# EFFECTIVE PRODUCTION RATE ESTIMATION USING CONSTRUCTION DAILY WORK REPORT DATA

FHWA/MT-19-001/9344-504

*Final Report*

*prepared for*
THE STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION

*in cooperation with*
THE U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION

*January 2019*

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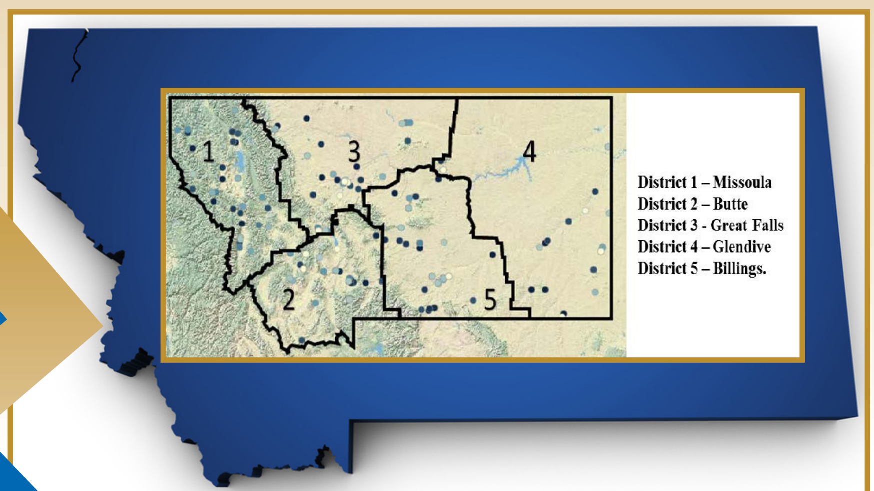


RESEARCH PROGRAMS

MDT

# Effective Production Rate Estimation Using Construction Daily Work Report Data

# Phase I Report

IOWA STATE UNIVERSITY
Institute for Transportation

Effective Production Rate Estimation Using Construction Daily Work Report Data

Phase I Report

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**Sponsored by**
Montana Department of Transportation

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**16. Abstract**

Accurate and practical production rate estimates are crucial for an accurate forecast of contract completion time. As costs of highway projects increase with time, the importance of estimating highway construction contract time has increased significantly, thereby emphasizing the need for effective production rates due to the interrelatedness between the two. By reviewing the literature, various aspects of production rate estimation were identified including factors that influence production rates, production rate adjustment factors, and statistical methods, and current practices of the Montana Department of Transportation (MDT). The purpose of this research was to develop historical data-driven estimates of production rates using daily work report (DWR) data in order to enhance current contract time determination practices.

The research team analyzed the MDT's DWR data along with bid data and GIS data to estimate realistic production rates. Descriptive analysis, regression analysis, and Monte Carlo simulation were deployed to offer insights into historical projects' characteristics and production rates of 31 controlling activities of MDT. The major findings of the descriptive analysis were statistical measures (i.e., mean, first quartile, median, and third quartile) of 31 controlling activities, which provide more practical, detailed, and updated estimates in comparison with the current published values. In addition, variations of production rates in terms of different seasons of work, districts, area types (urban/rural), and budget types were explored. The study also developed regression equations to estimate production rates of 27 out of 31 controlling activities. For each activity, factors that had a significant effect on production rate were included in the regression model as predictor variables. Besides, a production rate-based method was proposed to evaluate contractor's performances, and a Microsoft Excel based Production Rate Estimation Tool (PRET) was developed to assist MDT practitioners.

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# 1. Introduction

Contract time for state highway projects is the maximum time allowed in the contract for completion of all work contained in the contract documents (FHWA 2002). An accurate forecast of contract time is crucial to contract administration as the predicted duration and associated cost form a basis for budgeting, planning, monitoring and even litigation purposes (Jeong et al. 2008). Excessive contract time is costly because it extends the construction crew's exposure to traffic, prolongs the inconvenience to the public (unnecessary increase of road user costs), hinders local businesses, increases the construction costs, and subjects motorists to less than desirable safety conditions for longer periods of time (Chong et al. 2011). Insufficient contract time results in higher bids, overrun of contract time, increased claims, substandard performance, and safety issues. Due to significant importance of contract time determination, Title 23 Code of Federal Regulations (CFR) Section 635.121 requires that States should have adequate written procedures for the determination of contract time and most State Department of Transportations (DOTs), including Montana DOT (MDT) have a written document describing their procedure to determine a project's contract time. Since a transportation agency maintains numerous ongoing projects under its portfolio, accurate contract time estimation will lead to the timely completion of projects, better success rate and efficient use of funds.

The quantity of production accomplished over a specified period is termed as production rate. Realistic production rates are the key to determining reasonable contract times which are neither excessive nor inadequate (Herbsman and Ellis 1995). Conventionally, the state agencies publish the production rates to be used uniformly across the state. This practice helps to follow the Federal Highway Administration (FHWA) guidelines to implement uniform production rates across the states. However, it has intrinsic constraints – the production rates vary greatly depending upon the quantity to be produced, type of project, geographical location of the project, the budget allocated for the project, seasonal limitations, weather, and contractors' capacity (Aoun 2013).

This Phase I report summarizes the findings from extensive literature review on production rate estimation and the results of the descriptive and predictive analysis of daily work report (DWR) data. The findings from the literature are discussed in section 2. Current contract time determination procedures of MDT are reviewed in section 3. Section 4 provides an insight into parameters that significantly influence production rates, which are determined by the results of the descriptive analysis of DWR data. Section 5 consists of the development of regression models for production rate estimations, statistical measures of production rates from historical data, and a proposed method to evaluate contractors' performance using production rates obtained from past projects. A production rate estimation tool was developed based on the results of section 5 and is discussed in section 6.

# 2. Literature review

This section discusses major factors that affect production rates of controlling work activities for highway projects and the range of tools used for production rate estimation. FHWA (2002) recommends that in estimating production rates of work items, an accurate database should be established by using normal historical rates of efficient contractors. The most accurate data can be obtained from reviewing project records (i.e., DWR data and other construction documents) where the contractor's progress is clearly documented based on work effort, including work crew makeup during a particular time frame (Hildreth 2005).

Conventionally, most state DOTs use a rule of thumb and/or a published list of production rates that were developed years ago. Since highway construction is an outdoor construction operation that involves several types of activities that are heavily affected by a number of operational and environmental conditions, common production rate estimation methods such as expert opinion, engineering judgment, and production rate charts have serious limitations. One of the main limitations is that unique project factors and site conditions are very difficult to be considered quantitatively (FHWA 2002).

## 2.1. Production rate estimation

The production rates of major construction activities, which fall on the critical path in the project schedule, play an important role in planning project resources and tracking project progress (Jeong and Woldesenbet 2010). Use of static production rates was found in some form across numerous contract time determination manuals. The production rate tables provided by DOTs consisted of highway work items ranging from 20 to over 200 items. Penn DOT has only 20 work items, yet it is used consistently because it goes through multiple reviews from multiple stakeholders. Once the production rate estimates have been modified to the satisfaction of the stakeholders, it is then used to determine the project completion date and project duration. The accuracy of the estimated production rates is very crucial for effective contract administration. Studies suggest that the significant factors that influence production rates are weather and seasonal effects, project location, traffic impacts, project types, etc. (Jeong and Woldesenbet 2010).

### *2.1.1. Factors influencing production rates of major work items*

Establishing factors that influence the production rates in a region is critical for improving accuracy in production rate estimates. Numerous production rate estimation and validation studies clearly show that production rates vary widely depending upon project-specific factors (Jeong and Woldesenbet 2010). Some of the common factors which influence production rates are location, route type, weather, project type, and operating conditions. When those factors are appropriately incorporated into the production rate estimation process, the contract time determination process will be more accurate and become meaningful for contract administration. An advanced and consistent estimation system which accommodates unique project factors can provide production rate estimates with higher accuracy. Common factors found in the literature are portrayed in Figure 2-1.

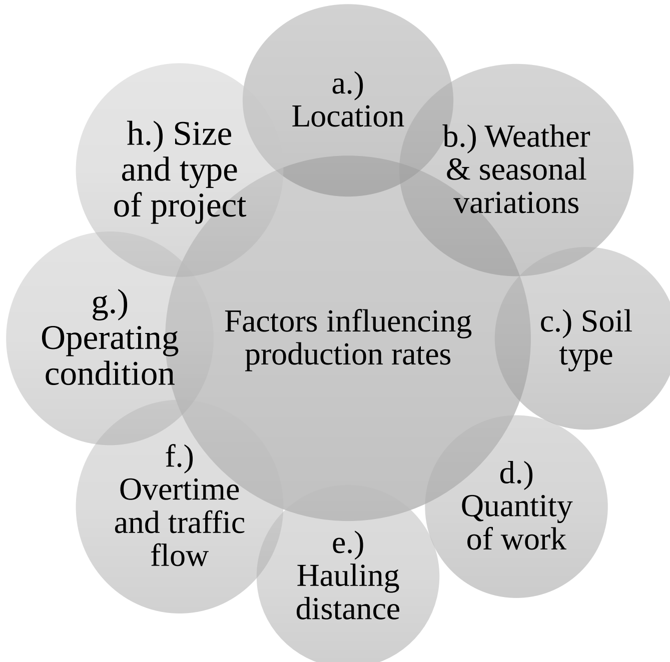



**Figure 2-1: Factors that significantly impact production rates**

*2.1.1.1. Effect of location on production rates*

The location of a project is an important factor that determines the terrain and area type. Studies show that rural and urban distinction can be made by classifying location using an indicator, such as population, annual average daily traffic, and terrain type. Figure 2-2 depicts the difference in production rates between urban and rural areas for six activities (Jeong and Woldesenbet 2010). Some DOTs classify location based on district topography as well as rural and urban classification. Rural areas are not prone to high average daily traffic which often causes disruptions to the activities like excavation in urban areas. The trend as shown in Figure 2-2 clearly justifies that rural production rates are higher for certain activities like borrow excavation.

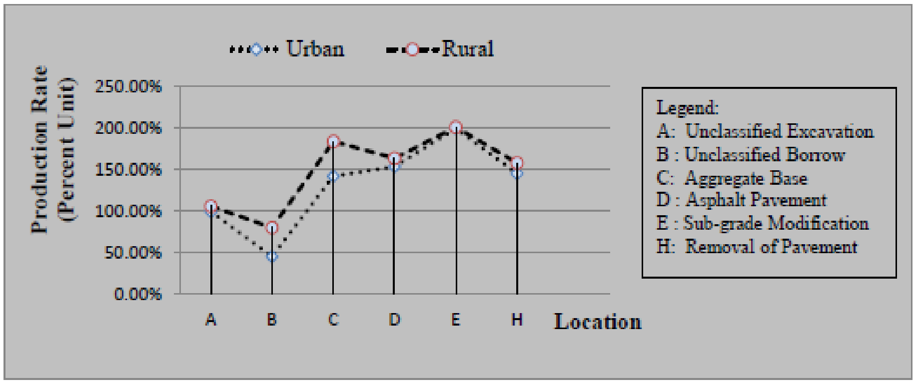



**Figure 2-2: Effect of location on production rates**

Figure 2-3 depicts a gradual increase in production rates among route types from city street to state highway, US highway, and interstate. City streets contain much traffic in a relatively congested area which might lead to frequent production delays. The production rate of unclassified highway excavation on an interstate is higher due to ease in management of traffic and availability of space.

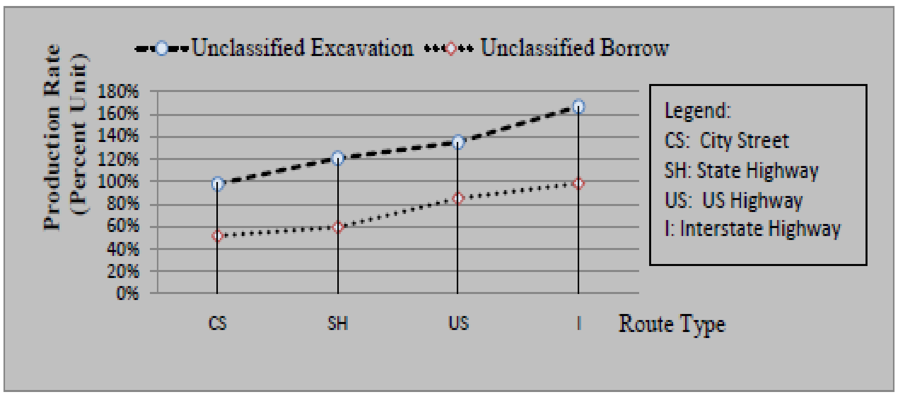



**Figure 2-3: Effect of route types on production rates**

*2.1.1.2. Effect of seasons on production rates*

Weather plays an important role in influencing production rates achieved for major work items. Sometimes due to extreme weather conditions, construction activities come to a halt. Rain and snow can hamper production rates significantly and therefore need to be considered during the contract time estimation process. Additionally, temperature has a significant impact on the production rates. Jiang and Wu (2007a) determined that the highest production rates occur at air temperature between 70 and 80 Fahrenheit. Considering high production rates during summer will produce erroneous estimates as extreme heat also hinders production rates. To accommodate production rate adjustments according to the weather conditions, production rates for asphalt concrete pavement across four seasons and the Oklahoma Department of Transportation (ODOT)'s range of production rate were compared using box plots as shown in Figure 2-4 (Jeong and

Woldesenbet 2010). The visual analysis shows that the median production rate in summer and fall is relatively much higher than that of winter and spring (Jeong and Woldesenbet 2010).

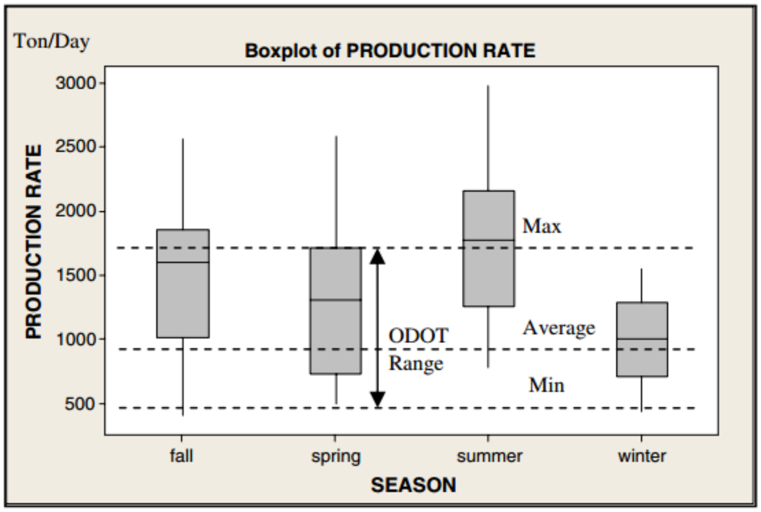



**Figure 2-4: Effect of seasons on production rates (Jeong and Woldesenbet 2010)**

*2.1.1.3. Effect of soil type on production rates*

"The type of soil encountered in a construction job site greatly affects the productivity of highway construction especially earthwork constructions" (Jeong and Woldesenbet 2010). Operating conditions of the soil type determine the production rate adjustment factor required for the job site. The American Standard for Testing Materials (ASTM) uses Unified Soil Classification System based on laboratory determination of particle size characteristics, liquid limit and plasticity index. This classification system identifies three major soil divisions: coarse-grained soils, fine-grained soils, and highly organic soils. These divisions are further divided into 15 basic soil groups (Jeong and Woldesenbet 2010). Information regarding the soil type can be used to develop adjustment factors to production rate estimates. Heavy clay or rock soils require heavy equipment and machinery while sandy or clay soils are easier to operate and handle. Understanding the soil types and developing appropriate adjustment factors for each soil type can guide DOT estimators to develop effective production rate estimates.

*2.1.1.4. Effect of quantity of work on production rate*

The amount or quantity of work to be accomplished in a construction project has impact on production rates of construction activities. Based on the quantity of work, the availability of materials, allocation of resources, construction management, and selection of construction means & methods determine the range of highway production rates. Increase in quantity of work increases production rates of construction operations as better equipment, resources, and construction methods are utilized to decrease the average cost of construction. The effect of quantity of work can be explained by the economies of scale (Jeong and Woldesenbet 2010). Figure 2-5 shows a scatterplot between production rate and quantity of work for lime treated sub-grade (O'Connor et al. 2004). The relation between production rates and quantities of work gradually keeps increasing following a log-linear curve.

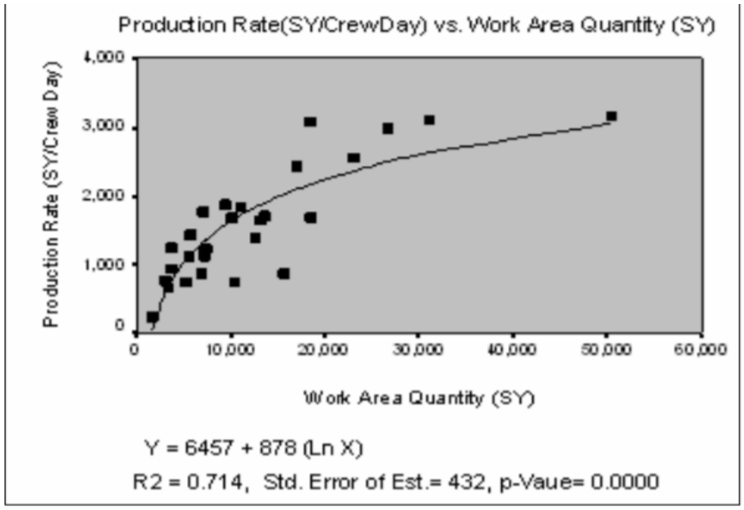



**Figure 2-5: Effect of quantities on production rates**

*2.1.1.5. Effect of haul distance on production rates*

The distance to move materials to and from the job site is another critical factor affecting highway construction production rates. Haul distance has a higher impact on bulk excavation and pavement construction activities. Considering an earthmoving activity, shorter haul distances (less than 1,000 feet) will result in a reduced cycle time which in turn increases production rates.

