ESTIMATING THE PROBABILITY OF SATISFACTORY CONDITIONS FOR MAIN ENTRY INTERSECTIONS IN A COAL MINE IN WEAK ROCK UNDER DEEP MINING DEPTH

by

Collin L. Stewart

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Golden, Colorado

Date __________________________

Signed: __________________________
Collin L. Stewart

Signed: __________________________
Dr. Mustafa U. Ozbay
Thesis Advisor

Golden, Colorado

Date __________________________

Signed: __________________________
Dr. Priscilla P. Nelson
Professor and Head
Department of Mining Engineering

ABSTRACT

The satisfactory condition of underground coal mine intersections is a fundamental requirement for the safe operation of any underground coal mine. A satisfactory intersection condition goes beyond prevention of a roof fall. It must include the ability of the intersection to safely perform its designed function. A satisfactory condition is especially important for those main entries that provide life-of-mine access; both to the current, active areas of the coal mine, and to the future mining areas of the coal reserve or resource. Life-of-the-mine access may be required for decades. The intersections in the main entries must provide safe, satisfactory conditions and performance during this time. Long-term, satisfactory intersection conditions are particularly problematic in a deep/weak rock coal mine environment characterized by: (1) mining depths greater than 800 ft, (2) a poor to fair quality rock mass above the coal seam (RMR ≤ 50); and, (3) very weak to weak rock strength conditions for the immediate rock strata above and below the coal seam (CMRR ≤ 35).

This research collected, compiled, and analyzed a data set of the geometries, environments, and conditions of 884 intersections in the main entries of a longwall coal mine, operating in the deep/weak rock coal mine environment. The database compiled from the data set included binary, categorical, and numeric predictor variables. The research developed a binary outcome variable from the database, an intersection condition rating as Satisfactory or Not satisfactory, that included the design function requirements of each intersection over the life of the intersection. The data were analyzed and a list was compiled of statistically significant predictor variables impacting the satisfactory condition of an intersection at the mine. An intersection condition probability estimation model was developed from the derived outcome variable, the list of predictor variables, and the data set. The probability estimation model was derived using logistic regression.

This research was unique because it collected a large database specific to the deep/weak rock coal mine environment in the main entries of an operating, longwall coal mine in the US. It is the first application of the logistic regression method to derive an equation for estimating the probability of satisfactory intersection conditions. The research developed a novel method for the in-mine evaluation and rating of the existing safety and conditions of a coal mine intersections that incorporates the conditions of the roof, ribs, floor, secondary and supplemental support, and function performance for use by the coal mining industry.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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The "Western Longwall Mine" provided the opportunity collect the data used to perform this study and use the data for this research project. Mr. Scott Jones, General Manager, supported this this project and provided the permission to use the data in this research project. Dr. Stephen Bessinger, Engineering Manager, provided active support and contributed greatly to the study concept, field work, data collection, and data compilation. Mine site technical staff, who gave generously of their time and expertise, providing data, support, insights, and general all around encouragement included, Dan Sypersma, John Mercier, Steve Korte, James Pile, and Dave Burkhard.

Many thanks to Roger Pihl who accompanied me on multiple visits to all 884 intersections in the East Mains. We walked many miles together.

DEDICATION

I dedicate this effort to the mining people at the mines where I have worked. They shaped my personal and professional development through these many years.

Dr. John Trapp planted the idea of working on a PhD in the mind of a new graduate engineer. Dr. Donald W. Gentry and Dr. John F. Abel, who with their exemplary professional careers and personal friendships, provided the inspiration for me to complete this effort. Dr. Mustafa Ozbay provided patience and support while I brought this effort to a successful completion.

I thank Sherida, my wife, for all she is to me in our life journey together.

To my Lord Jesus Christ.

CHAPTER 1

INTRODUCTION

The satisfactory condition of underground coal mine intersections is a fundamental requirement for the safe operation of any underground coal mine. This requirement is especially important for those main entries that provide life-of-mine access; both to the current, active areas of the coal mine, and to the future mining areas of the coal reserve or resource. This life-of-the-mine access typically is required for decades. The intersections in the main entries must provide satisfactory conditions and performance for this entire period. However, the long-term, satisfactory condition of intersections is problematic because they are “structurally weaker” areas (Gercek 1982) and subjected to “substantially different” conditions compared to other mine openings and structures (Hanna et al. 1991b). A Not satisfactory intersection condition was a contributing cause in approximately 70% of the fatal and non-fatal injuries reported in the US for the period from 2002 through 2007 despite being less than 25% of the total mined area (Abbasi 2010). Peng (2015) noted that the “great majority” of roof falls continue to occur in intersections. This problem of Not satisfactory intersection conditions increases with weaker roof rock and deeper mining depth (Fabjanczyk et al. 1999; Molinda et al. 2000; Mark et al. 2004; Molinda et al. 2010; Pappas et al. 2011). The design of safe, satisfactorily performing underground coal mine intersections with weak roof rock is a research priority of the National Institute of Occupational Health and Safety (NIOSH). They list roof fall evaluation and mediation in weak rocks as a research need under Mining Strategic Goal 6 – Reduce Ground Control Injuries (NIOSH 2014).

The objective of this research was the development of a method and equations to assess the probability of the satisfactory condition of an intersection design in a coal mine environment characterized as a deep/weak rock environment. This deep/weak rock environment is defined:

- By mining depths greater than 800 ft.
- By a poor to fair quality rock mass (RMR ≤ 50) above the coal seam.
- By very weak to weak rock strength conditions (CMRR ≤ 35) for the immediate rock strata above and below the coal seam.

The research method utilized a logistic regression analysis of a database of the geometries, environments, and conditions of 884 intersections in the main entries of an underground, longwall, coal mine, operating in the deep/weak rock coal mine environment. This database was designed, collected, compiled, and analyzed for this research. The database consisted of an outcome variable and predictor variables. The outcome variable was a binary categorical variable defined as an intersection condition rating of Satisfactory or Not satisfactory intersection conditions. Predictor variables consisted of measurements and descriptions of the intersection geology and geomechanical rock properties, geometry, roof support, and conditions.

The logistic regression analysis method is specifically used for the analysis of data sets consisting of a binary categorical outcome variable and all types of predictor variables, binary, categorical, and numeric. It is the most used method for this type of data (Hosmer et al. 2013). The method has wide use in the medical, life, social, and earth sciences and has been utilized in the development of a variety of hard rock and coal mining ground control methods and research (Mark 2016).

This research was the first application of the logistic regression method to derive an equation for estimating the probability of satisfactory intersection conditions from an empirical mining database of the geometries, environments, and conditions of intersections in the deep/weak rock coal mining environment.

1.1 Problem Statement

The development of the problem statement began with an empirical observation. Approximately 37% of all the 884 intersections in the main entries of an underground, longwall, coal mine located in the western US exhibited Not satisfactorily conditions (i.e. a Not satisfactory condition rating). These main entries were designated as the East Mains Study Area (EMSA) of the western longwall mine (WLM). The WLM was characterized by a mining environment and conditions that were considerably outside of the norms for underground coal mine. Mining depths at the WLM varied from 104 ft to 1058 ft. The geologic environment consisted of overburden rock strata with rock mass quality ratings of poor to fair (RMR≤50) using the Rock Mass Rating System (Bieniawski 1979). The rock strata immediately above and below the coal seam were classified as very weak to weak strength (Brown 1981) with Coal Mine Roof Rating (CMRR) values of ≤35, calculated using the CMRR method (Molinda et al. 1994; NIOSH 2013b).

A Satisfactory condition rating was given to an intersection that:

- Had no MSHA reportable roof fall.
- Had no additional ground support beyond the design ground support.
- Was capable of safely performing its’ designed function (e.g., escapeway, ventilation airway, travelway, etc.).

An initial literature review indicated that:

- The combination of mining operations, regulatory requirements, mining depth, and the geologic environment at the WLM were not well represented in the worldwide literature of coal mining ground control.
- There was a limited understanding of the impacts of deeper mining depth; geologic, geohydrologic, and geomechanical conditions and properties; opening geometry; ground support density; mine layout; and, mine operations variables that impacted satisfactory intersection conditions in the deep/weak rock coal mining environment.
- There were no accepted methods to estimate the probability of satisfactory intersection conditions in the deep/weak rock coal mine environment. Existing methods were based on and applicable to mining conditions characterized by generally shallower mining depths, a better-quality rock mass, and higher strength rock units immediately above and below the coal seam.
- The WLM had developed a site-specific, bulk rock mass, numerical model that indicated that the design of the primary, in-roof ground support should be adequate (Applied Research Associates 2008, 2010, 2011).

The life-of-mine plan for the WLM required a method for estimating the probability of satisfactory conditions for main entry intersections in the deep/weak rock environment. The method required an understanding of the variables impacting satisfactory intersection conditions for main entries. The method needed to incorporate key aspects of intersection design, ground support, intersection geometry, and anticipated operational, geologic, geomechanical, and geohydrologic conditions. This information would be used:

- To plan and design repairs to existing intersections in the EMSA with Not satisfactory condition ratings.
- To identify potentially Not satisfactory intersections in the EMSA and plan and design rehabilitation and reinforcement work for these intersections before Not satisfactory conditions developed.
- To design future mine workings under mining depths greater than 800 ft and as high as 2000 ft.
- For continued development of the WLM bulk rock mass numerical model.

These requirements established the objective of this research as the development of a method and equations to estimate the probability of the satisfactory condition of an intersection design in a deep/weak rock coal mine environment.

1.1 Research Questions

The problem statement resulted in the development of two research questions:

1. What are the significant variables in the areas of geologic conditions, mining depths, geohydrologic conditions, geomechanical rock properties, in situ stresses, mining-induced stresses, opening geometries, ground support densities, mine layouts, and mine operational functions that are significant predictor variables of the probability of satisfactory conditions for an intersection in an underground coal mine developed in a poor to fair quality overburden rock mass, with mining depths from approximately 800

ft to more than 2000 ft, and with very weak to weak strength, near-seam rock strata, characterized by CMRR values of less than 35?

2. Will an empirical, analytic observational, cross-sectional study of the 884 intersections in the East Mains of the WLM, developed in a poor to fair quality overburden rock mass, with mining depths varying from approximately 100 ft to more than 1050 ft, and with very weak to weak strength near-seam rock strata, provide adequate data for analysis to develop a theory, method and equation for estimating probability of satisfactory intersection conditions based on the significant variables identified in Research Question 1?

1.2 Methodology

The research methodology is outlined on Figure 1.1. The research method was derived from the concept that an empirical study using an analytic, observational, cross-sectional data collection method and logistic regression analyses of the observational data could address the research questions.

A literature review was performed with three goals:

- Review the use of logistic regression in mining-related ground control problems to determine the state-of-the-art and any existing studies or methods related to the research questions.
- Determine variables impacting satisfactory intersection conditions both in general and specific to weak rock and deep mining conditions.
- Review existing coal mine roof condition rating methods in the literature with respect to development of a rating method for use in this research.

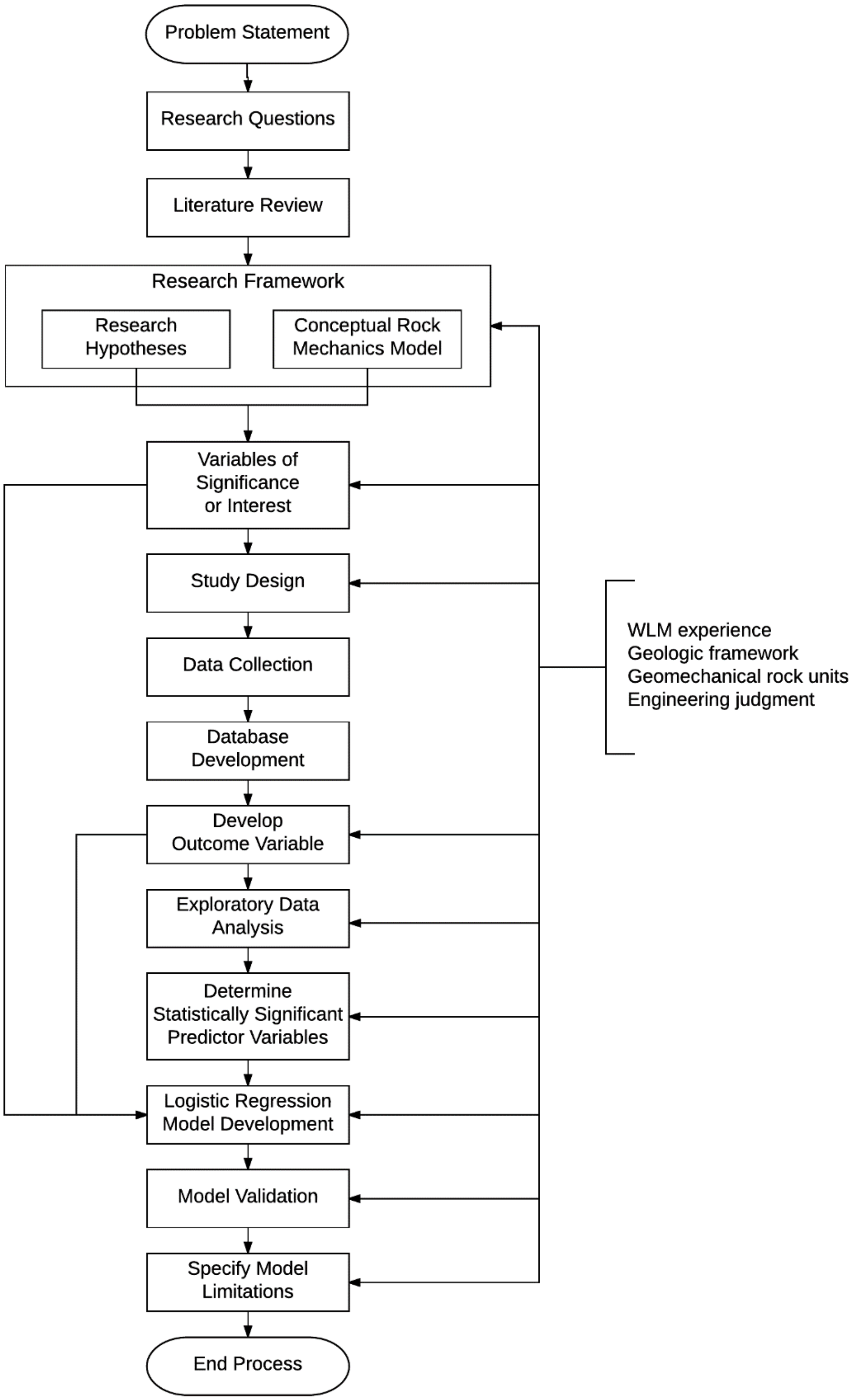


Figure 1.1 Research methodology flowchart.

The research framework consisted of the research hypotheses and the conceptual rock mechanics model. These two items were developed from the results of the literature review combined with WLM experience, the geologic framework, the geomechanical rock units, and engineering judgement. This overall research framework guided the development of the study design.

The study design was developed to specify the requirements for the observational data collection that was conducted in the EMSA of the WLM. The EMSA consisted of 884 intersections characterized by an outcome variable and predictor variables with variability in sufficient quantity and of acceptable quality to address the research questions and to statistically evaluate the research hypotheses. Data collection was performed in the field by two field teams and in the office from existing WLM maps, records, reports, databases, geologic models, and the geomechanics database. Data collection utilized, to the extent possible, variables and rating methods determined from the literature review to be applicable to the research questions. Data collection results were compiled into a database suitable for use in various statistical analysis computer programs. A binary outcome variable, the Intersection Condition Rating (*icr*) was developed from an analysis of the database. This method rated intersection conditions as either Not satisfactory (database value=0 [zero]) or Satisfactory (database value=1 [one]). This provided the binary categorical outcome variable required by the logistic regression method.

The exploratory data analysis process included four tasks:

- Corrected any data errors.
- Calculated descriptive statistics for the database variables.

- Checked for variables that were simply randomly distributed data.
- Determined the association or independence of the predictor variables with the outcome variable.

These results were used to develop a list of statistically significant predictor variables for use in the logistic regression analysis. The logistic regression analysis was an iterative process designed to develop a Predictive Model that was well fit with as few predictor variables as possible for estimating an intersection condition rating of Satisfactory. The predictive performance of the Predictive Model was validated using the internal, multi-fold, cross-validation method employing a sample split strategy of 90% of the EMSA data set for the training sample and 10% for the test sample split as described in Section 4.10. A summary of model limitations was developed based on the observations and experienced gained in the field data collection, on WLM mining experience, on the results of the statistical analyses, and engineering judgement.

1.3 Original Contributions

This dissertation represents original contributions in the following areas:

- A research emphasis on underground coal mine intersection conditions in a deep/weak rock coal mining environment.
- A research emphasis on underground coal mine intersection in long-life, main entry development.
- A comprehensive review of the use of logistic regression in the analyses of coal mine ground support design and ground support performance.

- A comprehensive review and tabulation of the variables reported in the literature as impacting coal mine intersection conditions with an emphasis on deep/weak rock coal mining conditions.
- Development of a coal mine intersection condition rating method applicable to weak rock strata and deep mining depth emphasizing the performance of the intersection using the functional and performance design requirements.
- Collection of a unique database of intersection geology, geometry, ground control systems, conditions and functional performance in a deep/weak rock coal mine environment.
- Conceptualized a probability-based intersection condition estimation method for intersections in a deep/weak rock coal mine environment based on environmental conditions and mine design parameters.
- Utilized logistic regression to derive an equation to estimate the probability of satisfactory intersection conditions in a deep/weak rock coal mine environment.

1.4 Thesis Organization

Thesis organization generally follows the research methodology presented in Section 1.2, Methodology, and illustrated on Figure 1.1.

CHAPTER 2 is presented in three sections. Section 2.1 presents the results of a survey of the literature of the use of logistic regression for the analysis of empirical data in coal mining in general and in the estimation of the probability of successful intersection conditions in long-term main entries characterized by a deep/weak rock coal mine environment. Section 2.2 summarizes the current understanding of those variables that impact satisfactory intersection conditions. Section 2.3 reviews and describes coal mine roof condition rating methods utilized to develop the Intersection Condition Rating method utilized in this research.

CHAPTER 3 describes the research framework in terms of the development of the conceptual rock mechanics model for the EMSA and the research hypotheses. Both were developed based on the results of the literature review, experience at the WLM, and engineering judgement.

CHAPTER 4 provides details of the research method. The terminology used in statistical analysis is presented and defined. The development process for the final study design is outlined. The research data sample is defined. Data collection methods are delineated, the database development methodology is explained, and the methods used for exploratory data analysis are explained. Hypotheses testing methodologies are presented. The method used to perform the logistic regression is described and the two methods introduced that validated the model.

CHAPTER 5 presents the results of the research. Development of a binary outcome variable for the Intersection Condition Rating is summarized. Hypotheses testing results are presented and summarized in terms of important predictor variables to be used in the initial logistic regression model (Full Model). The results of the logistic regression process are summarized starting with the development of the initial Full Model. The development of the Main Mode and the calculation of the Predictive Model are presented. The Predictive Model is that model used to estimate an intersection condition rating based on statistically significant predictor variables. The results of the successful model validation process are presented.

CHAPTER 6 is a discussion of the CHAPTER 5 research results. CHAPTER 7 summarizes the conclusions developed from the research. CHAPTER 8 concludes the formal text with recommendations for future work. A combined glossary and list of acronyms follows CHAPTER 8.

APPENDIX A and APPENDIX B present supplemental details of databased content and organization. Specific details of variable names, variable labels, values and value labels, and variable descriptions and notes are presented in these appendices. APPENDIX C and APPENDIX D present examples of the field data collection forms developed for and used in this research. APPENDIX E is a listing of intersection CMRR values and condition ratings resulting from this research.

CHAPTER 2

LITERATURE REVIEW

The literature review was focused on three areas. The use of the logistic regression method for analysis of empirical data in coal mining was reviewed. This review was focused on determining if the use of logistic regression for this research was an appropriate method. An understanding of the variables that impact intersection conditions was developed and used to guide the research study design and field sampling protocols. Existing methods used to describe and define the stability of coal mine structures were assessed to provide guidelines for developing the condition rating protocols used in this study.

Section 2.1 surveys the literature of the use of logistic regression for analysis of empirical data in coal mining. It concludes that logistic regression has been successfully applied to the evaluation of empirical databases of coal mining data. The method has not been applied to coal mine databases characterized by deep/weak rock conditions. There are no published studies utilizing logistic regression to develop an equation for estimating the probability of satisfactory intersection conditions.

Section 2.2 summarizes the current understanding of those variables that impact satisfactory intersection conditions. The results of this literature review were used to help guide the study design and sampling protocols for the data collection at the WLM.

Section 2.3 reviews existing guidelines and methods for assessing the stability of mine structures. This information was used to develop the condition ratings for field data collection in the EMSA and for the development of the Intersection Condition Rating used as the binary outcome variable for the logistic regression analysis.

The literature review showed that there many examples of statistically derived empirical design methods developed for mining ground control. Statistical design in general and logistic regression specifically have been used to address mining ground control problems. But, these methods have not been used to develop a probabilistic approach to estimation of coal mine intersection conditions. Current empirical methods quantify intersection performance as either “successful” or “unsuccessful” (Peng 2015), based primarily on whether a roof fall occurred. Nor were these methods developed from data representative of a deep/weak rock coal mining environment.

Specific findings from the literature review indicated that:

- There was a limited understanding of the variables and conditions impacting satisfactory intersection conditions in a deep/weak rock coal mining environment.
- The combination of mining operations, regulatory requirements, mining depth, and the geologic environment at the WLM were not well represented in the worldwide literature of coal mining ground control.
- There were no accepted methods to assess the probability of satisfactory intersection conditions in a deep/weak rock coal mine environment. Existing methods were based on and applicable to mining conditions characterized by generally shallower mining depths, a better-quality rock mass, and higher strength rock units immediately above and below the coal seam.

2.1 Logistic Regression in Coal Mine Ground Control Analyses

This section presents a survey of the literature of the use of logistic regression for analysis of empirical data in coal mining. The literature review indicated that logistic regression has been successfully applied to the evaluation of empirical databases of coal mining data through example studies from Australia, India, Indonesia, South Africa and the United States. The method has not been applied to coal mine databases characterized by a deep/weak rock coal mine environment. There are no studies utilizing logistic regression to develop a predictive equation for estimating the probability of satisfactory intersection conditions given the values for the geologic, mining and operating conditions represented in the EMSA database.

Salamon et al. (1967) utilized a maximum likelihood estimation technique to analyze a database consisting of empirical data of coal mine pillars and pillar performance in South African coal mines to develop method and design equation for the design of room and pillar workings (Salamon 1999). The maximum likelihood estimation technique is the basis of the logistic regression technique (Hosmer et al. 2013). This technique uses multiple iterations to converge estimates of the coefficients of the predictor variables to make the likelihood of the outcome variable a maximum.

Sheorey et al. (1987) utilized the methodology of logistic regression to develop a pillar strength equation for coal mines in India based on 23 unstable and 30 stable pillar cases. They emphasized the importance of actual case studies in the development of a pillar strength equation. Their work utilized analysis methods similar to those used by Salamon et al. (1967) that was based only on square pillars. Their work showed that logistic regression was an appropriate method for use in the analysis of coal mine empirical data.

The maximum likelihood method of Salamon et al. (1967) was applied to a database of failed and not failed Australian and South African underground coal mine pillar cases by Galvin et al. (1999) to develop an empirically based coal pillar strength formula that included the “effective width” of parallelepiped pillars. This expanded the original work by Salamon et al. (1967) that was based only on square pillars.

Mark et al. (2007a, 2007b) applied logistic regression in their analysis of an empirical database of 309 multiple seam coal mining cases. The result was an equation with an outcome variable of the likelihood of design success given five predictor variables, Table 2.1.

Table 2.1 Multiple seam mining predictor variables. After (Mark et al. 2007a).

Predictor Variable
Total vertical stress on critical pillar
Undermining or overmining
Interburden thickness
Extra support installation
Isolated remnant pillar or Gob-side boundary
ln (CMRR-20)

Note: The term **Predictor Variable** is defined in the Glossary.

Extensive use of logistic regression was made by Lawrence (2007, 2009) in developing a method and formula for the design of longwall gateroad roof support for coal mines located in the Bowen Basin of Australia. The analysis utilized an empirical database of mining experience in the Bowen Basin consisting 280 cases from 10 mines.

The database included the following variables for each case The following bullet list is a direct quote from Lawrence (2007):

- Mining stage (e.g., roadway development or longwall retreat).
- Roof behavior (e.g., stable, fall, supplementary support installed).
- Roof-bolt parameters (e.g., installed pattern, row spacing, length, etc.).
- Effectiveness of installed roof-bolts, particularly of placement and pattern.
- Long-tendon parameters, similar specification to roof-bolts.
- Long-tendon pretension.
- Effectiveness of installed long-tendons, particularly of placement and pattern.
- Grouting, encapsulation or point-anchoring of long-tendons.
- Roadway dimensions.
- Depth of cover.
- Pillar width.
- Longwall panel width.
- Distance to cut-through or intersection.
- Roof classification and geomechanical parameters of seam and immediate and upper roof and floor.
- Magnitude of in situ horizontal principal stresses, if available.
- Orientation of roadway relative to the in situ major principal horizontal stress.

This database is the closest analog in the literature to the conditions at the WLM. However, this database included only one case with a CMRR value less than 35 and a mining depth greater than 800 ft, as illustrated on Figure 2.1. Another key difference between the database and operations at the WLM, is the routine, extensive use of cable bolts (tendons) in most cases in the database as a part of the primary roof support. The WLM utilized cable bolts only in isolated cases and none were systematically installed in any of the EMSA intersections.

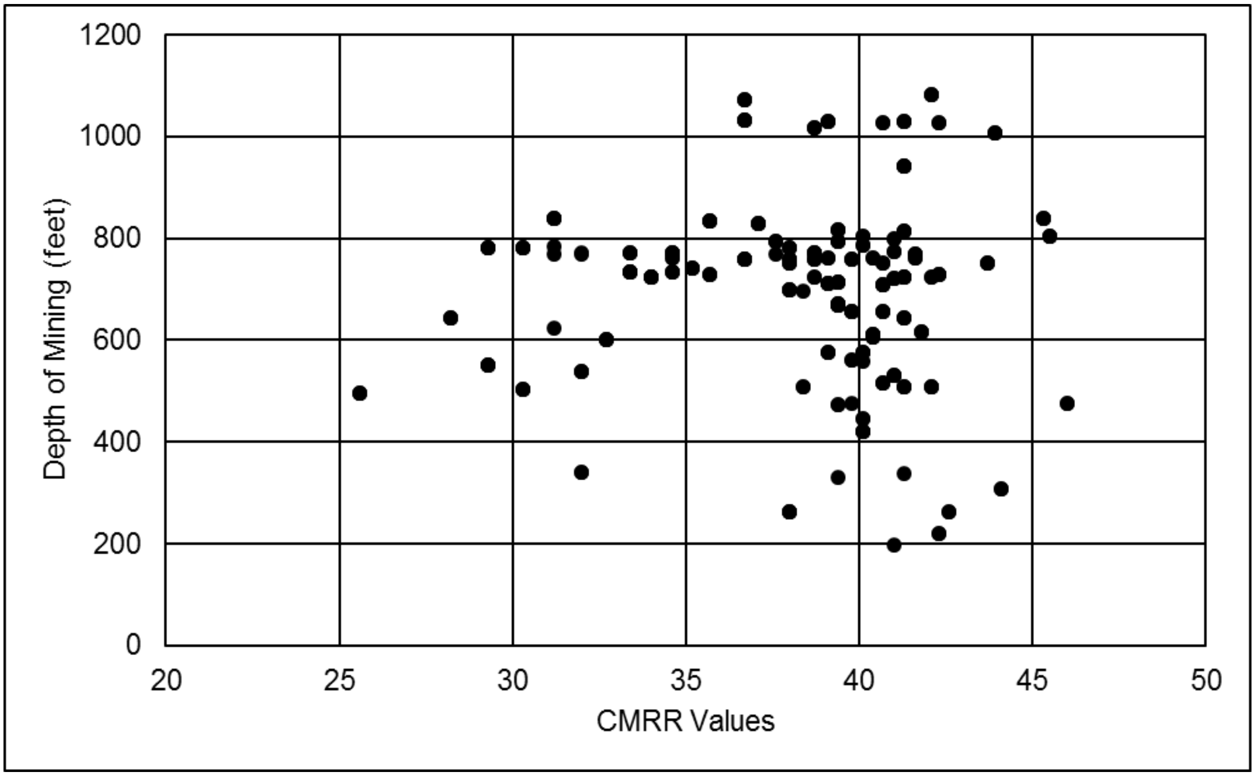


Figure 2.1 CMRR values versus depth of mine for Bowen Basin database. Data from (Lawrence 2007).

