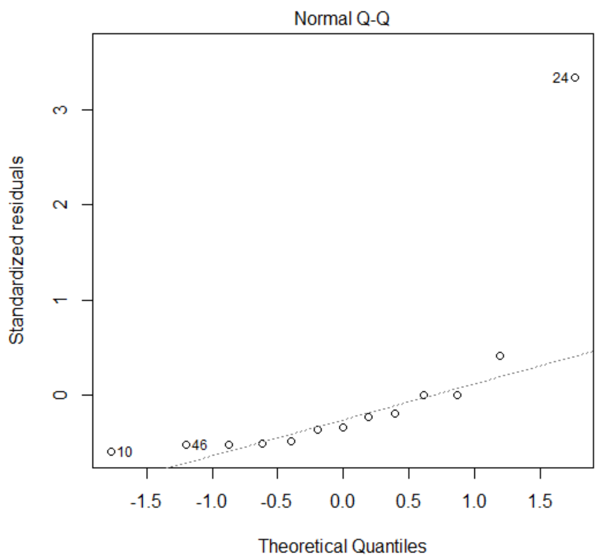


Straw Mulch | **Remove Pavement**

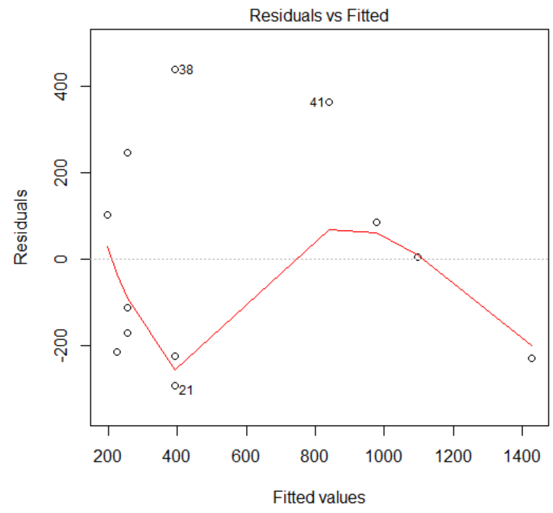


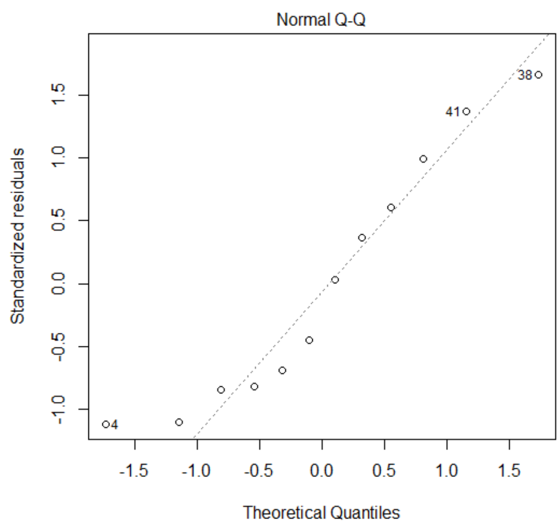






Geotextiles





Appendix E – Productivity Estimation Tool User Guide

The PET is a user-friendly tool which was designed to help Wisconsin's transportation engineers and designers quantitatively predict and estimate highway construction productivity rates for future projects. The PET is comprised of various types of sections, or tabs in Microsoft Excel (MS Excel), which include tabs for an introduction, main menu, five project information user input tabs, five hidden tabs for creating linear regression models, and five output tabs. With this tool, designers are able to interact with the current productivity database by inputting various project factor information corresponding to their current projects. The tool then takes the user's project information input into consideration when providing productivity rate estimates for various construction activities. Ultimately, it is hoped that WisDOT is able to utilize this tool to improve estimates of contract time awarded to contractors working on WisDOT projects.

Introduction to Tool

The PET is a MS Excel based tool that was originally created by Diane Aoun while completely her Master's degree under Dr. Awad Hanna at UW-Madison. In its original form, the PET provided a predicted productivity rate along with a confidence interval with a level of confidence specified by the user. The original tool only included four tabs in MS Excel for asphalt paving, bridge construction, concrete paving, and earthwork. However, significant changes were made to the tool during Phase II of this study. The main changes to the PET include that a confidence interval is no longer computed, an additional tab has been added for miscellaneous construction activities, and significant changes have been made to the output tab's displays, which will be described in detail later.

Introduction Tab

The "Introduction" tab in the PET primarily informs users how to use, apply, and read output from the tool. Users are reminded that the PET is a work in progress, and it will improve as more data is gathered every year. With that in mind, the production rates predicted by the PET are to be used as estimates and "starting points" while other factors, such as expert opinion and prior experience, are taken into consideration as well. The output generated for each particular construction activity depends on whether or not a model was generated for that activity using stepwise linear regression in R. If a models dataset would support the creation of a model, then an output similar to that shown in Figure 21 is shown below.

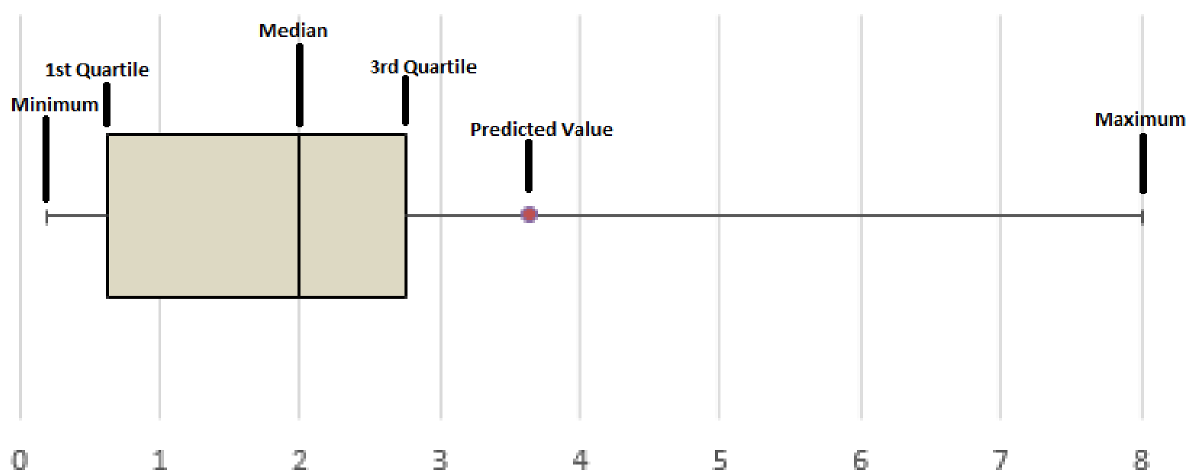


Figure 21: Output Display for Modeled Activities

In this type of output, the minimum and maximum values shown are the actual minimum and maximum values observed during the data collection phase. The first quartile is a value which is greater than 25% of the data observed, the median is a value greater than 50% of the data observed, and the third quartile is a value greater than 75% of the data observed. The predicted value represented by a red dot on Figure 21 is the value generated by the model created using project factors as inputs. While the models generated may predict a value outside of the observed range of values in some instances, the PET automatically truncates these predictions to either the minimum or maximum value observed accordingly. If a particular construction activity did not have a large enough sample size to create a linear model, then the output is modified as shown below in Figure 22.