*2.1.1.6. Effect of overtime and traffic flow on production rates*

Overtime also hampers labor productivity significantly. A decrease in efficiency of 10 to15 percent is observed for scheduled overtime scenarios of fifty working hours and sixty working hours per week when compared with a forty-hour work week (Thomas and Raynar 1997). Disruptions also lead to productivity loss as work is directed to overcome the constraints faced by the project (Halligan et al. 1994). More working days per week are required when there is a higher frequency of disruptions (Thomas and Raynar 1997). Rework, availability of tools, material availability and equipment availability have a significant impact on performance (Thomas and Raynar 1997). Location of a construction site can affect the production rates with a significant magnitude. Worker motivation (Borcherding and Garner 1981; Borcherding et al. 1980) and the availability of skilled labor (Koehn and Brown 1985) both have a significant impact on construction productivity.

Jiang and Adeli (2003) studied the effects of traffic flow on the construction productivity of hot mix asphalt pavement. He found that traffic delays increased the cycle time of transporting trucks. Due to this, the construction productivity, in terms of tonnage per hour, decreased. Advancement in technology has led to an increase in construction productivity due to the increased level of control, amplification of human energy, and information processing (Schexnayder and David 2002). Production rates under ideal conditions have increased 1.58 percent on average per year because of technology advancements (Bhurisith and Touran 2002).

*2.1.1.7. Effect of operating conditions on production rate*

Operating conditions also contribute significantly to production rates. Kannan (1999) defined operating conditions which affect earthmoving activities, such as load, haul, return, and dump. For example, the factors that influence the load activity are loading methods and operator efficiency. Three types of equipment (front shovel, backhoe, and wheel loader) were used to represent different kinds of loading methods. Operator efficiency depends on how skillful the operator is when operating the equipment. A detailed literature review reveals that there is a strong relationship between operating conditions and production rates (Smith 1999).

*2.1.1.8. Effect of size and type of project on production rate*

Another important parameter affecting the production rate of a construction activity is the size of a project. Every highway project is unique in design, size, and complexity, but to compare the projects, the total construction cost is an appropriate basis. This is because the construction costs directly impact the size and complexity of the project. There is a direct relation between the total project cost and construction duration (Jiang and Wu 2007b). Moreover, the construction duration of projects in the rural areas is found to be longer than that of urban areas for a given total construction cost. Factors like accessibility and procurement of labor and materials might be the reason for the extended duration in contract time in rural areas. Type of project has a considerable influence on the production rates due to different levels of work requirements.

Lack of frequent updates to production rate estimates among DOTs is a major drawback leading to inaccurate estimates. Identifying significant factors that influence production rates is the starting point for developing a production rate estimation tool. Next sections discuss the methods available for determining production rate estimates.

### *2.1.2. Production rate estimation methods*

Three methods were found to be most common among current methods used to estimate production rates. a.) Production rate charts and engineering judgment to determine production rates, b.) Use of adjustment factors for work items so that adjusted production rates are estimated as per operating parameters and c.) Statistical methods, where a range of statistical tools are used to analyze the field data, find patterns and accurately predict production rates.

*2.1.2.1. Production rate chart and engineering judgment*

Production rates of controlling work items are determined by estimators based on published tables, past project data, and experience. Factors influencing controlling work items must be considered accordingly as mentioned in section 2.1.1. Estimators use their experience to adjust production rates by considering influential factors. “The production rates used should be based on the desired level of resource commitment” deemed practical given the physical limitations of the project (FHWA 2002; Kiziltas and Akinci 2009). “Rates should be updated regularly to assure they accurately represent the statistical average rate of production in the area” (FHWA 2002). The estimators also consider the construction site related factors like soil condition and hauling information to make final adjustments to the estimated production rates.

*2.1.2.2. Use of systematic adjustment factor*

Production rates are calculated by some DOTs using adjustment factors. These DOTs maintain a standard table of production rates. Some main project characteristics like location, traffic, the complexity of the project, quantity, and soil conditions are used to adjust the base production rate. These adjustment factors play a crucial role as the production rates to be relevant in soil conditions, the topography of the location, and average daily traffic in the area. Quantity to be produced also has a high impact on production rates for certain work items. Depending on the general operating conditions, DOTs have different adjustment factors for these parameters. The production rate calculation involves the use of adjustment factors to make the estimate more project specific (Jeong et al. 2008). To adjust the production rates, experience-based judgment or predetermined adjustment factors can be implemented. Some examples of Ohio DOT and Oklahoma DOT which use the predetermined adjustment factors are provided in section 2.3.

*2.1.2.3. Using statistical methods*

“The statistical analysis is an approach in analyzing collected data in determining production rates of highway construction activities. Statistical methods include linear and nonlinear regression analysis, frequency plot, ANOVA, t-tests and multiple regressions modeling which are used to determine and quantify the relationship between production rate and factors influencing production rates as predictor variables in developing a model for highway production rate estimates” (Jeong and Woldesenbet 2010). As discussed in section 2.1.1, numerous factors influence the production rate. With the help of available data from the past projects, tools can be developed which will aid an estimator in attaining accuracy in production rate estimates.

# 3. Current practices of MDT

MDT utilizes documented production rates for major work activities to establish contract time. A design project manager is responsible for taking the lead on creating and maintaining contract time, during the design phase or at least before the Plan in Hand (PIH) review. During the PIH review, the production rates are adjusted if deemed unsatisfactory. If additional time is required to develop the schedule, or if the project is too complex to finalize at the time of PIH, the decision will be made at the Plan-in-Hand to schedule a Sequencing Coordination Meeting to establish a contract time (MDT 2008). The general process that is followed to make the initial estimate of contract time in MDT represented in Figure 3-1.

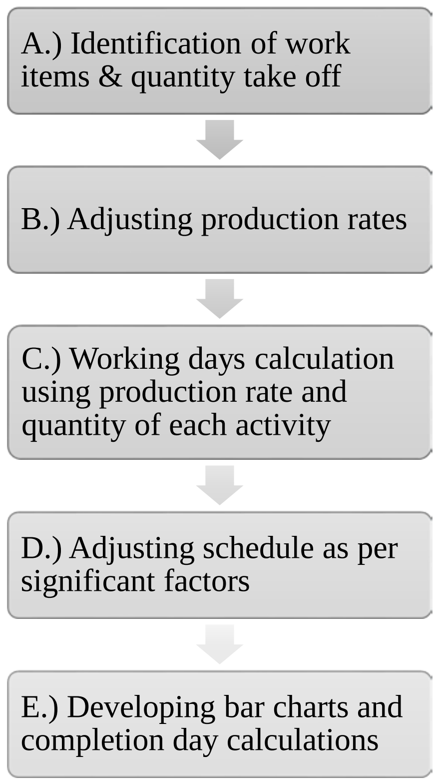



**Figure 3-1: Contract time determination process of MDT**

a.) A list of major construction activities that will take place on the project is developed by reviewing the plans. MDT maintains a list of 31 major work items that impact the critical path of a project. Small items or those that will be performed in conjunction with other items of work are considered incidental to the contract time. The quantities are a good indicator of the amount of work that needs to be performed. (MDT 2008)

b.) Determining the duration of activities using the standard production rates may be modified based on known project-specific information (MDT 2008). Factors that are considered for affecting the rate of production include regional differences (grading in mountainous terrain will be slower than on the prairie), construction in restricted areas, the need and availability of specialized construction equipment, and higher traffic volumes.

c.) Total duration calculated for each critical path activity will be the total number of working days. Timing restrictions like environmental commitments, commercial limitations (tourist season, fairs and other local events), irrigation season, weather/seasonal factors (spring runoff) are considered along with limitations on specific activities that have method specifications, sequenced construction for specific items, and specific segments of the project, particularly for developed/urban areas (MDT 2008).

d.) Utility relocations done as part of or in conjunction with the contract and providing access and maintaining traffic can also affect production rates. (MDT 2008) The predictive method for bridge contract time estimation is problematic for deck overlays and other types of rehabilitation projects where much depends on the expertise and ingenuity of the contractor. MDT has documented construction sequencing and published production rate for major activities in bridge construction. All the significant factors which affect the project schedule are accommodated before developing the bar charts.

e.) The bar chart is developed using the number of days calculated for controlling work items on the critical path as shown in Figure 3-2 (MDT 2008). The chart will show the resulting working days. For calendar day or completion date contracts, the days must be converted from a five-day workweek to a six or seven-day work week, depending on the requirements of the contract. For rural projects, a 10% contingency factor and for urban projects, a 20% contingency factor is added to the contract time (MDT 2008).

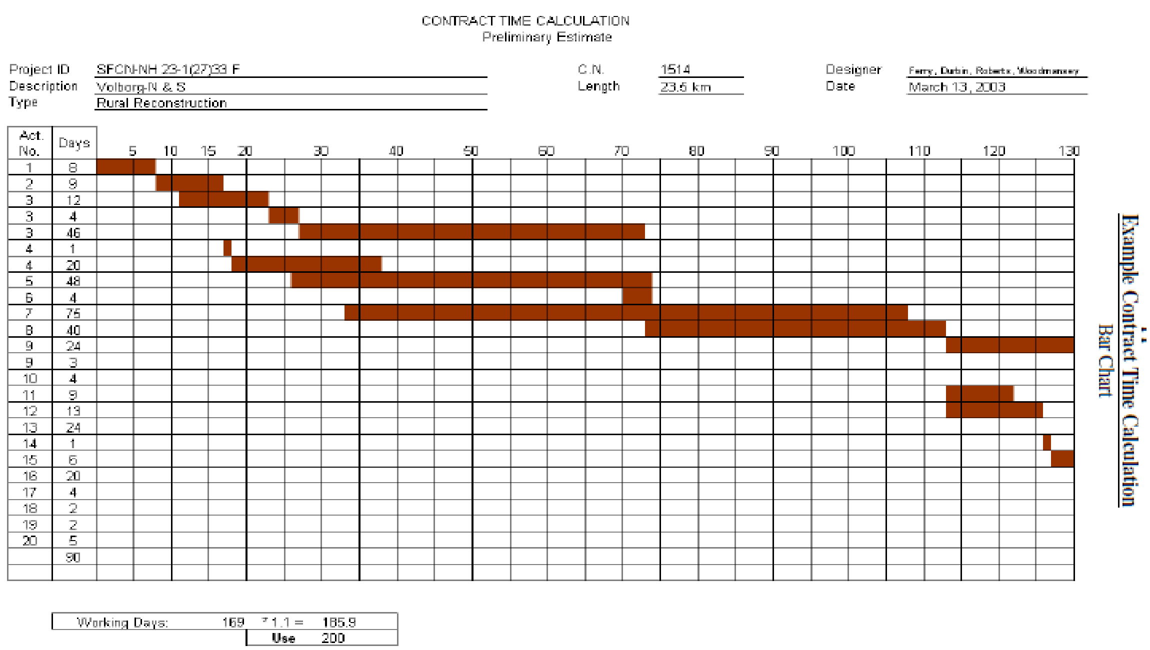



**Figure 3-2: Sample bar chart developed for rural reconstruction by MDT**

# 4. Descriptive analysis of DWR data

This section discusses various parameters available in the historical DWR data and bid data of MDT. The DWR data provides a rich dataset recorded in SiteManager by construction inspectors. Relevant data of MDT's controlling activities were extracted for production rate estimation. Descriptive analysis of the extracted dataset was employed to gain insight into which parameters significantly influence production rates.

## 4.1. Data description

Data obtained from MDT include ten years of historical DWR data and their associated bid data. The variables from the DWR data used for production rate analysis are shown in Figure 4-1. The data consist of contract ID, project number, item code and its description, vendor ID and name, the date on which quantities of work have been recorded, etc. The contractor data includes information regarding the number of supervisors and workers on the field, worked hours, and equipment availability and usage information. Bid data is used to map the total project cost with the DWR data. The budget category is defined as projects below $ 2 million and above $2 million. This basis is determined based on the median value of the project budget available from the data.

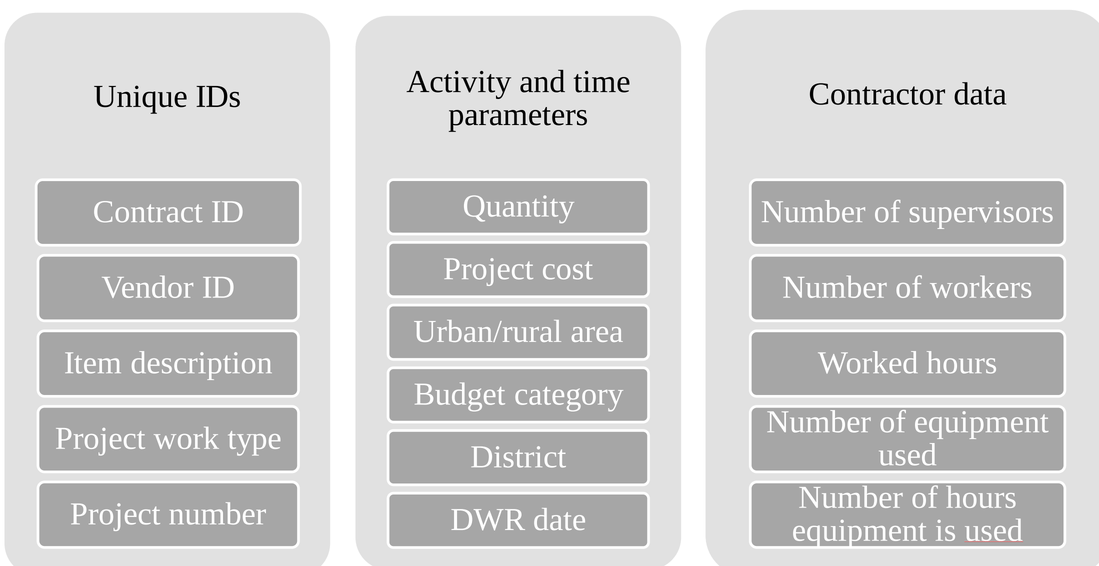



**Figure 4-1: Key variables selected from DWR data**

Montana is categorized into five maintenance districts: District 1 – Missoula, District 2 – Butte, District 3 - Great Falls, District 4 – Glendive, and District 5 – Billings (Figure 4-2). Using Tableau software, latitude and longitude coordinates from MDT bid data were used to determine the district location for each project. Maintenance district has a profound impact on production rates as Montana has a varying topography (mountains and plains). Production rates are historically higher in a plain region than a mountainous terrain as it is challenging to maintain ideal production rates on mountain terrain.

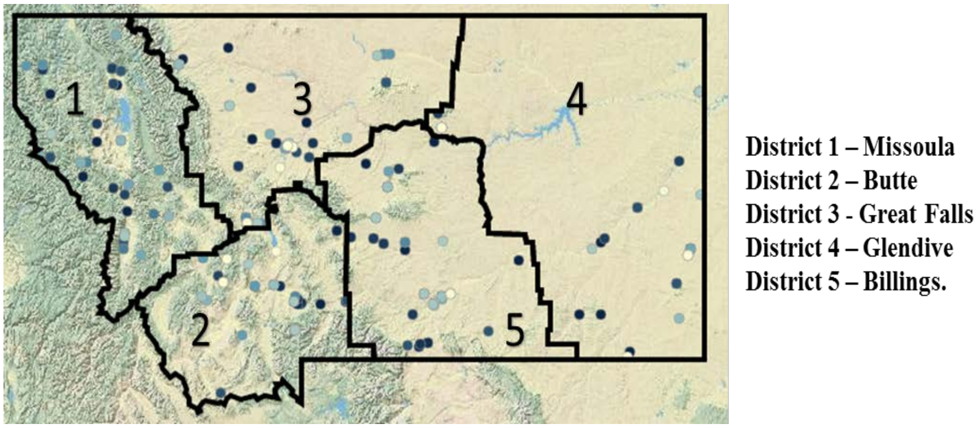



**Figure 4-2: District boundaries and project locations in Montana.**

A location indicator was established to differentiate between rural and urban projects in Montana. Rural or urban areas are distinguished by population. The major urban regions in Montana are identified using public data available on the MDT's website. This information was used to map all the projects available in the DWR dataset to determine which projects were in urban areas. If a project is located in an urban area, the location indicator of the project is equal to one. Otherwise, the location indicator is equal to zero. The descriptive analysis conducted using this data is discussed in section 4.2.

## 4.2. Descriptive analysis

This section discusses the findings of the descriptive analysis conducted on production rates with different parameters, such as seasonal variations of production rates, differences in production rates among districts, and variations between urban and rural areas in MDT.

Production rates are obtained when the total quantities of a work item in the projects are divided by the total number of unique DWR days recorded for the activity. Unique DWR dates are considered to avoid double-counting when the same activity is conducted on multiple locations or when an activity is recorded multiple times in a day. The average production rate is calculated for each controlling work item using the equation below.

$$\text{Average Production Rate} = \frac{\text{Total quantity of material produced}}{\text{Unique DWR dates when the particular activity is recorded}}$$

Table 4-1 shows the MDT's 31 controlling activities along with average production rates calculated from DWR data.