Lawrence (2007) used a roof conditions classfication method for the outcome variable similar to that applied to my analysis of the EMSA data. An unstatisfactory roof condition was defined as any one of the following conditions:

- Roof fall.
- Supplementary support required.
- Observed excessive deformation and deterioration.

Lawrence's logistic regression utilized three predictor variables that were based on regression analyses of multiple predictor variables:

1. A mining induced stress (the stress index) calculated using a three-dimensional numerical model.
2. A rock-mass classification value.
3. Quantification of installed support using a modification of the GRSUP method (Colwell et al. 2009) that replaced the standard input of row spacing distance and number of bolts per row with an average bolt spacing value calculated from the average of the spacing of bolts within a row and the row spacing.

Palei et al. (2009) used logistic regression of an empirical database of roof falls in Indian coal mines to develop an equation predicting the severity of an accident should a roof fall occur. Their outcome variable was accident severity ranging from one equaled a severe accident to zero equaled a minor accident. Their analysis used eight predictor variables, Table 2.2.

Table 2.2 Accident severity analysis predictor variables. After Table 2, (Palei et al. 2009).

Predictor variable description
Depth of cover
Gallery width
Seam thickness
Immediate roof strength
Mining height
Roof support status
Fall location
Mine location

Colwell et al. (2009), in their study on the design of support for longwall gateroad roof support in Australian coal mines, utilized logistic regression analyses of a database of 206 cases (58 maingate belt road and 148 tailgate) to develop support recommendations for satisfactory roof conditions in longwall gateroads subjected to longwall stress impacts. Their primary focus was development of roof support guidelines for longwall tailgates. The study did not specifically include intersections separate from entry support. Nor did the study include main entries. The database was proprietary so specific information on database variables was not available. No information on mining depths was presented in the paper. Data points plotted on Figure 7 from Colwell et al. (2009) showed no CMRR values less than 25 and a total of 19 data points with CMRR values from 25 up to and including 35.

Key variables in the statistical analysis were the competence of the immediate roof as measured by the CMRR, the magnitude of the horizontal stress on the gateroad roof resulting from longwall mining, and the total roof support level in the gateroad as measured by the Ground Support (GRSUP) rating. The concept and calculation of the GRSUP included all support installed as primary roof support rather than just the roof bolts. This method was used to calculate a value for the primary roof support installed in the intersections of the EMSA where the WLM routinely installed roof trusses in additional to roof bolts as the primary roof support.

Canbulat et al. (2009) reviewed a probabilistic approach to roof support performance prediction based on statistically-derived probability distributions for key variables. They used a database of 55 cases including intersections and roadways with mining depths from 105 ft to 560 feet. Cases represented room-and-pillar mining operations. Canbulat et al. (2009) provided Table IX, listing the predictor variables used in their analysis. Data on roof strength using CMRR values was not included in their analysis. Intersections were not specifically included in their study and analyses. Their study did not include conditions like those in the EMSA intersections in terms of mining depths. Their work did provide confirmation of statistically important predictor variables. Their work also illustrated the importance of accounting for the "natural variations that exist within the rock mass and the mining process" (Canbulat et al. 2009).

Colwell et al. (2013) successfully utilized logistic regression in their analysis of an empirical database to develop a roof support design methodology for wide roadways (i.e., roadways wider than 18 ft) that typically are used as the start-up room for a longwall installation. They selected logistic regression because of the ability to incorporate categorical predictor variables and a binary outcome variable. They noted that logistic regression "is able to distinguish which" predictor variables "are significant predictors of a particular outcome and to then rank and quantify the relative importance of these independent variables on said outcome" (Colwell et al. 2013). The paper did not present the database they used for their analysis.

Wattimena et al. (2013) utilized logistic regression to calculate the probability of stable coal pillars given a width to height ratio and ratio of pillar strength to pillar load. They provided an overview of the mathematics associated with the logistic regression method and the differences between logistic regression using a binary outcome variable with numeric predictor variables and regression using all numeric variables. Their database consisted of 29 pillars from various coal mines and coal seams in Indonesia. Reported mining depths varied from 75 ft to 886 ft. No data on roof strengths or roof conditions were provided. The authors reported that the logistic regression method provided a model with predictions “close to the actual stability data” (Wattimena et al. 2013).

Ghasemi et al. (2014) utilized logistic regression analysis to construct a predictive model of the probability of stability in room-and-pillar retreat mining panels. The analysis was based on seven variables:

- Panel geometry.
- Pillar geometry.
- Mining depth
- Mining height.
- Roof strength rating based on CMRR.
- Loading conditions.

Their study used a database of 80 retreat mining cases from West Virginia with CMRR values from 45 to more than 63 and mining depths 140 ft 1430 ft. They concluded that the logistic regression method and resulting predictive model provided reasonable predictive accuracy of approximately 81% (Ghasemi et al. 2014). The database used in this study and the analyses performed were not directly applicable to this research. However, the paper showed that the application of logistic regression to a coal mining problem was both an appropriate use of logistic regression and that logistic regression provided reasonably accurate results.

Mark (2016), in his paper on the science of empirical design in mining rock mechanics, cited numerous examples of the application of logistic regression in the analysis of empirical mining databases related to coal and hard rock mining. He stated that, when the outcome variable is binary, “logistic regression is the most common multivariate statistical technique” (Mark 2016). He described the use of the receiver operating characteristic (ROC) curve as an acceptable method for judging logistic model fit.

The review of the use of logistic regression in underground coal mine design indicated that the method has been used successfully for the analysis and prediction of coal mine safety and ground control issues. Several studies have specifically applied logistic regression to the design of coal mine roof support (Lawrence 2007; Colwell et al. 2009, 2013). The literature search illustrated the application of logistic regression to identify predictor variables that impact coal mine safety and ground control and indicated that the method has been used for many years. None of the studies specifically applied logistic regression to develop a probability of satisfactory intersection conditions in long-term main entries. None of the databases approached the size of the 884 cases in the EMSA database. None of the databases consisted of the range of conditions that exist in the EMSA database. None of the databases represented a deep/weak rock coal mine environment.

2.2 Variables Impacting Satisfactory Intersection Conditions

This section summarizes the development of the current understanding of those variables that impact satisfactory intersection conditions. These are the predictor variables that must be investigated as the starting point of an analysis with the objective of estimating probability of satisfactory intersection performance. In the literature, satisfactory intersection conditions equate to the successful performance of the primary roof support system. Since the early 1970s, the primary roof support system in coal mining has consisted of roof bolts (Peng 2015). Thus, most of the literature reviewed in this section refers to research specific to roof bolt system design. This research has, since the earliest times, worked to develop a broader understanding of those conditions beyond roof bolt strength, length, and installation pattern that impacted stable roof intersection conditions.

The literature review, experience at the WLM, and engineering judgement were used to develop the sample variable set for this study of variables impacting probability of satisfactory intersections conditions. This sample variable set consisted of 160 variables of one of three variables types: descriptive field variables, predictor variables, and a single binary categorical outcome variable. The variables were grouped into nine broad categories:

- Geology of the overburden above an intersection.
- Geology of immediate roof, coal seam and immediate floor.
- Geomechanical properties of the immediate roof rock units, the coal seam and related partings and splits, and the immediate floor rock units.
- Intersection geometry.

- Ground support, installed.
- Mine plan geometry.
- Stresses, in situ and mining induced.
- Mining operational function.
- Observed conditions both in an intersection and in any adjacent mine openings.

APPENDIX A is the sample variable set listing for the EMSA database with the variable name, variable label, value codes and value labels. APPENDIX B presents detailed descriptions and notes for each variable in the EMSA database.

Research into those factors that impacted Satisfactory intersection conditions began in the late 1940s. The United States Bureau of Mines (BOM) began to develop and publish suggestions for the design of roof bolt systems (Forbes et al. 1948; Thomas et al. 1948; Thomas 1950) as well as examples of roof bolt systems used in the mining and civil construction industries (Thomas et al. 1949; Kelly 1952; Platt 1952; Young 1954; Thomas 1954, 1962). This early work consisted principally of observational and empirical observations and development of empirically-based design methods from these observations and mining experience.

These studies developed concepts that are considered fundamentally sound today. They identified the function of roof bolting as that of creating a self-supporting, thick, laminated beam in the roof strata out of several individual rock layers. Other concepts identified in this early work included the influence of, and importance of, the geology of the roof rock, the excavated geometry of the mine opening, particularly the width or span, and the variability of these overall conditions within the mining environment. The need for timely installation of the roof bolts after excavation was stressed. Mine personal needed to perform ongoing observations of roof conditions and roof support responses. These observations were critical to the ongoing development of the overall roof bolt support design. The duration of the observations was to be determined based on “previous experience in that particular coal bed and field” (Thomas 1954). These initial analyses lacked an understanding of the geometry of the rock load acting on a mine roof (i.e., the development of an arched roof relaxation zone), and the importance of considering in situ stress magnitudes and directions. Most the observations related to these studies were from coal mines in the eastern coal fields of the US.

Panek (1956a, 1956b, 1956c, 1957, 1962a, 1962b, 1964b, 1964a) utilized physical models and analytical methods related to laminated beams to investigate variables impacting roof bolt support design. Panek identified two mechanisms of roof bolt reinforcement: (1) suspension (Panek 1962a) and (2) beam building (Panek 1962b). Panek listed bolt length, bolt tension, and bolt pattern as important design variables (Mark 2000).

Lang (1962) published a summary of the theory and practice of roof bolting. His theory included key rock mass and roof bolt variables to be considered in roof bolt support system design along with mathematical formulas to assist in roof bolt system design. He noted that intact and rock mass rock properties, including the joint, fracture and faulting patterns adjacent to the mine opening, were important design variables. Lang (1962) was one of the first researchers to note that the support needed to provide stable and adequate (Satisfactory) conditions for the excavated underground opening under the “specified conditions of usage” (functional requirements) of that opening. He identified the in situ stresses as an important design variable and described calculating these stresses based on elastic theory using the depth of overburden cover, the weight of the overburden, and Poisson’s ratio. Lang strongly cautioned that his stress calculation method tended to provide lower estimates of the in situ stresses when compared to actual measurements of horizontal in situ stresses. These stress measurements “often” provided stress levels “much greater” than the value calculated using his elastic theory method. Lang’s work was based on the general case of a fractured rock mass and civil construction; but, his observations and methods did apply to ground control in “stratified, horizontally bedded rock” (Lang 1962).

Stahl (1962) collected information on “junction-support” systems (i.e., intersection support systems), in use in underground coal mines based on correspondence with mines throughout the US and visits to local mines in the Pittsburgh, Pennsylvania, area. He identified several important intersection design variables and concluded the following variables were important in assessing satisfactory intersection conditions:

- Intersection geometry. His study noted that three-way intersections were no better than four-way and V-type (angled) intersections.
- Bolt length. He suggested that longer bolts be considered in the approaches to the intersection as well as within the intersection.
- Increased support density adjacent to intersections. He recommended installation of a steel channel with end bolts angled out over the pillars at the approaches to an intersection should be considered. This effectively acted as a passive truss system.

- The importance of monitoring. He stated that monitoring of intersection response using sag bolts should be performed to better define the response over time of the roof in the intersection.

Obert et al. (1967), in their book on the design of structures in rock, included a chapter on roof bolting that specified that the capacity of the roof bolt system needed to be designed to support the weight of the suspended layer of rock. Mark (2000) described this as the “dead-weight design method” and noted that it is, “The oldest, simplest, and probably still most widely used equation for bolt design”. Obert et al. (1967) specified important design variables as the presence of a competent roof rock layer at a reasonable distance into the roof, the weight of the layers of rock to be suspended from the overlying competent layer, bolt capacity, number of bolts per row, row spacing, entry width, and desired safety factor. Mark (2000) stated that their design equation probably was, “suitable for suspension bolting in low-stress environments.”

After a review of the status of roof bolt design Cox (1973) concluded that designs based simply on suspension or beam-building were flawed and that ongoing work indicated that a “theory and structural model” based on the concept of a rock arch was necessary. He credited Terzaghi (1946) with the general concept of a ground arch and Adler et al. (1968) with developing the concept as it applied to coal mining openings. The concept was that with the excavation of a coal mine opening, there was a zone of rock in the roof, generally arch shaped, that formed and needed to be supported. Understanding the geometry of the arch and the weight of rock within the arch were important design parameters. Roof bolt length and capacity needed to be designed accordingly. The key concept summarized in this paper was that roof bolt support systems needed to consider not just the weight of the rock mass within the bolted beam, but that there is an arch-shaped zone of rock that needed to be supported.

Adler et al. (1968) described design principals for various mine structures with respect to ground control in bedded formations, including stable mine roof and roof support systems. They recognized the concept of the formation of a “pressure arch” over an excavated mine opening and the need to use roof support systems to support the weight of this load. They investigated roof support based both on building a roof beam and with mining to an arched-shaped roof profile. They published results of centrifugal tests of the load bearing capacity and stability of roof arch structures based on various combinations of roof arch radii, opening width, and roof bed thickness, and concluded that for a constant roof bed thickness and opening width, lower arch radius values provide for stronger roof arch structures.

Mark (2000) cited other physical modeling work by Fairhurst et al. (1974), Dunham (1976) and Gerdeen et al. (1979) as other notable examples of the use of physical models in the evaluation and design of roof bolt systems. All these modeling exercises treated the roof rock as a uniform, bedded sequence of rock layers with no allowance for varying roof rock properties or structural features. These studies and models did identify or confirm key variables that needed to be considered in developing roof bolt systems:

- Confirmed that roof geology, both lithology and structure, played a role in roof stability.

- Confirmed the effectiveness of the concept of beam building in the layered roof rock by using the friction effect of tensioned roof bolts to clamp the rock layers into a beam.
- Emphasized the need for quality roof bolt installations.
- Emphasized the need for testing of roof bolts to ensure proper tension loading of roof bolts.
- Confirmed the importance of anchorage capacity.
- Confirmed roof span as an important design variable
- Confirmed that the geometry of the bolting pattern, specified as bolts per row and row spacing, was an important design variable.
- Identified the need for skin control in a roof bolt pattern to prevent falls of ground from between bolts.

Peng et al. (1978), noted that over 30% of all roof falls occurred at intersections, despite increased roof support at intersections, and initiated a study to develop roof support system design recommendations for intersections. Their study was one of the earliest applications of numerical modeling to coal mine roof support design, using a three-dimensional finite element modeling method (Peng et al. 1978). Their roof bolt support system design focused on using the immediate roof geology to select either suspension reinforcement or friction (beam-building) reinforcement. Anchorage capacity, bolt strength, bolt length, bolts per row and row spacing were key design variables. A key finding was the confirmation by modeling of the development of an arched zone above the intersection and that the height of this arched zone was related to both the entry width and the overburden stress.

Gercek (1982) analyzed variables impacting intersection stability. His key variables impacting intersection stability included:

- Presence, spacing, orientation, and persistence of discontinuities.
- Groundwater conditions.
- Induced stresses resulting from the excavation geometry.
- Importance of intersection geometry on induced stresses and stability (e.g., four-way, three-way, 90-degree versus angled, etc.).
- Influence of the thickness of roof beds.
- Rock mass strength.
- Increased roof span at intersections.

An empirical study of roof fall geometry conducted by Patrick et al. (1979) reinforced the concept of an arch-shape zone of rock in the roof. They noted that, for intersections, this arch-shape became dome-shape, showing that dome-type roof falls were most likely to occur over intersections and that approximately 80% of roof falls over intersections were of the dome type.

Unal (1983, 1986, 1989) emphasized the importance of designing a roof support system in a coal mine to support the anticipated roof rock load height. He proposed an empirical equation for calculating an estimated rock load height based on the use of the Bieniawski (1973, 1979) Geomechanics Classification Rock Mass Rating (RMR).

He presented two equations, one for entries and one for intersections.

for coal mine entries:

$$h_t = W_e\left(\frac{100 - RMR}{100}\right) \tag{2.1}$$

for intersections:

$$h_t = I_s\left(\frac{100 - RMR}{100}\right) \tag{2.2}$$

where:

h_t = Rock load height (ft)
W_e = Width of entry (ft)
I_s = Length of diagonal of an intersection (ft)
RMR = Rock Mass Rating

Unal (1983, 1986) developed this equation based on:

- a review of roof-fall records from published coal mine case histories.
- field data from published ground control studies.
- estimates derived from other empirical methods (Terzaghi 1946), (Barton et al. 1974).
- publications with the results of three numerical modeling analyses (Peng et al. 1978), (Hoek et al. 1980) and (Voegele 1979).

Mark (2000) stated that the CMRR value can be substituted in the above equation for the RMR value. This relationship is based on a linear relationship between two limits: for a rock mass with RMR or CMRR = 100, the value of h_t is zero and for a very poor quality rock mass where RMR or CMRR = 0, the value of h_t is equal to the width of the entry (Unal 1983). When evaluating an intersection, the diagonal intersection span, I_s, is substituted for W_e (Unal 1983).

Using his rock load height equations, Unal (1983) presented equations and a design approach for the support of entries and intersections using either mechanical or resin bolts, with or without additional standing supports (posts). Unal's design method used the following input variables:

- Overburden depth.
- In situ stresses.
- Mine opening geometry, height and width, or span.
- An overall rock mass rating for the roof rock based on a rock mass rating method.
- Roof bolt variables including:
    - Bolt length (ft).
    - Resin length (ft) / bolt length (ft).
    - Bolt spacing for a square pattern.
    - Grade of steel in roof bolt.
    - Diameter of roof bolt (inches).
    - Capacity of individual roof bolt (tons).
    - Diameter of standing support, posts (inches)

Mangelsdorf (1982) was an early advocate of using roof trusses as part of the primary support system but acknowledged that difficulties in truss installation had generally resulted in truss installation being completed off of the production shift by a separate installation crew. Mangelsdorf (1985) illustrated his design approach with the design of a truss support system at an underground coal mine in western Colorado with weak roof. Mangelsdorf (1982) provided criteria for variables to be considered in designing a truss system:

- Magnitude of up lift force provided by the truss system.
- Strength and ductility of the rod.
- Stiffness of the truss system defined as the resistance the support installation provided to downward movement of the roof rock.

A paper by van Kempen (1986) presented a method of design for a roof bolt plan based on simple in-mine measurements over time of roof bolt tension and roof sag in a test area of 16 to 25 bolts that was representative of the geologic and geomechanical characteristics of other areas to be bolted. Tadolini et al. (2006) describe this as one of the first attempts to define a systematic roof bolt roof support design method but noted that the fact that it is based on monitoring of conventional bolts made this method “somewhat dated.” The method did recognize the importance of in-mine observations and measurements of roof rock response, the importance of geologic and geomechanical variables, and the importance of understanding any variability in the geologic and geomechanical variables throughout a mine site.

Peng et al. (1989) and Peng et al. (1991) presented a design method for resin bolting developed using a hybrid numerical model consisting of a combination of boundary-element and finite element modeling. Their method focused on determining the bolt length and number of bolts required. Key design input variables included the following: entry opening width; entry mining height; and, the general geology of the immediate roof and the main roof in terms of unit thickness, lithology, number of units in the immediate roof, any significant geologic anomalies, and the Young's modulus values for the individual rock units. A determination as to the support method was made based on the immediate roof rock unit thicknesses and lithologies; either beam building with suspension to the main roof strata, or lacking any "strong massive layer above the opening" (Peng et al. 1991), beam-building using a bolt length that is "long enough to clamp several rock layers into a thick one" (Peng et al. 1991). The design method produced a recommended roof bolt length, the number of bolts per row and the spacing of rows of bolts. Intersection design was not treated specifically.

During the late 1980s, the US Bureau of Mines specifically studied coal mine intersection stability and design (Hanna et al. 1991a; Hanna et al. 1988; Conover et al. 1989; Hanna 1986; Conover et al. 1986). These studies were conducted in shallow coal mines in central Illinois where the immediate roof is stronger than that in the EMSA at the WLM and the main roof is much stronger than that at the WLM. The studies contained general design recommendations but did not provide specific design methodologies.

Maleki (1992) collected and analyzed information from 12 US coal mines, representing 20 different geologic roof sections. He developed an analytical method for selection of the primary roof support system roof bolt type based on the strength of the rock mass. His study was focused on tensioned mechanically point-anchored roof bolts. Input variables were the rock mass strength and average principal stress in the immediate roof. Maleki noted that his analysis was a "preliminary effort" applicable to a very specific set of parameters: an average principal stress determination for the first

0.3 m of the immediate roof and a rectangular opening geometry with a width-to-height ratio of 2:1.

Maleki (1992) used statistical analyses of his database to develop his results. He used a multiple regression process with stepwise inclusion of predictor variables to identify statistical significant variables. His work identified “roof sag at 2 months” as an outcome representing stable, or satisfactory, conditions. This variable was selected as the outcome variable. Key predictor variables identified in his analyses included roof lithology, dip of roof beds, bolt anchorage capacity, roof shape (relatively flat or uneven) and roof bolt tension. Intersection type (three- or four-way) was not a significant variable. Horizontal stresses in the roof, mining depth and groundwater conditions were listed as important variables but with insufficient variability in his database to determine statistical significance. The amount of time between mining and installation of roof bolts was shown to have a great significance on the development of bed separations above the bolted interval.

The work by Maleki (1992) focused on roof bolt tension but he did include fully resin grouted bolts in his analysis. His work concluded that weak roof rock (“uncohesive, laminated rock masses”) required some amount of roof bolt tension and closely-spaced bolts for satisfactory roof conditions. It utilized various statistical tests of variables for significance as predictor variables and developed a list of predictor variables to be included in a roof support design method. He applied linear regression to develop recommendations for roof support.

Gale et al. (1992) proposed a method of optimization of roof support in coal mine roadways based on the use of field measurement techniques to define rock mass response both before and after the installation of the roof support system and the use of numerical modeling to evaluate the effectiveness of roof bolt types and patterns. Based on their monitoring and modeling work, Gale et al. (1992) defined the concept of height of softening based on geology, mine opening geometry and the vertical stress regime acting on the mine roof. The height of softening was that height upwards into the mine roof “to which significant failure into the roof is generated” (Gale et al. 1992). For a given geology and mine opening geometry, the magnitude of height of softening was controlled by the stress level. Stress levels were grouped into three zones:

- Zone 1. Low stress. In this zone, the height of softening is reduced and support requirements are reduced.
- Zone 2. Moderate stress. This defined the stress level where the height of softening and roof failure increase significantly and the support must be carefully designed to limit significant displacements of the roof.
- Zone 3. High to very high stress. This stress level will require very high support densities for the primary support system. Primary support will need to be installed quickly after mining. Secondary and supplemental support systems probably will be required. Changes to mine geometry, layouts and mining methods may be required in this zone.

Stankus et al. (1996) and Stankus et al. (1997) proposed the high installed roof bolt tension was an important variable in their roof bolt design method they called the “Optimum Beaming Effect” (OBE). The concept was that “a much shorter bolt installed at higher than normal tensions (installed load) would produce a stronger roof beam” (Stankus et al. 1996). The theory was developed using finite element analysis and underground testing at four mines in the Pittsburgh coal seam (Stankus et al. 1996). Stankus et al. (2011) referenced the OBE method as part of the roof support design using the Stress, Geologic and Support Design System (SGSSM) developed and patented (Stankus et al. 2008) by Keystone Mining Services, LLC. Mark and Barczak (2000) stated that roof support and roof fall data collected and analyzed by Molinda et al. (2000) showed that in three of four cases where shorter, tensioned bolts and longer, non-tensioned were used in the same mine, there was a higher roof fall rate for roof supported with the shorter, tensioned bolts.

Fabjanczyk et al. (1999) studied reinforcement techniques for weak rock for the Australian Coal Association Research Program (ACARP) and found that roof support for weak rock requires “very high levels of reinforcement” even at low levels of in situ and induced stresses. They determined that moisture reduced unconfined compression strength and stiffness. Top coal thickness was a critical variable in roof stability with top coal less than 2 ft thick subject to buckling failure at stress levels as low as 300 psi. They concluded that there was “no single novel method of reinforcement specific to weak rock,” that different roof support systems had differing levels of effectiveness in the different environments investigated during the field work for the report, and that support designs for weak rock needed “to be considered on a site-specific basis.”

Mark and Barczak (2000) presented a comprehensive review of the variables impacting coal mine roof stability and support. They defined successful roof support as that which prevents large collapses of the mine roof, protects miners from smaller falls of rock, and controls deformations of the mine openings such that they remain useable for access, escape, and ventilation. Roof support design was based on four broad categories of input data, geology, geometry, stress, and mining function. Roof support design started with the geology and geomechanical properties of the roof, rib, and floor. The geometry of the mine structures, particularly width and height of the mine openings, defined the areas to be supported and probable locations, magnitudes and impacts of the mining-related stresses. The stresses acting on the rock mass, both in situ and mining-related, defined the loads imposed on the mine structures. The fourth parameter, mining function, related to the use of the entry for access, escape, and ventilation as well as the longevity required of the mine opening (i.e., life-of-mine versus panel gateroad). Roof bolts and other types of roof support must be selected and designed to an adequate factor of safety based on these areas. Key properties to consider in the design and deployment of roof support system based on roof bolts include:

- Mining function and life-span of the opening.
- Selection of an appropriate variable of safety for support system capacity versus anticipated rock loads.
- Capacity of roof support system.
- Stiffness of roof support system.
- Residual strength of the roof support system.
- Other variables; material handling requirements, skin control, etc.

Molinda et al. (2000) reported on the collection and statistical analyses of roof fall data at 41 underground coal mines in the US. The study focused on the stability of intersections as the area of interest and analysis. The data from this study was compiled into the National Roof Fall Database (Molinda et al. 2000). It should be noted that the study mines were heavily concentrated in the Appalachian coal field with fewer mines in the Illinois Basin, Alabama, and western Colorado, and a single mine in Wyoming. CMRR values for the mines in the database ranged from 30 to 78 with all but the value of 30 equal to or greater than 40. The database represents coal mine roof considerably stronger than those in the EMSA of the WLM.

The study identified data collection in the following areas:

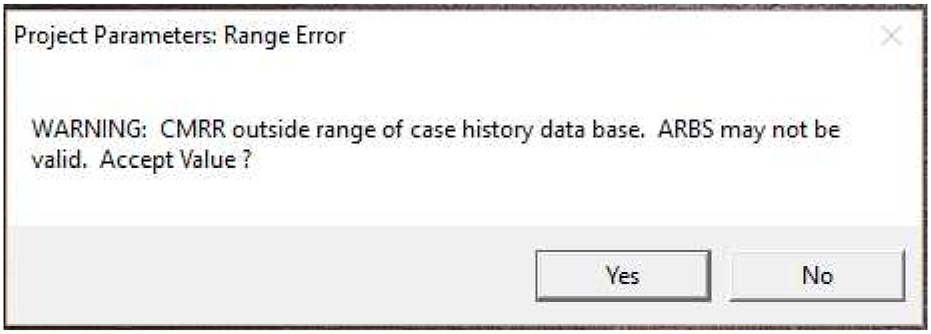
- Geology as expressed by the Coal Mine Roof Rating (Molinda et al. 1994).
- Mine opening geometry.
- Depth of overburden cover.
- Vertical stress.
- Horizontal stresses.
- Mining-induced stress changes.
- Roof fall rate.
- Installed primary roof support systems.
- Other installed roof support, secondary and standing.

The outcome, or dependent, variable in the study was defined as the roof fall rate and was calculated by dividing the number of MSHA-reportable roof falls by the linear length of drivage consisting of entry plus crosscut footage. Their analyses concluded that higher roof fall rates correlate with CMRR values of less than 50 and with deeper mining depths. Intersections tended to be more unstable and four-way intersections were more unstable than three-way intersections. They also identified roof bolt installation quality as a possible parameter impacting roof fall rates; but, they noted that this parameter cannot be easily measured or estimated, so it was not included in their analysis.

The Mark et al. (2001) statistical study of the roof support system data in the National Roof Fall Database identified and defined statistically-based parameters to be considered in the design of a coal mine roof bolt support system:

- Roof geology expressed as a value of the CMRR.
- Horizontal stresses and depth of overburden cover.
- Width of an entry or span of an intersection.
- Roof bolt specific parameters:
    - Anchorage mechanism.
    - The tension applied to a roof bolt at the time in installation
    - Bolt capacity.
    - Bolt length.
    - Roof bolt pattern (bolts per row and spacing between rows of bolts).
    - The timing of roof bolt installation with respect to when the excavation was completed.
    - Quality of the roof bolt installation.