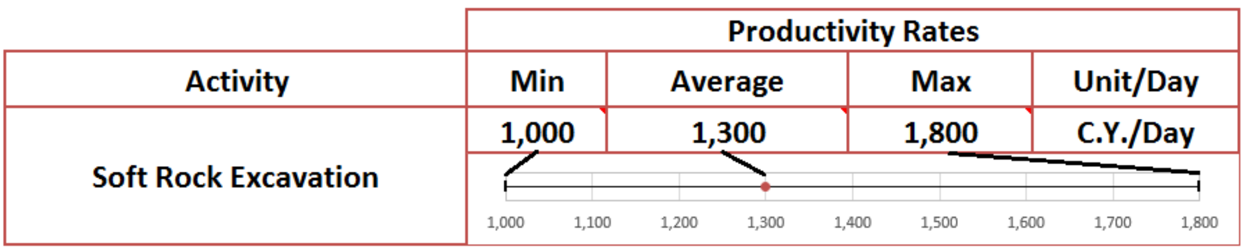


Figure 22: Output Display for Non-modeled Activities

In this type of output, the minimum value observed, average, maximum value observed, and unit of measurement are displayed for a particular construction activity. To serve as a word of caution to the users of the PET, a message indicating the sample size collected for each activity is displayed when the user hovers their mouse over the cells containing either the minimum, average, or maximum values. An example of the sample size warning message can be seen below in Figure 23.

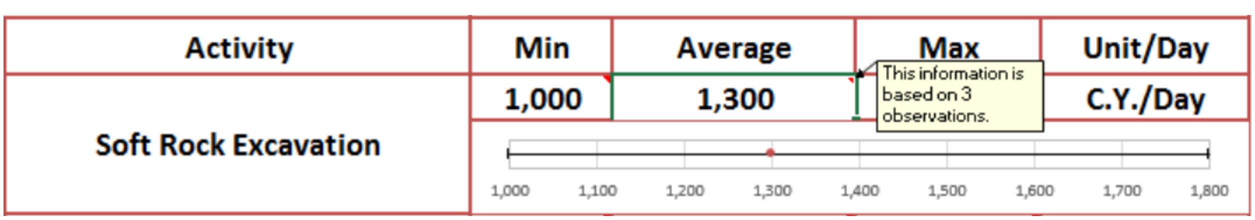


Figure 23: Sample Size Warning Message

Main Menu

After reading the instructions on the Introduction tab, users select the “Launch Tool” button at the bottom of the page, which brings them to the “Main Menu” tab. The Main Menu tab serves primarily in navigating the PET and entering basic project administrative information. A screenshot of the “Main Menu” tab can be found below in Figure 24. On the left side of the Main Menu tab, users can choose between shortcut icons that links to the user input tabs for the five construction types studied. On the right portion of the page, users can enter project ID, project location, date, description of the project, and their name. This information is then automatically linked to the succeeding user input and output tabs, which will be described in more detail later. The user is also warned to select “Enable Content” to ensure that the macros written into the PET’s MS Excel file function properly. Macros are programs and commands that can be written into a MS Excel file, and will be discussed further in Chapter 6.

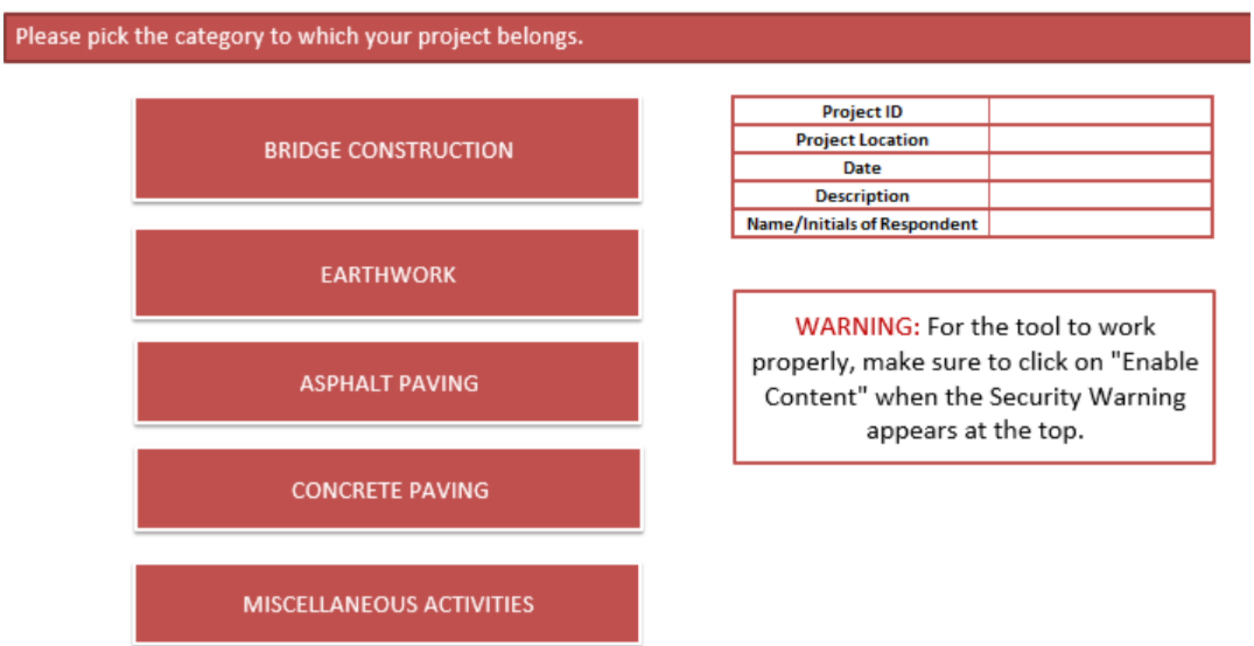
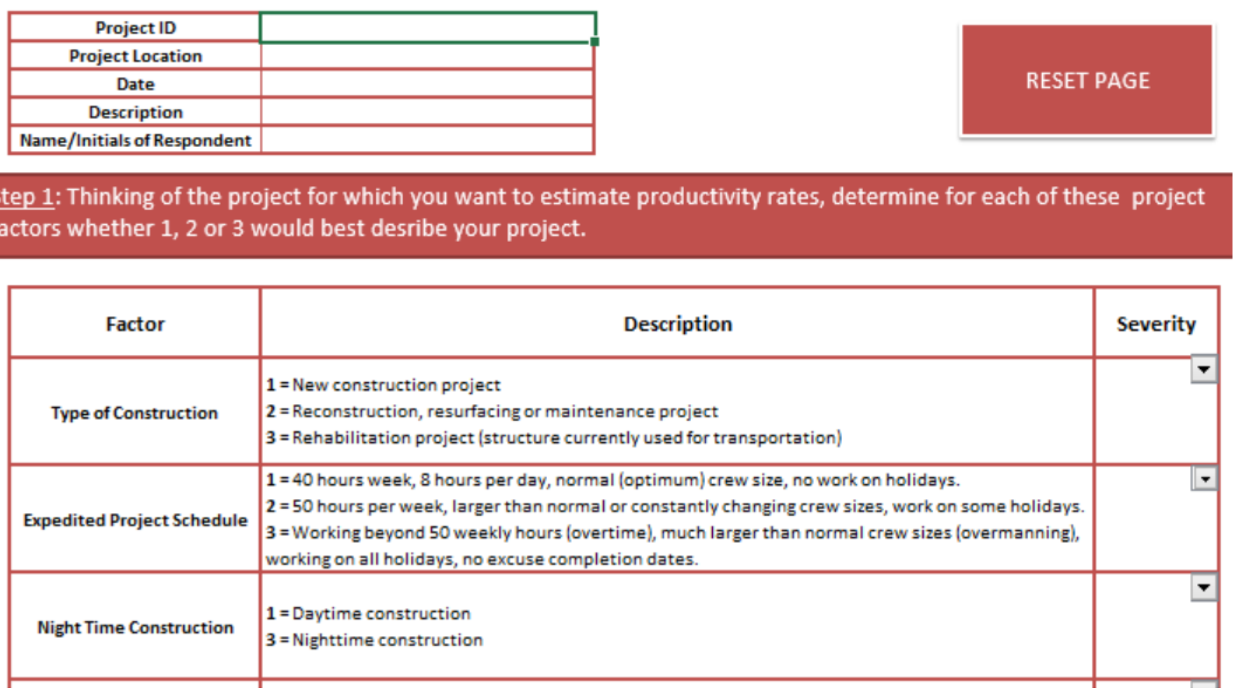