**Table 4-1: Production rates of controlling activities**

| No | Serial number | Activity description | Unit | Production rates from DWR data (Per day) |
|---|---|---|---|---|
| 1 | AA | Topsoil-Salvaging and Placing | CUYD | 2,313 |
| 2 | AB | Excavation-Unclassified | CUYD | 8,874 |
| 3 | AC | Special Borrow | CUYD | 3,640 |
| 4 | AD | Excavation-Street | CUYD | 1,518 |
| 5 | AE | Crushed Aggregate Course | CUYD | 2,088 |
| 6 | AF | Base-Cement Treated | CUYD | 3,453 |
| 7 | AG | Drainage Pipe (<= 24 In) | LNFT | 95 |
| 8 | AH | Drainage Pipe (> 24 In) | LNFT | 91 |
| 9 | AI | RCB | LNFT | 95 |
| 10 | AJ | SSPP | LNFT | 66 |
| 11 | AK | Riprap | CUYD | 136 |
| 12 | AL | Cold Milling | SQYD | 15,077 |
| 13 | AM | Plant Mix Surfacing | TON | 1,509 |
| 14 | AN | Cover | SQYD | 83,884 |
| 15 | AO | Micro-Surfacing | TON | 465 |
| 16 | AP | Crack Sealing | LB | 6,346 |
| 17 | AQ | PCCP | SQYD | 568 |
| 18 | AR | Curb and Gutter | LNFT | 408 |
| 19 | AS | Sidewalk | SQYD | 246 |
| 20 | AT | Farm Fence | LNFT | 2,206 |
| 21 | AU | Guardrail Steel | LNFT | 680 |
| 22 | AV | Concrete Barrier Rail | EACH | 58 |
| 23 | AW | Seeding | ACRE | 12 |
| 24 | AX | Reinforcing Steel | LB | 13,995 |
| 25 | AY | Drilled Shaft | LNFT | 103 |
| 26 | AZ | Concrete-Class Deck | CUYD | 73 |
| 27 | BA | Class A Bridge Deck Repair | SQYD | 14 |
| 28 | BB | Concrete Barrier Rail-Bridge | LNFT | 222 |
| 29 | BC | Concrete-Class Overlay | CUYD | 31 |
| 30 | BD | Bridge Deck Milling | SQYD | 473 |
| 31 | BE | Revise Bridge Concrete Barrier | LNFT | 200 |

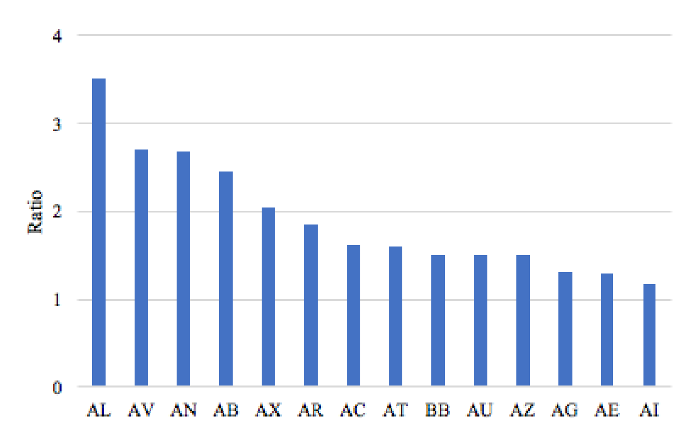
Descriptive analysis of the data was then conducted to check the effects of the input variables on production rates. Some of the analysis conducted shows the comparisons of production rates in different seasons, variations among the districts of MDT, and comparisons between urban and rural areas.

### *4.2.1. Seasonal variation of production rates*

An analysis was conducted on production rate variation in the construction and winter season. A comparison of production rates achieved in past projects reveals that for most of the activities production rates in the summer and fall season are higher than the production rates achieved in the winter period. Figure 4-3 shows the ratios of production rates obtained in the construction season to those of the winter season for fourteen controlling activities of MDT.

$$\text{Seasonal Ratio} = \frac{\text{Production rates achieved in the construction season}}{\text{Production rates achieved in the winter season}}$$

The data clearly shows differences in production rates of certain activities during both seasons. Seasonal variation is an important factor to be considered while estimating production rates. Cold milling, concrete barrier rail, cover, and excavation unclassified had production rates in the construction season more than twice those in the winter. This characteristic was included in the production rate estimation model with appropriate adjustments to attain realistic production rates according to the season of work.




| Legend | Work Item Description |
|---|---|
| AL | COLD MILLING |
| AV | CONCRETE BARRIER RAIL |
| AN | COVER |
| AB | EXCAVATION-UNCLASSIFIED |
| AX | REINFORCING STEEL |
| AR | CURB AND GUTTER |
| AC | SPECIAL BORROW |
| AT | FARM FENCE |
| BB | CONCRETE BARRIER RAIL-BRIDGE |
| AU | GUARDRAIL STEEL |
| AZ | CONCRETE-CLASS DECK |
| AG | DRAINAGE PIPE (<= 24 IN) |
| AE | CRUSHED AGGREGATE COURSE |
| AI | RCB |

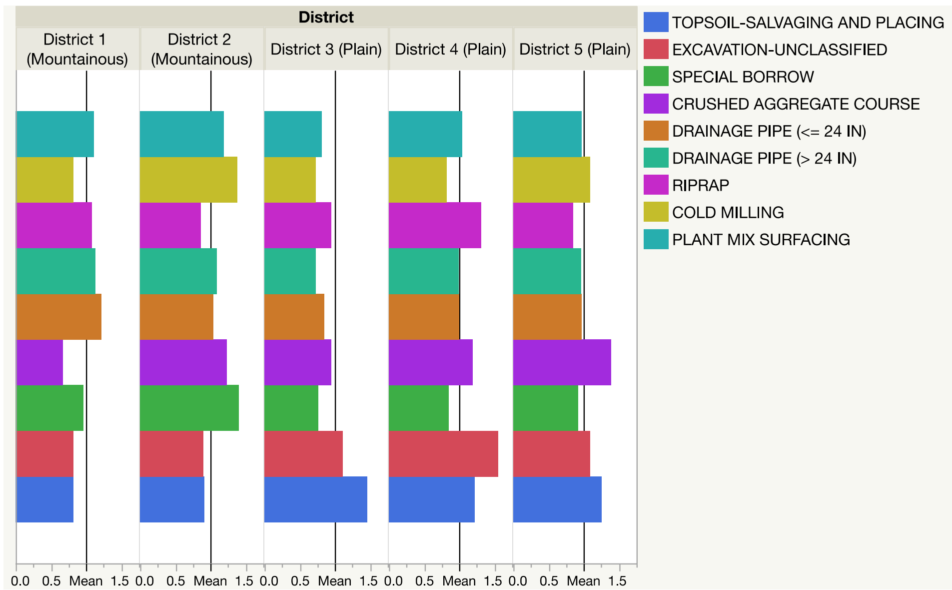
**Figure 4-3: Ratios of production rates between construction and winter season**

### *4.2.2. District level comparison of production rates*

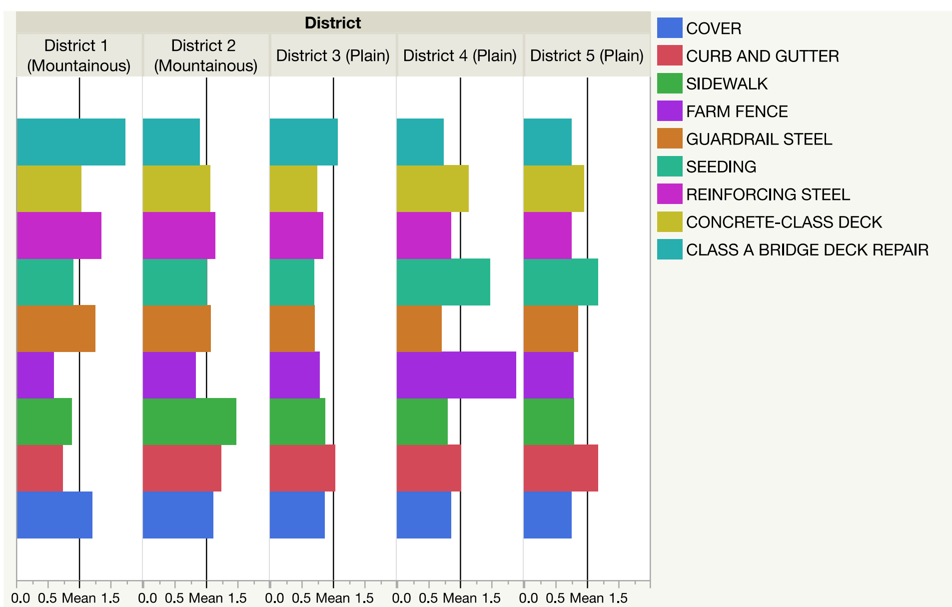
Production rates for controlling activities were calculated for each district and compared with the average production rate of these activities across Montana. Maintenance district's boundary location was obtained from the MDT Geographic Information Systems (GIS) data portal. Tableau software was used to create a map (Figure 4-2) to provide project locations along with district boundaries.

The ratio of production rate achieved by a district for an activity and the average production rate of the activity across Montana was calculated. This ratio allows for analyzing the performance of production rates in a district for each of the controlling work items. Of 31 controlling activities, only 18 activities were chosen to make comparisons among the five districts because each of the chosen activities was applied in at least three past projects per every district. The remaining thirteen activities did not have enough historical data for reliable comparisons among the districts.

A bar graph as shown in Figure 4-4 was developed. The ratio is represented on the horizontal axis. Each bar indicates an activity. Production rates of the same activity are aligned in the same row for visual comparison.




a. Ratios for nine controlling activities




b) Ratios for the other nine controlling activities

**Figure 4-4: Ratios of production rates of districts to those of state average**

The average production rate of Montana was taken as 1 for all activities. The district where the ratio is greater than 1 signifies better performance. The underperforming districts have ratios less than 1. Table 4-2 shows the number of underperforming activities and the average ratio of 18 activities for each district.

**Table 4-2: Districts and their low production rate controlling activities**

| District | Number of activities below average production rate (out of 18) | Average ratio of 18 activities |
|---|---|---|
| **District 1** | 9 | 1.02 |
| **District 2** | 5 | 1.11 |
| **District 3** | 14 | 0.89 |
| **District 4** | 9 | 1.08 |
| **District 5** | 12 | 0.97 |

As observed in Figure 4-4, most of the activities for District 3 fall below the average production rate. District 3 has the highest number of activities below average production rates and the lowest average ratio among five districts (Table 4-2). Considering the performance in District 3, the production rates of District 4 are deemed better as it performs significantly better than average production rates for many activities such as excavation-unclassified, topsoil-salvaging and placing, riprap, farm fence, and seeding. Lower production rates in Districts 1 and 2 for some activities (e.g., topsoil-salvaging and placing, excavation-unclassified, and farm fence) might be due to the presence of mountainous terrain since transportation of material and personnel takes longer duration in mountainous terrain than on plain terrain.

### *4.2.3. Urban and rural production rate comparison*

Another analysis was conducted to verify the effect of the location indicator (rural or urban) on production rates. Of the 31 controlling activities, only 24 activities were used to make comparisons between urban and rural areas. Each of these 24 activities had at least three past projects located in urban or rural areas. The remaining seven activities did not have enough data for reliable comparisons. For each activity, a rural/urban ratio was calculated. Figure 4-5 portrays the ratio of production rates achieved in the rural areas to those in the urban areas for 24 selected controlling activities of MDT.

$$\text{Rural/Urban Ratio} = \frac{\text{Production rates achieved in the rural areas}}{\text{Production rates achieved in the urban areas}}$$

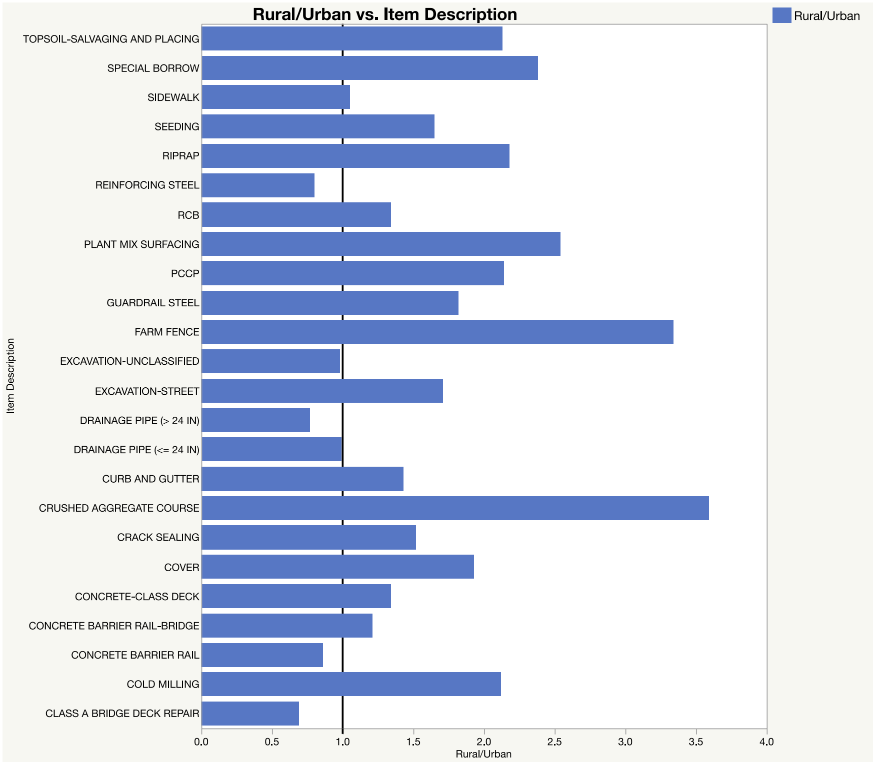



**Figure 4-5: Production rate comparisons between rural and urban areas**

Figure 4-5 clearly shows that there are differences in production rates of certain activities between urban are rural areas. Some activities such as crushed aggregate course, farm fence, plant mix surfacing, and special borrow had production rates in the rural areas more than twice those in the urban areas. Therefore, the location indicator to distinguish between urban and rural areas was included in the production rate estimation model.

### *4.2.4. Budget-based comparison of production rates*

An analysis was conducted to verify the effect of the budget type on production rates. Of the 31 controlling activities, only 25 activities were used to make comparisons. Each of these 25 activities had at least three past projects that belonged to every budget type. The remaining six activities did not have enough data for reliable comparisons. For each activity, a budget type ratio was calculated. Figure 4-6 shows the ratios for the 25 selected controlling activities of MDT.

$$\text{Budget Type Ratio} = \frac{\text{Production rates achieved in the projects with budget greater than \$2 million}}{\text{Production rates achieved in the projects with budget less than \$2 million}}$$

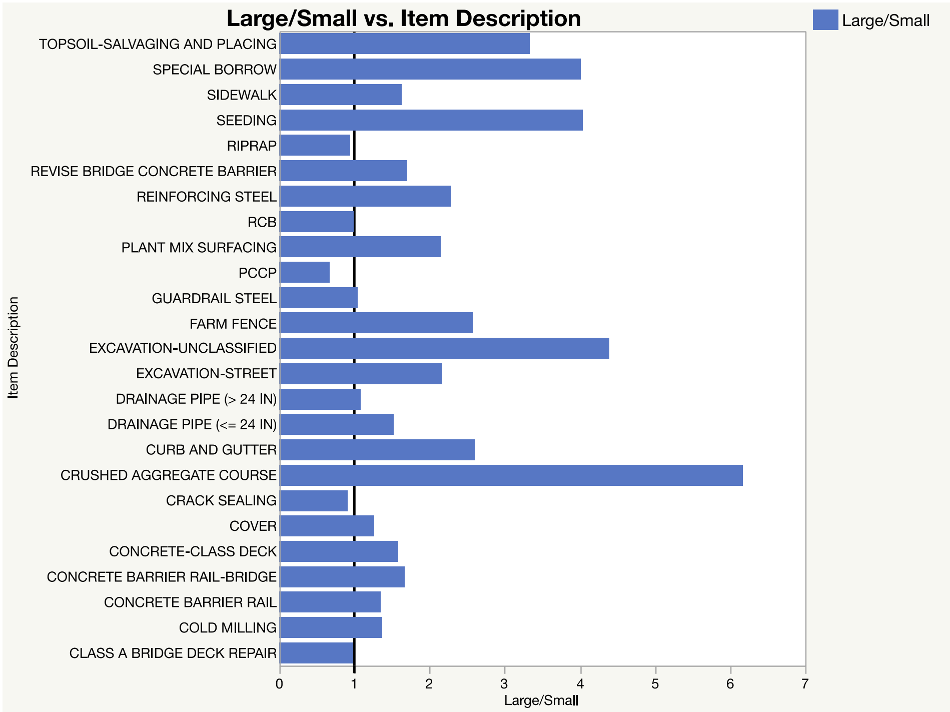



**Figure 4-6: Production rate comparisons between two budget types**

The figure clearly shows that there are differences in production rates between two types of budget. 20 out of 25 activities (80%) had the budget type ratio larger than 1. Some activities such as crushed aggregate course, excavation-unclassified, seeding, special borrow, and topsoil-salvaging and placing had production rates in the larger budget group more than twice those in the smaller budget group. Therefore, the budget type categories were included in the production rate estimation model.

# 5. Predictive analysis of DWR data

In this section, characteristics of historical projects from the DWR data were explored in terms of projection location and project work type. Regression analysis was used to develop regression equations to predict production rates of the controlling activities. Statistical measures were also used as references in addition to the results from the regression models. In addition, a method of evaluating contractors is proposed using production rates obtained from the DWR data.

## 5.1. Production rate database

This study has obtained historical bid data, DWR data, and GIS data from MDT and other online sources as shown in Figure 5-1. These data files were cleaned and combined to form a project-level database of production rates of controlling activities with relevant parameters (e.g., project amount, work type, location type, number of equipment, and number of supervisors). The database consists of 981 projects undertaken over a period of ten years from 2008 to 2017.