Mark (2000), using the data and analyses prepared by Mark and Barczak (2000) and Mark, Dolinar, et al. (2000) presented guidelines, required variables, and a method for the design of roof bolt support of entries and intersections. He named this method the Analysis of Roof Bolt Systems (ARBS) method. The ARBS method was developed from the statistical analysis of a database that consisted of 109 cases, a range of CMRR values from 28 to 78, and a range of mining depths from 150 ft to 1100 ft. Eleven of the cases had CMRR values of 35 or less and only one of the low CMRR values was obtained in mining conditions characterized by a mining depth of 800 ft or more. Overall, the data do not reflect the conditions at the WLM. Roof calculations using the NIOSH ARBS software (NIOSH 2013a) with a CMRR value of 30 and mining depth of 800 ft results in the warning dialog box shown in Figure 2.2.



Project Parameters: Range Error

WARNING: CMRR outside range of case history data base. ARBS may not be valid. Accept Value ?

Figure 2.2 ARBS program warning dialog for WLM mining conditions, CMRR=30 and mining depth=800 ft.

While not developed from a database representative of the conditions in the EMSA of the WLM, the ARBS method has gained wide acceptance as a design method. It also provides a standard method for calculating and reporting the roof support density of the primary roof bolt system. It was used that way in this research.

Gadde et al. (2007) reported on a study comparing the results of ARBS recommendations with actual experience at 13 Peabody US underground coal mines. The basis of comparison used the ARBS-based variable of MSHA-reportable roof falls per 10,000 ft of development. CMRR values for the mines in the Peabody study varied from 24 to 48 with no specification as to whether the presented ARBS values were corrected for moisture or water conditions. The depth of overburden cover at the study mines varied from 150 ft to 1400 ft. The study showed good agreement between the

ARBS suggested support recommendation and the actual ARBS calculated for each mine in the study, Figure 2.3.

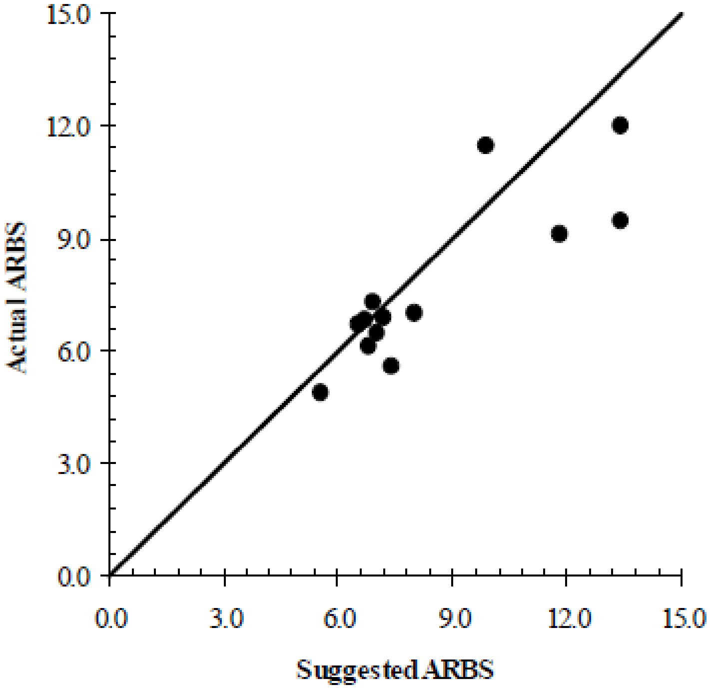


Figure 2.3 Comparison of suggested ARBS versus actual ARBS in the Peabody study mines. After Figure 3, page 52 (Gadde et al. 2007).

They noted that the strengths of the ARBS approach were:

- It is based on actual mining experience and data.
- The statistical analysis approach helps mitigate the "large number of uncertainties associated with coal mine ground control designs".
- It is simple to apply and use.

Gadde et al. (2007) cautioned that ARBS does have limitations. These limitations result from the empirical basis of ARBS. They noted these limitations generally are representative of empirical analyses and tools. The design equations only should be applied within the range of the database used to develop the equations. Limited databases were used to develop some of the equations so the results from ARBS must be applied with caution and subjected to experienced, engineering judgment.

ARBS does not provide any guidance or specifications as to the type of bolt to use (Gadde et al. 2007). The type of bolt is an important consideration in the design of a roof bolt support system (Dolinar et al. 2000). Key roof bolt characteristics to be considered are nontensioned or pretensioned and the anchorage length, expressed as full contact or point anchor (Dolinar et al. 2000). These roof bolt characteristics determine how the roof bolt interacts with and reinforces the rock mass.

To address the roof bolt type issue with ARBS, Peabody Energy developed the Integrated Support Design Methodology (ISDM) (Gadde et al. 2007). The ISDM process used ARBS to develop a roof bolt support pattern design and numerical modeling to assist in the selection of the type of roof bolt.

Steps in the ISDM are (Gadde et al. 2007):

1. Estimate the CMRR.
2. Use ARBS to determine the required bolt density.
3. Gather necessary inputs for numerical modeling to determine the most effective roof bolt type.
4. Build and solve the models with different bolt types.
5. Examine the model results and choose the final bolt type.

The Peabody study showed that the empirically derived CMRR and ARBS were valid tools for the design of roof support systems in underground coal mines when used within the range of the database and represented a valid methodology for analyzing data in support of the performance and design of roof support systems.

Colwell et al. (2009) described the development and application of the Analysis of Longwall Tailgate Serviceability (ALTS) for the Australian underground coal mining industry. ALTS is an empirical design methodology. While focused on overall longwall gateroad design, including pillars, it provided design recommendations for primary and secondary roof support that can be applied in the broader context of underground coal mine roof support design. A key contribution of ALTS was a modification to PRSUP (aka, ARBS) (Mark et al. 2001) to include not just the primary roof bolt installations but also the capacity of additional support that may be installed in the roof, specifically cable bolts, which are known as tendons in Australian terminology. The modification was applicable to and appropriate for the analysis of the primary roof bolt support system at the WLM that included the installation of roof truss systems as part of the primary roof support. The $PRSUP_{ALT}$ value was calculated as only that support installed off the miner (Colwell et al. 2009). The equation to calculate $PRSUP_{ALT}$ was (Colwell et al. 2009):

$$PRSUP_{ALT} = [(Lb \cdot Nb \cdot Cb) / (14.5 \cdot Sb \cdot we)] + [(Lb \cdot Nt \cdot Ct) / (14.5 \cdot St \cdot we)] \tag{2.3}$$

where:

Lb = Length of bolted horizon defined by the primary bolt type (m). Note (1).
Nb = Average number of bolts per row.
Nt = Average number of longer tendons per row.
Cb = Ultimate tensile strength (UTS) of the primary bolt (kN) based on values presented in roof support supplier catalogs.
Ct = Ultimate tensile strength (UTS) of the longer tendon (kN) based on values presented in roof support supplier catalogs.
Sb = Spacing between rows of the same bolt type (m).

St = Spacing between rows of the same longer tendon type (m).
we = Roadway width (m).

Note (1) Lb is defined as the of the length of the primary bolt even when longer cable bolts are installed because using the entire length of the cable bolt (tendon) unfairly influences the $\text{PRSUP}_{\text{ALT}}$ rating (Colwell and Frith 2009). For example, where the primary bolt length is 2.1 m and a cable bolt 4.6 m long is installed, Lb is assigned a value of 2.1 m, the same at the primary bolt length.

To account for all support elements that may be installed *within* the roof as support over time, Colwell et al. (2009) developed a variable named Ground Support Rating (GRSUP) defined as “all bolt and longer tendon roof support installed within the roof” regardless of when it was installed and “includes all roof bolts, longer tendons, cables and trusses.” Mathematically, GRSUP was calculated as (Colwell et al. 2009):

$$GRSUP = \frac{L_b}{14.5\ W_e} \sum N_m\ C_m \tag{2.4}$$

where:

L_b = Length of bolted horizon defined by the primary bolt type (m). Note (1).
m = Number of different support types.
N = Number of support elements per meter.
C = Ultimate tensile strength (UTS) of each support element (kN) based on values presented in roof support supplier catalogs.
We = Roadway width (m).

Note (1) Lb is defined as the of the length of the primary bolt even when longer cable bolts are installed because using the entire length of the cable bolt (tendon) unfairly influences the PRSUP rating (Colwell and Frith 2009). For example, where the primary bolt length is 2.1 m and a cable bolt 4.6 m long is installed, Lb is assigned a thickness value of 2.1 m, the same at the primary bolt length.

GRSUP was related to the CMRR (Colwell et al. 2009). The relationship they developed is reproduced on Figure 2.4 The Australian conditions used to develop this relationship do not include case histories with CMRR values as low as those typical of the WLM.

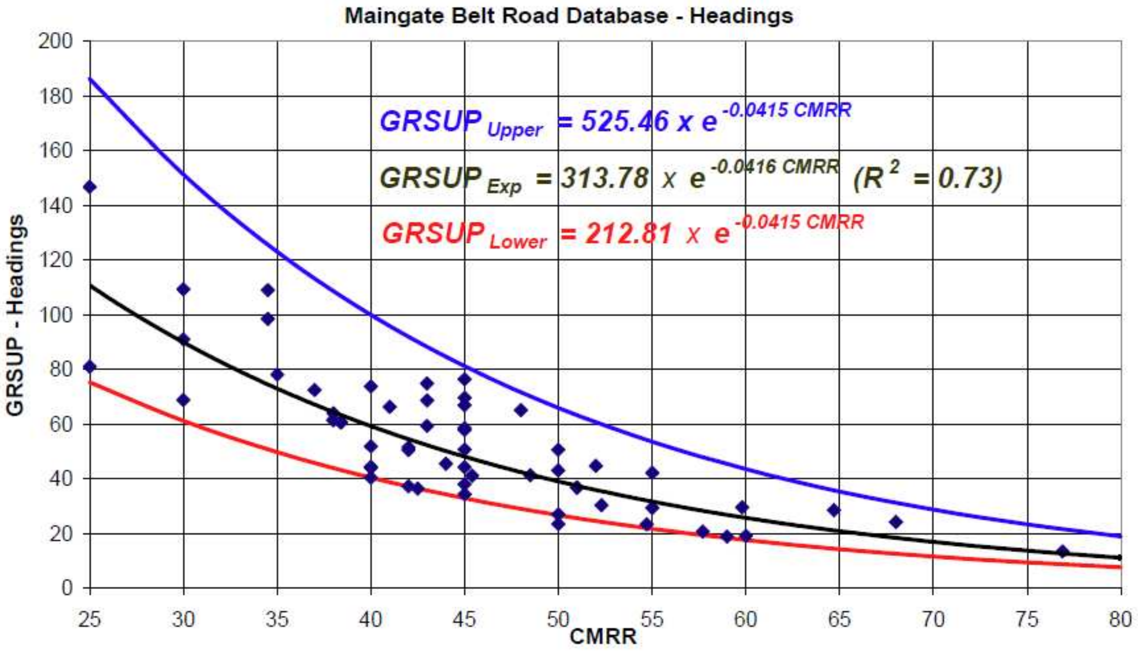


Figure 2.4 GRSUP versus CMRR roof values. After Figure 5, page 43 (Colwell et al. 2009).

This work by Colwell et al. (2009) reinforced the validity of the methods used to develop the US ARBS and the overall value of an empirical approach based on statistical analyses of actual mine response data. As with ARBS, the Australian experience and empirical methods were not developed from a database that included the very weak rock CMRR values representative of the WLM.

Seedsman et al. (2009) outlined a proposed analytical method for the design of roof-bolt based roof support systems based on the limit equilibrium method of estimating the magnitudes and distributions of driving forces at the limit of stability and designing a roof support system that provides the forces necessary to resist rock mass failure. Their method encouraged use of the CMRR as an empirical design tool and provided details on the specific parameters that were important to design:

- Discontinuities (spacing, orientation, persistence, roughness, shear strength).
- Lithology of the immediate roof rock.
- Strength of the rock mass (UCS).
- In situ stresses.
- Faulted ground.
- Topography.

In their discussion of topography they made two observations (Seedsman et al. 2009):

- “For most practical purposes, the influence of topography on the stress field is relatively small.”
- “The impact of the valley is negligible within about 1.5 times the depth of the valley”.

Canbulat (2010) provided a description of the empirical data for geologic, stress, mining, and rock mass response used in the Anglo American Metallurgical Coal (AAMC) roof support design methodology in Australia (after Figure 2, Canbulat 2010):

- Geology
- Unit thicknesses
- Unit weights
- Rock strengths (UCS, CMRR)

- Structures and discontinuities
- Young’s modulus
- Poisson’s ratio
- Coefficient of friction
- Height of softening
- Stresses, directions, and magnitudes
- Mining, sequence, dimensions, and orientation of workings

Frith et al. (2010) expanded on their work on roof support design presented in Colwell et al. (2008) and Colwell et al. (2009) to develop the Analytical Model for Coal Mine Roof Reinforcement (AMCMRR). This method was an analytical approach, balancing applied loads and reinforced roof beam strength. They used buckling slender beam theory and formulas to design a reinforced roof beam of sufficient thickness and strength to withstand the applied in situ and mining stresses. Key input variables included horizontal stresses acting on the roof rock units at various operational points in the mining process, material properties of the immediate roof rock geomechanical units, and details of the primary roof support system using the GRSUP method (Colwell et al. 2009).

Molinda et al. (2010), in their study of the causes of roof falls in coal mines with weak roof, described critical factors impacting roof stability as the presence of stack rock and horizontal stress and “defective roof”. Defective roof was defined as discontinuities within the roof rock that either paralleled bedding or crosscut the bedding. These discontinuities were related to various geologic features including, paleochannels, slips, shears, slickensides, fractures, joints, faults, coal washouts, etc.

They noted that the scale of these features could be “from inches to tens of feet.” Weak roof was defined as roof strata with a CMRR value of less than or equal to 40 or roof rock with an unconfined compression strength of less than or equal to 3500 psi.

Frith et al. (2011) critiqued the applications of the suspension design method used worldwide. Their paper outlined issues with the assumptions used in suspension design. They concluded “that in reality there is no need to use suspension design for roof support as credible methodologies are now available that directly address the design and application of reinforcing roof support” (Frith et al. 2011). They noted that AMCMRR (Frith et al. 2010) and ARBS (Mark et al. 2001) both provided for the “design of reinforcing roof support within a risk-based framework” (Frith et al. 2011) and that “these methodologies can be used at the mine site level by appropriately trained and supported strata control engineers” (Frith et al. 2011).” With respect to conditions at the WLM, these comments identified ARBS and GRSUP as reasonable approaches for quantifying the primary roof bolt systems installed in intersections in the EMSA.

Osouli et al. (2014) used case studies from an underground coal mine with weak, moisture sensitive roof in the Illinois Basin of the US to investigate the applicability of the CMRR roof quality calculation method to weak coal mine roof strata. Their paper included several key observations and conclusions:

- CMRR was a valid indicator of roof strength for weak roof conditions.
- It is important to use the wet CMRR value in moisture sensitive roof rock.
- CMRR strength index values of less than 35 resulted in a tendency for roof falls despite the installation of roof screening and installation of significant supplemental support in intersections.

The weak strength and “extremely moisture sensitive” roof rock resulted in ARBS-type design equations considerably modified from those in the ARBS method to divide successful cases from failure cases.

Their analysis noted the following key variables impacting roof stability in weak, moisture sensitive roof rock environment:

- Horizontal stress level.
- Intersection span.
- Roof bolt properties.
- Roof support installation pattern as defined by ARBS parameters.

Limitations of their study for direct application to conditions at the WLM were:

- Only approximately nine cases with a CMRR value of 35 or less.
- The maximum depth of mining for all the cases included in the paper was 400 ft.
- Maximum ARBS value (6-ft bolt length) in the study cases was slightly less than eight. This compares to an average ARBS value in the EMSA of 15.9 (7-ft and 8-ft bolt length) and a GRSUP value of 27.4, that includes primary support density including 6 bolts per row and the roof trussing on a 2-ft center spacing.

Stone (2016) analyzed a database of roof support installed in underground coal mines in Australia, the US, the UK, South Africa, New Zealand and Europe to determine the major factors impacting a successful design. A successful design was defined as, “those designs that were used on a repeated basis for the purposes of roadway development.” Major design factors impacting roof support design success included roof competence, defined as the CMRR value, and in situ stress. Entry height and mining depth were noted as factors impacting rib stability.

2.3 Coal Mine Roof Condition Rating Methods

The advent of numerical modeling tools applicable to mine stability modeling and the increased ease of access to these modeling tools has increased interest in developing guidelines for assessing the stability of mine structures. These guidelines are proposed to allow for comparing field stability assessments with numerical model results. This section reviews and describes coal mine roof condition rating methods utilized to develop the Intersection Condition Rating methods utilized in this research.

Karabin et al. (1994) and Karabin et al. (1998) described a deterioration index rating system based on deterioration indexes specific to the pillar, the roof, or the floor conditions that can be used to quantify pillar, roof, and floor conditions. With their system, a numeric rating of from 0 (best) to 5 (most severe) is assigned to each of the three mine structure elements (pillar, roof, or floor). Observed sites are assigned a numeric rating in each of the three categories.

Their system attempted to provide “deterioration index levels [that] are reasonably well defined to minimize subjectivity of observations and promote consistency in ratings from site to site” (Table 2.3).

Table 2.3 Roof deterioration index. After Table 4 (Karabin et al. 1994) and text (Karabin et al. 1998).

Roof Deterioration Index	Observed Conditions
0	Virtually no deterioration
1.0	Flaking or spalling
2.0	Cutter roof
2.5	Onset of roof stability concerns
3.0	Broken roof
3.5	Supplemental support required
4.0	Significant roof falls
5.0	Widespread and massive roof falls

Molinda (2003), included a Figure 44 that presented a roof fall data sheet developed by NOISH for mapping of roof conditions. This mapping form included a notation for “Condition of Nearby Roof” using the rating system listed in Table 2.4.

Table 2.4 Roof condition rating. After Figure 44 (Molinda 2003).

Numeric Rating	Condition
1	Good
2	Moderate
3	Ragged
4	Poor
5	Severe

Molinda et al. (2008) presented a roof damage rating system used at an eastern underground coal mine based on the amount of observable, post-mining, roof rock sloughage (Table 2.5).

Table 2.5 Roof damage rating system. After Figure 12 (Molinda et al. 2008).

Sloughage	**Rating**
0-2 in (0 – 51 mm)	1 Good
2-6 in)51 -	2 Moderate
6-12 in	3 Ragged
12-24 in	4 Poor
+24 in	5 Severe

In 2009, MSHA recognized the critical need for good, underground, observation response data and, in Program Information Bulletin No. P09-03 (Skiles et al. 2009), stated,

> **Observe Underground Areas** – This is an essential first step in solving ground control problems regardless of the methodology employed. Mine conditions should be categorized in a number of areas where differing pillar sizes, panel configurations and overburden levels are found. A deterioration index rating system, discussed later in this PIB, can aid in the description of in-mine ground conditions.

PIB 09-03 provided the following guidance with respect to establishing a set of deterioration indices.

> **Deterioration Indices** – As mentioned previously, the most critical phase of the simulation process is verifying the accuracy of a model through correlation with actual underground conditions. To aid in the evaluation of in-mine ground conditions and verification of model accuracy, a set of deterioration indices should be established to quantify pillar, roof and floor behavior. For example, observed in-mine locations could be assigned a numeric rating on a scale of 0–5 (0 being the best condition and 5 the most severe) in each of the three categories: pillar, roof and floor. The deterioration index levels should be reasonably well defined to minimize subjectivity of observations and promote consistency in ratings from site to site and from observer to observer.

Lawson et al. (2012), in a paper presenting a case study on ground condition mapping, referenced PIB P09-03 and used the principals outlined in PIB P09-03 to develop "Roof Rating Criteria" (Table 2.6). Their criteria were focused on the presence and degree of roof discontinuities.

Table 2.6 Roof Rating Criteria. After Table 6 (Lawson et al. 2012).

Numeric Roof Rating	**Observed Roof Conditions**
0	The roof shows no signs of deterioration. There is no sagging, tension cracking, deformation of roof bolts and mesh, or visible yield in standing support. Joint apertures are tight and there are no exposed slicks in the roof.
1	Tension cracks begin to form; most are parallel or sub-parallel to entries. Existing joints and newly formed tension cracks open slightly, with apertures smaller than 1.3 cm (½ inch). Open joint apertures are much more common than tension cracks. Tight slickensided discontinuities also justify this rating. These often occur as concentrations of radial and/or linear slicks, pre-bolting falls, and other local geological features. The roof does not sag and there is no observable yield on roof support.
2	Tension cracks extend and are more common. Discontinuity apertures open to an average of 1.3 cm to 2.5 cm (½ inch to 1 inch). Local distortion of roof support may be evident.
3	Tension cracks and joint apertures open to an average of 2.5 cm (1 inch) or greater. The roof is beginning to sag locally. Tension cracks are pervasive. Minor, local loss of roof material is apparent in the roof mesh. Bolt anchorage, however, is unaffected. Roof support may be yielding.
4	The mesh is visibly bagged with roof rock. Roof failure locally extends to and above the bolting horizon. Mesh and other support materials are locally damaged by dislodged roof rock. Roof support is yielding. Roof conditions are locally hazardous.
5	Roof failure is extensive, not merely local. Bolt anchorage and mesh are at least locally compromised, and have fallen along with broken roof rock. Roof conditions are hazardous through most of the entry.

2.4 Summary of Literature Review Findings

The literature review indicated that there were no studies specifically related to main entry intersections, to deep depth, and weak rock conditions. No existing design method for entries considered overall main entry intersection conditions beyond performance of the primary in-roof support. Intersection functional performance requirements were not specifically included in any design method. No method produced probability based estimates of satisfactory conditions for main entry intersections.

The literature review showed that the logistic regression method had been successfully applied to the evaluation of empirical databases of coal mining data and the analyses coal mining ground control problems.

The current understanding of those variables that impact satisfactory intersection conditions refers to research specific to roof bolt system design. As appropriate, variables in the literature such as roof bolt length, bolts per row, row spacing, intersection average diagonal length, CMRR, etc., were incorporated into the study design and sampling protocols for the data collection at the WLM.

The literature of existing guidelines and methods for assessing the stability of mine structures was reviewed. None of the methods specifically included the functional performance of the intersection as a rating criteria. All methods focused on roof conditions. Only a few methods included consideration of rib and floor conditions. This information was used to develop the condition ratings for field data collection in the EMSA and for the development of the Intersection Condition Rating used as the binary outcome variable for the logistic regression analysis.

CHAPTER 3

RESEARCH FRAMEWORK

The research framework consisted of the conceptual rock mechanics model and the research hypotheses. This chapter describes the development of these two items.

3.1 Conceptual Rock Mechanics Model

Mark (2016) identified the development of a conceptual rock mechanics model specific to the problem statement as the second step in the empirical design process. The purpose of the conceptual rock mechanics model is to present a manageable model of the real world within which the problem statement exists. Mark (2016) stated that this necessarily will be a “simplified model”. This model is intended to focus attention on variables that are known, or anticipated, to impact the results that constitute the problem described in the problem statement. Recognition of the appropriate outcome variable describing the results is also part of the conceptual rock mechanics model.

Definition of the conceptual rock mechanics model for this research used the results of literature review, the problem statement, the research questions, experience at the WLM, both within the EMSA and mine-wide, and engineering judgement. These were supplemented with the information from the general geologic characteristics of the WLM, the geomechanical rock units and related physical rock properties of the WLM, and the CMRR values calculated for the EMSA. The conceptual rock mechanics model developed for this study identified data requirements in the following areas that were key to both defining an outcome variable of satisfactory intersection conditions and the predictor variables that potentially impacted this outcome variable:

- General geologic conditions (stratigraphy and structure) of the rock mass above and immediately below the coal seam and of the coal seam.
- In situ stress regime.
- Mining depths.
- Geomechanical and physical rock properties of the coal seam and immediate roof and floor rocks.
- Moisture sensitivity of immediate roof and floor rocks.
- Presence of water in the roof and floor rock strata.
- Top coal thickness.
- Geologic structures in the coal seam, immediate roof and immediate floor.
- Mining induced stresses due to adjacent longwall mining.
- Intersection geometry, defined as height and diagonal lengths, for intersections and heights and widths for adjacent entries and crosscuts.
- Intersection type, defined as 2-way (generally a bend in an entry), 3-way, or 4-way.
- Ground support densities, primary, secondary, and supplemental.
- Mine ventilation as intake, return, or beltline.
- Existing conditions in the intersection and adjacent entries and crosscuts as to roof sag, tension cracking, cutters, rib spall, floor heave, etc.

The conceptual rock mechanics model was used to define those variables that were important to understanding the problem in the EMSA. The EMSA model provided the framework for developing a list of data variables to be collected in my research and the types of measurement scales to be applied to each variable.

3.2 Research Hypotheses

Research hypotheses were developed from the problem statement, research questions, literature review, conceptual rock mechanics model, WLM experience, and engineering judgement. The following hypotheses were developed for this research.

1. Depth of mining and the average overburden density of 150 lb/cu. ft provided reasonable estimates of in situ stress such that depth of mining was a significant predictor of the intersection condition rating.
2. Geologic structures, consisting of discontinuities, fractures, joints, faults, slickensides, weak bedding planes, etc., where present in an intersection roof, were significant predictors of the intersection condition rating. Channel sandstone deposits and related channel margin mudstone deposits also contribute to geologic structure due to differential compaction.
3. The CMRR calculation method (Molinda et al. 1994; NIOSH 2013b) was valid as a predictor variable in geologic conditions related to the roof rock lithology and strengths in an environment characterized by CMRR values less than 40.
4. Top coal thickness was a significant predictor of the intersection condition rating.

5. Intersection diagonal spans, minimum, maximum, and average, were significant predictors of the intersection condition rating.
6. Primary, in-roof support geometry and capacity, as expressed by the GRSUP support calculation method (Colwell et al. 2009), was a significant predictor of the intersection condition rating.
7. Transferred stresses from adjacent longwall mining areas were a significant predictor of the intersection condition rating.
8. Presence of water in the intersection roof or floor rock strata was a significant predictor of the intersection condition rating. This water could be introduced by geologic/geohydrologic variables or by mine operations processes such as belt line water, return airway moisture, etc.
9. The sizes of pillars adjacent to an intersection, as quantified by the development stability factors calculated using the Mark-Bieniawski pillar strength formula (Mark et al. 1997) and tributary overburden loading, were a significant predictor of the intersection condition rating.

CHAPTER 4

RESEARCH METHOD

The research method was an empirical study. The study used an analytic, observational, cross-sectional data collection method and logistic regression analysis of the collected data.

Study data collection was conducted in the EMSA, located underground in the East Mains mine workings at the WLM. The EMSA consisted of 884 intersections characterized by ranges of conditions for predictor variables in sufficient quantity and of acceptable quality to address the research questions and to statistically evaluate the research hypotheses.

The research developed a binary outcome variable, Intersection Condition Rating (*icr*), reported as Not satisfactory (0) or Satisfactory (1), from observations and analyses of each of the intersections in the EMSA. Statistically significant predictor variables were developed from the observational data, the conceptual rock mechanics model, and the research hypotheses. Statistical significance was determined using variable descriptive statistics, one-way table analysis, two-way cross tabulation with the outcome variable, and logistic regression against the outcome variable. Variable descriptive statistics and a one-way table analysis evaluated the distribution of each predictor variable to ensure that the variable was significantly ordered and not randomly distributed. The two-way cross tabulation process tested the strength of association between the outcome variable, *icr*, and each categorical predictor variable and tested the hypothesis that the predictor variable was a significant predictor of the outcome variable. Logistic regression tested the strength of association between the outcome variable, *icr*, and each categorical or numeric predictor variable and tested the hypothesis that the predictor variable was a significant predictor of the outcome variable.

This chapter presents a discussion of terminology specific to the research method in Section 4.1. Subsequent sections present the study design method, a description of the study sample, the development of the sample variables, the measurements of sample variable values, field data collection, database development and variable coding, data analysis, model development, and model validation.

4.1 Terminology

Study design and statistical analysis methods and procedures utilize terms specific to these fields of research. This section presents the terms and definitions used in my research study protocol developed for this research study as well as in the actual study.