Figure 24: Main Menu Page

User Input Tabs

Once a user selects one of the five shortcut icons in the Main Menu tab shown above in Figure 24, they are brought to a user input page where they are asked to provide project factor information. Screenshots of the user input page for miscellaneous construction activities are shown below in Figures 25 and Figure 26. At the top left of the user input pages on Figure CCV, the project administrative information entered into the Main Menu page is automatically populated. The body of the user input tabs consists of questions for the user to rate the various project factors to be used in providing predicted productivity rates in the output tab. Users can either type in 1, 2 or 3, or users can make their selection from dropdown menus located at the top right of each project factor's data entry cell. The "Data Validation" tool was used in MS Excel to ensure that users are only able to enter 1, 2 or 3 as values for each project factor. The "Reset Page" icon clears all of the project information user data inputted.



Project ID	
Project Location	
Date	
Description	
Name/Initials of Respondent	

RESET PAGE

Step 1: Thinking of the project for which you want to estimate productivity rates, determine for each of these project factors whether 1, 2 or 3 would best desribe your project.

Factor	Description	Severity
Type of Construction	1 = New construction project 2 = Reconstruction, resurfacing or maintenance project 3 = Rehabilitation project (structure currently used for transportation)	
Expedited Project Schedule	1 = 40 hours week, 8 hours per day, normal (optimum) crew size, no work on holidays. 2 = 50 hours per week, larger than normal or constantly changing crew sizes, work on some holidays. 3 = Working beyond 50 weekly hours (overtime), much larger than normal crew sizes (overmanning), working on all holidays, no excuse completion dates.	
Night Time Construction	1 = Daytime construction 3 = Nighttime construction	

Figure 25: Input Page 1 of 2

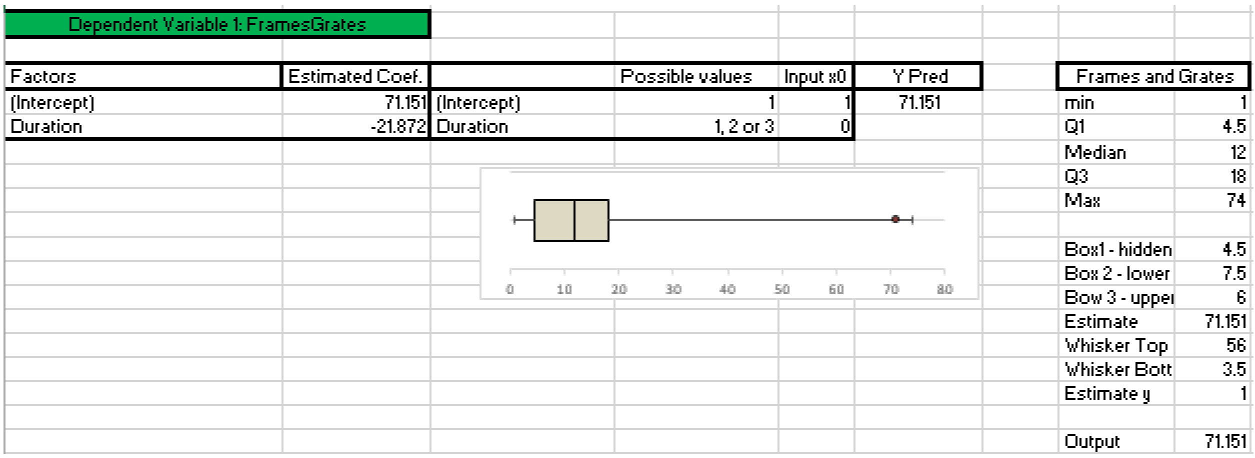
After completing an entry for each project factor, users then find three icons at the bottom of the user input page. The "Return to Main Menu" icon simply returns the user to the Main Menu page and hides all other tabs currently visible in MS Excel. The "Save as PDF" icon brings users to a windows navigation page where users can select precisely where they would like to save a copy of the user input page. Lastly, the "Get Estimated Productivity Rates" icon sends users to the "Output" tab.

Permit Restrictions	1 = Having approved environmental documents, no noise constraints, no vibration constraints 2 = Need to account for noise restrictions and/or vibration constraints during operating time 3 = Different permits needed for erosion control issues, water and dust constraints, storm water treatment, hazardous material, removal and disposal of underground fuel tanks, contaminated soils	
Materials Delivery	1 = Easy to get materials and equipment to paving site 2 = Difficult to get materials and equipment to paving site 3 = Very difficult to get materials and equipment to paving site	
Soil Moisture Condition	1 = Soil near optimum moisture 2 = Wet soil that must be dried 3 = Very wet soil	
Soil Type	1 = Soil is mainly sand 2 = Soil is granular and sandy with some silt and clay 3 = Soil is mainly wet silt, clay or silty clay	

Figure 26: Input Page 2 of 2

Hidden Tabs

The PET contains five tabs that are hidden to the user for each of the five types of highway construction activities investigated. The hidden tabs consist of two unique portions with one each for construction activities that were modeled with linear regression and construction activities that were not modeled with linear regression. In these tabs, the necessary regression coefficients and intercepts are stored until the required project factor user input is entered to compute predicted productivity rates. Various miscellaneous summary statistic information is stored in the hidden tabs as well for creating the visual output, which is then displayed in the output tabs. A screenshot of a portion of a hidden tab used to create the linear model and visual display for the construction activity “Adjust Frames and Grates” is shown below in Figure 27. An in depth explanation of the code written into MS Excel will be given later in Chapter 6 when updating the PET is discussed.