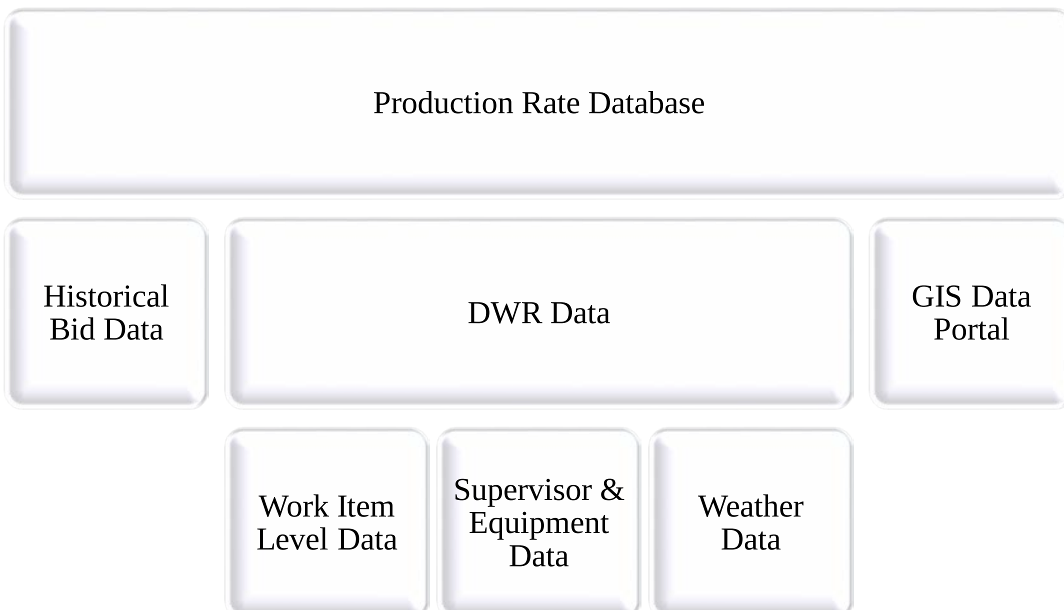



**Figure 5-1: Data sources to form the production rate database**

The production rate database includes data on 31 controlling activities. Each controlling activity is represented by one or more similar work items in the bid item list published by MDT. Each work item is accompanied by a unique item code and a corresponding work description. For example, the work item code “301020340” represents crushed aggregate course. Although MDT has an exhaustive list of 5,645 unique work item codes published in the specification manual, only a small number of items are mostly used for highway projects. Table 5-1 shows the list of controlling activities and their corresponding item codes.

**Table 5-1: Controlling activities and corresponding item codes**

| SN | Controlling activity | Item code |
|---|---|---|
| AA | Topsoil-Salvaging and Placing | 203080100, 203500000 |
| AB | Excavation-Unclassified | 203020100, 203100000 |
| AC | Special Borrow | 203020250, 203020310, 203220000 |
| AD | Excavation-Street | 203020225, 203120000 |
| AE | Crushed Aggregate Course | 301020340, 301270000 |
| AF | Base-Cement Treated | 304010005, 304115000 |
| AG | Drainage Pipe (<= 24 In) | 75 item codes start with 603, including drainage pipes with various diameters, such as 12 in, 15 in, 18 in and 24 in. |
| AH | Drainage Pipe (> 24 In) | 161 item codes start with 603, including drainage pipes with various diameters, such as 30 in, 36 in, 42 in and 48 in. |
| AI | RCB | 52 item codes start with 603, including RCB with various dimensions. |
| AJ | SSPP | 603011595, 603011722, 603011820, 603011827, 603011828, 603011830, 603011832, 603011973, 603012020, 603012262 |
| AK | Riprap | 613010000, 613020000, 613030000, 613100030, 613100040, 613100050 |
| AL | Cold Milling | 411000000, 411010000 |
| AM | Plant Mix Surfacing | 22 item codes start with 401, including plant mix surfacing with various parameters, such as PG 58-28 and PG 64-28. |
| AN | Cover | 301020718, 301020735, 301440010, 301440020, 409000010, 409000020, 409000030 |
| AO | Micro-Surfacing | 301020630, 401020067, 401020068, 401020070 |
| AP | Crack Sealing | 402020502, 403010255 |
| AQ | PCCP | 501010118, 501010119, 501010120, 501010122, 501010125, 501010126, 501010210, 501010215 |
| AR | Curb and Gutter | 609000000, 609010200 |
| AS | Sidewalk | 608010020, 608010050, 608100000, 608150000 |
| AT | Farm Fence | 43 item codes start with 607, including farm fence with various parameters. |
| AU | Guardrail Steel | 606000000, 606010030, 606010038,606010040 |
| AV | Concrete Barrier Rail | 605000080, 605000090, 605000090, 606011215, 606011244, 606011244, 606290000 |
| AW | Seeding | 610100101, 610100102, 610100103, 610110000, 610120000, 610130000 |
| AX | Reinforcing Steel | 555010100, 555010200, 555010210, 555010400, 555100000, 555200000 |
| AY | Drilled Shaft | 13 item codes start with 552 or 558. |
| AZ | Concrete-Class Deck | 551020107, 551410000 |
| BA | Class A Bridge Deck Repair | 552010300, 562000020 |

| | | |
|---|---|---|
| BB | Concrete Barrier Rail-Bridge | 605000030, 605100010, 606011106, 606300104 |
| BC | Concrete-Class Overlay | 563000000 |
| BD | Bridge Deck Milling | 552010155, 561020110 |
| BE | Revise Bridge Concrete Barrier | 557010542, 605000040, 606011130 |

For each controlling activity, the data was stored in a table. Each row or instance corresponds to a historical project that included the activity. Each column in the table represents an attribute of the project. The primary attributes in the database are as follows:

- ✓ Project number. Each number is unique, representing the project.
- ✓ Project amount: the total amount of the project.
- ✓ Project work type. Highway projects are divided into 17 main categories by MDT. Project work types and their codes are listed in Table 5-2.

**Table 5-2: Project work types and type codes**

| No. | Type code | Project work type |
|---|---|---|
| 1 | 110 | Reconstruction/New Construction |
| 2 | 111 | Facilities (Buildings) |
| 3 | 141 | Drainage |
| 4 | 150 | Major Rehabilitation |
| 5 | 160 | Overlay |
| 6 | 170 | Portland Cement Concrete Pavement |
| 7 | 183 | Seal & Cover |
| 8 | 185 | Crack Seal |
| 9 | 210 | Bridge Construction |
| 10 | 230 | Major Bridge Rehabilitation |
| 11 | 232 | Minor Bridge Rehabilitation |
| 12 | 310 | Safety |
| 13 | 410 | Traffic Signals & Lighting |
| 14 | 411 | Signing, Pavement Markings |
| 15 | 510 | Environmental |
| 16 | 520 | Landscaping |
| 17 | 620 | Bicycle & Pedestrian Facilities |

- ✓ District. There are five maintenance districts: District 1 – Missoula, District 2 – Butte, District 3 - Great Falls, District 4 – Glendive, and District 5 – Billings.
- ✓ Budget type. The dollar amounts of all the projects were compared. Based on the median value, the projects were divided into two categories, i.e., projects that are less than $2

million and projects that are greater than $2 million. This classification provides a categorical variable for analysis of production rates, giving insights into whether the budget of a project has significant impacts on the production rate of the activity.

- ✓ Area type (urban/rural). Project locations were mapped in Tableau software using latitude and longitudinal coordinates. Montana currently has 19 qualifying urban and urbanized areas with a population of 5,000 or greater (MDT 2017). The location of urban regions was superimposed on project locations, and projects that fall in urban regions were extracted to create an area-type parameter (urban/rural) in the database.
- ✓ The number of supervisors, number of workers, and worked hours. Labor data for the three attributes was documented in DWR. For each project, the average numbers per day were calculated and incorporated into the database.
- ✓ The number of available equipment, number of used equipment, and used hours. Equipment data for the three attributes was documented in DWR. For each project, the average numbers per day were calculated and incorporated into the database.
- ✓ Season of work (winter/construction season): the season that the activity was carried out.
- ✓ Vendor ID. The unique number represents a contractor.
- ✓ Quantity: the total quantity of the controlling activity in each project. There were two unit systems in DWR data. Conversion from one unit system to another was employed to have only one unit system for each activity in the database.
- ✓ Unique days: the total number of unique DWR dates recorded for the activity.
- ✓ Production rate: The production rate is the total quantity divided by the number of unique days.

## 5.2. Data characteristics

In this subsection, frequency analysis was deployed to explore the dataset in the database. Multiple attributes of past projects were considered to gain insight into projects' characteristics.

In terms of project types, the frequency of each type is shown in Figure 5-2. Overlay was the most common project type in Montana from 2008 to 2017, accounting for one-fourth of the total projects. Reconstruction/new construction, seal & cover, and safety accounted for 17%, 16%, and 14% respectively. The least common project types were major bridge rehabilitation, bicycle & pedestrian facilities, drainage, environmental, and crack seal, accounting for 1% or less of the total projects.

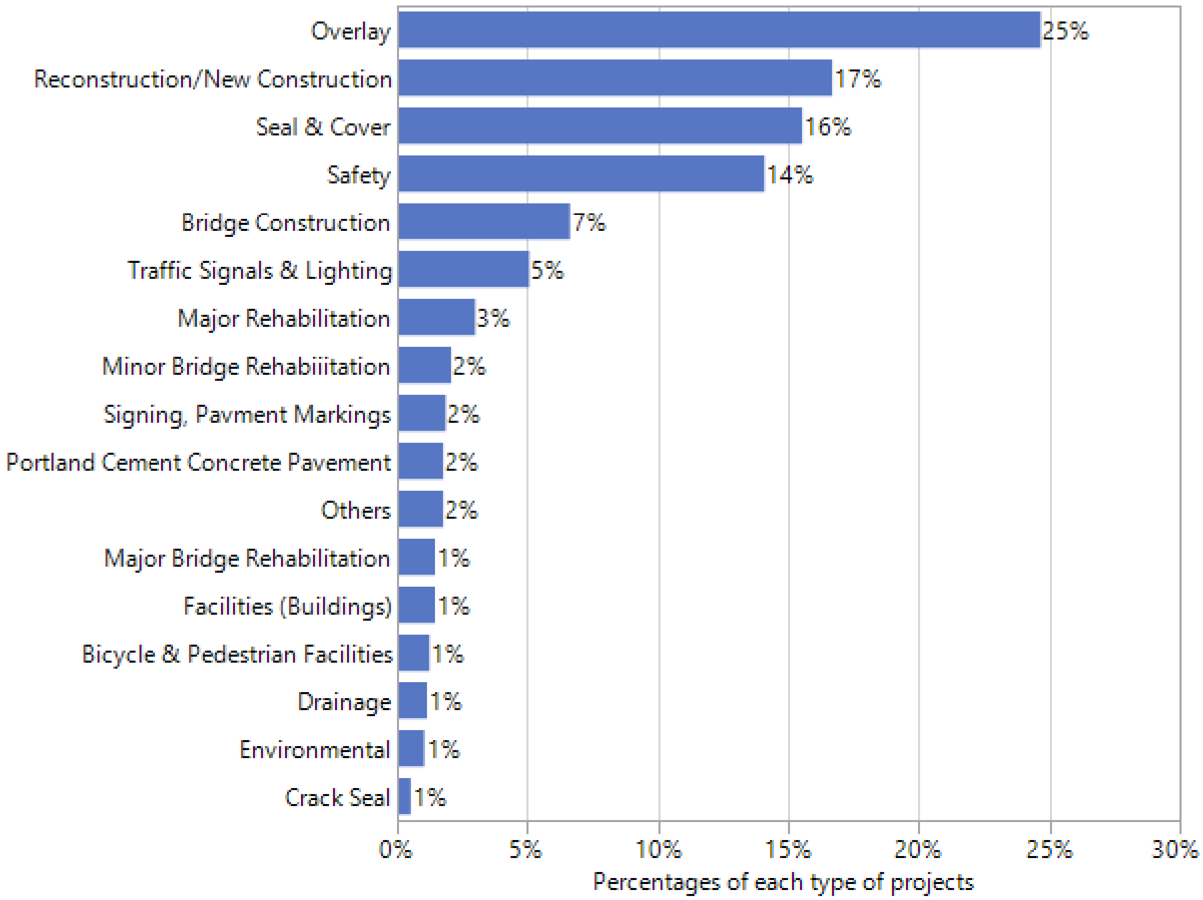



**Figure 5-2: Percentages of each type of projects in the dataset**

Regarding project locations, 14% of the projects were in urban areas while 86% of the projects were undertaken in rural areas. The result shows that the majority of the projects undertaken by MDT were in the rural areas. For a better understanding of how the location of the project has an impact on the production rates, the district locations of the projects were also considered. As shown in Figure 5-3, District 1, District 2, and District 3 were responsible for 25.5%, 23.3%, and 23.0% of the total project, respectively. District 4 accounted for the least proportion of the total projects, at 11.4%.

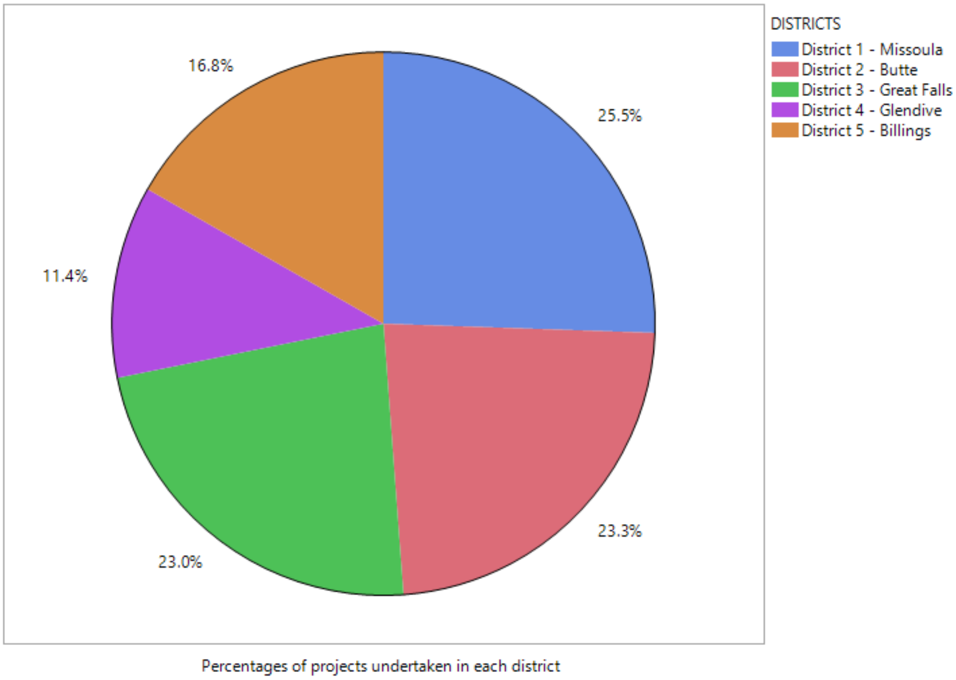



**Figure 5-3: Percentages of projects undertaken in each district**

Figure 5-4 shows the percentage of each project type in each district. Some patterns of project work types can be seen across the districts. Overlay, reconstruction/new construction, and safety were the most popular work types in every district.

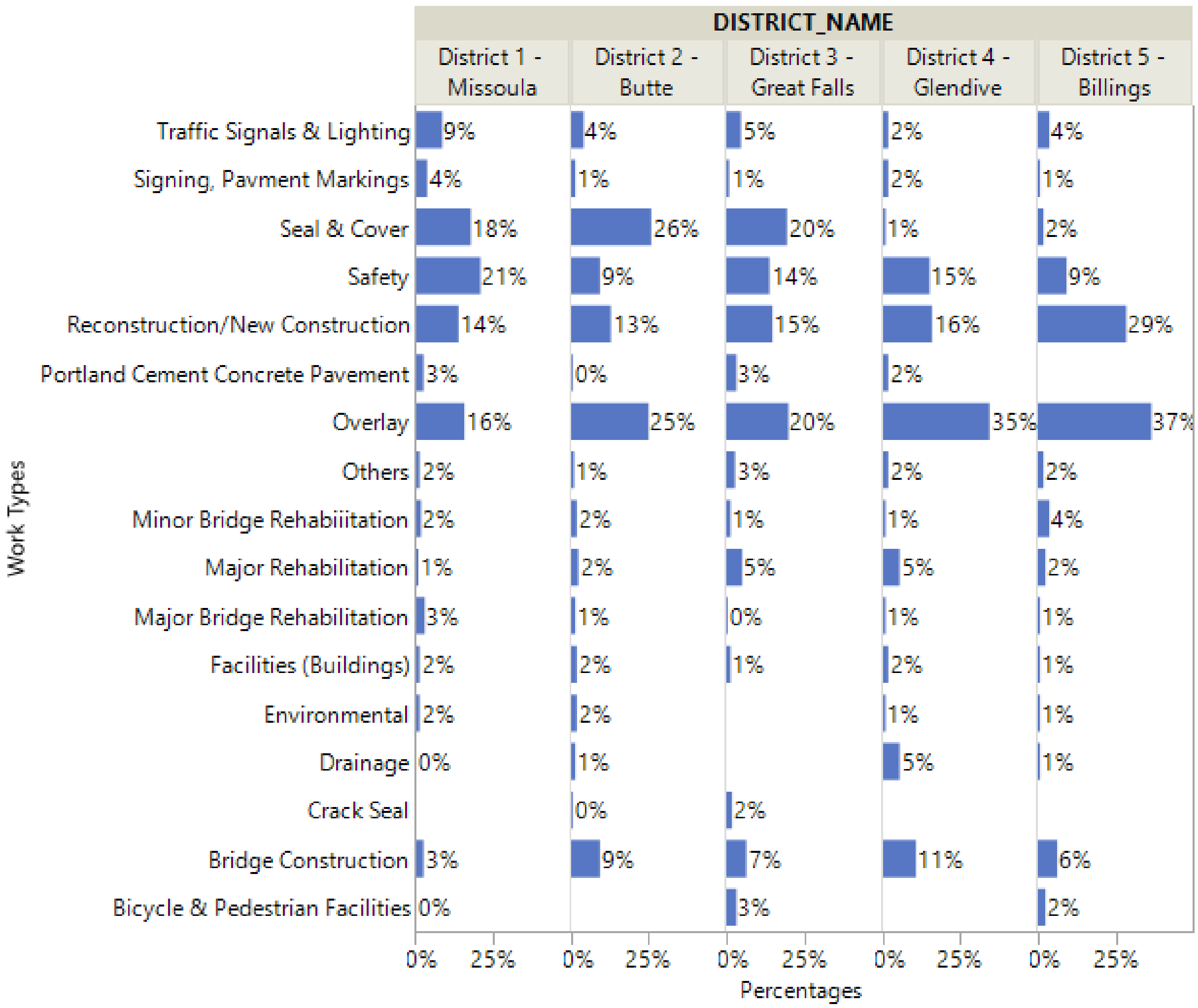



**Figure 5-4: Percentages of each type of projects in each district**

## 5.3. Regression models to predict production rates

This section describes the process of establishing regression models that are used to forecast production rates of controlling activities. For each activity, the predicted variable is the production rate, and the predictor variables are the ones which have significant effects on the production rate. Based on the literature review and the descriptive analysis in the previous sections and the availability of the data, potential predictor variables for regression models are project work type, district, budget type, urban or rural, project total amount, quantity, number of supervisors, number of workers, worked hours, number of available equipment, number of used equipment, and used hours. Of twelve potential variables, the first four are categorical or nominal variables.