The research study method used the collection of empirical data by observation and measurement using the cross-sectional study method. Merriam-Webster (2016) defines empirical as “originating in or based on observation of experience (empirical data)”. The cross-sectional study method is a type of observational study that consists of measurements of the current characteristics of a series of cases (intersections) that differ with respect to the desired outcome variable (intersection condition rating) at a specific point in time (Agresti 2007). Measurement is the process of assigning numbers to a characteristic of a thing, or case (Newton and Rudestam 2013). A case is the primary unit of analysis and may be measured on a variety of characteristics (Newton and Rudestam 2013). In this research study, each intersection formed a case. In the

EMSA at the WLM there were 884 cases, or intersections. The number of cases in a study also is referred to as the sample size, N (Newton and Rudestam 2013).

Variable is the term used to describe a particular characteristic of a case (Newton and Rudestam 2013). Examples of variables from the EMSA database that describe specific characteristics of an individual case, or intersection include intersection condition rating, height, diagonal span, coal mine roof rating, roof sag amount, presence of roof tension cracking, etc. A variable is assigned a value or several values, based on the measurements applied to the variable (Newton and Rudestam 2013). A measurement value is defined as either numeric or categorical and these two variable groups are subdivided into specific variable types. Table 4.1 lists and defines the variable types used in this research study.

Table 4.1 Variable types and definitions.

Variable type	**Variable group**	**Definition**
Continuous	Numeric	A variable that has a numeric value and is measured on a continuum (e.g., Coal Mine Roof Rating, *cmrr*).
Discrete	Numeric	A numeric variable that can take only specific values, generally positive integers (e.g., number of roof bolts).
Binary also Dichotomous	Categorical	A binary variable; a variable with only two categories (e.g., Intersection Condition Rating, *icr*, of either Not satisfactory (0) or Satisfactory [1]).
Nominal	Categorical	A variable with two or more categories but there is no order, ranking or value to the order of the categories (e.g., roof bolt manufacturer).
Ordinal	Categorical	A variable with two or more categories where the allowable categories are ordered, or ranked, and the order is important (e.g., number of entries across the mains, *mainwide*, with values of 3, 4, 5, 6, 7, or 8).

Variables also were characterized either as a predictor variable or as the outcome variable. Predictor variable is a term approximately equivalent to the term independent variable in ANOVA and linear regression; but, it specifically indicates that the variable was not changed by the researcher as a part of an active experiment; that the variable was just “observed” by the researcher (Ellis 2004). Outcome variable is a term equivalent to the term dependent variable in ANOVA and linear regression. In this research study, the outcome variable was the Intersection Condition Rating (*icr*). The outcome variable was binary with only two values, Not satisfactory (0) or Satisfactory (1).

4.2 Study Design

The study method was an empirical study that used an analytic observational, cross-sectional data collection method. This study design was selected based on the:

- Problem statement.
- Research questions.
- Conceptual rock mechanics model.
- Research hypotheses.
- Availability of the EMSA as the source of the study sample.
- Resource constraints of personnel and time.
- Availability of a well-developed literature of empirical analyses and methods of coal mine ground control issues (Mark 2016).
- Determination that the desired outcome was an estimation of the probability of a Satisfactory intersection condition rating given input of statistically significant predictor variable.

- Determination that the outcome variable would be a binary categorical variable.
- Determination that the data would include both categorical and numeric variables.
- Proposed analysis method using logistic regression.

The study design objectives were the collection, coding, and database compilation of variables identified as impacting satisfactory intersection conditions; and, the development of a predictive equation for estimating the probability of satisfactory intersection conditions using logistic regression. These objectives were to be met, if possible, using, or extending, existing knowledge and methods for the analysis and design of successful coal mine intersections. The literature review indicated that an understanding of the predictor variables impacting satisfactory intersection conditions and methods for determining the probability of satisfactory intersection conditions did not exist for intersections in the EMSA deep/weak rock coal mining environment. Experience and numerical modeling exercises at the WLM related to prediction of satisfactory intersection conditions also indicated a lack of understanding of the significant predictor variables. Mark (2016) noted this lack of understanding in the broader context of mining problems in general stating that, “Many problems in rock mechanics are limited by our imperfect knowledge of the material properties and failure mechanics of rock masses.”

Mark (2016) advocated the use of existing mining structures and experience as a source of “valuable experimental data” and that “harvesting these data” and “using the appropriate statistical techniques to interpret them”, provided “powerful design techniques”. The 884 intersections of the EMSA provided a source of “valuable experimental data” (Mark 2016) and represented a potential “study population” (Kleinbaum et al. 1982). Access to the intersections in the EMSA provided the opportunity for “harvesting these data” (Mark 2016) through underground site inspections and measurements. The WLM maintained extensive, quality databases related to surface elevations; mining depths; geologic stratigraphy and structure; geohydrologic conditions; geomechanical rock properties; mine layouts; opening geometries; ground conditions; ground support; mining plans, designs, issues and history; production records; mine operational functions; and, mine ventilation functions for the EMSA. Finally, resources were available that could collect the data. Data collection involved both underground visits and the collection of data from existing WLM databases. Underground visits to intersections included inspection, measurement, and, documentation of conditions for each of the intersections. It was determined that the collection of empirical data by observation and measurements underground at the intersection locations and from the related mine databases was the appropriate approach to address the research objectives. Resources were not available to change any intersection variables during the study (i.e., add roof support, remove roof support, etc.). A study using empirical data and where the experimenter does not manipulate any of the cases, or any of the case characteristics, is defined as an observational study (Kleinbaum et al. 1982). An observational study like this one, designed to test specific hypotheses, to generate new hypotheses, to suggest mechanisms of causation, and to suggest probabilities for success, is considered an analytic observational study (Kleinbaum et al. 1982).

The timing of the observations and collection of variable data were controlled by the availability of personnel to observe each intersection and record the data. Limited personnel availability dictated that the study was conducted based on an assessment of intersection conditions and success ratings during a period of months. Kleinbaum et al. (1982) defined this type of data collection as a cross-sectional study (i.e., a study of “single observations at one hypothetical point in time”). The use of the cross-sectional study method was considered appropriate because of the generally slow rate of change of intersection conditions in the EMSA. Therefore, the cross-sectional design method was adopted as the final part of the study design.

4.3 Sample Description

This section describes the sample used for the study in terms of the sample location and the number of cases. The basic unit of a sample is called a case. In this research, a case was one of the 884 intersections located in the EMSA of the WLM. The sample consisted of all the 884 located in the EMSA. All the 884 intersections were included in the study sample; no intersections were excluded from data collection or the exploratory data analysis.

4.3.1 Sample Location

The sample location was the EMSA in the East Mains of the WLM. Figure 4.1 (page 69) is a mine map of the WLM showing the underground development and mined-out longwall panels that existed at the time of this study in black detail. The mine workings within the EMSA are shown in red. The mined-out longwall panels (longwall gob) to the south are shaded dark gray. The projected life-of-mine plan is shown as black outlines of entries and longwall panels. The grid is on a 4000-foot spacing and north is towards the top of the figure. The area of the grid approximately indicates the extent of the current measured or indicated coal reserves, the reserve base and inferred reserve base as defined by US Geological Survey methods and terminology (Wood et al. 1983).

Figure 4.2 (page 70) shows the locations of intersections within the EMSA categorized by Not satisfactory condition ratings as red dots. The grid is on a 2000-foot spacing and north is towards the top of the figure. Contours represent mining depth in feet. The density of the red dots illustrates the trend that, as the mining depth increased, the percentage of Not satisfactory rated intersections in the EMSA increased to over 50% of the intersections under mining depths deeper than 1000 ft where impacted by adjacent longwall stresses.

The EMSA was selected as the sample location because it was the only operating underground coal mine in the United States with the range of conditions required to provide the data necessary to address the study objectives. The literature review showed that there were no mining operations worldwide with conditions like the EMSA of the WLM. These conditions specifically included:

- Poor to fair rock mass quality overburden.
- Very weak to weak rock strata immediately above and below the coal seam.
- A range of mining depths from approximately 100 ft to 1050 ft.
- Operating requirements, and regulatory requirements comparable to those that existed at the WLM.

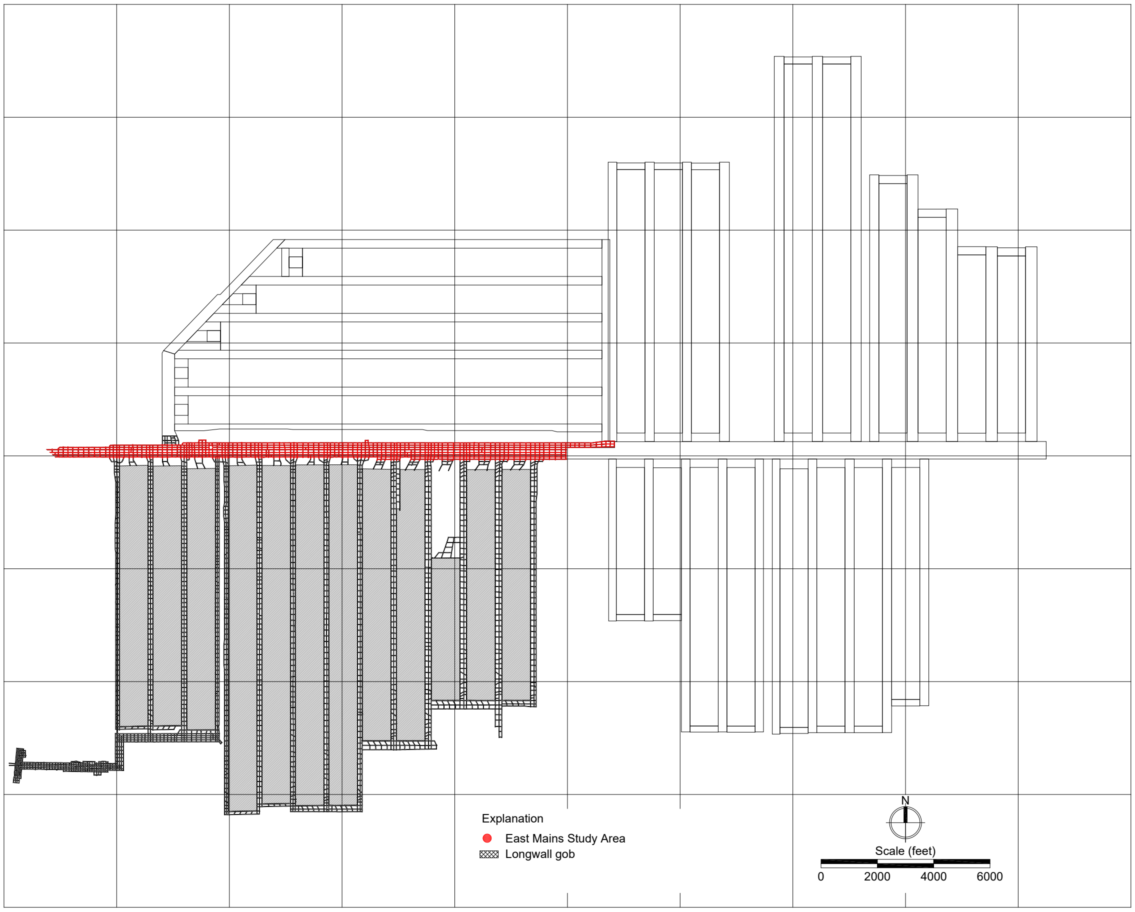


Figure 4.1 Location of the East Mains Study Area within the WLM life-of-mine plan. The EMSA is shown in red.

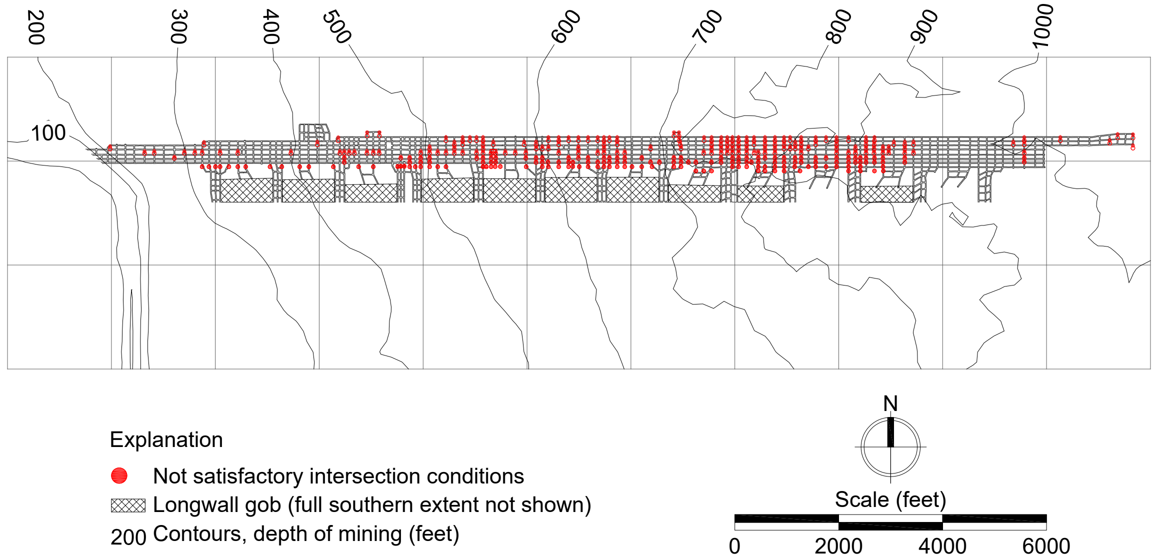


Figure 4.2 Locations of intersections with Not satisfactory condition rating (red dots) within the EMSA.

The EMSA was the sampling location that provided:

- The availability of access to all underground intersection locations for observation, mapping and data collection.
- The availability of personnel to conduct field surveys of the conditions existing at each intersection.
- A range of existing conditions sufficient for the development of the outcome variable of an intersection condition rating.
- Ranges in conditions for the predictor variables hypothesized to impact the intersection condition rating.
- The existence of extensive, quality databases and information related to surface elevations; mining depths; geologic stratigraphy and structure; geohydrologic conditions; geomechanical rock properties; mine layouts; opening geometries; ground conditions; ground support; mining plans,

designs, issues and history; mine operational functions; and, mine ventilation functions for each of the 884 intersections in the sample.

4.3.2 Sample Size

The sample size was set by the 884 intersections in the EMSA. This sample consisted of nine two-way intersections, 200 three-way intersections and 675 four-way intersections. A key component of the study design was to ensure that sample size of 884 intersections was adequate to determine the predictive equation for the outcome variable estimating the probability of satisfactory intersection conditions using up to 12 predictor variables.

Demidenko (2007) stated that, “There is no consensus on the approach to compute the power and sample size with logistic regression.” Hosmer et al. (2013) noted that there is, “surprisingly little work on sample size for logistic regression”. Newton et al. (2013) did not provide any mention of sample size calculations for logistic regression. Most conventional discussions of sample size in the literature generally are based on conventional sample size methods (Agresti 2007, 2010; Kleinbaum 2010). But these conventional methods only apply to models with a single predictor variable; an “univariable” model (Hosmer et al. 2013). Long et al. (2014) recommended an overall sample size of at least 100 samples and noted that “samples over 500 seem adequate” when performing logistic regression with the maximum likelihood method. Peduzzi et al. (1996) used a Monte Carlo study on the impacts of events per variable (EPV) in analyses using logistic regression and reported that, “For EPV values of 10 or greater, no major problems occurred.” Their modeling showed that when there were 10 or more events per variable, there were no further improvements in the model. Vittinghoff et al.

(2007) reported that problems with the logistic regression results were, “uncommon with 5-9 EPV”. Hosmer et al. (2013) provided general guidance on sample size based on their review of the literature, and recommended “ten events per parameter” (variable) “may be a good working strategy”. Long et al. (2014) stated that, “A rule of at least 10 observations per parameter seems reasonable.” The 10 cases per model predictor variable was the approach used in this study to determine the adequacy of the sample size of 884 intersections.

Using the 10 EPV recommendation, the sample size of 884 intersections was adequate for an analysis including up to 88 predictor variables. An objective of the study was to provide a predictive equation composed of as few predictor variables as necessary to provide adequate model fit. The sample size of 884 intersections was adequate to successfully complete this objective of the study.

4.4 Sample Variables

The sample variable set consisted of field descriptive variables, predictor variables and a single outcome variable. These variables represent the entire data set collected and the database developed for this research. All the variable types described in Table 4.1, continuous, discrete, binomial, nominal, and ordinal, were present in the sample variable data set. Field descriptive variables represented the raw data collected at the field level. Predictor variables were developed from the descriptive field variables either as a direct equivalency or by calculation, classification, or categorization. The outcome variable was developed from the descriptive field variable data by classification, categorization, calculation, and statistical analysis. This section describes each type of variable and presents discussions of variable selection, measurement scales used to collect, calculate, classify, or categorize the variable values, and the coding methods developed for each variable and its' values.

4.4.1 Field Descriptive Variables and Measures

A field descriptive variable (FDV) in this research was a variable obtained only by "observation". No FDVs were manipulated or changed during the study. One hundred sixteen FDVs were observed, measured, and coded into the preliminary EMSA database. Examples of a FDV include intersection number, east and north coordinate location, mining depth, intersection diagonal length, count of roof bolts per row, measurement of roof bolt row spacing, etc. A FDV was the field-level variable. The FDVs were collected underground in the EMSA or from the WLM maps, databases, files, and reports.

The selection of a FDV for data collection was based on the need to have a variable and related variable values to:

- Address the research questions.
- Define elements of the conceptual rock mechanics model.
- Test the research hypotheses.
- Provide values for variables shown from the review of the literature to impact intersection design and support.
- Provide values for variables shown from experience at the WLM to impact intersection success.

Existing variable value measurement scales from the literature were used to collect and code FDV values whenever possible. During the study, the list of data needs and associated FDVs were updated as needed to address evolving data needs and analysis issues.

The process of developing FDVs and their related values is illustrated using the need to calculate the capacity of the primary, in-roof, roof bolt system installed in an intersection. Analyses to address the research objectives and questions and the literature review indicated the need for a variable representing the installed capacity of the primary, in-roof, roof bolt support capacity in an intersection. The literature review indicated that the ARBS method (Mark et al. 2001) was an accepted standard and measure of primary in-roof, roof bolt support capacity in the US and worldwide. The calculation of the capacity of the primary in-roof, roof bolt support installed in an intersection using the ARBS method required the observation and measurement of six FDVs and recording of their values for each intersection:

- Roof bolt length, *rfbltlen*, 7 or 8 ft.
- Roof bolt diameter, *rfbltdia*, 0.804, 0.875, or 1.0 in.
- Roof bolt grade, *rfbltgrd*, 60 or 75.
- Roof bolts per row, *rfbltrow*, 4, 5, or 6.
- Roof bolt row spacing, *rfbltspc*, 4 or 5 ft.
- Average entry width, *entwid*, 17 to 33 ft.

The preceding list shows the variable label, the *variable name*, and the range of variable values. APPENDIX B provides specific information on *variable name* and variable label. For a categorical variable, the categorical variable value code and value code labels are listed. For a numeric variable, the variable value range is listed. APPENDIX B provides detailed descriptive notes for each variable.

4.4.2 Predictor Variables

In this research, a predictor variable (PV) was defined as one developed from a single FDV, several FDVs, or other PVs. PVs were created through calculation, classification, or categorization of FDVs or other PVs. A PV in this research was not manipulated or changed during the study. Examples of a PV include:

- *grsupact*, the load carrying capacity of the primary, in-roof, roof support system, inclusive of roof bolts, roof trusses, and any other primary, in-roof support elements, installed in an intersection roof as part of the development mining cycle.
- *diagsod*, average intersection diagonal length calculated as the sum of the two FDV measurements of intersection diagonal length, *diagnesw* and *diagnwse*.
- *cmrr*, Coal Mine Roof Rating for strength of the immediate roof of the intersection.

Development of PVs for use in the research study followed an interactive process. This process began with development of an initial PV list. This list was modified during both the data collection and data analysis phases. The initial PV list was created from the need to:

- Have variables and variable values to address the research questions.
- Define elements of the conceptual rock mechanics model.
- Allow for statistical testing of the research hypotheses.

- Provide values for variables shown from the review of the literature to impact intersection design and support.
- Provide values for variables shown from experience at the WLM to impact intersection success.
- Incorporate engineering judgement.
- Satisfy the need for “prudent simplification” (Mark 2016).

Mark (2016) described “prudent simplification” as necessary because the number of FDVs usually was too great for the number of cases in the database and some of the FDVs may interact with (are collinear with) each other, requiring a variable that combines and represents the interaction of these individual FDVs.

The initial list of PVs utilized existing PV calculation methods and value measurement scales from the literature. This list was reviewed to ensure that the appropriate FDVs were included in the data collection plan to allow for calculation of the PVs. The calculation of the CMRR as a value for the strength of the immediate roof of each intersection is an excellent example of the development of and need for a PV.

The literature review indicated that CMRR was an internationally recognized method for calculating and reporting coal mine roof strength in the US and worldwide. Use of the CMRR methods was adopted for this research. The calculation of the CMRR for a single intersection with three geomechanical rock units in the immediate roof required data on 17 FDVs (Mark et al. 2002; Office of Mine Safety and Health Research (OMSHR) 2013):

- Depth to the roof of the intersection.

- Number of geomechanical rock units in the immediate roof above the intersection.
- For each geomechanical rock unit:

    - Unit thickness
    - Unconfined compression strength
    - Diametric point load strength
    - Moisture sensitivity index
    - Fracture intensity as RQD or fracture spacing

Use of the CMRR as a PV provided the analysis with a recognized method for calculating immediate roof strength. It provided a method for determining those FDVs required for data collection to allow for the calculation of the immediate roof rock strength. Use of the CMRR provided a basis for comparing the immediate roof rock strengths in the EMSA with coal mines in the US and worldwide.

The final list of PVs evolved to meet the needs of the data analysis, the goal of “prudent simplification”, and the development of the final intersection condition probability estimation model.

4.4.3 Outcome Variable, Intersection Condition Rating

The research questions, hypotheses, and the logistic regression method required a binary outcome variable for the intersection condition rating with values of “0” or “1”, representing “Not satisfactory” and “Satisfactory”, respectively. This section describes the method used to develop the outcome variable for my research Intersection Condition Rating (*icr*), from the EMSA data. Steps in the method included:

1. Development of the method and measurement in the field of intersection condition, the Intersection Condition Rating, Field (*icrf*), using results of the literature review of coal mine roof condition rating methods (Section 2.3); experience at the WLM, and engineering judgement.
2. Development of the method and measure of intersection condition using data available on the East Mains Standing Support Map.
3. Development of the method and measures used for input of in-roof secondary or supplemental support.
4. Development of the method and measures used for input of standing support.
5. Development of the method and measure for the Intersection Condition Rating, Preliminary (*icrp*).
6. Development of the method and measures for determination of PVs indicating a Not satisfactory intersection condition based on observed intersection roof and roof support conditions.
7. Development of the method and measure for the analysis outcome variable, the Intersection Condition Rating (*icr*).

The literature review of the various coal mine roof condition rating methods, Section 2.3, experience at the WLM, and engineering judgement, were used as a basis to develop a 5-point roof rating scale of intersection roof conditions for this research as defined in Table 4.2 (page 80). The key design considerations in developing this intersection condition rating method included:

- Simplicity and ease of use in the field during data collection with minimal ambiguity in what rating needs to be applied to a section of roof.
- Incorporated general mining practices in use in the WLM. For instance, installation of trusses and carrier trusses at all intersections.
- Applicable for use in a geomechanical environment consisting of very weak to weak roof rock strengths.
- Allowed for incorporation of other FDV measured and collected in this study.
- Included consideration of the required uses of the intersection and contiguous mine openings (i.e., function requirements). While applied only to the main entries, the rating method was designed to include longwall related mine developments for use as a mine-wide data collection tool.
- Included a worst-case category for a MSHA reportable roof fall.

The East Mains standing support mine map was compiled and maintained by the WLM Engineering Department. This map showed the standing support installed in the East Mains entries and adjacent crosscuts. This map was reviewed and an intersection condition rating measurement scale was developed to classify intersection success based on the mapped standing support, Table 4.3 (page 81). The result of this exercise was the creation of the FDV *icrss* in the EMSA database.

The FDV *inroof*, was collected on the presence and type of in-roof secondary support installed in an intersection. The FDV was converted to a binary categorical predictor variable coded as support not present (0) or support present (1) for use in the analysis to develop the outcome variable.

Table 4.2 Field Intersection Condition Rating (*icrf*), categories, and categorization criteria.

Numeric and Condition Rating	Condition Category	Categorization Criteria
1 Good	Satisfactory	All the following must be present: 1. Intersection has only original roof bolting. 2. No travel or ventilation restriction. 3. Intersection fully serves intended / functional design (intake, travelway, escapeway, return, belt line, overcast, etc.).
2 Fair	Satisfactory	Any of the following may be present: 1. Intersection shows minor roof cracking or presence of water. 2. Original roof support supplemented with additional roof bolting, meshing, etc. 3. May include some minor standing support located at corners or for rib control. 4. Original functional design not currently compromised.
3 Poor	Not satisfactory	Any of the following may be present: 1. Significant additional standing support installed in the intersection or to either side of the intersection in the crosscuts. 2. Roof failure / fall below the top of the bolted interval. 3. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. 4. Belt maintenance operations compromised due to clearance issues with standing support.
4 Very poor	Not satisfactory	Any of the following may be present: 1. Longwall tailgate blockage. 2. Escapeway routed around area. 3. Steel sets or equivalent installed to maintain access for underground mobile equipment. 4. Significant additional standing support installed in the crosscuts to either side of the intersection in the crosscuts.
5 MSHA Reportable	Not satisfactory	MSHA reportable roof fall. Roof failure above bolted horizon.

Table 4.3 Intersection Condition Rating (*icrss*) and rating basis using the East Mains Standing Support Map.

Map Condition Rating	Condition	Rating Basis
1	Good	Intersection has no to very little standing support shown on map. Intersection travelway not impacted by the installed supplemental standing support.
2	Fair	Intersection has some standing support shown on the map, either in the intersection or in the adjacent crosscuts. Intersection travelway function somewhat impacted by the installed supplemental standing support.
3	Poor	Significant supplemental standing support installed in the intersection or to either side of the intersection in the crosscuts. Intersection travelway function either significantly impacted or routed around intersection. Escapeway routed around intersection. Also, includes MSHA-reportable roof fall.

The FDVs listed in Table 4.4 were collected on the presence and type of standing support installed in an intersection. These FDVs were reviewed, tabulated, categorized, and coded as standing support not present (0) or standing support present (1). Table 4.4 summarizes the FDVs used in this analysis. APPENDIX A and APPENDIX B present details related to these FDVs.

Table 4.4 Field Data Variables, Standing Support Determination.

Variable name	Variable label
can	Standing, supplemental roof support, pumpable crib or can type.
combo	Standing, supplemental roof support, combined support type.
crib	Standing, supplemental roof support, wood crib type.
prop	Standing, supplemental roof support, prop type.
set	Standing, supplemental roof support, steel set type.

A preliminary categorization of intersection conditions as either Satisfactory or Not satisfactory was made utilizing the following criteria for satisfactory intersection conditions:

- Field Intersection Success Rating of 1 or 2.
- WLM East Mains standing support intersection rating of 1.
- No secondary or supplemental in-roof support installed.
- No supplemental standing support installed.

The method used to determine the Intersection Condition Rating (*icr*) consisted of two steps: a review of the EMSA database to select FDVs that were evidence of unsuccessful roof support system performance; and, a statistical analysis of the significance of the selected FDVs. The selection of FDVs as indicators of Not satisfactory intersection roof support system performance was based on experience at the WLM and engineering judgement. The following categories of FDVs were determined to be probable indicators of roof movement and roof loading higher than projected design loading; and, therefore, were indicators of a Not satisfactory intersection condition. Intersections exhibiting these characteristics would be considered, based on the results of statistical analysis, Not satisfactory:

- Roof fall prior to bolting.
- Roof tension cracking.
- Roof sag.
- Truss shoe deformation due to loading.

4.5 Data Collection Methods

The study used an empirical, observational cross-section data collection method. Section 4.3.1 described the sample location in the EMSA of the WLM. Section 4.4 described sample variables and APPENDIX A and APPENDIX B provide details of the variables included in the final database used for this research. The data collection activities described in this section were performed both by me or under my direct supervision.

The data collection method consisted of three activities:

- Field data collection at each intersection location in the mine.
- Office data collection from existing WLM databases, maps, models, plans, and reports present in the technical and operational files of the WLM.
- Development of the codebook and database for storage and manipulation of the data.