Dependent Variable 1: FramesGrates

Factors	Estimated Coef.		Possible values	Input x0	Y Pred
(Intercept)	71.151	(Intercept)	1	1	71.151
Duration	-21.872	Duration	1, 2 or 3	0	

Frames and Grates	
min	1
Q1	4.5
Median	12
Q3	18
Max	74
Box1 - hidden	4.5
Box 2 - lower	7.5
Bow 3 - uppe	6
Estimate	71.151
Whisker Top	56
Whisker Bott	3.5
Estimate y	1
Output	71.151

Figure 27: Hidden Tab Modeled Activities

In instances where construction activities were unable to be modeled using linear regression techniques in R, a different output was generated in the hidden tab as shown below in Figure XXX. For each activity, the minimum value observed, average value, maximum value observed, and sample size were stored to be used to create visual outputs and sample size warning messages. The first quartile, median, third quartile, and prediction are no longer shown. This portion of the PET does not rely upon user inputs to make a prediction, and will only change when the PET’s database is updated as more data is gathered.

	Min	Average	Max	N
Catch Basins	2	6	23	20
Chain Link Fence	349	741	2000	6
Culvert Pipe	40	179	589	16
Electrical Conduit In Trench	350	1057	2500	10
Electrical Wire Pulling(Lighting)	1000	7362	16300	8
Electrical Wire Pulling(Signals)	1000	2748	5593	4

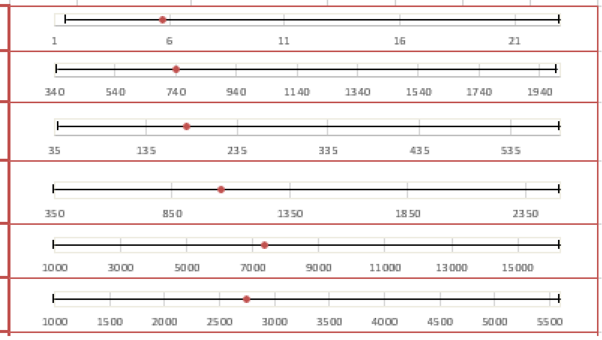
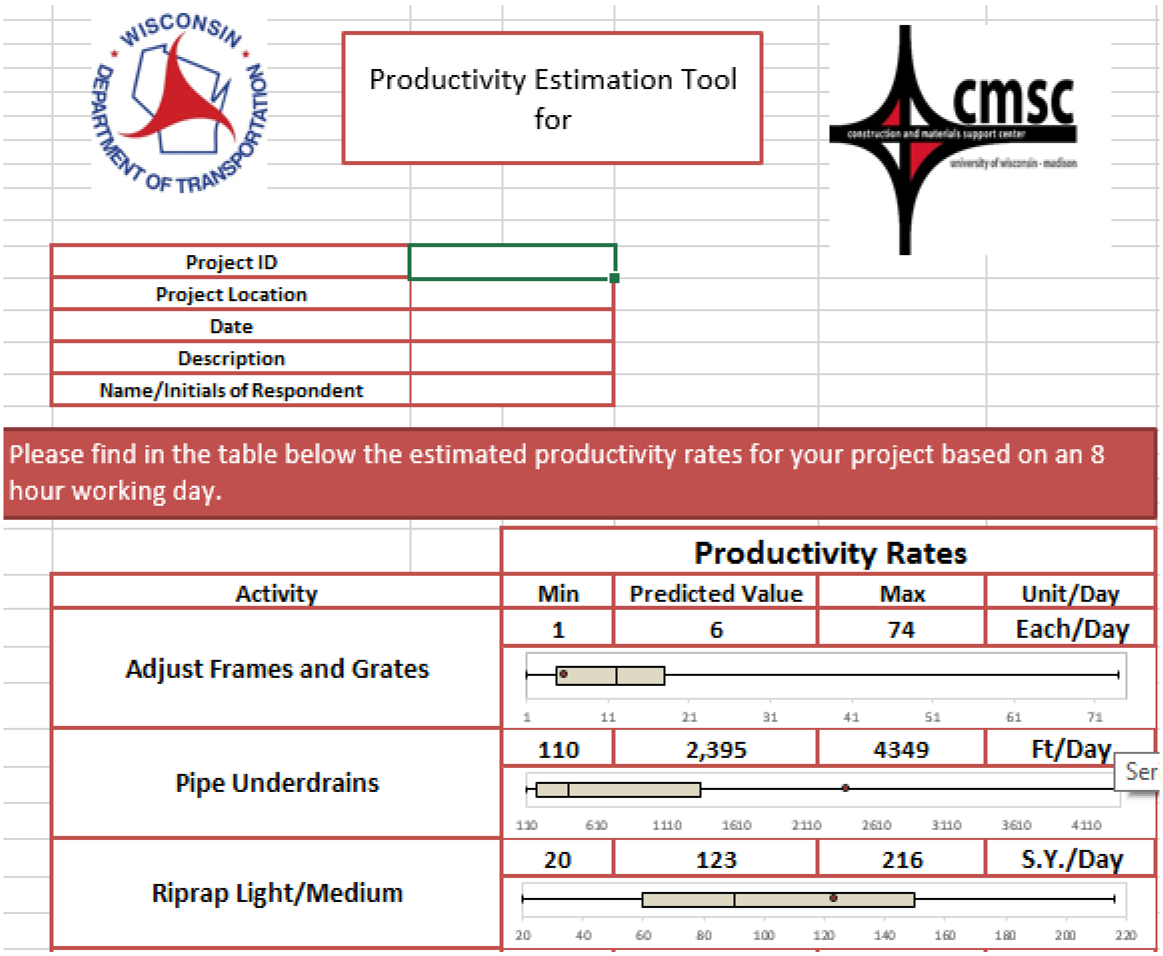


Figure 28: Hidden Tab Non-Modeled Activities

Output Tab

The output tabs in the PET are where the user ultimately acquires the information that this tool was designed to convey. A screenshot of the miscellaneous construction output tab can be found below in Figure XXX. At the top left of the output tab, users will again find the project administrative information that was entered into the Main Menu page. The user can then find productivity rates for each of the construction activities modeled. For each activity, the minimum value observed, value predicted by the PET, maximum value observed, and unit of measurement are displayed both in text and graphically.



Productivity Estimation Tool for

Project ID	
Project Location	
Date	
Description	
Name/Initials of Respondent	

Please find in the table below the estimated productivity rates for your project based on an 8 hour working day.