JMP Pro. Statistical software (JMP) was used to run standard least squares analysis to find the final predicted variables for regression models. The effect of each variable on production rate in the regression model was tested and represented by a P-value. A small P-value indicates strong evidence against the hypothesis that the factor has no effect on production rate in the model. In this study, only factors with a P-value smaller than or equal to 0.1 were considered. Regression models were then developed using JMP. Each regression model is accompanied by an R-squared value, which is a statistical measure of how well the model explains the variability of the predictive variable. Higher R-squared values provide more accurate predictions. Table 5-3 shows the factors that were included in the final regression models, their corresponding P-value, and the R-squared value of the regression model.

**Table 5-3: Factors included in the regression models**

| SN | Activity Description | Quantity | Project Amt. | Work Type | District | Budget Type | Area Type | Season of Work | Av. Equip. | Used Equip. | Used Hours | No. of Supvrs | No. of Workers | Worked Hours | R2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| AA | Topsoil-Salvaging and Placing | 0.00 | | 0.02 | 0.00 | | | | | | | | | 0.02 | 0.8 |
| AB | Excavation-Unclassified | 0.00 | | | | 0.02 | | | 0.00 | | | | | | 0.6 |
| AC | Special Borrow | 0.00 | | | | | | | 0.00 | 0.00 | | 0.05 | | | 0.6 |
| AD | Excavation-Street | 0.00 | | | | | | | | | | | | | 0.5 |
| AE | Crushed Aggregate Course | 0.00 | | | | | | | 0.00 | | | | | | 0.7 |
| AF | Base-Cement Treated | Not enough data for regression models | | | | | | | | | | | | | |
| AG | Drainage Pipe (<= 24 In) | 0.00 | 0.00 | 0.10 | | | | | | 0.06 | | | | | 0.3 |
| AH | Drainage Pipe (> 24 In) | 0.00 | 0.10 | | | | | | | | | 0.05 | | | 0.2 |
| AI | RCB | 0.01 | 0.06 | | | | | | | | | | | | 0.2 |
| AJ | SSPP | Not enough data for regression models | | | | | | | | | | | | | |
| AK | Riprap | 0.00 | 0.03 | 0.01 | | | | | | | | | | | 0.4 |
| AL | Cold Milling | 0.00 | | | | | | | | | | 0.00 | | 0.00 | 0.4 |
| AM | Plant Mix Surfacing | 0.00 | | 0.00 | 0.00 | | 0.00 | | 0.00 | 0.01 | | | 0.00 | | 0.4 |
| AN | Cover | 0.00 | | 0.03 | 0.02 | | | | | | 0.02 | | | 0.01 | 0.5 |
| AO | Micro-surfacing | 0.01 | | | | | | | | | | | | | 0.5 |
| AP | Crack Sealing | 0.01 | | 0.00 | | | | | | | | | | 0.02 | 0.6 |
| AQ | PCCP | 0.04 | | | | | | | | | | | | | 0.4 |
| AR | Curb and Gutter | 0.00 | | | 0.08 | 0.00 | | | | | | | | | 0.5 |
| AS | Sidewalk | 0.00 | | | | 0.02 | | | 0.01 | | 0.01 | | | | 0.4 |
| AT | Farm Fence | 0.00 | | 0.06 | 0.00 | | | | | | | | | | 0.5 |
| AU | Guardrail Steel | 0.00 | | 0.01 | | | | | | | | | | | 0.4 |
| AV | Concrete Barrier Rail | | | 0.00 | 0.00 | | 0.01 | | 0.00 | | 0.00 | 0.02 | 0.01 | | 0.9 |
| AW | Seeding | 0.00 | | | | | | | | | | | | | 0.6 |
| AX | Reinforcing Steel | | 0.00 | 0.00 | 0.10 | 0.00 | | | 0.01 | 0.06 | | | 0.04 | | 0.6 |
| AY | Drilled Shaft | Not enough data for regression models | | | | | | | | | | | | | |
| AZ | Concrete-Class Deck | | | 0.01 | | 0.00 | | | 0.04 | | 0.03 | | 0.00 | 0.00 | 0.5 |
| BA | Class A Bridge Deck Repair | 0.00 | | 0.01 | 0.00 | | 0.01 | | | 0.07 | | | | | 0.7 |
| BB | Concrete Barrier Rail-Bridge | 0.02 | | 0.00 | 0.01 | 0.00 | | 0.01 | | 0.00 | 0.01 | 0.01 | 0.00 | | 0.9 |
| BC | Concrete-Class Overlay | Not enough data for regression models | | | | | | | | | | | | | |
| BD | Bridge Deck Milling | 0.02 | | | | | | | | | | | | | 0.7 |
| BE | Revise Bridge Concrete Barrier | | | | 0.00 | 0.02 | | | | | 0.06 | | 0.00 | 0.00 | 0.9 |

Of 31 controlling activities, four activities did not have enough data for regression analysis. Therefore, 27 regression models were developed. All potential predictor variables were included in at least one regression model. Quantity was proved to have a significant effect on production rates of controlling activities since the majority of the regression models (23 out of 27) included quantity as a regressor. Project work type, district, number of available equipment, and budget type were also proved their significant effects on production rates of more than 25% of controlling activities. Detailed discussions on several controlling activities are provided as follows.

### *5.3.1. Excavation - unclassified*

Data from 148 past projects were used to develop the regression model for production rates of excavation - unclassified (EU). Quantity, number of available equipment, and budget type are three variables that have significant effects on the production rate. The R-squared value of the model is 0.57, and the detailed equation is given below.

$$PR = 4570.3 + 0.02737 \times Q + 144.738 \times AE + CVB$$

Where:

- ✓ PR is the estimated production rate (CUYD/day)
- ✓ Q is the quantity of EU (CUYD)
- ✓ AE is the number of available equipment
- ✓ CVB represents a corresponding numeric value of the budget type and the numeric value assigned to each budget type for the equation is provided as follows (Budget type 0, less than \$2 million: CVB = -3452.5; budget type 1, greater than \$2 million: CVB = 0)

Based on the prediction equation, production rates increase when quantities and the number of available equipment increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-5 and Figure 5-6. Also, the equation implies that the larger budget type tends to have higher production rates, which is also consistent with the comparison between two budget types as shown in Figure 5-7.

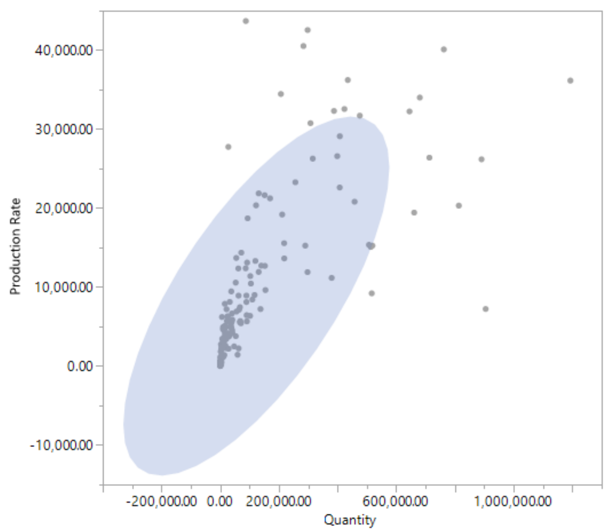



**Figure 5-5: Quantity versus production rate from DWR data (EU)**

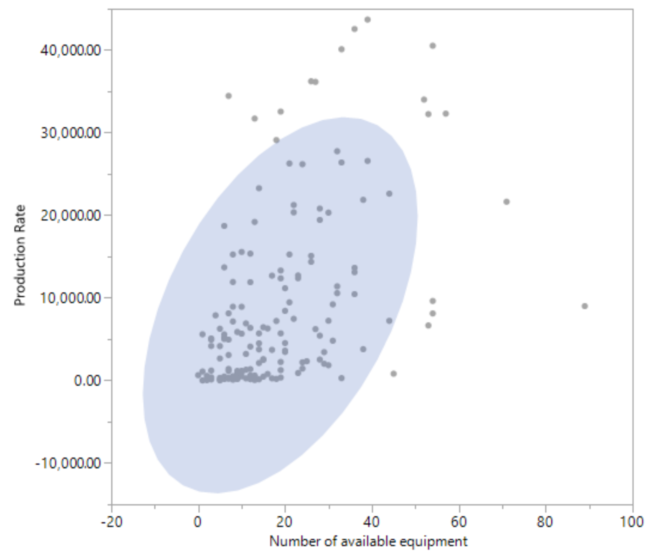



**Figure 5-6: Available equipment versus production rate from DWR data (EU)**

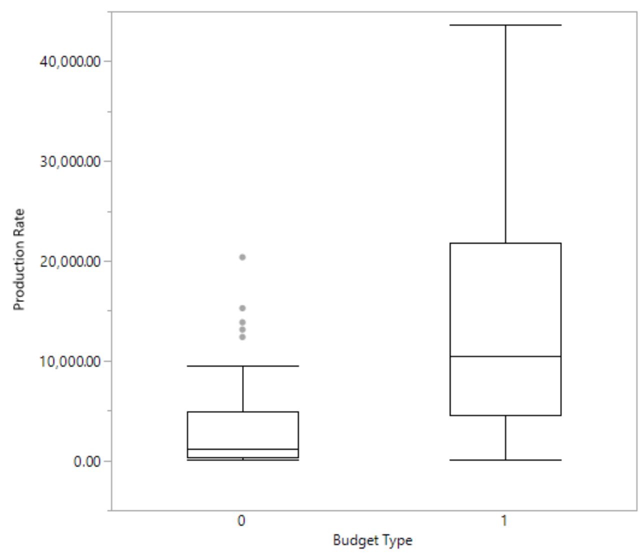



**Figure 5-7: Budget versus production rate from DWR data (EU)**

### *5.3.2. Crushed aggregate course*

Data from 269 past projects were used to develop the regression model for production rates of crushed aggregate course (CAC). Quantity and number of available equipment are two variables that have significant effects on the production rate. The R-squared value of the model is 0.71, and the detailed equation is given below.

$$PR = 70.9 + 0.11615 \times Q + 35.898 \times AE$$

Where:

- ✓ PR is the estimated production rate (CUYD/day)
- ✓ Q is the quantity of crushed aggregate course (CUYD)
- ✓ AE is the number of available equipment

Based on the prediction equation, production rates increase when quantity and number of available equipment increase. Figure 5-8 shows the relationship between quantity and production rate of crushed aggregate course obtained from historical data, and it is consistent with the result from the regression model. The relationship between the number of available equipment and production rates is confirmed in Figure 5-9.

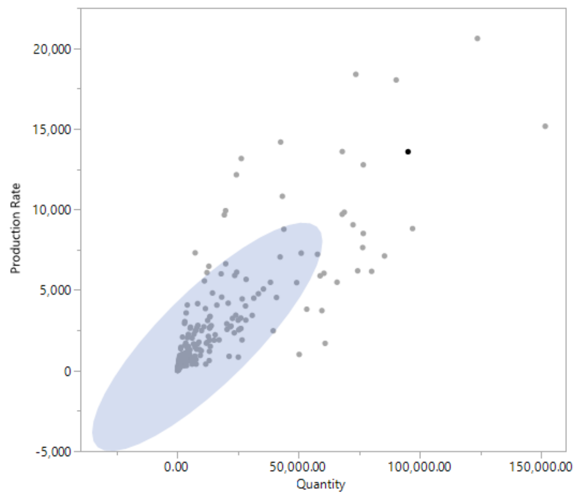



**Figure 5-8: Quantity versus production rate from DWR data (CAC)**

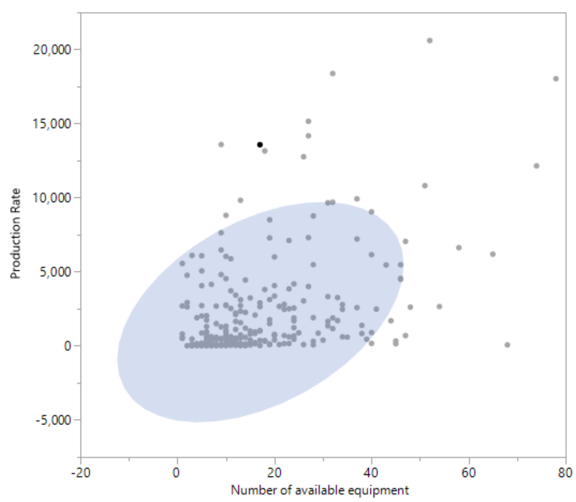



**Figure 5-9: Available equipment versus production rate from DWR data (CAC)**

### *5.3.3. Topsoil-salvaging and placing*

Data from 193 historical projects were used to develop the regression model for production rates of topsoil-salvaging and placing (TSP). Quantity, district, worked hours, and work types are four variables that have significant effects on the production rate. The R-squared value of the model is 0.78, and the detailed equation is given below.

$$PR = -283.1 + CVWT + CVD + 5.440 \times WH + 0.14178 \times Q$$

Where:

- ✓ PR is the estimated production rate (CUYD/day)
- ✓ CVWT represents a corresponding numeric value of the work type and the numeric value assigned to each work type for the equation is provided in the table below

| Work type code | CVWT | Work type code | CVWT |
|---|---|---|---|
| 110 | 1,166.1 | 230 | 1,654.5 |
| 111 | 735.7 | 232 | 714.1 |
| 141 | 1,199.9 | 310 | 1,550.4 |
| 150 | 1620.1 | 410 | N/A |
| 160 | 1,541.5 | 411 | N/A |
| 170 | N/A | 510 | 4,064.5 |
| 183 | 4,569.0 | 520 | N/A |
| 185 | N/A | 620 | 2,462.2 |
| 210 | 1,068.3 | | |

- ✓ CVD represents a corresponding numeric value of the district and the numeric value assigned to each district for the equation is provided as follows (District 1: CVD = -1462.1, District 2: CVD = -425.8, District 3: CVD = -749.6, District 4: CVD = - 1353.8, and District 5: CVD = 0)
- ✓ WH is worked hours
- ✓ Q is the quantity of TSP (CUYD)

For this controlling activity, production rates also increase when quantities increase. The tendency based on the prediction equation is consistent with the data obtained from DWR as shown in Figure 5-10.

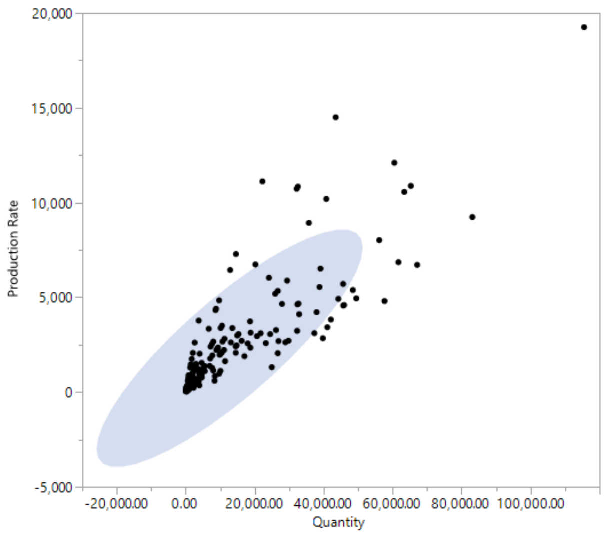



**Figure 5-10: Quantity versus production rate from DWR data (TSP)**

### *5.3.4. Special borrow*

Data from 122 historical projects were used to develop the regression model for production rates of special borrow (SB). Quantity, number of available equipment, number of used equipment, and number of supervisors are four variables that have significant effects on the production rate. The R-squared value of the model is 0.61, and the detailed equation is given below.

$$PR = 1176.9 + 0.07290 \times Q + 146.717 \times AE - 150.382 \times UE - 619.306 \times S$$

Where:

- ✓ PR is the estimated production rate (CUYD/day)
- ✓ Q is the quantity of special borrow (CUYD)
- ✓ AE is the number of available equipment
- ✓ UE is the number of used equipment
- ✓ S is the number of supervisors

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-11.

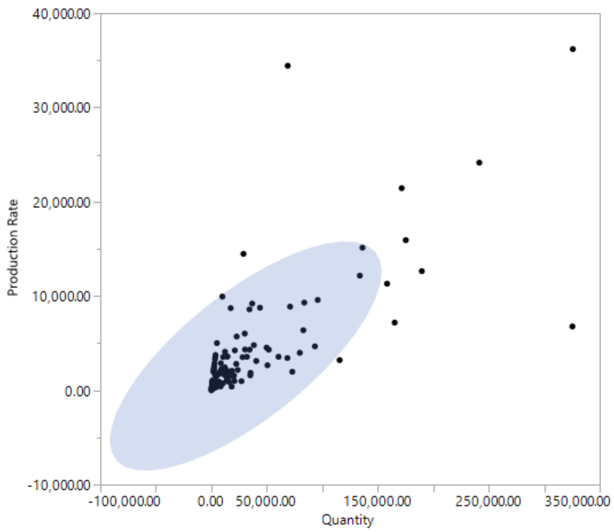



**Figure 5-11: Quantity versus production rate from DWR data (SB)**

### *5.3.5. Cold milling*

Data from 271 historical projects were used to develop the regression model for production rates of cold milling (CM). Quantity, worked hours, and number of supervisors are three variables that have significant effects on the production rate. The R-squared value of the model is 0.4, and the detailed equation is given below.

$$PR = 9287.3 + 0.09024 \times Q + 72.026 \times WH - 4120.669 \times S$$

Where:

- ✓ PR is the estimated production rate (SQYD/day)
- ✓ Q is the quantity of cold milling (SQYD)
- ✓ WH is the worked hours
- ✓ S is the number of supervisors

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-12.