4.5.1 In-mine Field Data Collection

In-mine, field data were obtained through multiple field visits to each of the 884 intersections in the EMSA by teams of observers. Teams consisted of two to three persons. Each intersection and adjacent mine entries and crosscuts were visited at least twice. The first visit was to observe, measure, and record the physical attributes of the roof, rib and floor and the installed roof support. The second visit was to assess, assign, and document the overall Satisfactory or Not satisfactory condition of the intersection with respect to the field intersection condition rating method, Table 4.2 (page 80). The field data collection and mapping procedures were consistent throughout the project. The variable measures worked well and no changes to measurement scales or data collection methods occurred during the study.

The first site visit was performed by Team 1 and the second site visit was performed by Team 2. The same individuals were assigned to each team to provide for consistency in the observational descriptions and data collected at that visit by that team. Different individuals were assigned to Team 1 and Team 2 to provide for a broader set of interpretations of the observed conditions. I lead Team 2 and visited each intersection.

The Team 1 site visit was designed to observe and record:

- The exposed geology.
- The physical dimensions of the mine openings.
- The presence and amount of water on the floor or in the roof.
- The type and spacing of in-roof support (primary and secondary).
- The rib support.
- The presence and type of supplemental roof and ground support systems.

Team 1 mapped and recorded visible indications of existing or potential roof and rib stress or failure. They recorded the following ground response parameters:

- Tension crack development.
- Gutter and cutter development.
- Rib sloughing.
- Roof and floor movements.
- Roof potting.

- Roof fall prior to bolting, if the information was available.

Team 1 made and recorded observations at each intersection with each intersection's observations recorded on a separate documentation sheet. The documentation sheets consisted of boxes to record observations as well as a grid used to map and document locations of supplemental roof support, roof tension cracks, and changes in types of in-roof support (Burkhard 2012). APPENDIX C presents a completed example of the field data documentation sheet used by Team 1 for this phase of the data collection and rating process.

The review and preliminary assessment of the Team 1 data indicated that there was no statistically significant outcome variable within the data set. The literature review indicated, and the logistic regression method required, a binary outcome variable value coded as Satisfactory (1) or Not satisfactory (0) for each intersection. I developed an intersection condition rating procedure based on the literature and regulatory guidance from MSHA as described in Section 4.4.3 for the Field Intersection Condition Rating (*icrf*). I then lead Team 2 on underground visits to inspect, describe, and rate both each intersection and the immediately adjacent entries and crosscuts. Team 2 focused on the assigning an intersection condition rating to the intersection and immediately adjacent entries and crosscuts as well as the confirmation of the Team 1 field data. APPENDIX D presents a completed example of the field data documentation sheet used by Team 2 for this phase of the data collection and rating process.

4.5.2 Office Data Collection Method

The in-mine field data were supplemented with the collection of data from office maps, files, databases, and reports. These data were related to:

- Surface elevations.
- Mining depths.
- Geologic stratigraphy and structure.
- Geohydrologic conditions.
- Mine-site geologic hazard mapping.
- Geomechanical rock properties.
- Mine layouts.
- Opening geometries.
- Ground conditions.
- Ground support.
- Mining plans.
- Mine designs.
- Mining issues and history.
- Mine operational functions.
- Mine ventilation functions.

4.6 Database Development Method

The objective of the database development method was to provide a quality set of sample data in a format that permitted analysis of the data using statistical analysis software. Other goals of the method were to guide and facilitate both data collection and data entry. The software tools used in the database development method were Microsoft Excel, Systat 13 (Systat Software 2013) and Stata 14.1 (StataCorp LP 2016). The results of the database development method flowed back through all phases of sample variable selection, development, measurement and collection; and, flowed forward into the exploratory data analysis and model development phases of the research. Database development consisted of the following steps:

1. Development of the method of data organization to be used in the research study based on the variables identified in in Section 4.4 for field collection or subsequent calculation or categorization as a PV.
2. Development of the overall codebook nomenclature, structure and content.
3. Data input of coded FDVs and PVs into a Microsoft Excel database.

APPENDIX A and APPENDIX B provide a complete list and details of the variables included in the EMSA database.

4.6.1 Data Organization

Newton et al. (2013) provided guidelines to be used in data coding and organization:

- Use numeric value codes for all data.
- Numeric codes must be unique within each variable coding method.
- Each variable should be coded “to obtain maximum information”.
- For each case, there must be a numeric value assigned to each variable.

Variable names were selected based on the requirements of Stata 14.1 for variable names without any spaces. Variable labels were developed that provided short, sentence-type descriptions of the variable to “enable anyone to identify” (Newton et al. 2013) what the variable was actually measuring. Value codes and value labels were developed for those variables that required them. Self-coding variables did not require value labels and codes (Newton et al. 2013). Examples of self-coding variables included most of the continuous-type variables in the sample data set (e.g., depth from the surface to the intersection, *depth*, the intersection number, *intno*, and the Coal Mine Roof Rating, *cmrr*). Figure 4.3 (page 89) illustrates these concepts and presents examples for numeric and categorical variables.

4.6.2 Database Codebook Development

Following the variable coding guidelines presented in Section 4.6.1, the database codebook was developed. No issues or problems occurred during the development of the study database codebook. Codebook content and organization were modified interactively throughout the data collection, data input, and exploratory analysis steps to address issues as they developed and provide clarity, utility and simplicity to the final database. APPENDIX A presents the complete database codebook of FDVs and PVs used for the research study and APPENDIX B presents detailed notes for each variable.

4.6.3 Data Input

Field-level FDVs were collected on data sheets as described in Section 4.5.1. These data sheet were reviewed by technical personnel for completeness and proper coding. Corrections were noted on the field data sheets. Where necessary, additional underground visits were performed to provide final data for database input. This step also included checking data for proper coding in compliance with the database codebook. The reviewed and edited field data sheets were transcribed clerically into the Microsoft Excel spreadsheet that was the sample variable database. No data checking or validation was performed during this step.

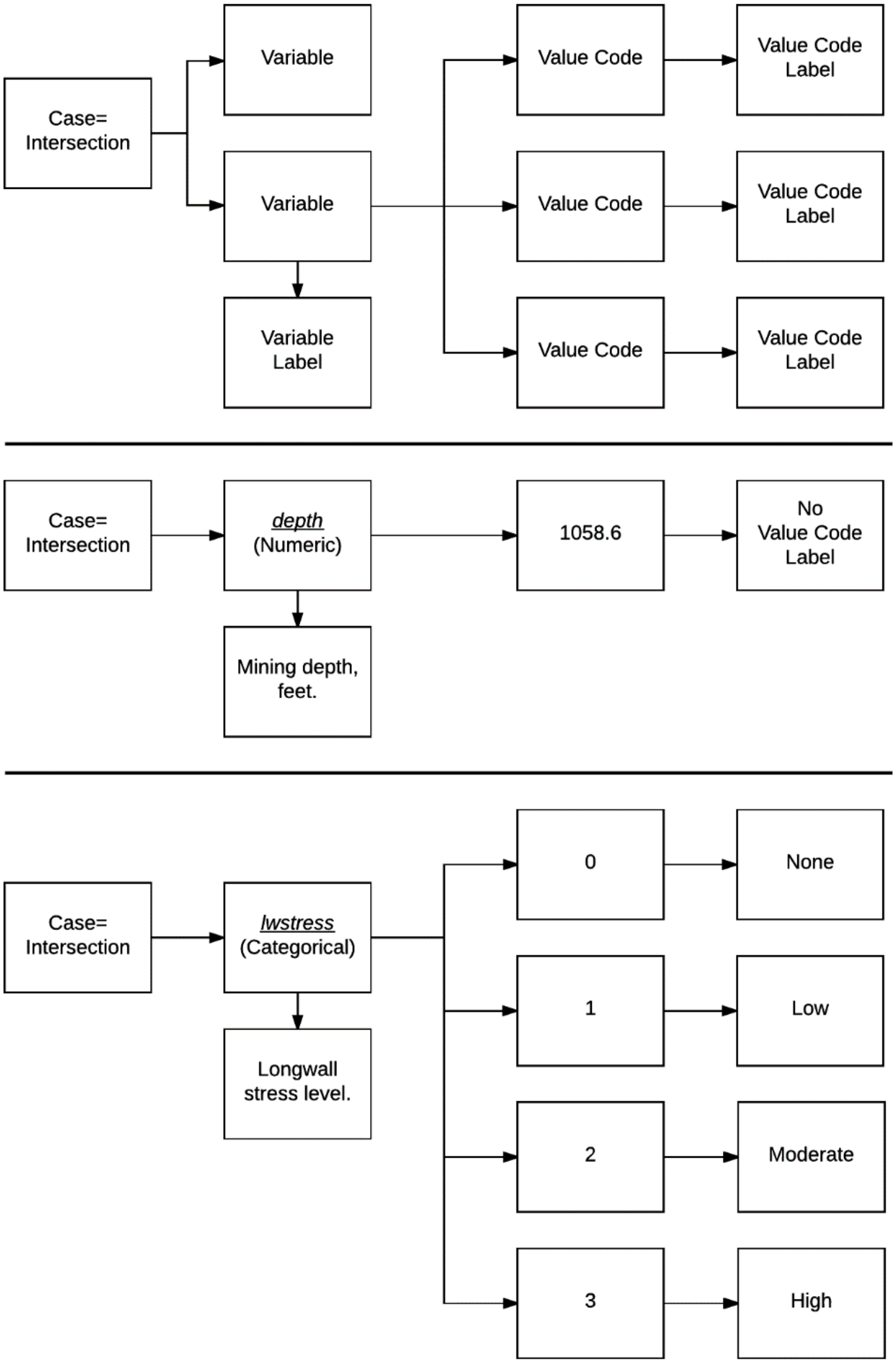


Figure 4.3 Variable nomenclature with examples.

Office-level FDVs were transcribed by qualified technical personnel into spreadsheets that were then copied into the sample variable database. Data checking and consistency with database codebook requirements were performed by the technical personnel developing the data.

Quality control during data input into the database was provided by Team 1 and Team 2 personnel, qualified technical personnel, and me. The quality checks ensured that the data were logical with respect to the variable being measured (e.g., a mining depth coded as 14 feet was not possible). Data quality checks also ensured that input values, either from field-level or office-level data collection, or subsequent data input, followed the variable and value measure and coding methods. Missing or problem data were noted and either corrected, supplied through additional underground visits, or office data collection. This was an iterative process of review, correct, review, and repeat. The result of this phase of the database development method was my determination that the database was complete, consistent, and logical to a point where the exploratory data analysis could begin.

4.7 Exploratory Data Analysis

The explanatory data analysis process is outlined on Figure 4.4 (page 93). It was designed to accomplish two tasks (Newton et al. 2013):

1. It was “the second step in the quality control process”, continuing the data cleaning and data screening started in the database development phase.
2. It provided an examination of the statistical characteristics of the data.

The exploratory data analysis followed the general methods for statistical analysis of numeric and categorical data as outlined in Agresti (2007, 2010), Hosmer et al. (2013), and Newton et al. (2013). These methods required the selection of a statistical level of confidence.

In the exploratory data analysis, the selected level of confidence was 95%. This represented a high level of confidence that the correct decision was made, based on the data. The selection of the 95% confidence level was based on the results of the literature review of statistical hypothesis testing and my requirement for a high level of confidence in my results. McKillup et al. (2010) stated that the confidence level of 95% “is the probability level that many researchers use as a standard for a ‘statistically significant level.’” Davis (2002) indicated that this confidence level might be too high for some problems involving geologic variables and processes. He stated that by “setting more modest levels of significance” for geology problems, “we may be able to come to conclusions more frequently”. He cautioned that, if the consequences of an incorrect conclusion could result in harm, a higher level of significance was appropriate. The higher level of confidence, 95%, was the approach utilized in this research.

The confidence level is used to determine the required significance level for the statistics used in hypothesis testing. A 95% confidence level is the compliment to a significance level of 0.05 and is noted in this text as $Pr=0.05$. In hypothesis testing, the goal is a test statistic with a $Pr<0.05$. If the calculated $Pr<0.05$, the null hypothesis was rejected.

The explanatory data analysis consisted of four tasks:

- Univariate analysis of individual variables to provide descriptive statistics for both numeric and categorical variables.

- Test for randomness of individual variables: plotting of histograms for both numeric and categorical variables, the statistical runs test for numeric variables, and a one-way table test for categorical variables.
- Test for association or independence between a categorical PV and the outcome variable using a two-way contingency table test analysis.
- Test for association or independence between either a categorical or numeric PV using logistic regression analysis of the single PV against the outcome variable.

The exploratory data analysis began with a univariate analysis of each variable in the sample database to develop descriptive statistics for each variable. The univariate analysis methods depended on variable type, numeric or categorical. Table 4.5 summarizes the analysis methods employed for numeric and categorical variable types.

The objectives of developing and reviewing the descriptive statistics included:

- Check for missing variable values.
- Check for miscoding of variable labels and values.
- Check for extreme outliers in the variable value data range.
- Review and describe the general frequency distributions (random, normal, bi-model, skewed, etc.) of the individual variable values.

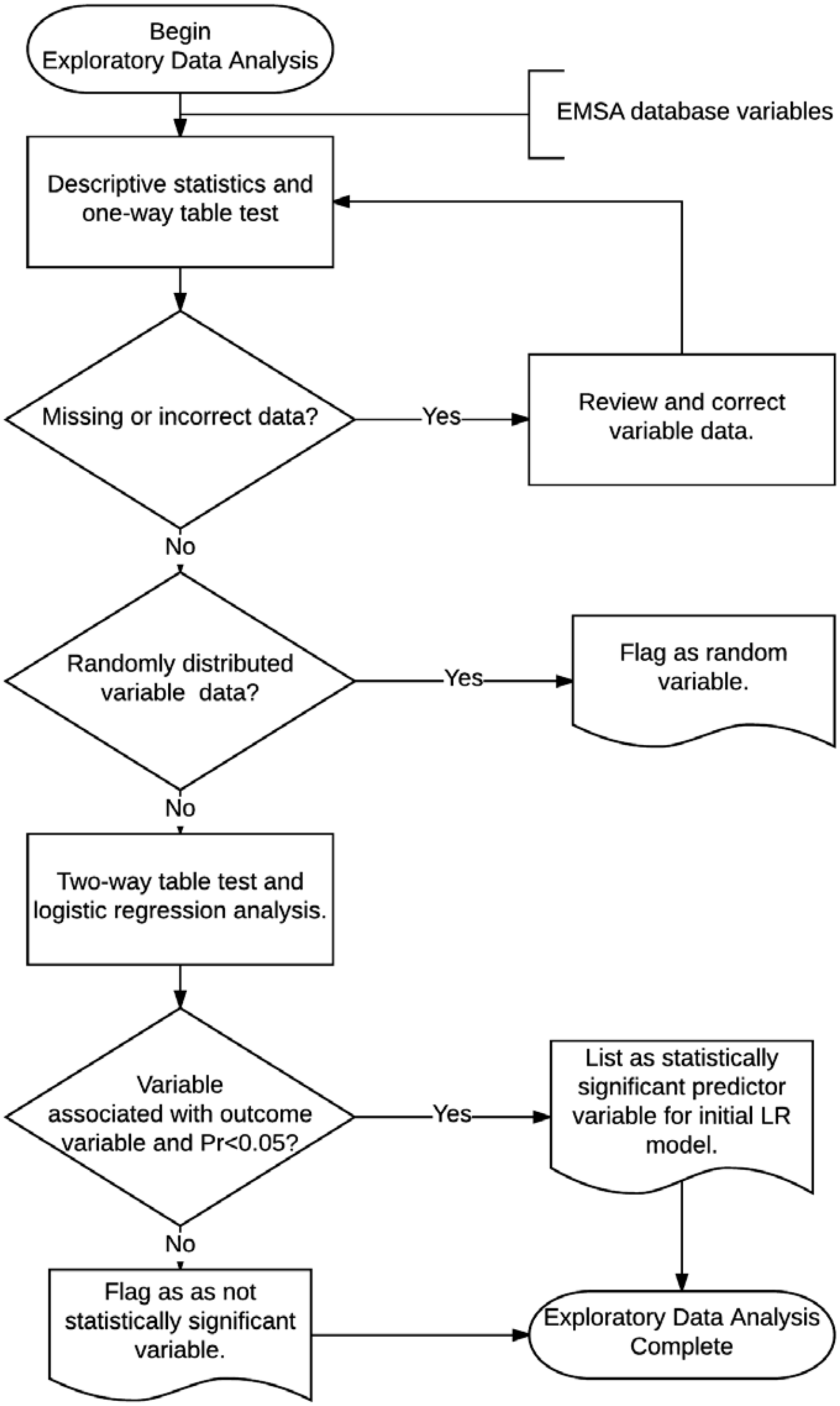


Figure 4.4 Exploratory data analysis process flowchart.

If the data checks indicated problems with the data for a variable, these problems were confirmed and corrected in the database. If the check for outliers relative to the range of the variable data showed extreme values, these outliers were checked for data quality and integrity (e.g., a mining depth value of 14 feet was not possible with this data set). If there were no data errors, the outliers were left in the database.

Frequency plots and tables were reviewed to assess the distribution of a variable's data. Randomly distributed variables tended to have approximately equal frequency value counts and percentages. Histograms provided a view of the type of distribution of the variable data, normal, bi-modal, skewed, etc.

The runs test (NIST 2016) was used to test a numeric variable data set for a random or non-random distribution. The test used the Z statistic to test the null hypothesis that the data set is randomly distributed against the alternative hypothesis that the data is non-randomly distributed. At the significance level $Pr<0.05$ used in this research, the null hypothesis was rejected if $|Z|>1.96$ for a two-tail test.

The one-way table test for randomness tested the distribution of the variable data set for a random distribution for a categorical variable. The goal was to confirm that the variable data are significantly ordered rather than just a randomly distributed collection of data. If the data were randomly distributed, the variable was dropped from further analysis. The test statistic was the Pearson statistic based on the chi-squared distribution (Agresti 2007). This statistic tested the null hypothesis that the probability of occurrence of each data point is randomly distributed. In a one-way table, this means that the frequency values for each category of a randomly distributed variable were approximately equal. The alternate hypothesis was that the data set was not randomly distributed. The Pearson statistic calculated a value for the Pearson chi-square statistic (chi2) and a Pr value. A Pr<0.05 allowed for rejection of the null hypothesis of a randomly distributed data set. The calculated Pearson statistic takes a value of zero when the data set is completely randomly distributed (Agresti 2007). Values of the Pearson statistic greater than zero indicate a non-randomly distributed data set,

Table 4.5 Univariate variable testing by variable type.

Statistical test	**Numeric**	**Categorical**
Number of observations in the database	Yes	Yes
Check for missing data	Yes	Yes
Mean	Yes	Yes
Standard deviation (1)	Yes	Yes
Frequency distribution by percentiles (2)	Yes	No
Frequency distribution by categories	No	Yes
Variance (3)	Yes	No
Skewness (4)	Yes	No
Kurtosis (5)	Yes	No
Histogram graph	Yes	Yes
Box plot graph (6)	Yes	No

Notes quoted from (UCLA: Statistical Consulting Group):

(1) This is the standard deviation of the variable and gives information regarding the spread of the distribution of the variable.

(2) Percentiles are calculated by ordering the values of the variable from the lowest value to the highest value and then finding the value that corresponds to the percent of interest, typically, 25%, 50%, 75% and 100%, or quartiles.

(3) The variance is the standard deviation squared and is a measure of spread of the distribution.

(4) Skewness measures the degree and direction of asymmetry. A symmetric distribution such as a normal distribution has a skewness of 0, and a distribution that is skewed to the left (e.g., when the mean is less than the median) has a negative skewness. A histogram is used to graphically display the distribution of the variable.

(5) Kurtosis is a measure of the heaviness of the tails of a distribution. A normal distribution has a kurtosis of 3. Heavy tailed distributions will have kurtosis greater than 3 and light tailed distributions will have kurtosis less than 3.

(6) The box plot displays outliers in the variable values, if any.

with larger values of the statistic providing stronger evidence for the rejection of the null hypothesis of a randomly distributed data set. Results of this analysis are reported as the Pearson chi-square statistic value with the degrees of freedom and the Pr value [e.g., (chi2(1)=7893, Pr=0.025)]. Variables that were randomly distributed were reviewed for data quality and integrity; and, if no errors were found, they were dropped from further analysis.

Non-randomly distributed, significantly ordered, categorical variables were tested against the outcome variable of intersection condition rating using the two-way contingency table test for independence or association. The two-way contingency table analysis tested for the independence or association of two variables and, if associated, the strength of the association. Conceptually, it is an extension of the one-way table test. The null hypothesis was that the two variables are completely randomly related (independent). The alternative hypothesis was that the two variables were related (associated). A Pr<0.05 allowed for rejection of the null hypothesis of independence between the two variables. The Pearson chi-square statistic and the Likelihood-Ratio chi-square statistic (LRchi2) were used to evaluate the measure of association between the two variables. When the two variables were completely independent, both the Pearson and Likelihood-Ratio statistic were equal to zero (Agresti 2007). Values of the Pearson and Likelihood-Ratio statistics greater than zero indicate a non-random association exists between the two variables, with larger values of the statistic providing stronger evidence for the rejection of the null hypothesis of variable independence. Results of this test were reported in the text using the format (chi(df)=25, Pr=0.003 and

LRchi2(df)=25, Pr<0.001), where “df” represents degrees of freedom, for Pearson and Likelihood-Ratio, respectively.

Once an association between the two variables has been established, there were various test statistics that provided a measure of the strength of the association. Agresti (2007, 2010) and Newton et al. (2013) provided descriptions of the analysis of association of categorical variables in general and ordinal variables specifically. Specific test statistics used in my analysis were:

- Goodman-Kruskal's gamma (gamma)
- Somers' D (somers’d)

Goodman-Kruskal's gamma applies to both nominal and ordinal categorical data. Somers’ D was applicable to ordinal categorical data. Agresti (2010) specifically recommends Goodman-Kruskal's gamma and Somers' D for measuring the degree of association between ordinal categorical variables. As with Pearson and Likelihood-Ratio statistics, all these tests were for the null hypothesis of no association (random, complete independence) and the alternative hypothesis that the variables were associated (not independent). The two test statistics have values that vary from −1 to +1, with larger absolute values providing evidence of a stronger association (Table 4.6).

Table 4.6 Strength of association between two variables.

Strength of Association	gamma, somers'd
None	0.00
Weak	± 0.01 – 0.09
Moderate	± 0.10 – 0.29
Moderately strong	± 0.20 – 0.29
Strong	± 0.30 – .099
Perfect association, strongest possible	± 1.00

Non-randomly distributed, significantly ordered, numeric variables were tested against the outcome variable of intersection condition rating using logistic regression (LR) to test for independence or association. The LR tests for the independence or association of two variables and, if associated, the strength of the association. Conceptually, it tests the null hypothesis that the two variables were completely randomly related (independent); that in the LR, the coefficient of the PV is zero. The alternative hypothesis is that the two variables were related (associated) and the coefficient of the PV is greater than zero. Long et al. (2014) recommended using the Likelihood-Ratio chi-square statistic test for this analysis. A Pr <0.05 allowed for rejection of the null hypothesis of independence between the two variables. The Likelihood-Ratio statistic was used to evaluate the measure of association between the two variables. When the two variables were completely independent, the Likelihood-Ratio statistic was equal to zero (Agresti 2007). Values of the Likelihood-Ratio statistic greater than zero indicated a non-random association existed between the two variables, with larger values of the statistic providing stronger evidence for the rejection of the null hypothesis of variable independence.

The conclusion of the exploratory data analysis was a clean data set with no missing data, no data issues, a summary of the descriptive statistics for each variable, a determination that a variable was significantly ordered and not randomly ordered, the determination of a variable's association with or independence from the outcome variable of the intersection condition rating, the strength of the association, and a list of statistically significant PVs ordered by the strength of the association with the outcome variable. A PV listing as a statistically significant PV was based on a significance level of Pr<0.05 with the respect to the outcome variable, *icr*. This indicated that there was a less than a 5% probability that the result occurred by random chance. Lower Pr values indicated a higher level of statistical significance. The statistically significant PV list provided input into the model development.

4.8 Hypothesis Testing

This section describes the methodology used to test the research hypotheses described in Section 3.2. The testing methodology was the same as that described for two-way table and logistic regression analyses in the exploratory data analysis text, Section 4.7.

Each hypothesis was reviewed and a list of probable PVs impacting the hypothesis were selected. This varied from one PV (e.g., *depth* for the hypothesis concerning depth of mining as a predictor of intersection condition) to the 10 PVs tested for the hypothesis on geologic structures as a predictor of intersection condition. For each PV, the exploratory data analysis results for variable descriptive statistics, non-random distribution and distribution histograms were reviewed for trends or issues. Two-way table (categorical variables only) and logistic regression analyses (categorical and numerical variables) were performed to test for independence or association and strength of the association. The test statistics were Likelihood-Ratio chi-squared [LRchi2(df)] statistic based on the degrees of freedom (df) and the calculated Pr value. The null hypothesis tested was that there was complete independence between the PV and the outcome variable, *icr*. A LRchi2 $Pr<0.05$ allowed for rejection of the null hypothesis. Where the PV and *icr* were associated, the strength of the association, generally measured with the somers'd statistic, was reviewed. Strong association resulted in accepting the research hypothesis. Weak association involved additional testing and review; through re-categorization of the PV or tests of results when the PV was tested with other PVs. These test results were used to determine if a hypothesis was accepted, modified and conditionally accepted, or rejected.

4.9 Logistic Regression Model Development

This section begins with a general discussion of logistic regression (LR) modeling; the model form, the calculation procedure, and the calculation outputs. The LR model development process is defined, beginning with the selection of input PVs to populate the initial Full Model and ending with the Predictive Model. The LR model development process flowchart is presented on Figure 4.5.

The general logistic regression model takes the form:

$$\text{logit}(Pr) = \text{cons}+(B1\bullet PV1)+(B2\bullet PV2)+(Bn\bullet PVn) \qquad (4.1)$$

where:

Pr = The probability of the outcome of interest (e.g., a satisfactory intersection condition).

logit(Pr) = Outcome as the logit transformation of the probability, or likelihood, of the outcome of interest (e.g., a satisfactory intersection condition). The logit transformation gives the probability as the natural logarithm of the odds (i.e., log-odds).

cons = Constant value.

B_1–B_n = Coefficient values applied to the predictor variables PV_1–PV_n.

PV_1–PV_n = Predictor variables.

Probability, Pr, is calculated from:

$$\text{Pr}= \frac{e^{\text{logit(Pr)}}}{1+e^{\text{logit(Pr)}}} \tag{4.2}$$

Calculation of the results using the LR method used a maximum likelihood estimate approach to develop the best-fit equation of the input PVs (PV_1–PV_n). This approach assigns a set values to the intercept (cons, or constant) and to the coefficients (B_1–B_n) associated with the input PVs. The result is calculated and compared to the actual observed outcome values in the data set. This process continues until the set of coefficient values resulted in outcome probabilities (i.e., likelihoods, that were closest to the actual observed outcomes in the data set). Long et al. (2014) described this as an iterative calculation process that continued until, “the maximum of the likelihood function is found, called convergence”. The iterative calculation process stopped at this point and the resultant constant and coefficient values were reported.