	Productivity Rates			
Activity	Min	Predicted Value	Max	Unit/Day
Adjust Frames and Grates	1	6	74	Each/Day
Pipe Underdrains	110	2,395	4349	Ft/Day
Riprap Light/Medium	20	123	216	S.Y./Day

Figure 29: Output Tab 1 of 2

Non-modeled construction activities are again separated in the output tabs to show their appropriate display. As seen below in Figure XXX, the minimum value observed, average value, maximum value observed, and unit of measurement are given for each construction activity. The red triangles in each of the "min, average, and max" cells indicate the sample size warning messages waiting to be discovered by the user. At the end of the output tabs, users can select from three icons. The "Return to Main Menu" icon simply returns the user to the Main Menu and hides all other tabs in MS Excel. The "Return to Project Factors" icon returns users to the project factor user input tab and hides the output tab. Finally, the “Save as PDF” icon brings users to a windows navigation page to choose specifically where to save a copy of the output tab.

	Productivity Rates			
Activity	**Min**	**Average**	**Max**	**Unit/Day**
Catch Basins	**2**	**6**	**23**	**Each**
Chain Link Fence	**349**	**741**	**2000**	**Ft**
Culvert Pipe	**40**	**179**	**589**	**Ft**

Figure 30: Output Tab 2 of 2

This concludes a brief tour of the various sections of the PET created in MS Excel. The tool is designed to be intuitive and guide the user through the tool as it is being used, if even for the first time. There are many processes and computations that are hidden from the end user, and aesthetically pleasing displays allow designers to extract necessary information. The PET is part of a larger framework or process for improving estimates of contract time awarded for completion. The PET will require periodic updates as more data is collected, and future iterations of the framework put in place to update the PET will strive to improve its utility and accuracy. Updates to the PET will require specialized training in MS Excel and the statistical program R, and will be explained in detail in Chapter 6.

Appendix F – Updating the Productivity Estimation Tool

Stepwise Regression in R

Once more data has been collected, administrators then need to acquire the R statistical software program to use in developing models with stepwise regression. The R software can be found and downloaded for free from http://www.r-project.org/. After a quick installation process, administrators can then upload the dataset and begin creating models. Before proceeding, it is important to note that there are often multiple ways for accomplishing the same task in most computer software packages. R and MS Excel are no different, and the information contained in the following chapters describes the particular methods applied by the research team. In general, the methods applied utilized the "R Console" window which appears when first launching R, rather than utilizing the R Commander user interface. In the R Console window, coding language is typed in and ran by R when the "enter" button is stricken. The results and summary of running a particular command then appear below in the R Console window, if applicable.

To upload the database into R, administrators must first ensure that the database is in the correct format. This is accomplished by transferring the information from the Google Forms databases into MS Excel CSV files. Inside of the online Google Forms database file, clicking on "File" then "download as" and then "Microsoft Excel" will create new MS Excel files containing the database's information. The preceding step simply converts the information to a generic MS Excel file, and it is necessary to save the newly created MS Excel file as the file type "CSV (Comma delimited)" when using the "save as" function inside of MS Excel.

Once the database files are converted to the CSV file format, two lines of code are used in R to load the database into the R program. First, the "working directory" in R must be set to convey where the MS Excel CSV database files to be used are stored on a particular computer.

Second, R must be given information regarding which file to upload. For this example, database files are stored in the location "C:\Users\user\Documents\Rproject" on a computer used by the research team. The name of the database CSV file to upload will be "APData.csv" and "APData" will indicated the variable R creates to hold this data. The code used to set a working directory and load a MS Excel CSV database file into R is given below by:

```
setwd("./Rproject")
APData <- read.csv("APData.csv")
```

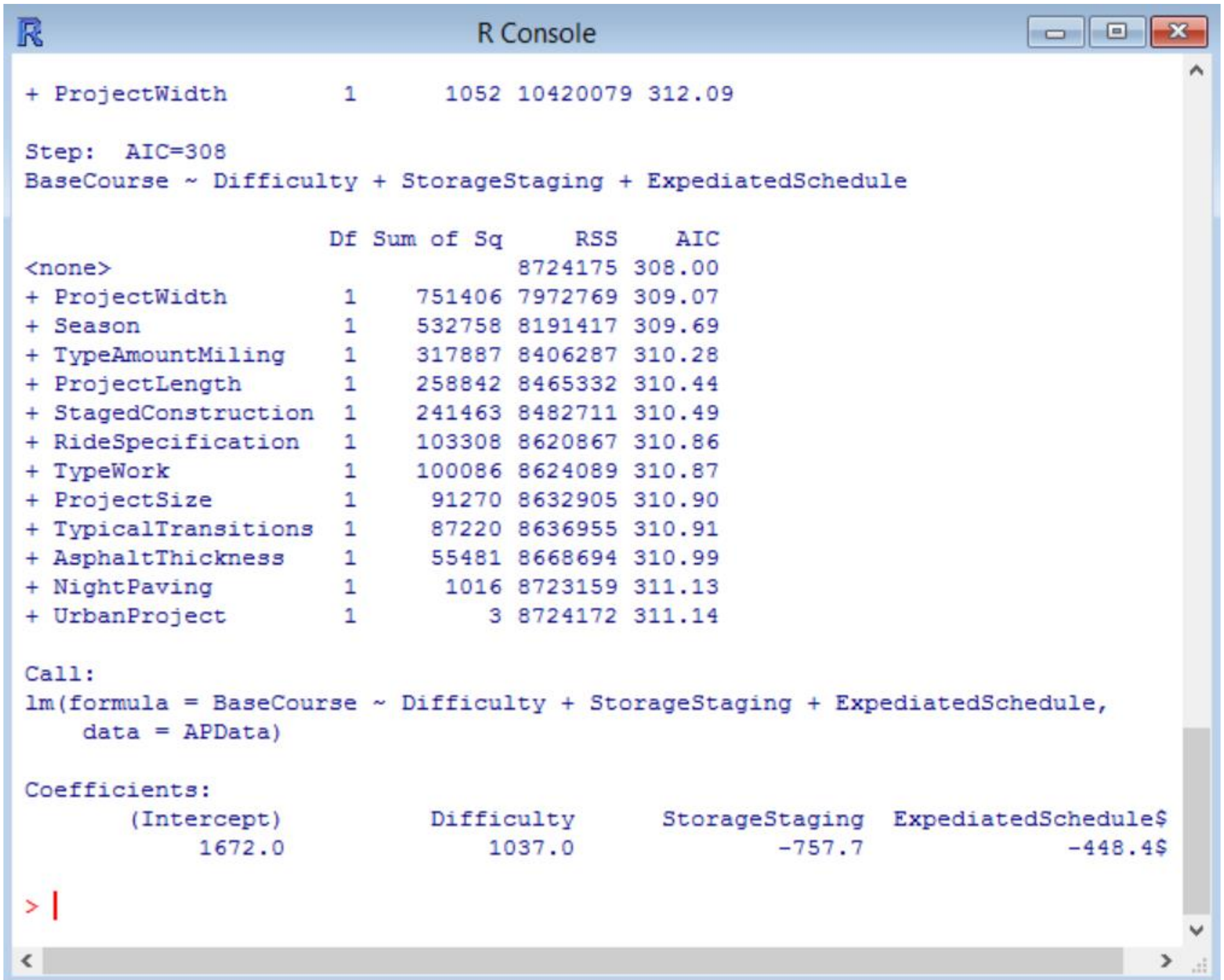
Next, a few more lines of code are required to run the stepwise function and display the results in a useful form for updating the PET. In this example, "BaseCourse" is the name of the dependent variable (construction activity) being used to create a model, and "LinearModel" is a generic name that will be given to the model once it is created in R. First, a base model must be created for "BaseCourse" which contains all of the project factors being investigated as show below by:

```
LinearModel <- lm(BaseCourse ~ Difficulty + TypeWork + ProjectSize + ExpediatedSchedule + NightPaving + ProjectLength + ProjectWidth + UrbanProject + StorageStaging + TypicalTransitions + Season + StagedConstruction + AsphaltThickness + TypeAmountMiling + RideSpecification, data = APData)
```