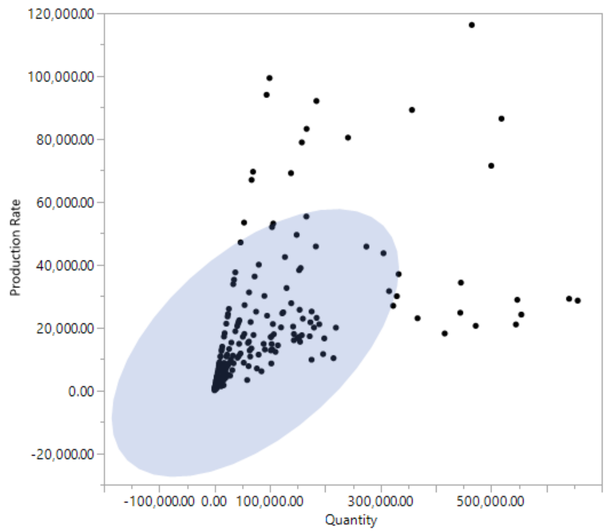



**Figure 5-12: Quantity versus production rate from DWR data (CM)**

### *5.3.6. Plant mix surfacing*

Data from 359 historical projects were used to develop the regression model for production rates of plant mix surfacing (PMS). Quantity, number of available equipment, work type, area type, district, other workers, and number of used equipment are seven variables that have significant effects on the production rate. The R-squared value of the model is 0.4, and the detailed equation is given below.

$$PR = -324.7 + 0.03 \times Q + 53.02 \times AE + CVWT + CVAT + CVD - 33.24 \times OW - 36.75 \times UE$$

Where:

- ✓ PR is the estimated production rate (Ton/day)
- ✓ Q is the quantity of PMS (Ton)
- ✓ AE is the number of available equipment
- ✓ CVWT represents a corresponding numeric value of the work type and the numeric value assigned to each work type for the equation is provided in the table below

| **Work type code** | **CVWT** | **Work type code** | **CVWT** |
|---|---|---|---|
| 110 | 253.6 | 230 | -1,004.9 |
| 111 | -696.8 | 232 | -482.3 |
| 141 | -454.1 | 310 | -548.4 |
| 150 | 514.8 | 410 | -859.4 |
| 160 | 921.7 | 411 | -974.2 |
| 170 | 49.8 | 510 | N/A |
| 183 | -1.3 | 520 | N/A |
| 185 | N/A | 620 | -475.0 |
| 210 | -116.8 | | |

- ✓ CVAT represents a corresponding numeric value of the area type and the numeric value assigned to each area type for the equation is provided as follows (Area type 0, rural: CVAT = 734.7; area type 1, urban: CVAT = 0)
- ✓ CVD represents a corresponding numeric value of the district and the numeric value assigned to each district for the equation is provided as follows (District 1: CVD = 969.7, district 2: CVD = 379.6, district 3: CVD = 379.0, district 4: CVD = 181.8, and district 5: CVD = 0)
- ✓ OW is the number of workers
- ✓ UE is the number of used equipment

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-13. In addition, the equation implies that rural areas have higher production rates than urban areas, which is consistent with the box plot generated from historical data as shown in Figure 5-14.

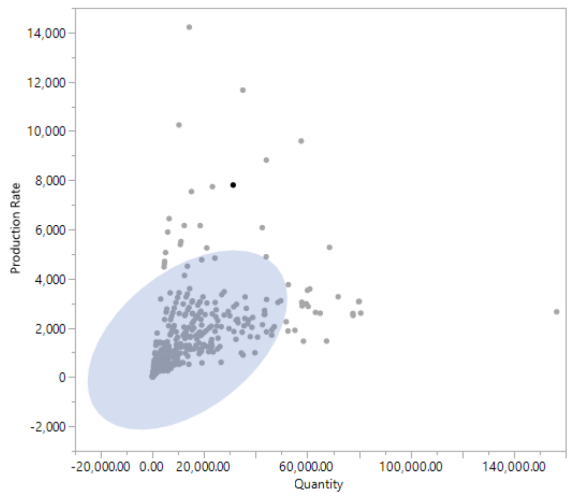



**Figure 5-13: Quantity versus production rate from DWR data (PMS)**

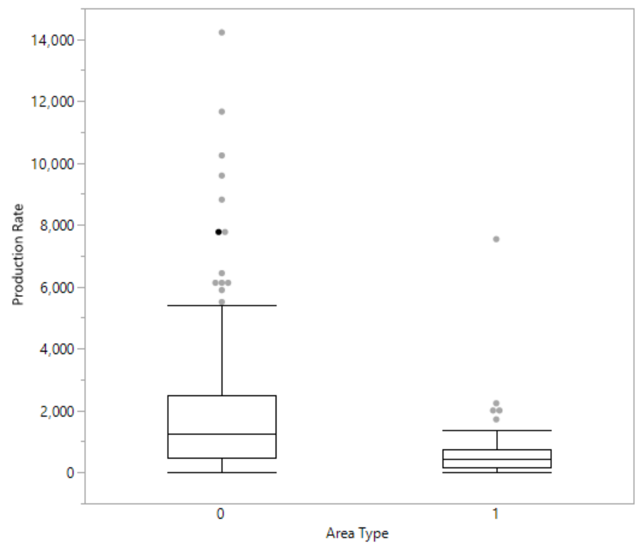



**Figure 5-14: Area type versus production rate from DWR data (PMS)**

### *5.3.7. Guardrail steel*

Data from 215 past projects were used to develop the regression model for production rates of guardrail steel (GS). Quantity and work type are the two variables that have significant effects on the production rate. The R-squared value of the model is 0.4, and the detailed equation is given below.

$$PR = 410.5 + 0.06216 \times Q + CVWT$$

Where:

- ✓ PR is the estimated production rate (LNFT/day)
- ✓ Q is the quantity of GS (LNFT)
- ✓ CVWT represents a corresponding numeric value of the work type and the numeric value assigned to each work type for the equation is provided in the table below

| Work type code | CVWT | Work type code | CVWT |
|---|---|---|---|
| 110 | -66.6 | 230 | -192.1 |
| 111 | N/A | 232 | 487.4 |
| 141 | -81.8 | 310 | 348.8 |
| 150 | -98.6 | 410 | N/A |
| 160 | 95.8 | 411 | -194.5 |
| 170 | 781.6 | 510 | N/A |
| 183 | -84.0 | 520 | N/A |
| 210 | -205.5 | | |

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-15. In addition, the equation implies that the work type 170 (Portland Cement Concrete Pavement) has higher production rates than other work types, which is consistent with the descriptive comparisons among project types as shown in Figure 5-16.

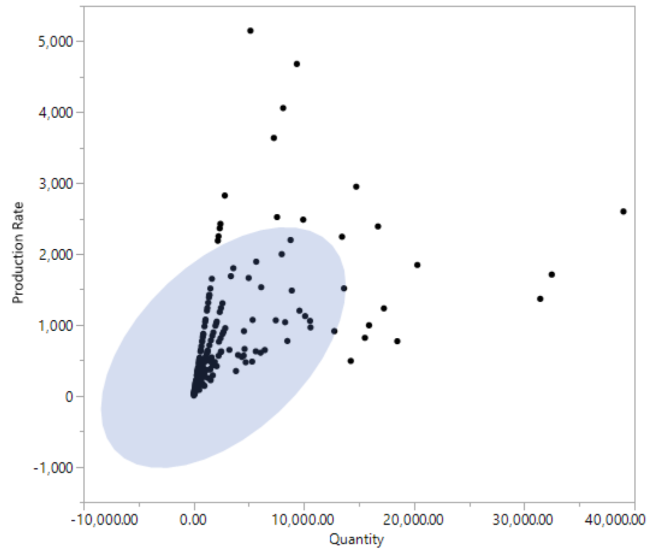



**Figure 5-15: Quantity versus production rate from DWR data (GS)**

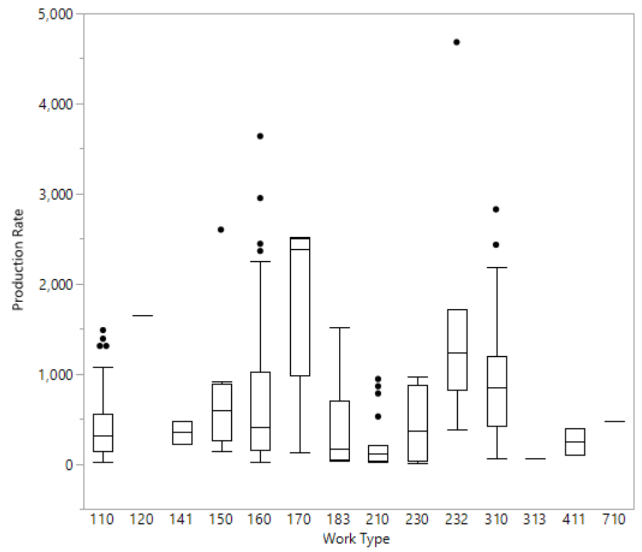



**Figure 5-16: Work type versus production rate from DWR data (GS)**

### *5.3.8. Curb and gutter*

Data from 102 past projects were used to develop the regression model for production rates of curb and gutter (C&G). Quantity, budget type, and district are the three variables that have significant effects on the production rate. The R-squared value of the model is 0.5, and the detailed equation is given below.

$$PR = 452.6 + 0.02590 \times Q + CVB + CVD$$

Where:

- ✓ PR is the estimated production rate (LNFT/day)
- ✓ Q is the quantity of C&G (LNFT)
- ✓ CVB represents a corresponding numeric value of the budget type and the numeric value assigned to each budget type for the equation is provided as follows (Budget greater than \$2 million: CVB = 0, budget less than \$2 million: CVB = -286.6)
- ✓ CVD represents a corresponding numeric value of the district and the numeric value assigned to each district for the equation is provided as follows (District 1: CVD = -49.4, district 2: CVD = 181.7, district 3: CVD = 90.8, district 4: CVD = 39.0, and district 5: CVD = 0)

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-17.

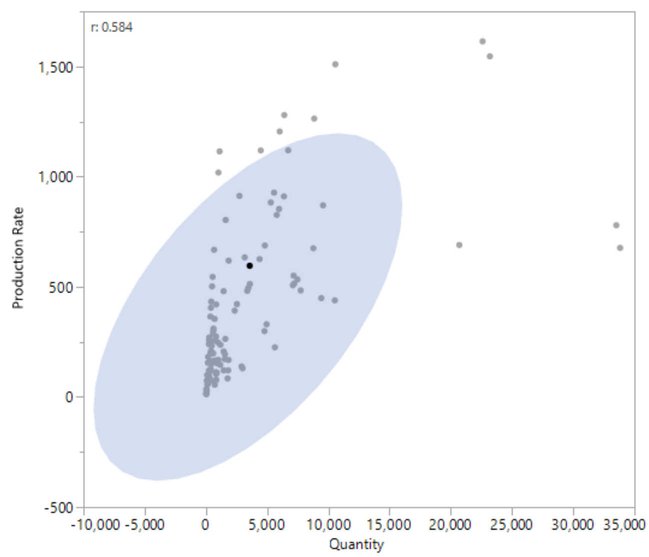



**Figure 5-17: Quantity versus production rate from DWR data (C&G)**

### *5.3.9. Farm fence*

Data from 151 historical projects were used to develop the regression model for production rates of farm fence (FF). Quantity, district, and work type are three variables that have significant effects on the production rate. The R-squared value of the model is 0.53, and the detailed equation is given below.

$$PR = 1682.4 + 0.05205 \times Q + CVD + CVWT$$

Where:

- ✓ PR is the estimated production rate (LNFT/day)
- ✓ Q is the quantity of farm fence (LNFT)
- ✓ CVD represents a corresponding numeric value of the district and the numeric value assigned to each district for the equation is provided as follows (District 1: CVD = -193.1, District 2: CVD = 649.8, District 3: CVD = 1,039.5, District 4: CVD = 2,173.9, and District 5: CVD = 0)
- ✓ CVWT represents a corresponding numeric value of the work type and the numeric value assigned to each work type for the equation is provided in the table below

| **Work type code** | **CVWT** | **Work type code** | **CVWT** |
|---|---|---|---|
| 110 | -915.3 | 230 | -2,190.0 |
| 111 | N/A | 232 | -1,329.9 |
| 141 | -2,564.2 | 310 | -2,122.6 |
| 150 | -734.0 | 410 | N/A |
| 160 | 697.0 | 411 | N/A |
| 170 | N/A | 510 | N/A |
| 183 | N/A | 520 | N/A |
| 185 | N/A | 620 | 1,613.6 |
| 210 | -1,935.0 | | |

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-18. In addition, the equation implies that District 4 has higher production rates than other districts, which is consistent with the comparisons among districts as shown in Figure 5-19.

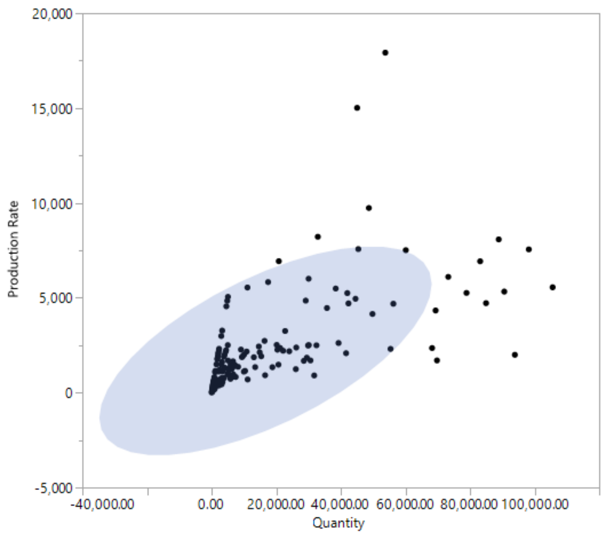



**Figure 5-18: Quantity versus production rate from DWR data (FF)**

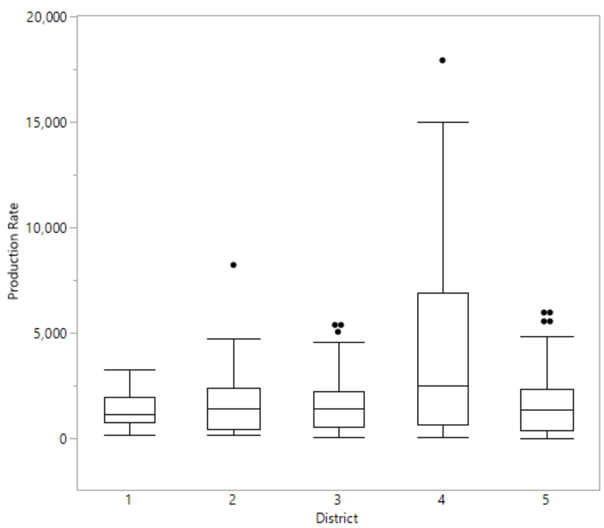



**Figure 5-19: District versus production rate from DWR data (FF)**

### *5.3.10. Seeding*

Data from 175 historical projects were used to develop the regression model for production rates of seeding. Quantity is the only variable that has a significant effect on the production rate. The R-squared value of the model is 0.64, and the detailed equation is given below.

$$PR = 4.23 + 0.23097 \times Q$$

Where:

- ✓ PR is the estimated production rate (acre/day)
- ✓ Q is the quantity of seeding (acre)

Based on the prediction equation, production rates increase when quantities increase. This tendency is consistent with the data obtained from DWR as shown in Figure 5-20.

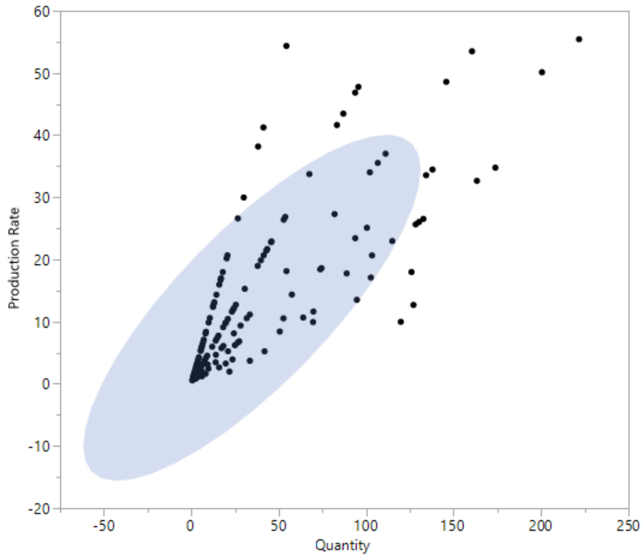



**Figure 5-20: Quantity versus production rate from DWR data (Seeding)**

## 5.4. Statistical measures of production rates of controlling activities

Statistical measures of production rates were also calculated from the DWR data. These measures can be used as references in addition to the results obtained from the regression models in section 5.3. The measures can also be used for some work which did not have enough historical data for regression analysis (i.e., base-cement treated, SSPP, drilled shaft, and concrete-class overlay).

Table 5-4 includes mean, first quartile (Q1), median (Q2), and third quartile (Q3) values of production rates for 31 controlling activities. The mean production rate of an activity is the average production rate of all past projects in the database that contained the activity. The quartiles provide with the distribution of production rates achieved in historical projects. For example, Q1 means 25% of the projects available in DWR data have production rates lower than Q1. Similarly, approximately 50% and 75% of the projects have production rates lower than median and Q3, respectively.