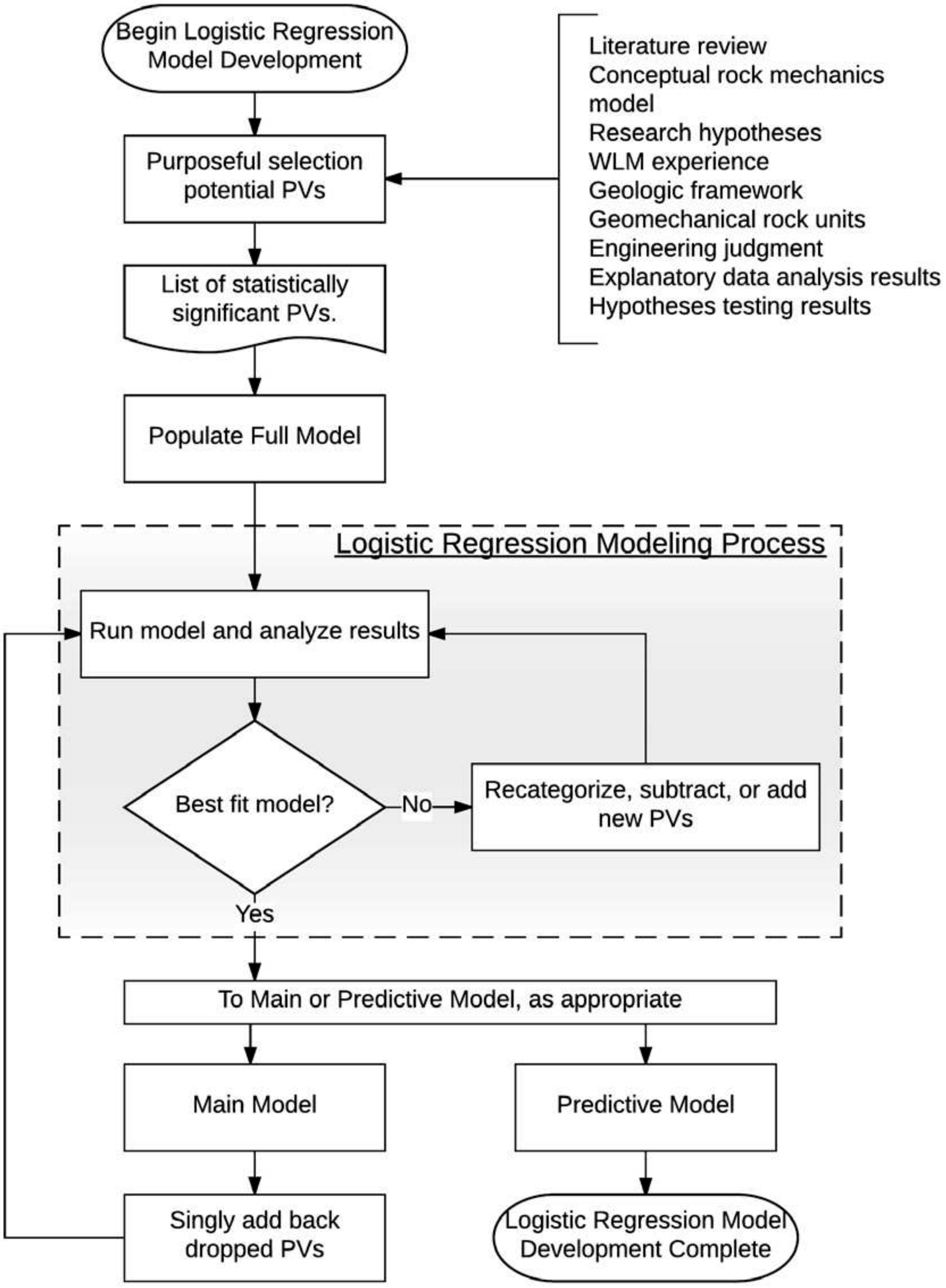


Figure 4.5 Logistic model development process flowchart.

The statistical analysis software, Stata 14.1 (StataCorp LP 2016) reported the constant value and values for the coefficients for each of the PVs input into the model. The software reported the following statistics for the constant and each PV coefficient:

- Coefficient value.
- The standard error of the coefficient.
- The z test statistic.
- The probability of the z test statistic against the null (H0:) hypothesis that the coefficient value equals zero (H0: coefficient=0).
- The 95% confidence interval of the coefficient.

The software also reported several statistics used to assess model fit:

- The Likelihood-Ratio chi-square statistic, LRchi2 and the probability (Pr) of the likelihood of the null hypothesis (H0:) that all the model coefficients are equal to zero.
- The AIC.
- The BIC.
- The AUC/ROC.

Akaike's information criterion (AIC) and Bayesian information criterion (BIC) were measures of model fit that were used to compare the fit of two or more models by calculating the absolute difference between one model and a second model with the model with the lower AIC or BIC values being the better fit model (Long et al. 2014). Long et al. (2014) presented a table summarizing "the strength of evidence" favoring the model with the lower AIC or BIC values. AIC and BIC are preferred for model comparisons because they do not require that one of the models be nested in the other model. Table 4.7 presents the absolute difference values and the related strength of evidence favoring the model with the lower AIC or BIC values.

Table 4.7 Strength of model fit based on AIC and BIC values. After (Long et al. 2014).

Absolute difference	Strength of model, Model2 versus Model1
0 - 2	Weak
2 - 6	Positive
6 – 10	Strong
>10	Very strong

When using AIC or BIC values two important facts must be remembered:

- The values are used to compare two models. A single model value of AIC or BIC has no intrinsic value. But the difference in the two AIC or BIC values calculated for each of two models does indicate how much stronger or weaker one model is with respect to the other model.
- Both models to be compared must have the same number of cases (N_1=N_2) as the number of samples used to fit the model is part of the calculation of both AIC and BIC.

The area under the receiver operating characteristic curve (AUC/ROC) method was developed by Hosmer et al. (2013) who provided criteria for assessing model fit as shown in Table 4.8.

Table 4.8 Model fit using AUC/ROC. After (Hosmer et al. 2013).

ROC value	Model fit
= 0.5	No discrimination, similar to a coin flip
0.5<ROC<0.7	Poor
0.7≤ROC<0.8	Acceptable
0.8≤ROC<0.9	Excellent
ROC≥0.9	Outstanding

Model development began with the purposeful selection process to select PVs for populating the Full Model. This selection process was based on the literature review, the conceptual rock mechanics model, the research hypotheses, WLM experience, the geologic framework, the geomechanical rock units, and engineering judgement. These PVs were evaluated using the results of the exploratory data analysis, Section 4.7, and the hypotheses tests, Section 4.8. This evaluation resulted in the development of the statistically significant PV list. The variables on this list were reviewed again using the purposeful selection process as a guide. This review added a few variables that, while not statistically significant, were considered important based on the literature review, WLM experience, and engineering judgement. The result was the PVs used to populate the initial logistic regression model, the Full Model, labelled fullmodel00.

The results of the fullmodel00 run were evaluated in terms of PV coefficients, z-test statistics, the Pr values, and the 95% confidence intervals. The AIC, BIC, and AUC/ROC were also noted for comparison with later models. The coefficient with the highest Pr value was dropped from the model to create a new model, model01, and logistic regression of model01 was performed. This began the iterative approach to dropping, modifying or replacing PVs included in the LR with the goal of obtaining the fewest PVs, minimizing PV Pr values, and optimizing overall model fit (Mark et al. 2007a, b; Agresti 2007, 2010; Carlberg 2012; Hosmer et al. 2013; Long et al. 2014). Each new model was built by changing one PV at a time, even if the model results indicated multiple PVs with Pr>0.05. The variable with the largest Pr value was modified or dropped from the model and a new model fit with the model name incremented by one [e.g., model(n) incremented to model(n+1)]. The AIC, BIC and AUC/ROC for new model(n+1) were compared both to the fullmodel00 and the preceding model(n) to assess the model fit. This iterative process continued through succeeding models until the model was calculated with the fewest predictor variables, all of which met the Pr<0.05 criteria, the lowest AIC and BIC values, and the highest AUC/ROC value compared to all the fitted models. This iteration of the LR model was called the Main Model.

Hosmer et al. (2013) recommended adding, one at a time, a PV considered as a potential predictor variable. Usually it was a PV dropped from the Full Model for lack of statistical significance; but, was considered a potentially important PV. Some PVs not included in the Full Model also were tested. Each potential PV was added to the Main Model a new model fitted with LR. The new model and Main Model were compared using the values of AIC, BIC and AUC/ROC. PV coefficients were evaluated both in terms of Pr<0.05 and the percent change between the common PVs in each model. Hosmer et al. (2013) described this step as designed to identify any PVs that were not individually statistically significant but made “an important contribution” to the model. The resulting model at the end of this step was called the Predictive Model.

The final step in the process was to confirm the predictive performance of the Predictive Model. Predictive performance is defined as the model's ability to predict a true outcome versus predicting a false outcome for a given a set of values for the input predictor variables. Hosmer et al. (2013) stated that the AUC/ROC "has now become the standard for evaluating a fitted model". The Receiver Operating Characteristic curve originated from signal detection theory and is a plot of the model's "sensitivity", the model's ability to predict a true outcome, versus the model's reporting of a false positive, defined as "1 – specificity". Figure 4.6 provides an illustration of a Receiver Operating Characteristic curve and the statistical software report of the area under the curve. The AUC/ROC was the method used in this research to assess the classification performance of each model. The goal of the research was to provide a Predictive Model with an AUC/ROC of greater than 0.8, an "excellent" model fit (Table 4.8).

4.10 Model Validation

Steyerberg (2008) defined model validation as the method of testing the validity of a model; and, validity as the "reproducibility" of the model in successfully predicting outcomes. Reproducibility is the ability to produce accurate predictions among cases not included in the development of the model but from an identical population (Justice et al. 1999). The model was validated using the 10-fold, cross-validation method employing a sample split strategy of 90% for the developmental sample data set and 10% for the validation sample data set (Hosmer et al. 2013), which is the terminology used in this research.

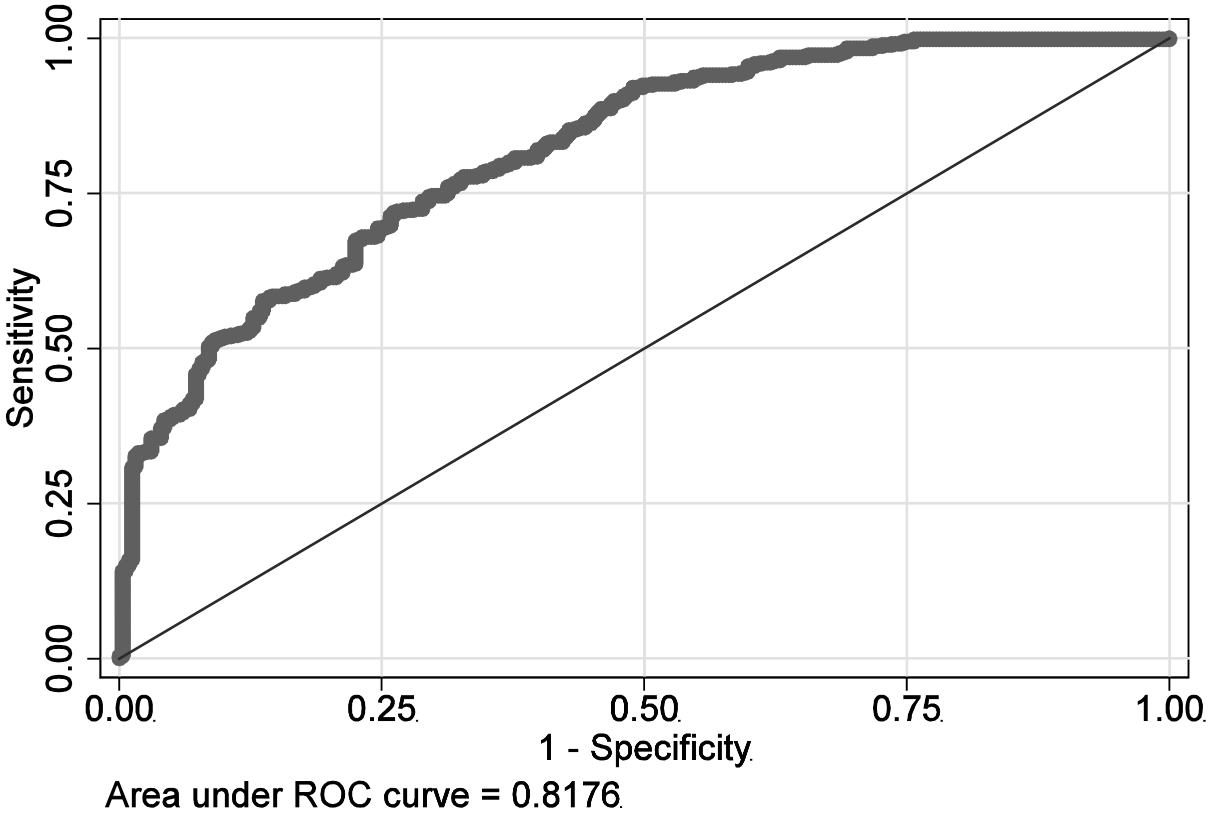


Figure 4.6 Receiver Operating Characteristic curve and calculation of the area under the curve.

The 10-fold, cross-validation method used ten iterations of individual cross-validation tests. Using this method, the EMSA data set was divided into 10 subsets of 88 or 89 intersections. Each intersection was only included in one of the 10 subsets. For each of the 10 iterations, one subset was selected as the validation data set and the remaining nine subsets became the developmental data set. The logistic regression model was developed using the developmental data set. Then the results of the developmental data set model were used to predict the outcomes in the validation data set. The results of each iteration were reported as the model AUC/ROC. If the original predictive model was well fit, the original Predictive Model AUC/ROC values would closely match both the individual iteration model results as well as the averaged results of all 10 iterations.

CHAPTER 5

RESULTS

This chapter describes the results of the statistical analysis of the EMSA database. The chapter starts with the results of the development of the research outcome variable, the intersection condition rating, *icr*, for each intersection in the database. The testing of the research hypotheses is described in terms of predictor variable (PV) selection and the results of the hypotheses testing. The derivation of the Predictive Model using the logistic regression (LR) process is described and the Predictive Model is presented. The presentation of the results of model validation complete the chapter.

Names of EMSA database variables in this chapter are indicated in lower-case, italic, underlined letters (e.g., *icr*). The terms data set and database refer to the complete set of EMSA data. APPENDIX A presents the data codebook for the EMSA database. This data codebook includes the variable name, variable label, variable measures, variable value labels and value measures and ranges of measures. APPENDIX B presents notes for the variables in the database.

5.1 Intersection Condition Rating Outcome Variable

The logistic regression (LR) method used for this research required a binary categorical outcome variable as input into the LR calculations. The research questions required an outcome variable related to the condition of each intersection. After a review of the problem statement, research questions, literature review, conceptual rock mechanics model, experience at the WLM, engineering judgement, and the results of the data collection process, it was decided to define the outcome variable as a calculated intersection condition rating (*icr*). This section outlines the variables and process used to calculate the *icr*, the results of the analyses, and the outcome variable. The method used to derive the *icr* is illustrated on Figure 5.1.

The intersection condition rating development process involved six activities:

1. Determine a field intersection condition rating for each intersection.

    a. Develop a field intersection condition rating variable (*icrf*) and variable measures.
    b. Visit each intersection, conduct an inspection, and assign a field intersection condition rating to each intersection.

2. Determine an EMSA Standing Support Map intersection condition rating for each intersection, *icrss*.
3. Review secondary, supplemental, and standing support variables in the database.
4. Determine a preliminary intersection condition rating (*icrp*) for each intersection based on the *icrf*, the *icrss*, and the criteria that no secondary, supplemental, or standing support was installed for ground control in the intersection.
5. Determine and evaluate database variables that were evidence of Not satisfactory roof conditions.
6. Determine Intersection Condition Rating (*icr*).

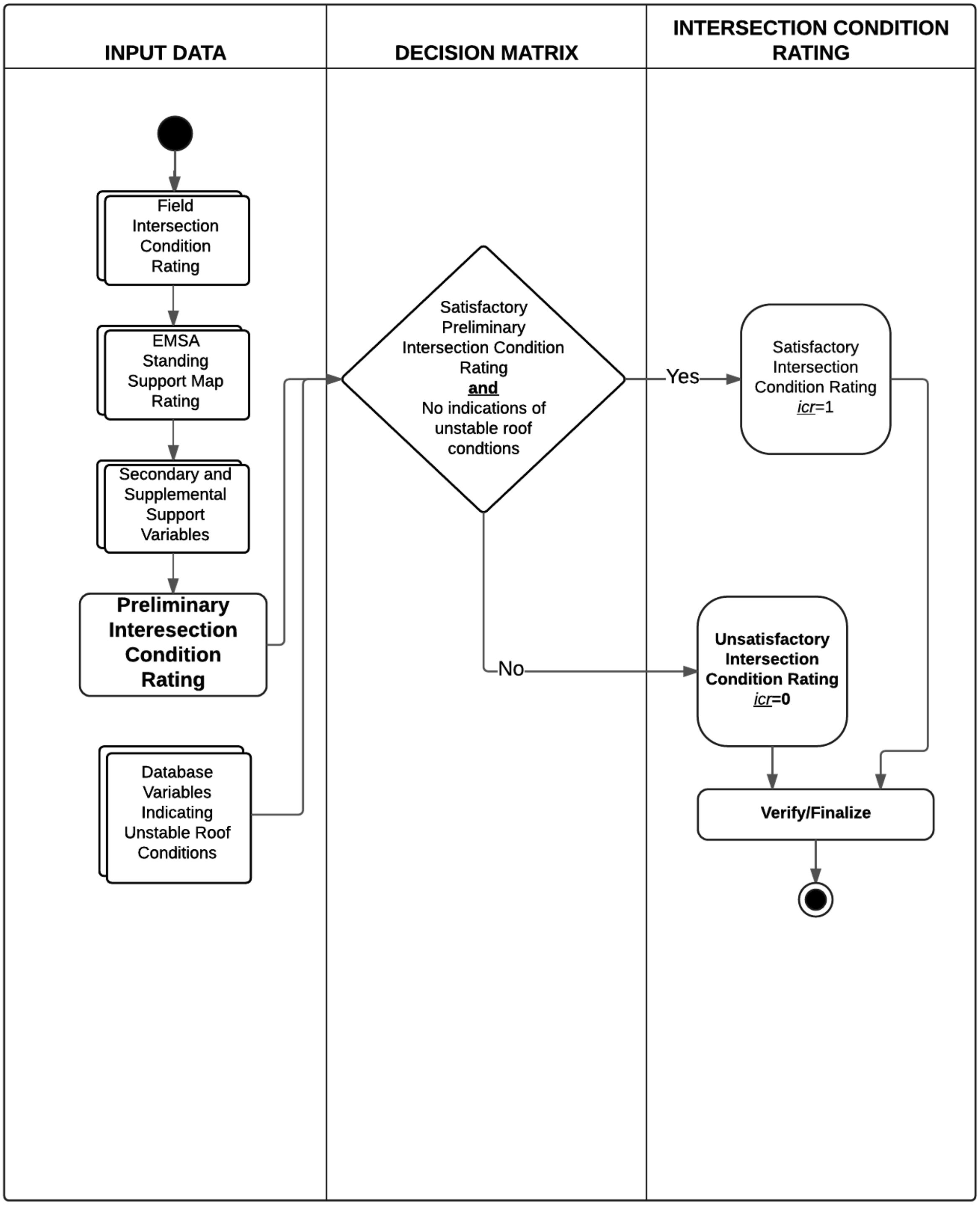


Figure 5.1 Intersection condition rating development process flowchart.

5.1.1 Field Intersection Condition Rating Variable Development

The literature review of coal mine condition rating methods (Section 2.3), experience at the WLM mine, and engineering judgement were used to develop a new Field Intersection Condition Rating method for use in the unique combination of conditions in the EMSA. This rating classification method expanded upon aspects of existing roof condition classification methods. It considered both the overall conditions of the intersection and the current functional utility. Overall intersection condition included conditions of the roof, ribs, and floor in the intersection and in the immediately adjacent crosscuts and entries. Current functional utility was determined based on the current use of the intersection compared to the original design and functional requirements of the intersection. Table 5.1 summarizes the field intersection condition rating categories developed and used in the research to assign a field intersection condition rating, *icrf*, to each intersection. Table 5.2 (page 115) tabulates the results of the field data collection and rating of each intersection.

5.1.2 EMSA Standing Support Map Intersection Condition Rating

Intersection conditions were categorized based on a review of the East Mains Standing Support Map. This standing support map was compiled by the WLM Engineering Department and showed the standing support installed in the East Mains entries and adjacent crosscuts at the time of this research. A three-category condition rating scale was developed to categorize intersection conditions using the information on this map. Table 5.3 (page 115) summarizes these condition rating categories. The presence of standing support in categories 2 and 3, in addition to an intersection’s

Table 5.1 Field Intersection Condition Rating (*icrf*), categories, and categorization criteria.

Numeric and Condition Rating	Condition Category	Categorization Criteria
1 Good	Satisfactory	All the following must be present: 1. Intersection has only original roof bolting. 2. No travel or ventilation restriction. 3. Intersection fully serves intended / functional design (intake, travelway, escapeway, return, belt line, overcast, etc.).
2 Fair	Satisfactory	Original functional design not currently compromised. And any of the following are present: 1. Intersection shows minor roof cracking or presence of water. 2. Original roof support supplemented with additional roof bolting, meshing, etc. 3. May include some minor standing support located at corners or for rib control.
3 Poor	Not satisfactory	Any of the following are present: 1. Significant additional standing support installed in the intersection or to either side of the intersection in the crosscuts. 2. Roof failure / fall below the top of the bolted interval. 3. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. 4. Belt maintenance operations compromised due to clearance issues with standing support.
4 Very poor	Not satisfactory	Any of the following area present: 1. Longwall tailgate blockage. 2. Escapeway routed around area. 3. Steel sets or equivalent installed to maintain access for underground mobile equipment. 4. Significant additional standing support installed in the crosscuts to either side of the intersection in the crosscuts.
5 MSHA Reportable	Not satisfactory	MSHA reportable roof fall. Roof failure above bolted horizon.

Table 5.2 Frequency of intersections in each category of the field intersection condition rating.

Field Intersection Condition Rating	Frequency Count Intersections	Percentage Intersections
1 – Good	393	44.5
2 – Fair	324	36.7
3 – Poor	46	5.2
4 – Very Poor	112	12.7
5 – MSHA reportable roof fall	9	1.0
Total	884	100.0

Table 5.3 EMSA standing support map intersection condition rating categories.

Map Condition Rating	Basis for rating
Good (1)	Intersection has no to very little standing support shown on map. Intersection travelway or function not impacted by the limited installation of supplemental standing support.
Fair (2)	Intersection has some standing support shown on the map, either in the intersection or in the adjacent crosscuts. Intersection travelway function somewhat impacted by the installed supplemental standing support.
Poor (3)	Significant supplemental standing support installed in the intersection or to either side of the intersection in the crosscuts. Intersection travelway function either significantly impacted or routed around intersection. Escapeway routed around intersection. Also, includes MSHA-reportable roof fall in the intersection.

designed primary roof support, was judged to indicate Not satisfactory performance of the primary roof support design and to result in a Not satisfactory intersection condition. Table 5.4 summarizes the frequency of intersections in each category developed from the analysis of the East Mains Standing Support Map. The East Mains standing support map variable is coded as <u>*icrss*</u> in the EMSA database. The data show a good correlation between the number of intersections with *icrf* ratings of good or fair (717) and the *icrss* rating of good (691).

Table 5.4 Frequency of intersections in each category of the EMSA standing support map.

Map Intersection Condition Rating	Frequency Count Intersections	Percentage Intersections
1 – Good	691	78.2
2 – Fair	65	7.4
3 – Poor	128	14.5
Total	884	100.0

5.1.3 Preliminary Intersection Condition Rating

The preliminary intersection condition rating was developed to incorporate data from both field observations and office databases sources following the method presented on Figure 5.2.

A Satisfactory condition rating was based the following criteria and data sources:

- Field intersection condition rating of Good (1) or Fair (2), *icrf*≤2.
- EMSA standing support map rating of Good (1), *icrss*=1.
- No supplemental standing support installed in intersection for ground control as reported by Team 1 (i.e., EMSA database variables *can*, *combo*, *crib*, *prop*, and *set* all equal zero). A variable value of zero represents no reported installed standing support used for ground control.
- No secondary or supplemental in-roof support installed in intersection, *inroof*=0.

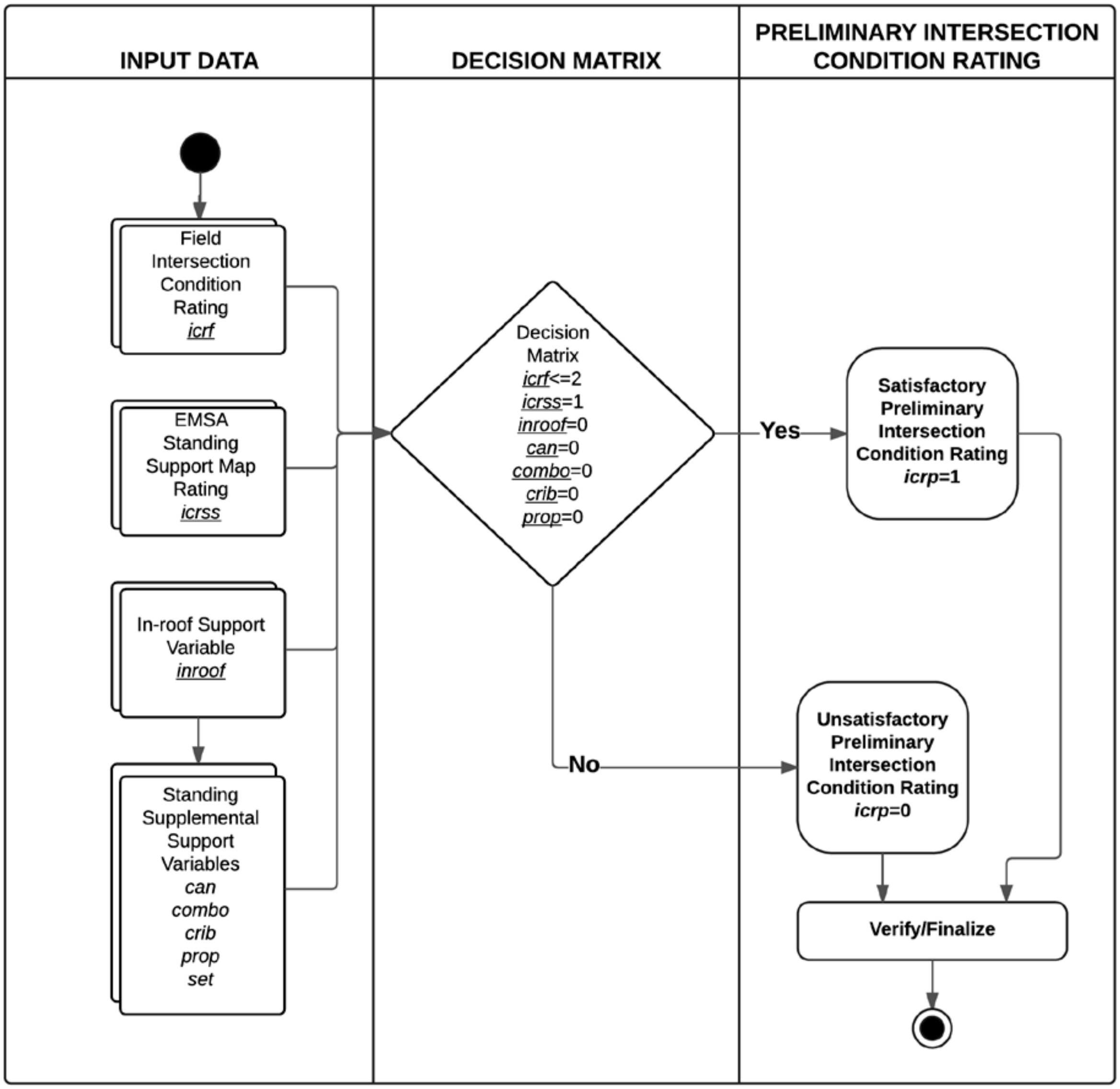


Figure 5.2 Preliminary intersection condition rating method flowchart. Variable *names* are defined in Appendix A and described in Appendix B.

Table 5.5 summarizes the results of the categorization of intersection conditions using the preliminary intersection success rating method.

Table 5.5 Frequency of intersections in each category of the preliminary intersection success rating analysis.

Preliminary Intersection Condition Rating	**Frequency Count Intersections**	**Percentage Intersections**
Satisfactory	601	68.0
Not satisfactory	283	32.0
Total	884	100.0

5.1.4 Intersection Condition Rating Outcome Variable

The results of the preliminary intersection condition analysis were used as the basis for the determination of the outcome variable intersection condition rating. The method incorporated variables from the EMSA database that were possible indicators of intersection roof instability; and, therefore, Not satisfactory intersection conditions. The database included the following variables that were indicators of intersection roof movement or loading:

- Roof fall prior to bolting. Database variable *fptb*.
- Roof tension cracking. Database variables, *tn*, *tnc*, *tne*, *tnn*, *tns*, and *tnw*.
- Roof sag. Database variables *rfsag* and *rfsagamt*.
- Truss shoe deformation due to loading. Database variable *trsload*.

The analysis of each of the selected variables is described and the result presented. A summarization of the calculated intersection condition rating for the 884 intersections is presented. APPENDIX E presents a tabulation of the intersection condition rating, *icr*, for all 884 EMSA intersections by intersection number, *intno*.

The database included the variable, *fptb*, roof fall prior to bolting, that represented the occurrence and report of a roof fall prior to bolting. As part of the production reporting process, production reports for each shift indicated if a roof fall before bolting occurred because this caused a delay in the production cycle. The database included 49 intersections where field inspection or production records indicated a roof fall prior to bolting. The one-way table test for randomness results (chi2(1)=698, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test for association between *fptb* and *icrp* results (chi2(1)=5.309, Pr=0.021, gamma= −0.3235) indicated a strong association between *fptb* and a Not satisfactory intersection condition rating. Therefore, *fptb* was included as a PV for determining the intersection condition rating.