It is necessary to first create a base model with all of the project factors because of the requirements of stepwise regression. If "backwards selection" is chosen instead of "forward selection," R requires a full or base model to begin removing project factors from one at a time. If forward selection is chosen instead, then R can create a linear model with stepwise by building a model from nothing by adding project factors one at a time to an "empty" model. Additionally, the "R Commander" package must be loaded in R in order to run the stepwise function. The code to load R Commander and run stepwise linear regression in R are given below by:

```
library(Rcmdr)
stepwise(LinearModel, direction='forward', criterion='BIC')
```

To designate between forward and backward selection, one must specify either "forward" or "backward" in the above equation after "direction=." Similarly, to designate between the AIC and BIC stepwise criterion, one must specify either "AIC" or "BIC" in the above equation after "criterion=." It is important to note that "LinearModel" appears in the above line of code to tell R which linear model to run stepwise on. Once the stepwise function's code is ran in the R Console window, R will return a model with the project factors selected for optimizing the stepwise regression criterion. The output returned by R for the "BaseCourse" activity after running stepwise regression in our example is shown below in Figure 31.



```
R Console
+ ProjectWidth        1      1052 10420079 312.09

Step:  AIC=308
BaseCourse ~ Difficulty + StorageStaging + ExpediatedSchedule

                     Df Sum of Sq     RSS    AIC
<none>                            8724175 308.00
+ ProjectWidth        1    751406 7972769 309.07
+ Season              1    532758 8191417 309.69
+ TypeAmountMiling    1    317887 8406287 310.28
+ ProjectLength       1    258842 8465332 310.44
+ StagedConstruction  1    241463 8482711 310.49
+ RideSpecification   1    103308 8620867 310.86
+ TypeWork            1    100086 8624089 310.87
+ ProjectSize         1     91270 8632905 310.90
+ TypicalTransitions  1     87220 8636955 310.91
+ AsphaltThickness    1     55481 8668694 310.99
+ NightPaving         1      1016 8723159 311.13
+ UrbanProject        1         3 8724172 311.14

Call:
lm(formula = BaseCourse ~ Difficulty + StorageStaging + ExpediatedSchedule,
    data = APData)

Coefficients:
       (Intercept)          Difficulty      StorageStaging  ExpediatedSchedule$
            1672.0              1037.0              -757.7               -448.4$

>
```

Figure 31: Stepwise Function Output in R

In the figure above, R has returned the results of the stepwise function to include the R code for generating the model selected, model intercept, and project factor regression coefficients. It is important to note that the results from stepwise regression should be further investigated before accepting the equation given by the intercept and coefficients returned. Stepwise optimizes either the AIC or BIC criterion, and this does not always lead to project factors with p-values lower than 0.05. Instead it is vital to run a summary of the results to gain a further understanding of the results. The code required to load the model selected by stepwise regression and view a summary of the results are shown below:

LinearModel <- lm(formula = BaseCourse ~ Difficulty + StorageStaging + ExpediatedSchedule, data = APData)

summary(LinearModel)

The first line above creates a model called "LinearModel" for the construction activity "BaseCourse" using the project factors difficulty, size and proximity to storage and staging areas, and the presence of an expedited schedule, as suggested by stepwise. The second line of code runs a summary of the model "LinearModel" that was created in the prior step. A screenshot of the summary output returned by R is shown below in Figure 32.

```
> LinearModel <- lm(formula = BaseCourse ~ Difficulty + StorageStaging + Exped$
+     data = APData)
> summary(LinearModel)

Call:
lm(formula = BaseCourse ~ Difficulty + StorageStaging + ExpediatedSchedule,
    data = APData)

Residuals:
     Min       1Q   Median       3Q      Max
-1442.95  -388.51   -24.61   472.59   997.05

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
(Intercept)          1672.0      471.8   3.544 0.002169 **
Difficulty           1037.0      259.2   4.001 0.000764 ***
StorageStaging       -757.7      271.1  -2.794 0.011565 *
ExpediatedSchedule   -448.4      233.3  -1.922 0.069675 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 677.6 on 19 degrees of freedom
  (51 observations deleted due to missingness)
Multiple R-squared:  0.4699,    Adjusted R-squared:  0.3862
F-statistic: 5.614 on 3 and 19 DF,  p-value: 0.006267
```

Figure 32: R Summary Output

In the summary output above, the intercept, project factors selected, and the estimated regression coefficients can be found for updating the MS Excel based PET. After further investigation in Figure 18, the "ExpediatedSchedule" project factor has a p-value of 0.069, and further consideration is required to decide whether or not to include this project factor in the final model. If a project factor is selected for removal, the project factor simply needs to be removed from the model's R code as shown below by:

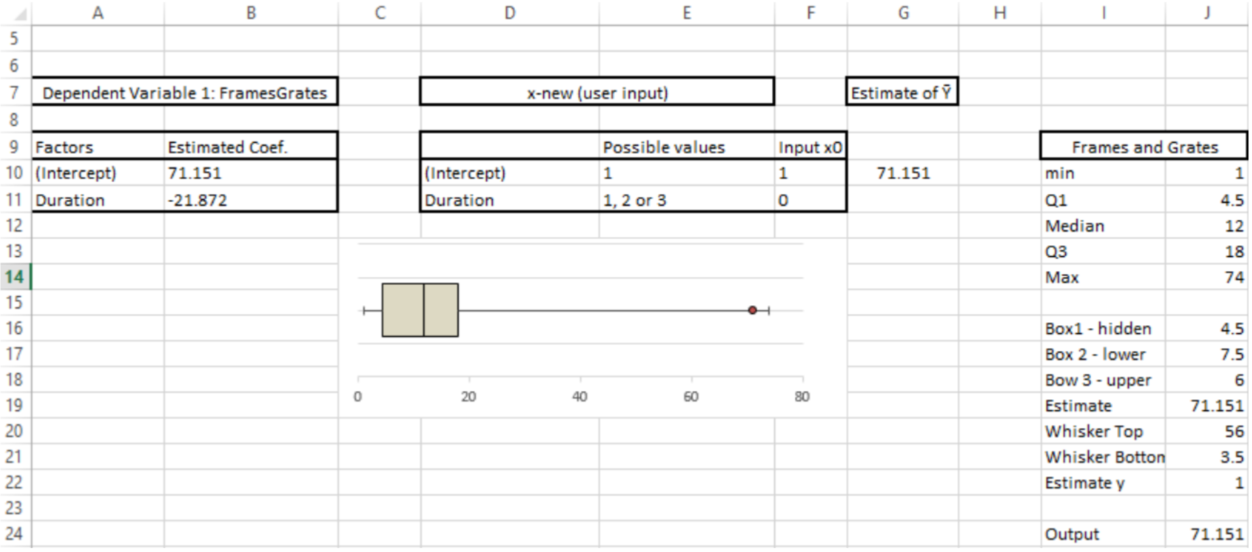
```
LinearModel <- lm(formula = BaseCourse ~ Difficulty + StorageStaging,  data = APData)
```