**Table 5-4: Statistical measures of production rates of controlling activities**

| SN | Activity description | Unit | Statistical measures from historical data | | | |
|---|---|---|---|---|---|---|
| | | | Mean | Q1 | Median | Q3 |
| AA | Topsoil-Salvaging and Placing | CUYD | 2,313 | 306 | 1,267 | 3,071 |
| AB | Excavation-Unclassified | CUYD | 8,874 | 941 | 4,950 | 12,542 |
| AC | Special Borrow | CUYD | 3,640 | 645 | 1,808 | 3,710 |
| AD | Excavation-Street | CUYD | 1,518 | 518 | 978 | 2,426 |
| AE | Crushed Aggregate Course | CUYD | 2,088 | 132 | 636 | 2,654 |
| AF | Base-Cement Treated | CUYD | 3,453 | 1,550 | 3,566 | 5,045 |
| AG | Drainage Pipe (<= 24 In) | LNFT | 95 | 59 | 87 | 112 |
| AH | Drainage Pipe (> 24 In) | LNFT | 91 | 55 | 73 | 119 |
| AI | RCB | LNFT | 95 | 49 | 66 | 140 |
| AJ | SSPP | LNFT | 66 | 21 | 54 | 99 |
| AK | Riprap | CUYD | 136 | 24 | 94 | 203 |
| AL | Cold Milling | SQYD | 15,077 | 1,911 | 8,220 | 20,472 |
| AM | Plant Mix Surfacing | TON | 1,509 | 378 | 1,028 | 2,177 |
| AN | Cover | SQYD | 83,884 | 15,892 | 56,360 | 120,458 |
| AO | Micro-Surfacing | TON | 465 | 408 | 443 | 525 |
| AP | Crack Sealing | LB | 6,346 | 3,004 | 5,130 | 8,003 |
| AQ | PCCP | SQYD | 568 | 237 | 448 | 1,105 |
| AR | Curb and Gutter | LNFT | 408 | 137 | 261 | 562 |
| AS | Sidewalk | SQYD | 246 | 61 | 131 | 283 |
| AT | Farm Fence | LNFT | 2,206 | 540 | 1,423 | 2,422 |

| | | | | | | |
|---|---|---|---|---|---|---|
| AU | Guardrail Steel | LNFT | 680 | 150 | 424 | 902 |
| AV | Concrete Barrier Rail | EACH | 58 | 12 | 25 | 84 |
| AW | Seeding | ACRE | 12 | 3 | 7 | 18 |
| AX | Reinforcing Steel | LB | 13,995 | 5,195 | 10,517 | 18,271 |
| AY | Drilled Shaft | LNFT | 103 | 59 | 88 | 139 |
| AZ | Concrete-Class Deck | CUYD | 73 | 43 | 61 | 85 |
| BA | Class A Bridge Deck Repair | SQYD | 14 | 5 | 8 | 17 |
| BB | Concrete Barrier Rail-Bridge | LNFT | 222 | 88 | 141 | 252 |
| BC | Concrete-Class Overlay | CUYD | 31 | 23 | 35 | 44 |
| BD | Bridge Deck Milling | SQYD | 473 | 312 | 394 | 584 |
| BE | Revise Bridge Concrete Barrier | LNFT | 200 | 69 | 157 | 245 |

## 5.5. Evaluation of contractors' performance

Contactor's expertise and performance can determine the project success. Contractors' performance can be defined by the level and quality of the projects delivered to clients. It is difficult for the project owner to make appropriate decisions in selecting the best fit for the project. However, it has been a common practice to select the lowest bidder among competing contractors to perform the job, which might experience inefficient management of construction project and result in low performance and productivity (Doloi et al. 2011; Lee et al. 2014).

Currently, performance bonds are being used as a pre-qualification to protect the owner in the event that a contractor fails to complete a bridge or highway construction contract and is unable to provide a remedy for the failure, which typically arises from the contractor's deteriorated financial condition (Dye et al. 2014). However, performance bonds are not considered as an insurance for the performance of the contractor. In practice, contractors are evaluated on three sets of criteria: character (e.g., letters of reference, presence of certain systems and procedures, and quality management systems), capacity (the contractor's management practices, personnel, and equipment), and capital (the contractor's funding capacity) (Dye et al. 2014). A contractor with a marginal track record for quality and time performance but having a strong financial record is still able to furnish performance bonds and therefore has the same opportunity to bid.

Many state DOTs have mentioned different factors that are significant in the evaluation of a contractor. Table 5-5 shows some of the major factors along with the number of DOTs that claim significance for these factors (Dye et al. 2014). The schedule is one of the most recognized factors by DOTs. Previous studies have focused on various methodologies to evaluate contractor performance; however, research using production rates achieved on past projects from DWR data to assess contractors' performance is limited. While determining the contract completion time for a project, it is important to determine if a contractor can achieve the desired production rates. If the contractor cannot maintain the desired production rates, the project may encounter cost and schedule overruns.

**Table 5-5: Major factors in evaluation of a contractor (Dye et al. 2014)**

| Categories | Number of DOTs claiming significance |
|---|---|
| Quality, Workmanship, and Materials | 20 |
| Safety | 12 |
| Schedule | 12 |
| Organization | 9 |
| Equipment | 10 |
| Project Management | 14 |
| Prosecution of Work | 12 |
| Traffic Control | 9 |

For this reason, this research focuses on using DWR data to develop a method to evaluate the capability of contractors to maintain their production rates. Two major construction activities are selected for this analysis. They are (1) crushed aggregate course and (2) plant mix surfacing. These activities are chosen based on their importance to the critical path of highway construction projects as any delay would directly impact the schedule of the project.

The calculated production rate of a controlling activity for each project is compared with the average production rate of that activity (section 5) to categorize production rates into three tiers.

a) Tier 1 - High performance: production rate > 1.5 x the average production rate.
b) Tier 2 - Medium performance: 0.8 x the average production rate ≤ production rate ≤ 1.5 x the average production rate
c) Tier 3 – Low performance: production rate < 0.8 x the average production rate

### *5.5.1. Comparisons of production rates of three tiers*

Each category of production rates was analyzed separately to gain insight into the distribution of each category. @Risk software was used to build the specific distribution of production rates for each tier. For graphical representation, tiers 1, 2, and 3 are respectively represented in green, blue, and red colors.

#### *5.5.1.1. Crushed aggregate course (CAC)*

For this controlling activity, tiers 1, 2, and 3 consist of 62, 44, and 204 values of production rates from the DWR data, respectively. Based on these values, the most appropriate distribution model was identified for each tier, and then simulations (10,000 iterations) were run to form the distribution for that tier. Distributions for tier 1, tier 2, and tier 3 are shown in Figures 5-21, 5-22, and 5-23. As can be seen from Figure 5-21, the mean production rate of tier 1 is 7,313 CUYD/day and the probability of a tier-1 production rate greater than 3,385 CUYD/day is 95%. As shown in Figure 5-22, the mean production rate of tier 2 is 2,425 CUYD/day and the probability of a tier-2 production rate smaller than 3,030 CUYD/day is 95%. Similarly, the mean production rate of tier 3 is 423 CUYD/day, and the probability of a tier-3 production rate smaller than 1,302 CUYD/day is 95%.

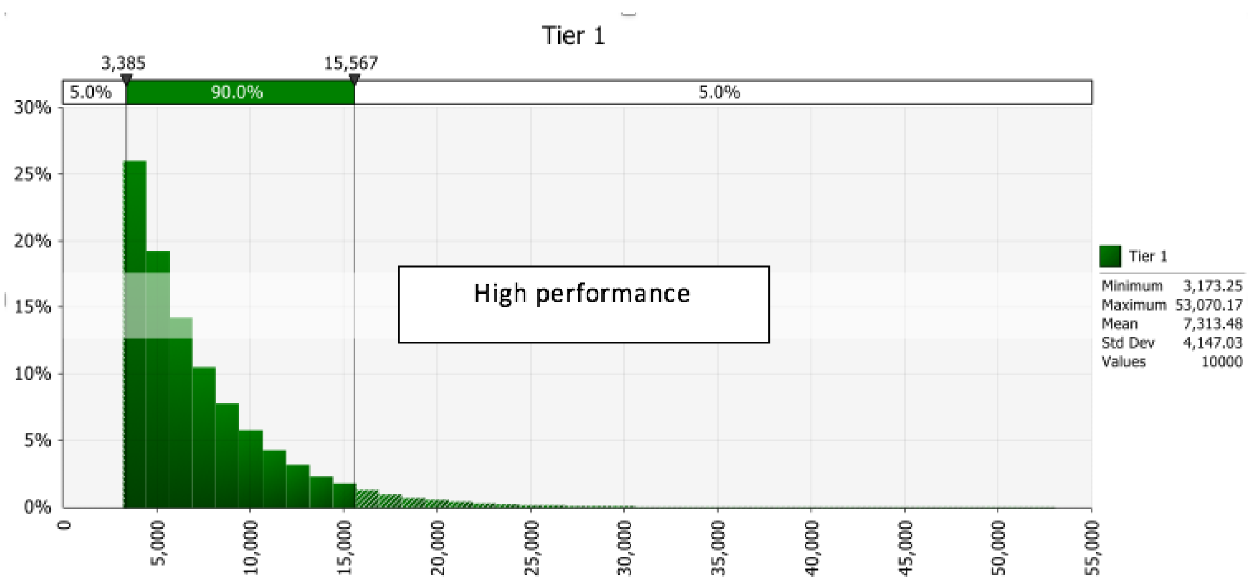



**Figure 5-21: Production rate distribution of tier 1, CAC**

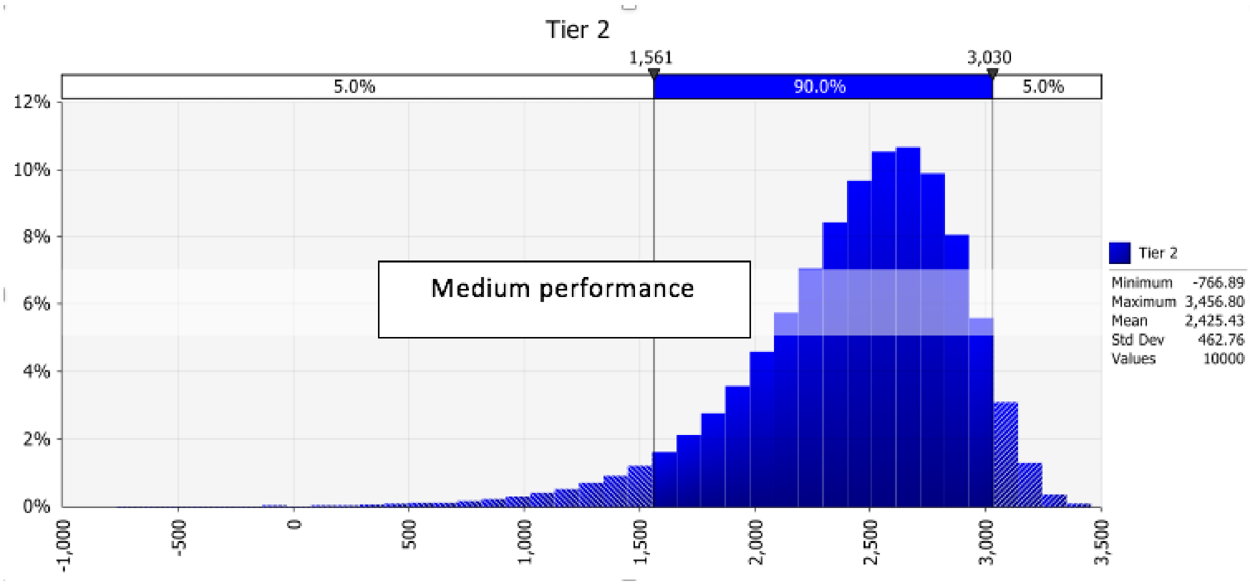



**Figure 5-22: Production rate distribution of tier 2, CAC**

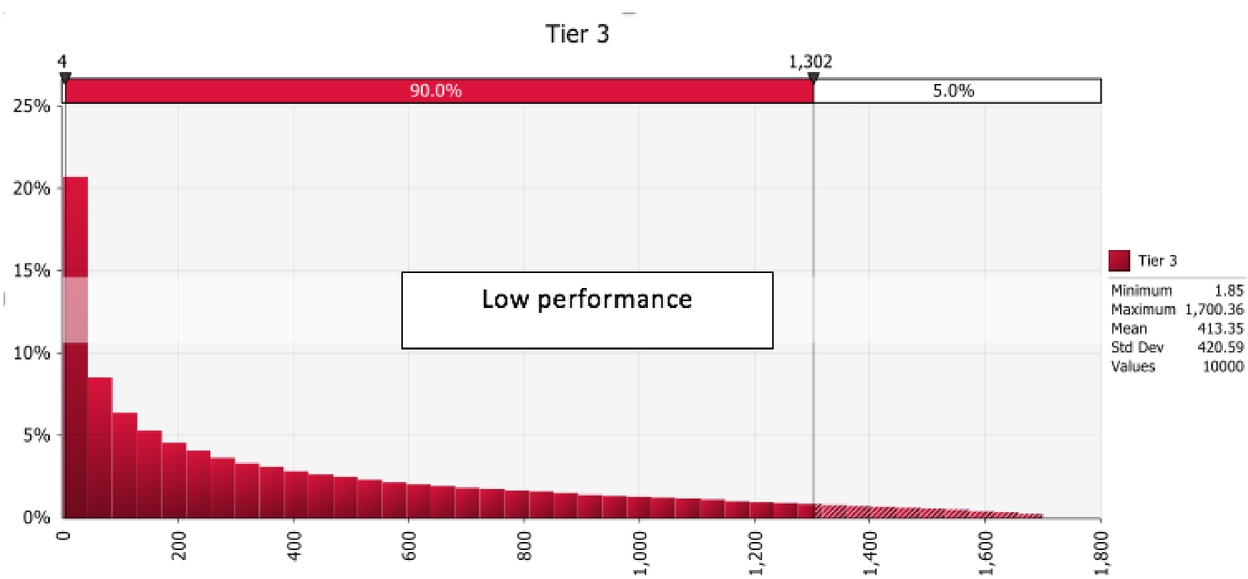



**Figure 5-23: Production rate distribution of tier 3, CAC**

Figure 5-24 compares production rates between tier 1 and tier 2. A good distinction between tier 1 and tier 2 is 3,385 CUYD/day because the probability of a tier-1 production rate larger than 3,385 CUYD/day is 95% and that of a tier-2 production rate smaller than 3,385 CUYD/day is 100%. Similarly, 1,561 CUYD/day can be considered a good distinction between tier 2 and tier 3 since the probability of a tier-2 production rate larger than 1,561 CUYD/day is 95% and that of a tier-3 production rate smaller than 1,561 CUYD/day is 99%.

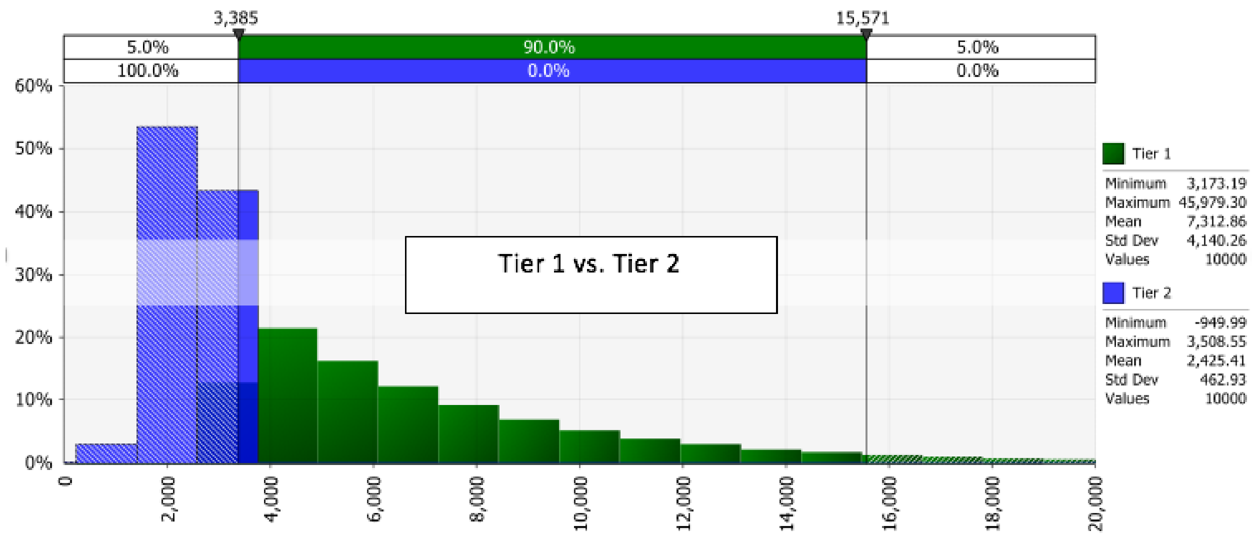



**Figure 5-24: Production rate distributions of tier 1 and tier 2, CAC**

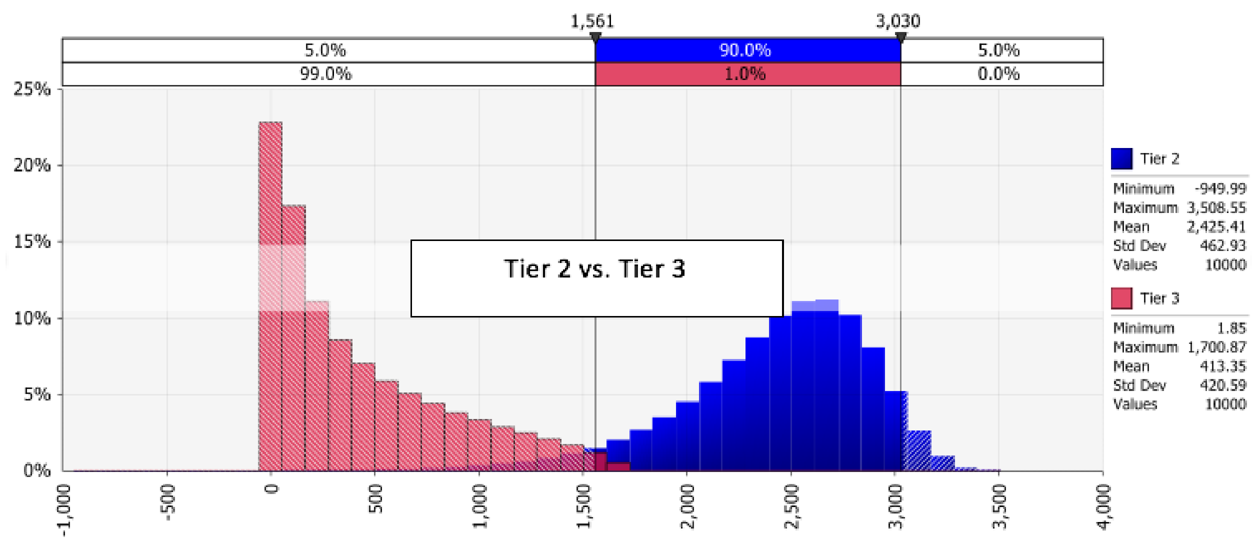



**Figure 5-25: Production rate distributions of tier 2 and tier 3, CAC**

*5.5.1.2. Mix plant surfacing (PMS)*

For this controlling activity, tiers 1, 2, and 3 consist of 110, 94, and 248 values of production rates from the DWR data, respectively. Based on these values, the most appropriate distribution model was identified for each tier, and then simulations (10,000 iterations) were run to form the distribution for that tier. Distributions for tier 1, tier 2, and tier 3 are shown in Figure 5-26, 5-27, and 5-28. As can be seen from Figure 5-26, the mean production rate of tier 1 is 3,771 ton/day and the probability of a tier-1 production rate greater than 2,322 ton/day is 95%. As shown in Figure 5-27, the mean production rate of tier 2 is 1,729 ton/day and the probability of a tier-2 production rate smaller than 2,209 CUYD/day is 95%. Similarly, the mean production rate of tier 3 is 463 ton/day, and the probability of a tier-3 production rate smaller than 1,386 ton/day is 95%.