The database included a variable related to the presence or absence of any tension cracks in an intersection, *tn*, and variables reporting the location and magnitude of any tension cracks in the intersection roof, *tnc*, *tne*, *tnn*, *tns*, and *tnw*. Several statistical tests were performed using these variables, *tn* directly and two PVs created from *tnc*, *tne*, *tnn*, *tns*, and *tnw*.

The database included 414 intersections where the presence of a tension crack anywhere in the intersection was noted. The results of the one-way table test for randomness of the *tn* variable (chi2(1)=3.547, Pr=0.060) did not allow for rejection of the null hypothesis of randomly distributed data. The two-way table test of independence did indicate that *tn* and *icrp* were strongly associated (chi2(1)=32.508, Pr<0.001, gamma= −0.393). The variable *tn* was not included in further analyses because of the potential that it was a randomly distributed variable.

A PV, *tanylarge*, was created to test for the significance of the presence of a large (>0.25 in crack width) tension crack anywhere in the intersection. The database included 86 intersections where the presence of a large tension crack anywhere in the intersection was noted. The one-way table test for randomness result (chi2(1)=573, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(1)=122, Pr<0.001, gamma= −0.880) indicated a strong association between *icrp* and the presence of a large tension crack anywhere in the intersection roof.

A calculated PV for the total magnitude sum, *tsum*, was created that represented the total intensity of all tension cracking that was reported in an intersection. It was calculated as the sum of the magnitudes of reported maximum tension crack size categories for the tension crack variables *tnc*, *tne*, *tnn*, *tns*, and *tnw*. The PV *tsum* varied from zero to a maximum of 12 in with a mean value of 1.2-in and a standard deviation of 1.6-in. As noted above for the *tn* variable, the database included 414 intersections where a tension crack was present anywhere in the intersection. The one-way table test for randomness results (chi2(10)>2500, Pr<0.001) provided strong evidence for the rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(10)=144, Pr<0.001, gamma= −0.469) indicated a strong degree of association between *tsum* and *icrp*. Both the presence of a large tension crack and the tension crack magnitude sum were selected to categorize Satisfactory and Not satisfactory intersection conditions using the following criteria:

- The presence of a large tension crack, a crack wider than 0.25 in, located anywhere in the intersection, indicated a Not satisfactory intersection condition.
- A sum of the magnitudes of all observed cracks in an intersection of greater than 3 in indicated a Not satisfactory intersection condition rating.

The database included two variables related to the presence and magnitude of roof sag of the intersection roof. These two roof sag variables were:

- Roof sag present. Database variable *rfsag*.
- Roof sag amount. Database variable *rfsagamt*.

The database included 156 intersections where any amount of roof sag was reported. The one-way table test for randomness results (chi2(1)=370, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test for association (*rfsag* and *icrp*) results (chi2(1)=156, Pr<0.001, gamma = −0.813) indicated that the null hypothesis of independence could be rejected and that there was a strong degree of association between the two variables *rfsag* and *icrp*.

Based on the association between presence of roof sag and the intersection condition rating, the significance of the magnitude of the observed sag was investigated. The database variable was *rfsagamt*. Some roof sag was observed in 156 intersections. Roof sag amounts varied from 0.01 ft to a maximum of 1.5 ft, measured in 0.25-ft increments, with a mean value of 0.48 ft and a standard deviation of 031 ft for the 156 intersections reported with roof sag. The one-way table test results (chi2(10)>5800, Pr<0.001) allowed for rejection of the null hypothesis of a randomly distributed data set.

The two-way table test of association results (chi2(10)=189, Pr<0.001, gamma = −0.804) indicated that the null hypothesis of independence could be rejected and that there was a strong degree of association between the two variables *rfsagamt* and *icrp*.

Various simplifying categorization methods for the magnitude of roof sag were evaluated. The final categorization method selected for evaluating intersection condition rating based on roof sag amount is shown in Table 5.6. The PV *rfsagcat* was created for the analysis.

Table 5.6 Categorization method for magnitude of roof sag.

Preliminary Intersection Condition Rating	Magnitude of roof sag
Satisfactory	≤0.25 ft
Not satisfactory	>0.25 ft

The database included 80 intersections where the amount of roof sag was greater than 0.25 ft. The one-way table test for randomness results (chi2(1)=592, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test for association results (chi2(1)=130, Pr<0.001, gamma = −0.913) indicated that the null hypothesis of independence could be rejected and that there was a strong degree of association between the two variables *rfsagcat* and *icrp*.

The final criteria for intersection condition rating using the amount of roof sag were:

- An intersection with Satisfactory conditions exhibited no roof sag or roof sag equal to or less than 0.25 ft.

- An intersection with Not satisfactory conditions exhibited roof sag greater than 0.25 ft.

The database included the variable, *trsload*, indicating the observed amount of loading on a truss shoe, measured in feet. Truss shoe loading was the approximate amount of roof movement downward at the location of the truss shoe. This variable was evaluated for statistical significance as a predictor of Satisfactory or Not satisfactory intersection conditions. The database included 149 intersections with reported truss shoe loading. Truss loading amount varied from zero to a maximum of 1.5 ft. For intersections exhibiting truss shoe loading, the mean value was 0.39 ft and a standard deviation of 0.29 ft. The one-way table test results (chi2(11)>6500, Pr<0.001) allowed for rejection of the null hypothesis of a randomly distributed data set. The two-way table test of association results (chi2(11)=176, Pr<0.001, gamma = −0.778) indicated that the null hypothesis of independence could be rejected and that there was a strong degree of association between the two variables *trsload* and *icrp*.

Various simplifying categorization methods for the magnitude of truss shoe deformation due to loading were evaluated. The final categorization method selected for evaluating intersection condition rating based on truss shoe amount is shown in Table 5.7. The PV *trsloadcat* was created for the analysis. The PV *trsloadcat* was calculated in inches.

Table 5.7 Categorization method for magnitude of truss shoe deformation due to loading.

Intersection Condition Rating	Magnitude of Truss Shoe Deformation
Satisfactory	≤2 in
Not satisfactory	>2 in

The database included 125 intersections where the amount of truss loading was greater than 2 inches. The one-way table test for randomness results (chi2(1)=454, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test for association results (chi2(1)=148, Pr<0.001, gamma= −0.845) indicated that the null hypothesis of independence could be rejected and that there was a strong degree of association between the two variables *trsloadcat* and *icrp*. The final criteria for intersection condition rating using categorization of the magnitude of truss shoe deformation from loading indicated that a Not satisfactory intersection condition exhibited truss shoe deformation of more than 2 in.

The analysis method for the categorization of intersection condition as Satisfactory or Not satisfactory used the criteria in Table 5.8 for a Satisfactory intersection condition rating.

Table 5.8 Satisfactory Intersection Condition Rating Criteria.

Variable	Criteria
Field Intersection condition rating	Good or Fair
WLM East Mains Standing Support Map rating	Good
Roof fall prior to bolting?	No
Secondary or supplemental in-roof support installed	None

Table 5.8 Continued

Variable	Criteria
Standing supplemental support installed	None
Any large (>0.25-in) tension crack present anywhere in the intersection	None
Tension crack magnitude sum	less than or equal to 3 in
Roof sag	less than or equal to 0.25 ft
Truss shoe deformation	less than or equal to 2 in

The results of the final intersection success rating are summarized in Table 5.9. Figure 5.3 shows the distribution of intersections with Not satisfactory conditions in the EMSA.

Table 5.9 Summary of Intersection Condition Ratings.

Intersection Condition Rating	Frequency Count Intersections	Percent Intersections
Satisfactory	555	62.8
Not satisfactory	329	37.2
Total	884	100.0

5.2 Hypothesis Testing

This section summarizes the results of the tests of the research hypotheses outlined in Section 3.2. Each hypothesis is presented, the PVs used to test the hypothesis against the outcome variable, *icr*, are described, the results of statistical tests of variable significance are discussed, and the validity of the hypothesis is presented. Table 5.10 (page 127) summarizes the nine hypotheses in this research and the related PVs.

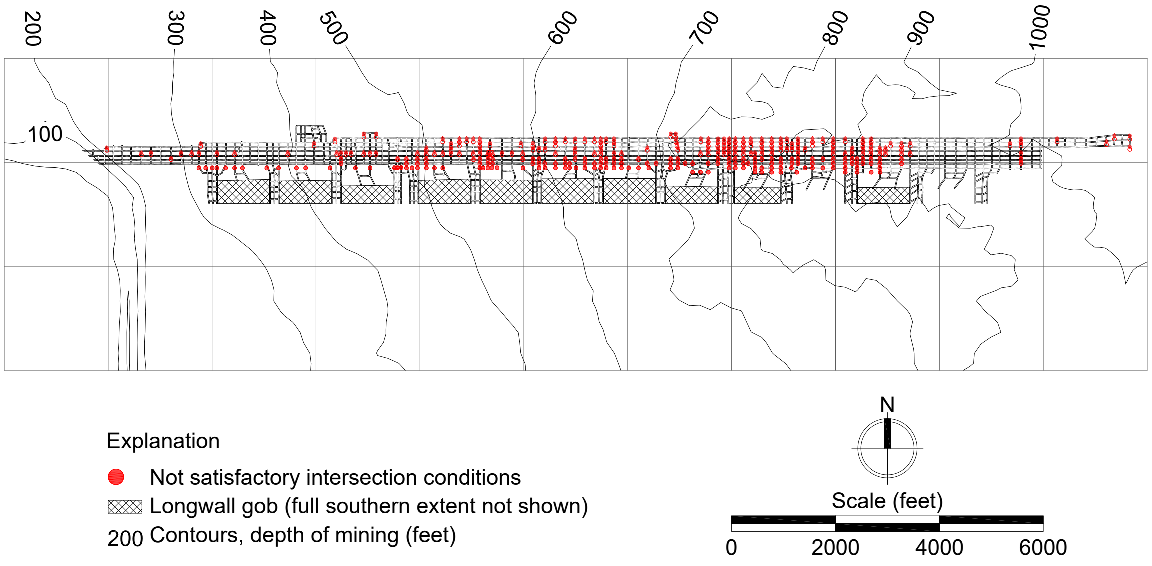


Figure 5.3 Locations of intersections with Not satisfactory condition rating (red dots) within the EMSA.

5.2.1 Depth of mining as a predictor of intersection condition.

Mining depth was hypothesized as a statistically significant predictor of the condition of the intersection. In the EMSA database, mining depth was represented by the variable, _depth_, a continuous numeric variable measured in feet. The following table summarizes the descriptive statistics for _depth_.

Variable	Obs	Unique	Mean	Std.Dev.	Min	Max
depth	884	822	682.0 ft	247.5 ft	104.2 ft	1058.4 ft

Table 5.10 Hypothesis and related testing predictor variables.

Hypothesis **database predictor variables**
Depth of mining is a predictor of intersection condition. *depth*
Geologic structures are predictors of intersection condition. *delam, dome, fault, slicks, ss1, ss2, sspc, ss1margin, ss2margin, sspcmargin*
CMRR of roof is a predictor of intersection condition. *cmrr*
Top coal thickness is a predictor of intersection condition. *rfcoalthk*
Intersection diagonal spans are a predictor of intersection condition. *diagnesw, diagnwse*
$\text{GRSUP}_{\text{ACT}}$ (installed primary, in-roof support) is a predictor of intersection condition. *grsupact*
Longwall stresses are predictors of intersection condition. *lwstress*
Water in roof or floor are predictors of intersection condition. *flwater, rfwater*
Pillar stability factors are predictors of intersection condition. *plrnesf, plrsesf, plrswsf, plrnwsf*

The variable was tested for randomness both visually with a histogram, Figure 5.4, and using the statistical runs test (NIST 2016). The distribution of data shown on Figure 5.4 with unequal counts in the depth categories and the results of the runs test for a random distribution of the *depth* variable ($z = -29.6$, $Pr<0.001$) allowed for rejection of the null hypothesis of randomly distributed data.

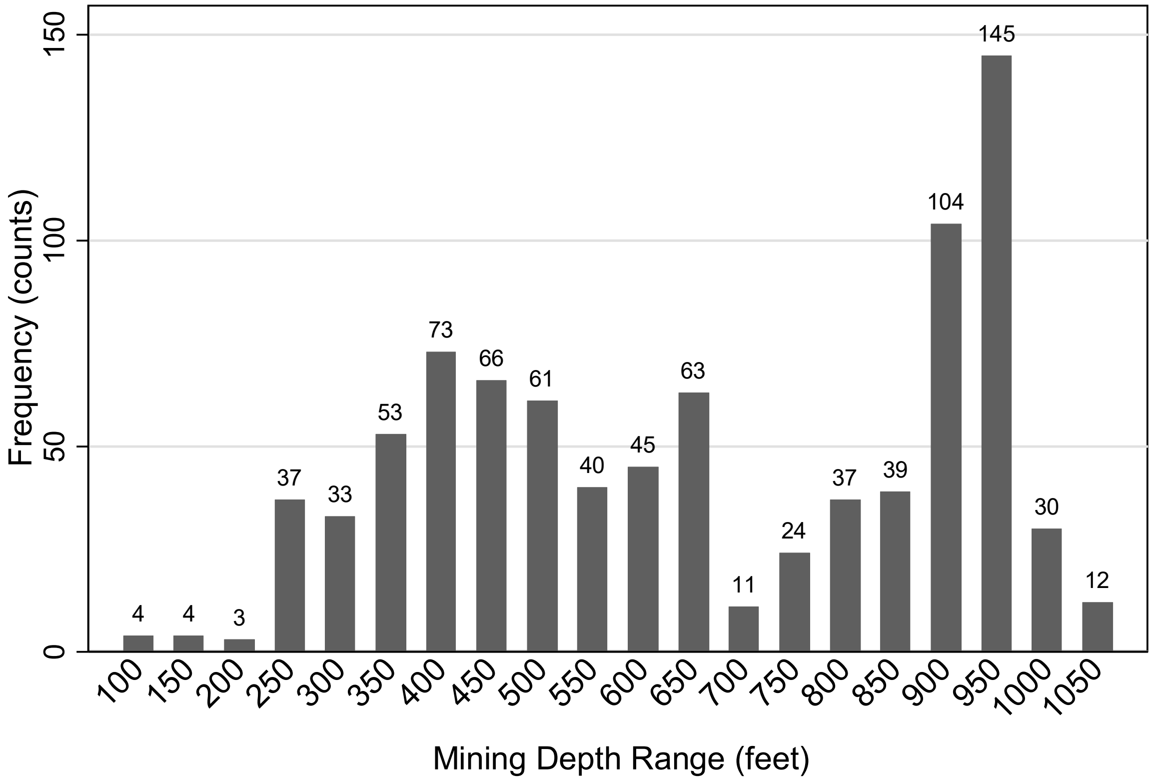


Figure 5.4 Distribution of mining depths. Bars in 50-ft depth increments. The x-axis value labelled 100 represents all depth values ≥100 ft and <150 ft.

The test of the hypothesis of an association between mining depth and intersection condition was tested using logistic regression of *depth* and *icr* and was explored graphically, Figure 5.5. The logistic regression test for association between *depth* and *icr* results (LRchi2(1)=17.3, Pr<0.001, somers'd= −0.134) allowed for rejection of the null hypothesis that *depth* and *icr* were independent and indicated a moderate degree of association. Figure 5.5 illustrates the trend of poorer intersection conditions with increasing depth of mining. In reviewing the deepest intersections shown on Figure 5.5, it must be noted that the deepest intersections represented a mining geometry characterized by 3-entry mains development, with mostly three-way intersections, and with no imposed longwall gob stresses, Figure 5.3 (page 126). Given that this should represent a very stable mining layout; the generally 30%-plus Not satisfactory condition ratings are a concern.

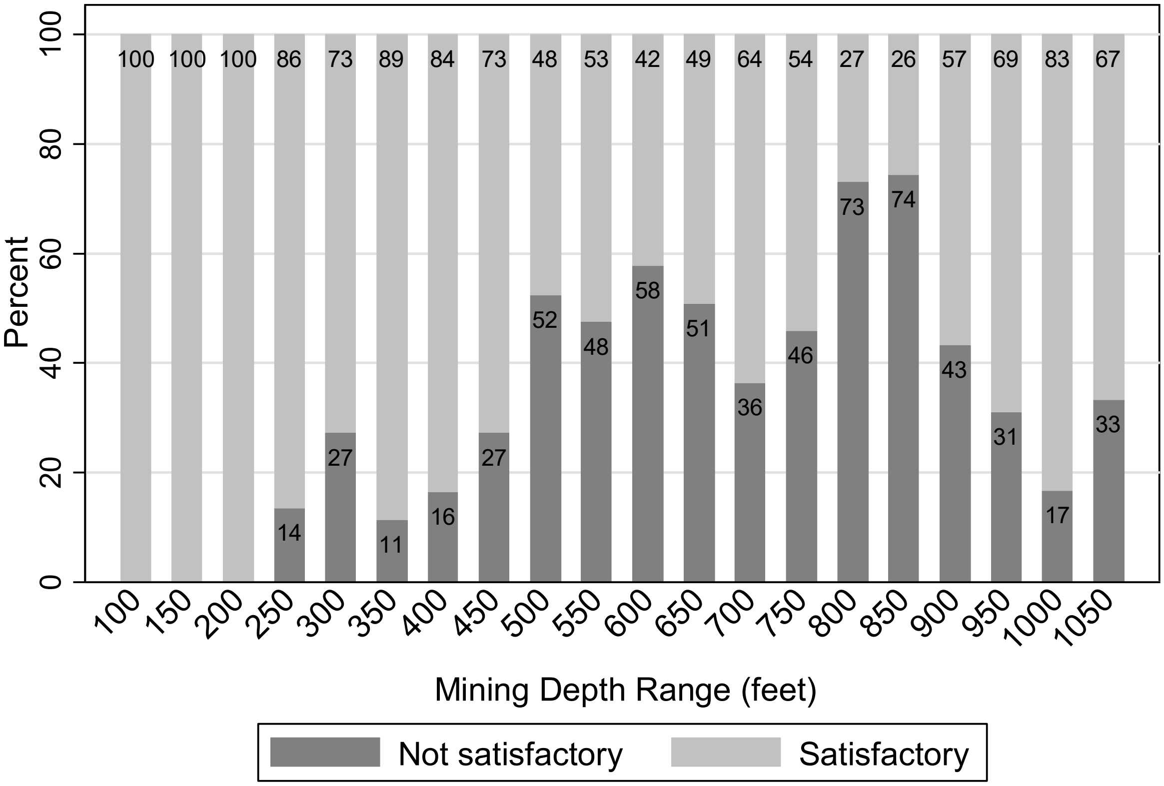


Figure 5.5 Distribution of intersection condition rating by mining depths. Bars in 50-ft depth increments. The x-axis value labelled 100 represents all depth values ≥100 ft and <150 ft. Deepest intersections were not impacted by longwall stress and were three-entry development.

The statistical analysis indicated that there was sufficient strength of the data to reject the null hypothesis of no association between *depth* and *icr*. The hypothesis that depth of mining had an impact on intersection condition was confirmed. The PV *depth* was retained as a PV for the logistic regression model development.

5.2.2 Geologic structures as predictors of intersection condition.

The presence of geologic structures and discontinuities was hypothesized as a statistically significant predictor of the condition of the intersection based both on the literature and experience at the WLM. Field data collection forms, APPENDIX C included notations of any observations of roof or floor faulting, slickensides, evidence of delamination of roof strata, and the existence of doming in the intersection roof. The EMSA database included information from the geologic models of the presence of the identified sandstone channels in the roof, _ss1_ and _ss2_, and in the floor _sspc_, and the projected areas of overbank margin deposits of weak mudstones adjacent to these sandstone channels. Table 5.11 lists the database variables related to geologic discontinuities and sandstone channels in the EMSA database used in the analysis and in the testing of this hypothesis. These variables were reported as binary categorical variables with values of No=0 and Yes=1 indicating absence or presence, respectively, of each geologic feature. APPENDIX A and APPENDIX B provide additional details on these variables.

Table 5.11 Database geologic discontinuities and channel sandstone variable list.

Variables	Value (code)	Frequency	Percent
delam Visible delamination of intersection roof rock?	No (0) Yes (1)	823 61	93.1 6.9
dome Visible doming of roof in intersection?	No (0) Yes (1)	846 38	95.7 4.3
fault Visible fault anywhere in the intersection?	No (0) Yes (1)	854 30	96.6 3.4
slick Slickensides in intersection?	No (0) Yes (1)	879 5	99.4 0.6
_ss1_ SS1 channel sandstone above intersection?	No (0) Yes (1)	747 137	84.5 15.5

Table 5.11 Continued

Variables	Value (code)	Frequency	Percent
ss2 SS2 channel sandstone above intersection?	No (0) Yes (1)	613 271	69.3 30.7
sspc SSPC channel sandstone below intersection?	No (0) Yes (1)	772 112	87.3 12.7
ss1margin SS1 channel margins above intersection?	No (0) Yes (1)	690 194	78.0 22.0
ss2margin SS2 channel margins above intersection?	No (0) Yes (1)	772 112	87.3 12.7
sspcmargin SSPC channel margins below intersection?	No (0) Yes (1)	742 142	83.9 16.1

The statistical analysis looked at three areas, geologic structures (discontinuities), sandstone channels and channel margins. This was because the geologic structure data was based on in-mine observations while the sandstone channel and margin data were based on the geologic models. The sandstone channel model was based on interpretations of widely-spaced drill hole data and the channel margins were inferred from the geologic model of the sandstone channels.

The analysis of observed geologic structures indicated that, in the case of observed slickensides in the intersection roof, the sample sizes of n=5 resulted in too few occurrences of the geologic condition for statistical analysis. In the cases of observed faulting, bedding layer delamination, or doming:

- The sample sizes, while adequate, tended to be small, from 3% to 6% of intersections had identified geologic structures, Table 5.11.

- All one-way tests for variable randomness resulted in values for Pr<0.001 and chi2>0, allowing for rejection of null hypotheses that the variables were randomly distributed.
- All two-way tests for association of each geologic variable with *icr* resulted in all Pr>0.05 and chi2 values very close to zero, which did not allow for rejection of the null hypothesis that the variables were independent.

It was probable that the field teams did not pick up the subtler geologic discontinuities in their inspections. Both teams were composed of mining and geotechnical personnel. Detailed intersection geologic mapping and data did not exist to provide database input. It was interesting that the more obvious geologic discontinuities described by the field teams were not statistically correlated to the intersection condition rating. It is probable that top coal in the roof of an intersection obscured geologic structures in the roof rock. I concluded that the overall weak nature of the intersection roof rock, the moisture sensitivity of the roof mudstone units, and the presence of water were much greater negative factors than the impacts of geologic discontinuities on intersection condition rating in a weak rock environment. Any additional weakness in the intersection roof rock introduced by an observable geologic discontinuity was not statistically significant relative to the very weak nature of the rock units. The PVs *delam*, *dome*, *fault*, and *slick* all were dropped from further analysis.

Experience at the WLM indicated that problem intersections tended to be located under channel sandstone units. All but one of the nine MSHA-reportable roof falls were associated with one or more sandstone channels, Table 5.12. Channel sandstones were projected to cause structural weakening of the surrounding rock mass due to differential compaction and to serve as a source of water from perched water zones within the channel sandstone units.

Table 5.12 Correlation of MSHA-reportable roof falls and channel sandstones.

intno	***msha***	***ss1***	***ss2***	***sspc***
324	Yes	Yes	Yes	No
325	Yes	Yes	Yes	No
332	Yes	No	Yes	No
333	Yes	Yes	Yes	No
373	Yes	No	Yes	No
389	Yes	No	Yes	No
393	Yes	No	Yes	No
533	Yes	No	No	No
570	Yes	No	No	Yes

The sandstone channel PVs all were binary categorical variables. Table 5.11 summarized the variable value measures, the value coding, and the frequency distribution of the variable value measures for the three sandstone channel variables. Table 5.13 (page 134) summarizes the statistical test results for the sandstone channels and the correlations with *icr*.

The channel margin PVs all were binary categorical variables. Table 5.11 (page 130) summarized the variable value measures, the value coding, and the frequency distribution of the variable value measures for the three sandstone channel variables. Table 5.14 summarizes the statistical test results for the channel margins and the correlations with *icr*.

Table 5.13 Statistical test results for correlation of *icr* with sandstone channels.

Variable	One-way test	Two-way test and LR
ss1	Not randomly distributed chi2(1)=420, Pr<0.001	Moderate association with *icr* chi2(1)=24.9, Pr<0.001, gamma=0.509 somers'd=0.125 LRchi2(1)=27.3, Pr<0.001
ss2	Not randomly distributed chi2(1)=132, Pr<0.001	Moderate association with *icr* chi2(1)=29.7, Pr<0.001, gamma= −0.383 somers'd= −0.174 LRchi2(1)=29.2, Pr<0.001
sspc	Not randomly distributed chi2(1)=492, Pr<0.001	Weak association with *icr* chi2(1)=10.2, Pr=0.001, gamma= −0.311 somers'd= −0.074 LRchi2(1)=9.96, Pr=0.002

Table 5.14 Statistical test results for correlation of *icr* with channel margins.

Variable	One-way test	Two-way test and LR
ss1margin	Not randomly distributed chi2(1)=278, Pr<0.001	Weak association with *icr* chi2(1)=8.36, Pr=0.004, gamma=0.249 somers'd=0.083 LRchi2(1)=8.61, Pr=0.003
ss2margin	Not randomly distributed chi2(1)=492, Pr<0.001	Weak association with *icr* chi2(1)=10.2, Pr=0.002, gamma= −0.311 somers'd= −0.074 LRchi2(1)=9.96, Pr=0.002
sspcmargin	Not randomly distributed chi2(1)=407, Pr<0.001	Independent of *icr* chi2(1)=1.83, Pr=0.178, gamma= −0.125 somers'd= −0.034 LRchi2(1)=1.81, Pr=0.178

The statistical analysis indicated that two of the three geologic components hypothesized to impact intersection conditions were not statistically significant; geologic structures and channel margins. Only the presence of sandstone channels provided correlations of sufficient strength to reject the null hypothesis of independence of sandstone channel PVs and *icr*. The hypothesis that geologic structures, sandstone channels and channel margins impacted the intersection condition rating was rejected. However, PVs *ss1*, *ss2*, and *sspc* were retained as PVs for the logistic regression model development.

5.2.3 Coal Mine Roof Rating values as a predictor of intersection condition.

The hypothesis was that the CMRR calculation method was appropriate for defining the strength of the immediate roof in conditions of weak roof rock and deep mining depth. The analysis indicated two issues with the current calculation method (NIOSH 2013b):

- The method always applies the moisture sensitive correction to the immediate roof rock unit.
- The method only applies the moisture sensitive correction to the immediate roof rock unit; but not to other moisture sensitive units in the CMRR calculation interval.

The current NIOSH calculation method always applies the moisture sensitive correction to the first rock unit of the immediate roof. While this is appropriate for the high humidity conditions in the eastern and mid-western US mining areas, I do not believe that it applies to the dry conditions that exist in the western US, especially in intake entries. I modified the calcuation approach to only apply the moisture sensitive correction to intersections located in return airways or along beltlines or in intake airways where roof water was noted as present.

The current calculation method only applies a moisture sensitive correction to the first rock unit in the mine roof. Experience in the EMSA and at other locations in the WLM indicates that where moisture sensitve rocks are present at any distance up into the roof or down into the immediate floor rock and water is present, these moisture sensitive units will be impacted and their strength reduced. I modifed my calculation procedure to reduce the strength of any moisture sensitive rock unit in the bolted interval when data indicated water was or had been present.

The PV *cmrr* was considered statistically significant. It was a continuous numeric variable measured in units from 0 to 100. The following table summarizes the descriptive statistics for *cmrr*.

Variable	**Obs**	**Unique**	**Mean**	**Std.Dev.**	**Min**	**Max**
cmrr	884	203	22.4	5.2	0.9	40.8

The results of the runs test for randomness of the *cmrr* variable (z= −17.1, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The logistic regression test for association between *cmrr* and *icr* results (LRchi2(1)=68.1, Pr<0.001, somers'd=0.329) allowed for rejection of the null hypothesis that *cmrr* and *icr* were independent and indicated they were strongly associated. The hypothesis that CMRR values had an impact on intersection condition was confirmed. The PV *cmrr* was retained as a PV for the logistic regression model development.