Updating the Productivity Estimation Tool in MS Excel

While R was used to derive linear regression models, MS Excel allowed the research team to organize and incorporates vast amounts of information into an intuitive user interface. Consequently, it is required to transfer the intercepts, project factors, and regression coefficients obtained from R into MS Excel to update the PET. However, updating the PET in MS Excel will require other methods as well due to not all of the construction activities included in the data collection tool being able to generate linear models. In the case of non-modeled construction activities, information such as the average value observed need to be ascertained from the database and updated in the PET instead. Additionally, it is likely that the next iteration of updates to the PET will possess a larger dataset that will support the creation of additional models for construction activities that currently do not have models generated. In this instance, administrators will be required to create visual outputs and create specific relationships between cells in MS Excel.

First and foremost, when updating the PET administrators will first have to unprotect the tabs or sheets in MS Excel to make updates. Sheets are protected with a password that when entered will allow an administrator to make revisions to the PET. To unlock a sheet, administrators must navigate to the “Review” tab in MS Excel and select the “Unprotect Sheet” icon. The current password for unlocking the PET is simply “1” and can be changed at any time. Sheets can have their protection restored by selecting the “Protect Workbook” icon next to the “Unprotect Sheet” icon and entering a new password for sheet protection. Additionally, there are hidden sheets in the PET for each of the five construction types where the calculations are performed to generate the results to display on the output sheets. To unhide a tab, administrators must right click on any visible sheet, select unhide, and then select a sheet to unhide. After completing the previous steps, administrators will have gained access to the portions of the PET required for making revisions.

Once the necessary protections have been removed from sheets in MS Excel, administrators must update current models, generate new models where possible, and update the production rates provided for non-modeled activities. For the most part, the work needed to update the PET will occur in the hidden sheets of the MS Excel file. The workspace used to create linear models that rely on user input in the PET’s hidden sheets is shown below in Figure 33.



	A	B	C	D	E	F	G	H	I	J
5										
6										
7	Dependent Variable 1: FramesGrates			x-new (user input)			Estimate of Ŷ			
8										
9	Factors	Estimated Coef.			Possible values	Input x0			Frames and Grates	
10	(Intercept)	71.151		(Intercept)	1	1	71.151		min	1
11	Duration	-21.872		Duration	1, 2 or 3	0			Q1	4.5
12									Median	12
13									Q3	18
14									Max	74
15										
16									Box1 - hidden	4.5
17									Box 2 - lower	7.5
18									Bow 3 - upper	6
19									Estimate	71.151
20									Whisker Top	56
21									Whisker Botton	3.5
22									Estimate y	1
23										
24									Output	71.151

Figure 33: PET Hidden Sheet

In the above example, the construction activity "Adjust Frames and Grates" is used to convey the composition of the hidden sheets. Cells A10:A11 contain the linear model's intercept and the project factor duration which was found by stepwise regression to have a significant relationship with this particular activity's production rate. Cells B10:B11 contain the numerical values for the regression coefficients obtained from R. The cells contained in the range D9:F11 pull and hold information from the user input tab to be used in computing a predicted productivity rate. Cell G10 holds the linear regression equation that was created, and automatically computes the predicted rate when users complete the user input tab. The equation stored in cell G10 adds the equation's intercept to the product of the project factors and their respective user inputted project factor values and is shown below by:

=B10*F10+B11*F11

Cells I9:J24 contains the information required for making the graph that is displayed on the output tabs. Specifically, cells J10:J14 contain the minimum value observed, first quartile, median, third quartile, and maximum value observed. These values can be obtained from the MS Excel CSV files that were generated by transferring the database from Google Forms to MS Excel to be used in. The cells in the range of I16:J22 contain equations that were developed to create the box-and-whisker plot output as seen in cells C13:F19, and most will update automatically when the construction activity's sample population summary statistics (minimum, median, etc.) are updated. However, the error bars or whiskers on the visual display will not update automatically, and administrators must ensure that the error bars are updated on the output tab as well. To update the error bars, administrators must select the graph to highlight it, select the "Design" tab under "Chart Tools," select "Add Chart Element," select "Error Bars" and select "More Error Bar Options" to navigate to the "Format Error Bars" window. Alternatively, administrators can navigate to the "Format Error Bars" window by selecting the graph and double clicking on one of the error bars. Next, administrators must select "Custom" to specify a value for the error bars. The error bar on the left of the graph indicates the minimum value observed and its magnitude can be found under cell J:21. Once the magnitude of the error bars has been revised, the updates required for a previously modeled activity are complete. To reiterate, no further revisions are required on these activities because the production rates displayed on the output tab will update automatically when revisions to summary statistics and regression coefficients are made in the hidden tab.

Next, new models will likely be generated from previously non-modeled activities. These construction activities will require more work to update because each new model will need a workspace created in the hidden tab similar what currently exists for modeled activities.

Explaining the steps required to recreate the workspace for modeled activities in the hidden sheets does not fall under the scope of this chapter because the steps involved more closely resemble a guide for using MS Excel than a guide to the logic and equations used to develop this tool. However, MS Excel will copy the equations presently used in a workspace, and only minor adjustments are required. If an administrator were to simply copy cells A5:J24 and paste them below in the hidden sheets workspace, all of the equations used to generate a prediction and box-and-whisker plot will transfer as well. With this advantage, administrators then only need to update the information contained in cells that store the intercept, regression coefficients, and summary statistics to generate a new predicted value and box-and-whisker plot. Next, administrators must transfer the newly created model's information to the output tab. Similarly, administrators can copy and paste the output of a previously created model and update the values to reflect the model being created in the hidden tab. Finally, administrators will then need to delete the newly modeled construction activity's display from the lower section of the output sheet that conveys summary statistics for non-modeled activities.

Finally, the remaining non-modelled construction activities require updates to their summary statistics stored below the modeled activities in the hidden tab. A screenshot of the workspace used to generate output for the non-modeled activities can be found below in Figure 34. In this workspace, it is necessary to update the minimum value observed, average value computed, maximum value observed, sample size, and scale on the visual output's horizontal axis. Changing summary statistics in the hidden tab will again automatically update the values reported on the output tab. However, it is important to note that the horizontal scales on the visual outputs will not automatically update. To update a graphs scale, simply double click on the scale below the graph's number line to navigate to the "Format Axis" window, and change the minimum and maximum bounds of the axis to reflect the minimum and maximum values observed.