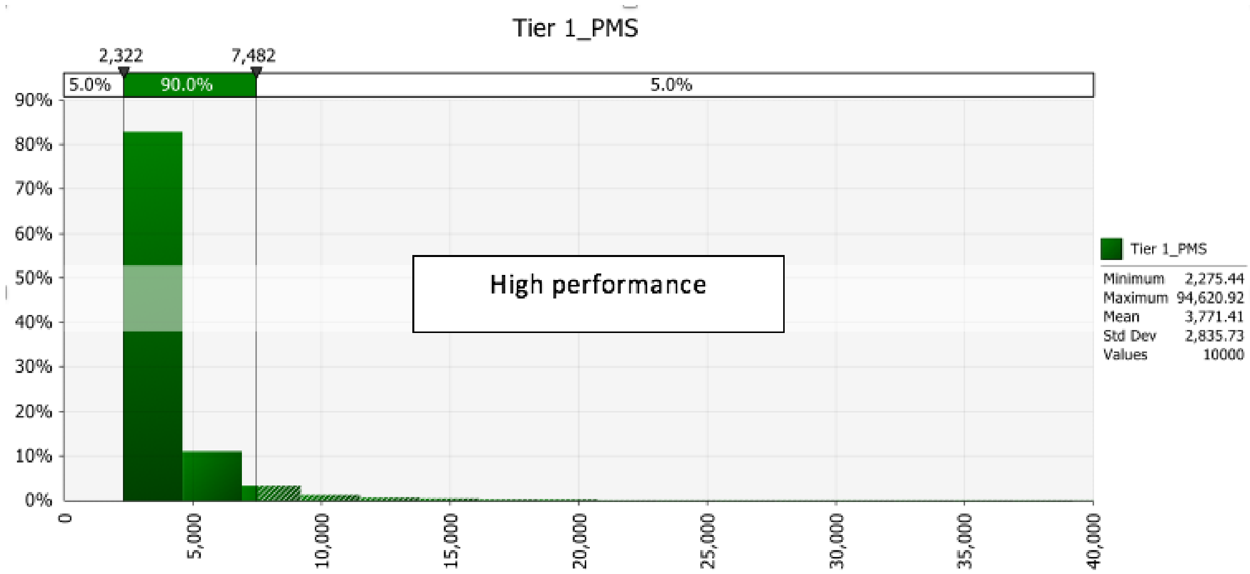



**Figure 5-26: Production rate distribution of tier 1, PMS**

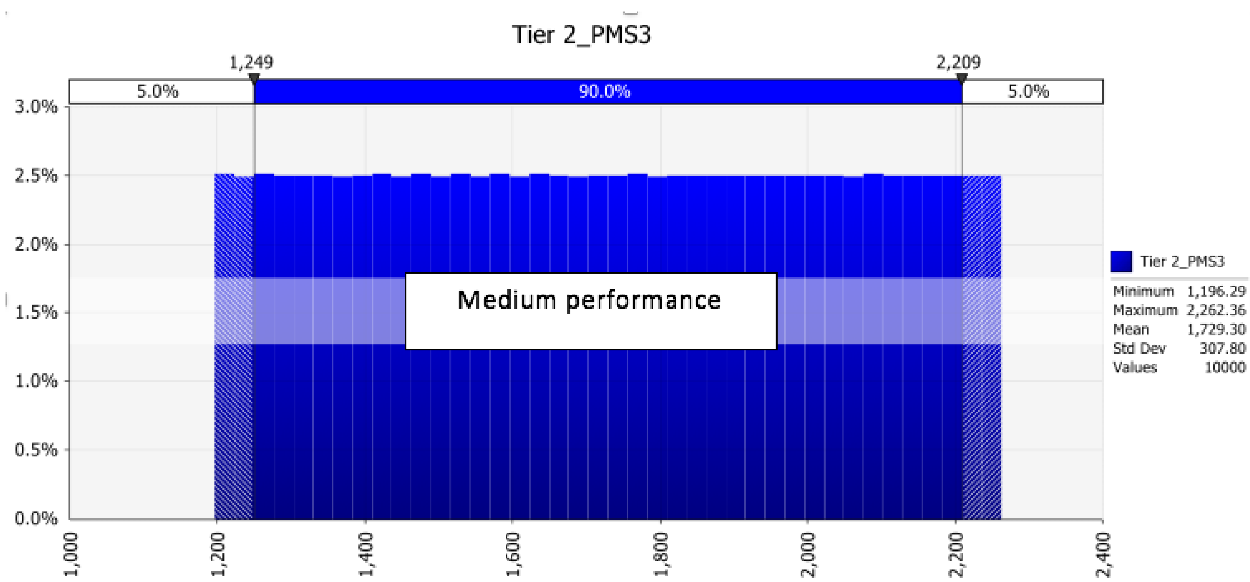



**Figure 5-27: Production rate distribution of tier 2, PMS**

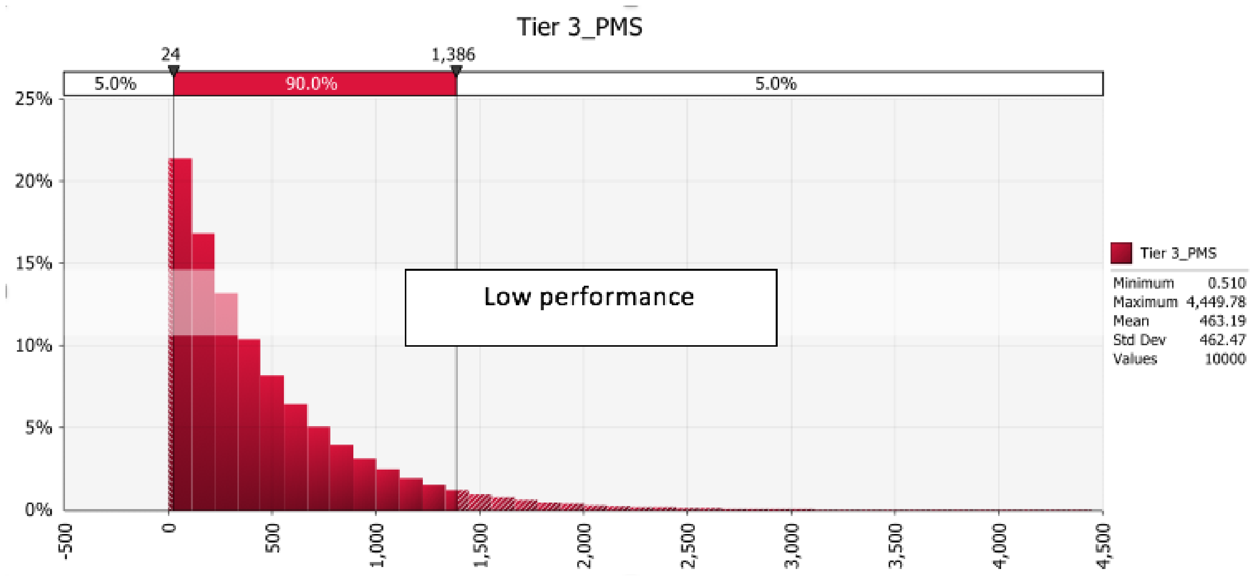



**Figure 5-28: Production rate distribution of tier 3, PMS**

Figure 5-29 compares production rates between tier 1 and tier 2. A good distinction between tier 1 and tier 2 is 2,322 ton/day because the probability of a tier-1 production rate larger than 2,322 ton/day is 95% and that of a tier-2 production rate smaller than 2,322 ton/day is 100%. Similarly, 1,249 ton/day can be considered a good distinction between tier 2 and tier 3 since the probability of a tier-2 production rate larger than 1,249 ton/day is 95% and that of a tier-3 production rate smaller than 1,249 ton/day is 93%.

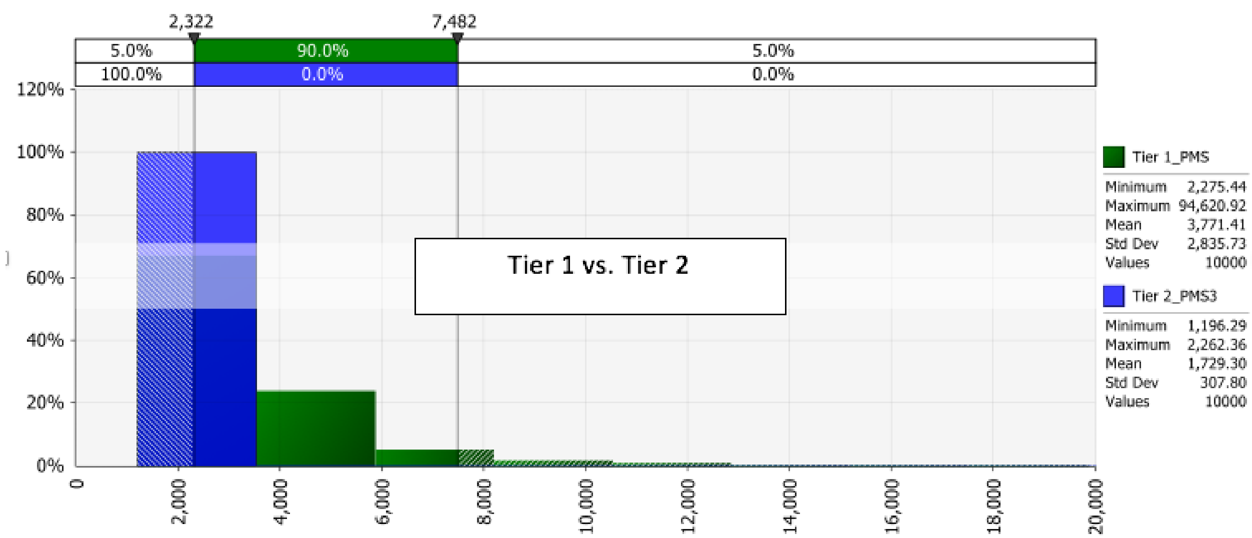



**Figure 5-29: Production rate distributions of tier 1 and tier 2, PMS**

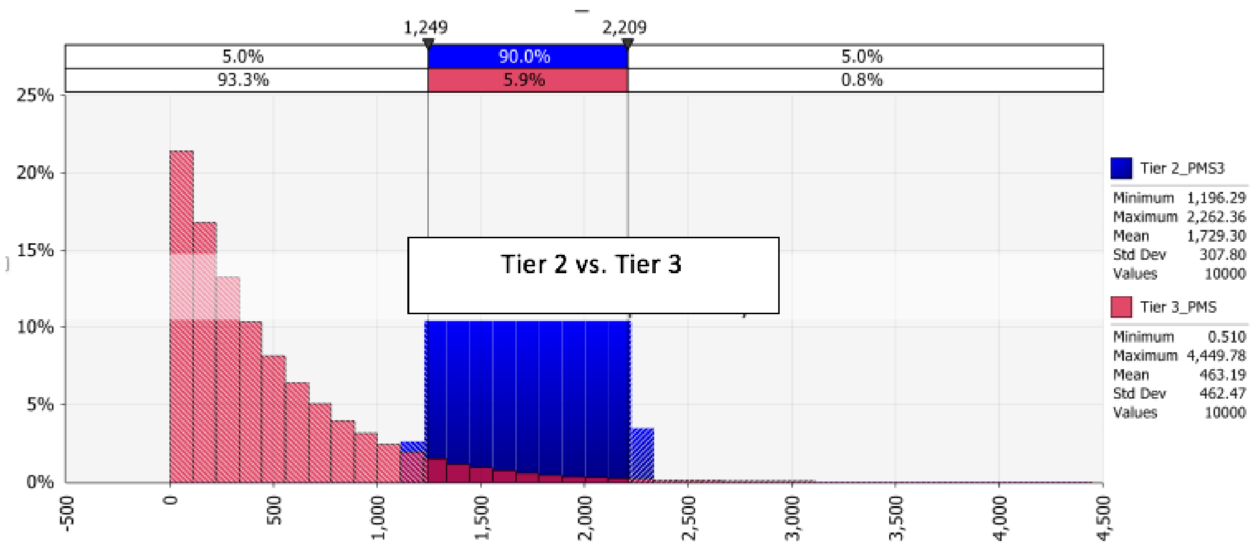



**Figure 5-30: Production rate distributions of tier 2 and tier 3, PMS**

### *5.5.2. Production rate comparison among contractors*

With the same process applied for crushed aggregate course and plant mix surfacing, categorizations for 31 controlling activities can be developed. Production rates of all contractors available in the DWR data can be calculated for each controlling activity and classified based on the developed categorizations. To evaluate whether a contractor is suitable for a project, past performances of the contractor on those controlling activities relevant to the project should be evaluated and the proposed categorizations can be used for this purpose. If a contractor has poor performances across the activities, careful considerations from the DOT are needed before awarding the contractor a contract.

# 6. Production rate estimation tool (PRET)

This section describes the final task of this research which involves the development of a MS Excel based Production Rate Estimation Tool (PRET). This section explains the development of the tool and also provides guidelines on how it can be used by MDT engineers to obtain production rate estimates. This section also discusses the limitations of the tool.

## 6.1. The significance of the tool

The MDT Production Rate Estimation Tool (MDT-PRET) is of significant importance. This tool allows MDT engineers to estimate production rates for future projects more systematically and efficiently while considering the main factors that significantly affect production rates of each controlling activity. Since this tool is based on the statistical relationships found between the production rates and various factors from the DWR data, MDT personnel can obtain more accurate and realistic estimates of production rates.

## 6.2. Development of the tool

The MDT-PRET is based on the regression equations and the historical measures obtained in section 6. To estimate production rates of a work item using the regression equations, values of predictor variables need to be identified. The tool allows users to provide the input of major factors, i.e., the district, location type, season of work, project work type, project amount, and quantity of work of the project. Average values obtained from the DWR data are used for labor and equipment variables and embedded in the tool. Given the input, the tool can automatically generate production rates.

## 6.3. Guideline for usage of the tool

Please refer to the Production Rate Estimation Tool (PRET) – User's Manual.

## 6.4. Limitations of the tool

One of the major limitations of the MDT-PRET developed in this research is that it cannot take account of all possible factors that might affect production rates in a project. The factors are restricted to data availability in the DWR data. The fact that the DWR data has a wide range of production rates along with various project work types for each controlling activity leads to an increase in variability in the prediction accuracy of the activity.

# 7. Conclusions

Accurate and practical production rate estimates are crucial for an accurate forecast of contract completion time. As costs of highway projects increase with time, the importance of estimating highway construction contract time has increased significantly, thereby emphasizing the need for effective production rates due to the interrelatedness between the two. By reviewing the literature, various aspects of production rate estimation were identified including factors that influence production rates, production rate adjustment factors, and statistical methods, and current practices of MDT.

The MDT's DWR data, bid data, and GIS data were cleaned and combined to form a central database to estimate realistic production rates. The major attributes in the database are the project number, project amount, work type, district, budget type, area type, labor and equipment variables, vendor ID, season, quantity, and production rate. Descriptive analysis, regression analysis, and Monte Carlo simulation were deployed to offer insights into historical projects' characteristics and production rates of 31 controlling activities of MDT.

The major findings of the descriptive analysis were statistical measures (i.e., mean, first quartile, median, and third quartile) of 31 controlling activities, which provide more practical, detailed, and updated estimates in comparison with the current published values. In addition, variations of production rates in terms of different seasons of work, districts, area types (urban/rural), and budget types were explored. Regarding project characteristics, overlay, reconstruction/new construction, and safety were the most popular work types in every district in Montana.

The study developed regression equations to estimate production rates of 27 out of 31 controlling activities. For each activity, factors that had a significant effect on production rate were included in the regression model as predictor variables. Quantity, project work type, district, number of equipment, and budget type were proved to have a significant effect on many of the controlling activities. In addition, the regression models have provided meaningful relationships between predictor variables/influencing factors and the predicted variable/production rate. Some examples are that production rates of excavation – unclassified increase when quantities and the number of units of available equipment increase and that production rates of plant mix surfacing in rural areas are higher than those in urban areas.

In this study, a production rate-based method was proposed to evaluate contractor's performances. Based on the historical data of each controlling activity, a three-tier categorization (i.e., high performance, medium performance, and low performance) was suggested for each activity. Monte Carlo simulation was used to establish a distribution for each tier in order to make distinctions among the three tiers. For a specific project, contractors can be evaluated based on categorizations of those activities relevant to the project.

Based on the results of the descriptive and predictive analysis, an MS Excel based Production Rate Estimation Tool (PRET) was developed to help MDT practitioners obtain production rate information and estimated production rates based on historical performance data. Once users of the tool provide input parameters specific to a new project, production rates can be automatically estimated based on embedded regression models. Statistical measures from the DWR data are also provided in the tool as references to compare with the results from regression models to ensure reliable estimates.

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