	Min	Average	Max	N
Catch Basins	**2**	**6**	**23**	**20**
Chain Link Fence	**349**	**741**	**2000**	**6**
Culvert Pipe	**40**	**179**	**589**	**16**
Electrical Conduit In Trench	**350**	**1057**	**2500**	**10**
Electrical Wire Pulling(Lighting)	**1000**	**7362**	**16300**	**8**
Electrical Wire Pulling(Signals)	**1000**	**2748**	**5593**	**4**

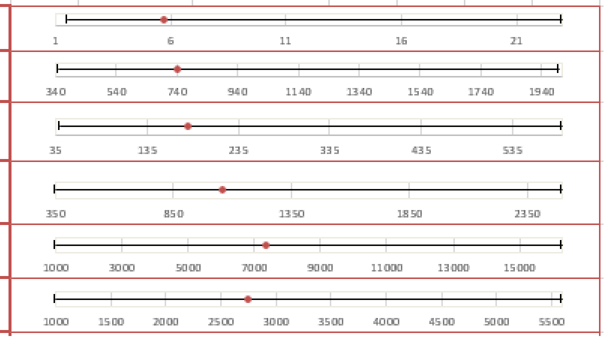


Figure 34: Hidden Tab Non-Modeled Activities

Lastly, the sample size warning messages on the output tab must be updated to reflect any increase in sample size for a particular activity. To do so, select a cell which contains a warning message to be updated, hold "Shift," and press "F2" on the keyboard to bring up a window for modifying comments. After completing these steps, the non-modeled activity revisions are complete, and an improved version of the tool is ready to be redistributed for future use.

Appendix G – R Code Samples

The following information serves as examples of the code developed and used in R to conduct the statistical analysis for this study. First, the code shown for the activity “Hot Mix Asphalt Lower Layer” (HMALL) details how to run stepwise linear regression. Next, the code for the activity “Frames and Grates” shows the code used to run five-fold cross validation on the model that was generated by stepwise regression.

1. HMALL Stepwise Regression Model Selection

```
LinearModel <- lm(HMALL ~ Difficulty + TypeWork + ProjectSize
+ ExpediatedSchedule + NightPaving + ProjectLength + ProjectWidth
+ UrbanProject + StorageStaging + TypicalTransitions + Season
+ StagedConstruction + AsphaltThickness + TypeAmountMiling
+ RideSpecification, data = APData)

stepwise(LinearModel, direction='forward', criterion='BIC')

LinearModel <- lm(formula = HMALL ~ ProjectSize, data = APData)

summary(LinearModel)
```

2. Frames and Grates Validation

```
data <- read.csv("FramesGrates.csv")
index <- cvFolds(15, K = 5, R = 1,type = "random")
LinearModel <- lm(formula = FramesGrates ~ Duration, data = data)
for(i in 1:5){
  print(paste("fold:",i))
  newdata <- data[-index$subsets[index$which == i],]
  fit.tmp <- update(LinearModel,data = newdata)
  pred.tmp = predict(fit.tmp,newdata=data)[index$subsets[index$which == i]]
  print(pred.tmp)
  print(data[index$subsets[index$which == i],"FramesGrates"])
}
```

Appendix I – Sample Survey

Data Collection Tool for
Earthwork Projects

Project ID	1133-10-72
Project Location	US 41 brown county
Date	
Name of Respondent	

Step 1: Determine for each of these factors whether 1, 2 or 3 would best desribe the level of severity of your project.

Factor	Description	Severity
Project Duration	**1 =** Short (≤ 20 calendar weeks) **2 =** Mid-range (20-30 calendar weeks) **3 =** Long (≥ 30 calendar weeks)	3
Project Size	**1 =** Small (≤ 135,000 total cubic yards) **2 =** Medium (135,000 - 300,000 total cubic yards) **3 =** Large (≥ 300,000 total cubic yards)	2
Type of Construction	**1 =** New construction project **2 =** Reconstruction, resurfacing or maintenance project **3 =** Rehabilitation project (structure currently used for transportation)	1
Expedited Project Schedule	**1 =** 40 hours week, 8 hours per day, normal (optimum) crew size, no work on holidays. **2 =** 50 hours per week, larger than normal or constantly changing crew sizes, work on some holidays **3 =** Working beyond 50 weekly hours (overtime), much larger than normal crew sizes (overmanning), working on all holidays, no excuse completion dates.	2
Night Time Construction	**1 =** Daytime construction **3 =** Nighttime construction	1
Project Length	**1 =** Short stretch **2 =** Medium stretch **3 =** Long stretch	2
Urban Project	**1 =** Rural area no traffic **2 =** Rural area under traffic **3 =** Urban area with city streets, nearby residents, commercial buildings, urban cross-sections	1
Materials Delivery	**1 =** Easy to get materials and equipment to construction site **2 =** Some delays in getting materials on site (long distances, traffic congestion) **3 =** Very difficult to deliver materials to site	2
Project Constraints	**1 =** No site constraints (few utilities, intersections, driveways, gaps, roundabouts) **2 =** Moderate site constraints (some utilities, ramps, limited space for equipment, adjacent buildings) **3 =** Difficult site constraints (presence of significant utilities, conflict with other operations)	2
Season	**1 =** Summer, air temperature above 60 °F, some rainfall (minimum level) **2 =** Spring or fall, air temperature between 35 and 60 °F, moderate level of rainfall **3 =** Winter, air temperature below 35 °F, extreme rainfall and snow	2
Soil Moisture Condition	**1 =** Soil near optimum moisture **2 =** Wet soil that must be dried **3 =** Very wet soil	3
Soil Type	**1 =** Soil is mainly sand **2 =** Soil is granular and sandy with some silt and clay **3 =** Soil is mainly wet silt, clay or silty clay	3
Staged Construction	**1 =** Single phase **2 =** Two phases, project done half at a time **3 =** Three or more phases, portions of project done in different stages and multiple mobilizations	2
Project Complexity	Based on your experience and your past projects, you consider this project to be: **1 =** Normal Project **2 =** Difficult Project **3 =** Very Difficult Project	2

Figure 35: Sample Survey 1 of 2

Step 2: Determine the productivity rates achieved on your project for the activities listed below.

Activity	Productivity Rates	Unit
Excavation: Truck	4,986	C.Y./Day
Excavation: Scraper		C.Y./Day
Excavation: Articulated Truck		C.Y./Day
Base Course Roadway	1,988	Ton/Day
Base Course Shoulders	737	Ton/Day
Breaker Run	1,228	C.Y./Day
Shallow Excavation: Shoulders + Ditches		C.Y./Day
Soft Rock Excavation		C.Y./Day
Hard Rock Excavation		C.Y./Day
Topsoil Placement		C.Y./Day
Marsh Excavation (depth ≤8')		C.Y./Day
Marsh Excavation (depth >8')		C.Y./Day
Excavation Below Subgrade (EBS)		C.Y./Day
Clearing and Grubbing		Stations/Day

Step 3: Provide your input to improve the data collection tool by including activitie that you already track or activities that should be tracked in the future.

Activity	Productivity Rates	Unit

Figure 36: Sample Survey 2 of 2