5.2.4 Top coal thickness values as a predictor of intersection condition.

The hypothesis was that the thickness of top coal in the roof of the intersection impacted the intersection condition rating. The EMSA database included the PV *rfcoalthk* that provided information on the thickness of the roof coal in an intersection roof measured in feet. The PV *rfcoalthk* was an discrete numerical variable with discrete values measured in feet as shown in column 1 of Table 5.15 which also summarizes the variable value measures, the value coding, and the frequency distribution of the variable value measures. A second PV, *rfcoalcat*, was developed from *rfcoalthk* and used the categories and the associated value codes listed in parentheses in column 1 of Table 5.15 rather than the actual thickness values. The PV *rfcoalcat* was a four-category, ordinal variable.

Table 5.15 Frequency of roof coal thickness ordinal categories.

rfcoalthk **thickness categories (*rfcoalcat* value code)**	**Frequency Count**	**Frequency Percent**	**Cumulative Percent**
None = 0 ft (0)	8	0.90	0.90
Thin = 0.5 ft (1)	566	64.03	64.93
Moderate =1.8 ft (2)	54	6.11	71.04
Mod. Thick = 2.1 ft (3)	256	28.96	100.00
Total	884	100.00	

The one-way table test for randomness of the *rfcoalthk* variable results (chi2(3)=875, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(3)=16.9, Pr<0.001, gamma=0.096, somers'd=0.048) allowed for rejection of the null hypothesis of independence of *icr* and *rfcoalthk* but indicated only a weak association. The PV *rfcoalcat* was used for the logistic regression test for association between *rfcoalcat* and *icr*. The results (LRchi2(2)=12.1, Pr=0.002) allowed for rejection of the null hypothesis that *rfcoalcat* and *icr* are independent but indicated only a weak level of association between the two variables.

Experience in the EMSA indicated that top coal in the 2-ft thickness range did generally improve roof conditions in the absence of water in the roof. The binary categorical PV *topcoal* was created to reflect this condition. The PV *topcoal* categorization and distribution is shown in Table 5.16.

Table 5.16 Frequency of roof coal thickness greater than 2 feet.

Top coal thickness (value code) *topcoal*	**Frequency Count**	**Frequency Percent**	**Cumulative Percent**
<2 ft (0)	628	71.04	71.04
≥2 ft (1)	256	28.96	100.00
Total	884	100.00	

The one-way table test for randomness of the *topcoal* variable results (chi2(1)=156, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(1)=7.02, Pr=0.008, gamma=0.201, somers'd=0.083) and the logistic regression test for association between *topcoal* and *icr* results (LRchi2(1)=7.15, Pr=0.008) allowed for rejection of the null hypothesis that *topcoal* and *icr* were independent and indicated a moderate to moderately strong level of association between the two variables. This result confirmed the experience in the EMSA.

The statistical analysis indicated that there was sufficient strength of the data to reject the null hypothesis of no association between top coal thickness and *icr*. The hypothesis that roof coal thickness impacted intersection was confirmed. The PV *rfcoalthk* was retained as a PV for the logistic regression model development.

5.2.5 Intersection diagonal spans as a predictor of intersection condition.

The hypothesis was that the length of the diagonal spans impacted the intersection condition rating. The literature used the measure of the average sum-of-the-diagonals, or SOD (Molinda et al. 1998; Mark et al. 2001).The EMSA database included three PVs related to intersection diagonal length, *diagnesw*, *diagnwse*, and *diagsod* representing the length of the diagonal from the northeast corner to southwest corner, the length of the diagonal from the northwest corner to the southeast corner, and the average sum-of-the diagonals, respectively. The term corner refers to a corner of the intersection in the indicated compass direction. All three PVs were continuous numeric variables with measures in feet. Table 5.17 summarizes the descriptive statistics for the three PVs. These statistics were calculated only on the three-way and four-way intersections in the EMSA. The nine two-way intersections were not included in the calculations. This resulted in 875 cases in the statistical analyses presented in this section. The data in Table 5.17 indicate that intersection diagonals lengths were an average of 21% longer compared to the design specification for intersection diagonals lengths in the EMSA of 26.2 feet (based on the design entry width of 18.5 feet).

Table 5.17 Descriptive statistics for intersection diagonal predictor variables.

Variable	Obs	Unique	Mean	Std.Dev.	Min	Max
diagsod	875	138	31.7	3.0	24.4	46.5
diagnesw	875	253	31.7	3.5	22.4	46.9
diagnwse	875	251	31.7	3.7	22.4	46.2

The statistical test data in Table 5.18 indicate very little association between *icr* and any of the intersection diagonal measures. This lack of correlation is illustrated in Figure 5.6 which plots *diagsod* versus intersection number, *intno*, and indicates the intersection condition rating. The figure shows no discernable trends in the data.

Two additional PVs based on intersection diagonals were generated and tested. The PV *diagmin* was generated by selecting the minimum length diagonal in each intersection. The PV *diagmax* was generated by selecting the maximum length diagonal in each intersection. Both variables were continuous numeric variables measured in feet. Table 5.19 (page 141) presents the descriptive statistics for *diagmin* and *diagmax*. Table 5.20 (page 142) summarizes the results of the statistical tests of the generated PVs.

Table 5.18 Statistical test results for correlation of *icr* with intersection diagonal length.

Variable	Runs test	Logistic Regression
diagsod	Not randomly distributed z= −5.18, Pr<0.001	Weak association with *icr* LRchi2(1)=3.86, Pr=0.049 somers'd= −0.051
diagnesw	Not randomly distributed z= −5.65, Pr<0.001	Weak association with *icr* LRchi2(1)=5.76, Pr=0.016 somers'd= −0.090
diagnwse	Not randomly distributed z= −4.44, Pr<0.001	Independent of *icr* LRchi2(1)=0.83, Pr=0.363 somers'd= −0.002

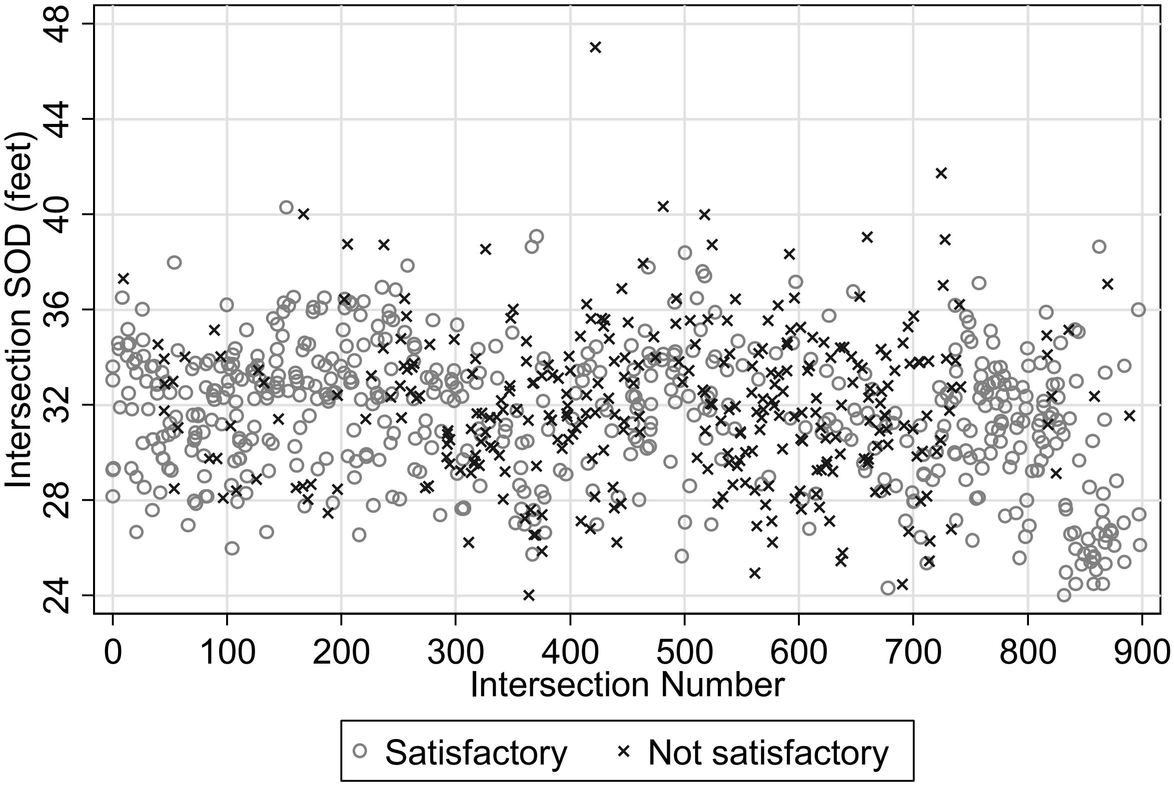


Figure 5.6 Intersection number showing predictor variable *diagsod* and intersection condition rating.

Table 5.19 Descriptive statistics for generated predictor variables *diagmin* and *diagmax*.

Variable	Obs	Unique	Mean	Std.Dev.	Min	Max
diagmin	875	226	30.3	3.0	24.2	46.2
diagmax	875	205	32.9	3.6	24.8	46.2

Table 5.20 Statistical test results for correlation of icr with generated predictor variables diagmin and diagmax.

Variable	Runs test	Logistic Regression
diagmin	Not randomly distributed z= −5.31, Pr<0.001	Independent of icr LRchi2(1)=2.00, Pr=0.157 somers'd= −0.051
diagmax	Not randomly distributed z= −3.97, Pr<0.001	Weak association with icr LRchi2(1)=3.90, Pr=0.048 somers'd= −0.040

The statistical analysis indicated that there was evidence to reject the null hypothesis of no association between intersection diagonal lengths and icr. But the evidence indicated only a weak strength level of association between PVs for intersection diagonal length and icr. The hypothesis that intersection diagonal lengths had an impact on intersection condition was conditionally accepted pending the development of the final logistic regression model. All five PVs related to intersection diagonal lengths were retained for testing in the logistic regression model development.

5.2.6 Primary, in-roof support as a predictor of intersection condition.

The hypothesis was that the density of primary, in-roof support, $\mathrm{GRSUP}_{\mathrm{ACT}}$ as calculated using the GRSUP method (Colwell et al. 2009) was a statistically significant predictor of intersection condition. The GRSUP calculation method for the specification of the primary, in-roof support density was selected rather than the ARBS method (Mark 2000) because the GRSUP method included the support capacity of the roof truss systems that the WLM installed on-cycle during development in the EMSA. Roof trusses were installed on either 4-ft or 2-ft centers in all intersections in the EMSA and on 4-ft to, locally, 2-ft centers, in all entries and crosscuts in the EMSA.

Primary roof support in the EMSA consisted of a 4-bolt per row pattern with roof trusses on 4-ft centers up to intersection 334. Thereafter, a 6-bolt per row pattern with roof trusses on 2-ft centers was adopted. This change occurred at a mining depth of approximately 550 feet and reflected a response to an increase in intersections with Not satisfactory condition ratings. The 4-bolt pattern was characterized by a $\text{GRSUP}_{\text{ACT}}$ value of 19.1 kips/ft (Std.Dev.=2.3 kips/ft) and the 6-bolt pattern was characterized by a $\text{GRSUP}_{\text{ACT}}$ value of 27.4 kips/ft (Std.Dev.=1.4 kips/ft). Figure 5.7 (page 144) illustrates the distribution of $\text{GRSUP}_{\text{ACT}}$ values by intersection number.

The EMSA database included the PV *grsupact*, which represented the calculated $\text{GRSUP}_{\text{ACT}}$ for each intersection in the EMSA. A review of the data indicated that there was not sufficient variability in the $\text{GRSUP}_{\text{ACT}}$ data for a meaningful statistical analysis. The logistic regression results, Table 5.21 (page 144), show that there was a moderate association (somers'd= −0.196) between *icr* and *grsupact*; but, it was a negative association. Higher *grsupact* values were associated with lower probabilities of Satisfactory intersection conditions.

The plot of predicted probabilities of *ic*r based on *grsupact*, Figure 5.8, shows this trend and confirms that *grsupact* was not a reasonable PV of *icr*. For all but the highest values of *grsupact*, the logistic regression equation predicted a better than 50% probability of Satisfactory intersection conditions. The hypothesis that roof support density, as measured by $\text{GRSUP}_{\text{ACT}}$ values, was an indicator of intersection conditions could not be statistically validated. However, because of the importance of roof support to intersection conditions, the PV *grsupact* was included in the logistic regression model development to confirm that, with interactions with other variables, it was not a statistically significant contributor to the multiple-PV model.

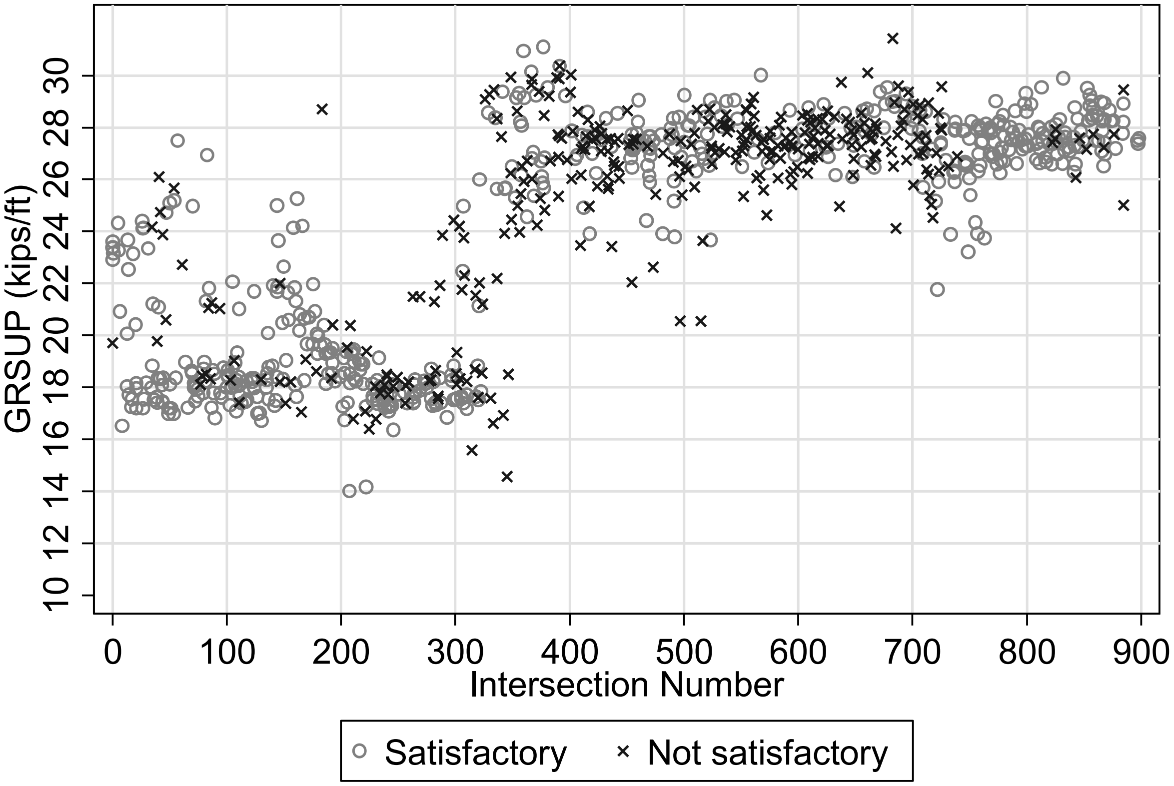


Figure 5.7 Distribution of $GRSUP_{ACT}$ values by intersection number.

Table 5.21 Logistic regression results, ***icr*** and ***grsupact***.

Logistic regression results Number of obs = 884 LR chi2(1) = 34.58 Pr<0.001 Log likelihood = -566.24038 somers'd = −0.196					
Coef.	Std.Err.	z	Pr>z	[95% Conf.Interval]	
grsupact = −.0978564	.0171712	−5.70	<0.001	−.1315113	−.0642015
cons = 2.926589	.4326311	6.76	<0.001	2.078648	3.77453

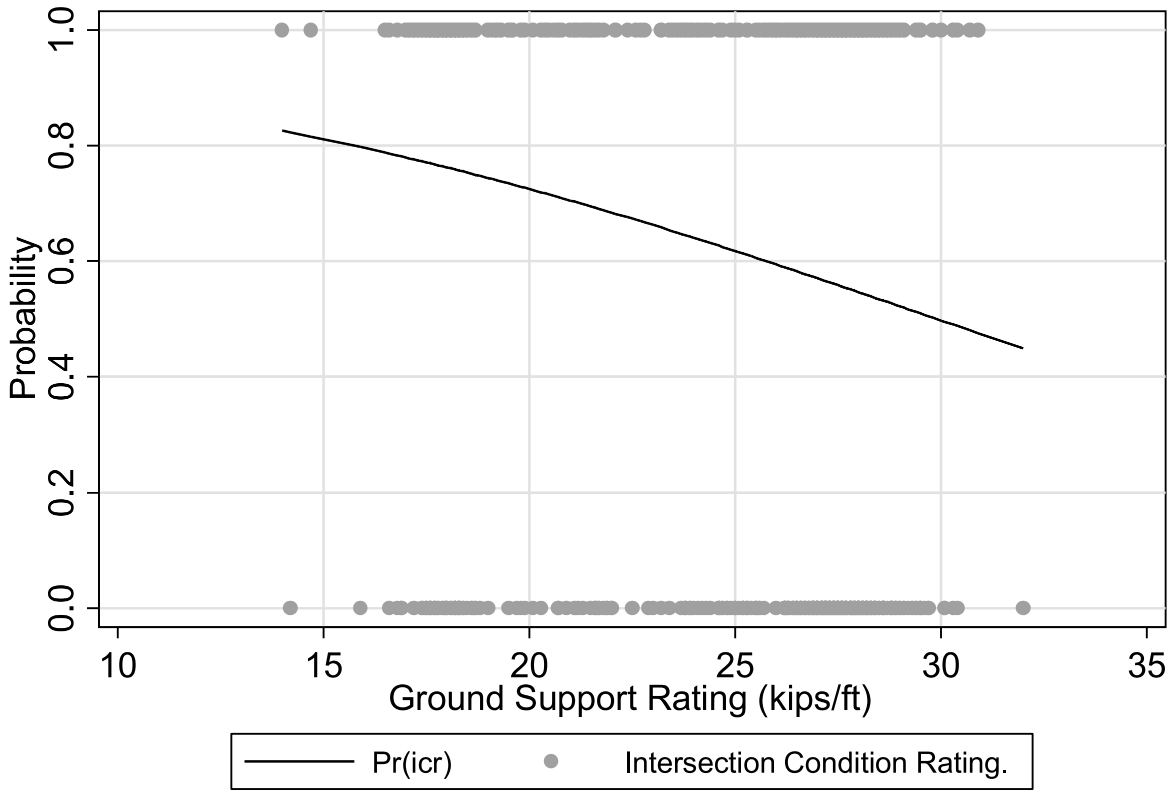


Figure 5.8 Probability of Satisfactory (Pr(*icr*)=1) intersection conditions based on $GRSUP_{ACT}$ value.

5.2.7 Transferred stresses from adjacent longwall mining areas as a predictor of intersection condition.

The hypothesis was that the stresses from adjacent longwall gobs negatively impacted intersection conditions. The EMSA database included the PV *lwstress* that was developed to measure the estimated impact of stresses from adjacent longwall gobs on intersection conditions. The initial categorization values for *lwstress* are described in Table 5.22. Summaries of the variable value measures, the value coding, and the frequency distribution of the variable value measures are presented in Table 5.23.

The one-way table test for randomness of the *lwstress* variable results (chi2(4)=653, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(4)=112, Pr<0.001, gamma= −0.542, somers'd= −0.389) and the logistic regression test for association between *lwstress* and *icr* results (LRchi2(1)=99.8, Pr<0.001) allowed for rejection of the null hypothesis that *lwstress* and *icr* were independent and indicated a strong level of association between the two variables. The plot of predicted probabilities of *icr* based on *lwstress*, Figure 5.9, illustrates the strength of this relationship.

Because of the low frequency count, 10 cases, for the *lwstress* level of Very high, Table 5.23, the variable was recategorized by combining the High and Very high categories to create the variable *lwstress2*. The logistic regression test for association between *lwstress2* and *icr* results (LRchi2(1)=101.7, Pr<0.001) allowed for rejection of the null hypothesis that *lwstress2* and *icr* were independent and indicated a strong level of association between the two variables. The PV *lwstress2* was retained as a PV for the logistic regression model development.

Table 5.22 Longwall stress categories.

Variable value label (Value code)	Description
None (0)	All longwall gobs at a horizontal distance from the intersection of the lessor of: 1000 ft, or >depth of the intersection.
Low (1)	One longwall gob at a horizontal distance from the intersection of the lessor of: 1000 ft, or ≤depth of the intersection.

Table 5.22 Continued

Variable value label (Value code)	Description
Moderate (2)	Two longwall gobs, both at horizontal distances from the intersection of the lessor of: 1000 ft, or ≤depth of the intersection.
High (3)	Two longwall gobs. One at a horizontal distance from the intersection of the lessor of: 500 ft, or ≤0.5•depth of the intersection. One at a horizontal distance from the intersection of the lessor of: 1000 ft, or ≤depth of the intersection.
Very high (4)	Two longwall gobs, both at a horizontal distance from the intersection of the lessor of: 500 ft, or ≤0.5•depth of the intersection.

Table 5.23 Frequency of longwall stress impacts.

Longwall stress level (Value code)	Frequency Count	Frequency Percent	Cumulative Percent
None (0)	422	47.74	47.74
Low (1)	256	28.96	76.70
Moderate (2)	165	18.67	95.36
High (3)	31	3.51	98.87
Very high (4)	10	1.13	100.00
Total	884	100.00	

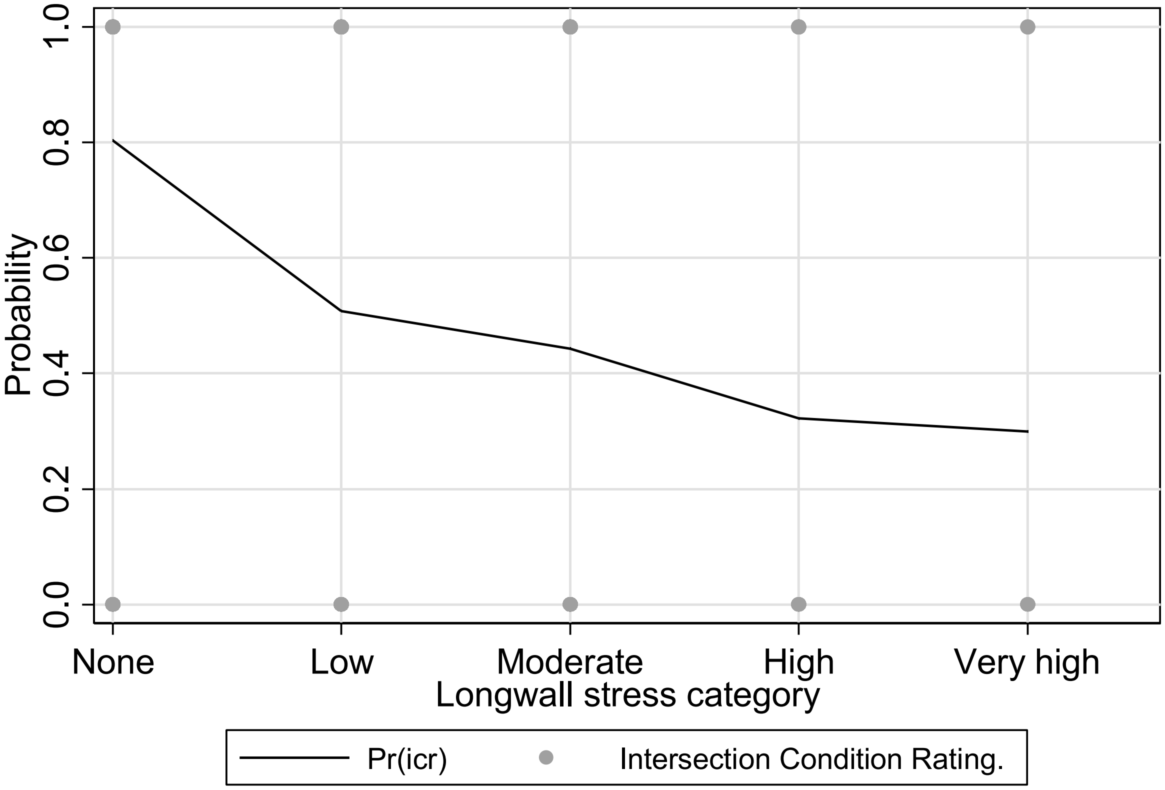


Figure 5.9 Probability of Satisfactory (Pr(*icr*)=1) intersection conditions based on predictor variable *lwstress* value.

5.2.8 Roof or floor water as a predictor of intersection condition.

The hypothesis was that the presence of water in the intersection roof or floor rock strata was a significant predictor of the intersection condition rating. This water could be introduced by geologic or geohydrologic variables or by mine operations processes such as belt line water, return airway moisture, etc. The EMSA database included two variables related to the presence of roof or floor water, *rfwater* and *flwater*.

The PV *rfwater* was an ordinal, categorical variable as shown in column 1 of Table 5.24 which also summarizes the variable value measures, the value coding, and the frequency distribution of the variable value measures.

Table 5.24 Frequency of roof water condition as four categories.

Roof water condition categories (value code)	**Frequency Count**	**Frequency Percent**	**Cumulative Percent**
Dry (0)	176	19.91	19.91
Damp (1)	578	65.38	85.29
Light drip (2)	50	5.66	90.95
Heavy drip (3)	80	9.05	100.00
Total	884	100.00	

The one-way table test for randomness of the *rfwater* variable results (chi2(3)=808, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(3)=174, Pr<0.001, gamma=0.507, somers'd=0.300) and the logistic regression test for association between *rfwater* and *icr* results (LRchi2(3)=191, Pr<0.001) allowed for rejection of the null hypothesis that *rfwater* and *icr* were independent and indicated a strong level of association between the two variables.

The logistic regression results, Table 5.25, indicated that the *rfwater* category "damp" was not statistically significant (Pr=0.383). The tabulation of *icr* and *rfwater* indicated that over 72% of the intersections categorized as "damp" had satisfactory conditions, Table 5.26. The plot of predicted probabilities of *icr* based on *rfwater*, Figure 5.10, indicated that the "damp" category of *rfwater* was not a good predictor of *icr*.

The PV *rfwater* was simplified and re-categorized as a binary categorical variable *rfdry*. The PV *rfdry* was coded as Yes (=1) when *rfwater* was either "Dry" or "Damp" and No (=0) when *rfwater* was "Light drip", "Heavy drip", or "Flowing" (no intersection was categorized with flowing water conditions in the database). Table 5.27 (page 152) presents the category counts and percentages for PV *rfdry*. The logistic regression results (LRchi2(1)=162, Pr<0.001, somers'd=0.312) indicated a strong association between *icr* and *rfdry*. The probability distribution, Figure 5.11 (page 153), confirmed that *rfdry* was a very good representation to use in the development of the logistic regression model.

The PV *flwater* was evaluated to determine its statistical significance as a predictor of intersection condition. It was an ordinal, categorical variable developed to measure the amount of water, if any, observed on the floor of the intersection.
Table 5.28 (page 153) summarizes the variable value measures, the value coding, and the frequency distribution of the variable value measures.

Table 5.25 Logistic regression results, *icr* and *rfwater*.

Logistic regression results
Number of obs = 884
LR chi2(1) = 191.14
Pr<0.001
Log likelihood = −487.961
somers’d = −0.300

rfwater	Coef	Std.Err.	z	Pr>z	[95% Conf.Interval]	
Damp	.163	.187	0.87	0.383	−.203	.530
Light drip	−1.542	.344	−4.48	0.000	−2.216	−.867
Heavy drip	−5.157	1.019	−5.06	0.000	−7.155	−3.159
_cons	.788	.162	4.85	0.000	.469	1.107

Table 5.26 Two-way tabulation of *icr* and *rfwater*.

	Roof water flow rating				
Intersection Condition Rating	**Dry Count / Percent**	**Damp Count / Percent**	**Light drip Count / Percent**	**Heavy drip Count / Percent**	**Total Count / Percent**
Not satisfactory	55 31.2%	161 27.8%	34 68.0%	79 98.8%	329 37.2%
Satisfactory	121 68.8%	417 72.2%	16 32.0%	1 1.2%	555 62.8%
Total	176 100.0%	578 100.0%	50 100.0%	80 100.0%	884 100.0%

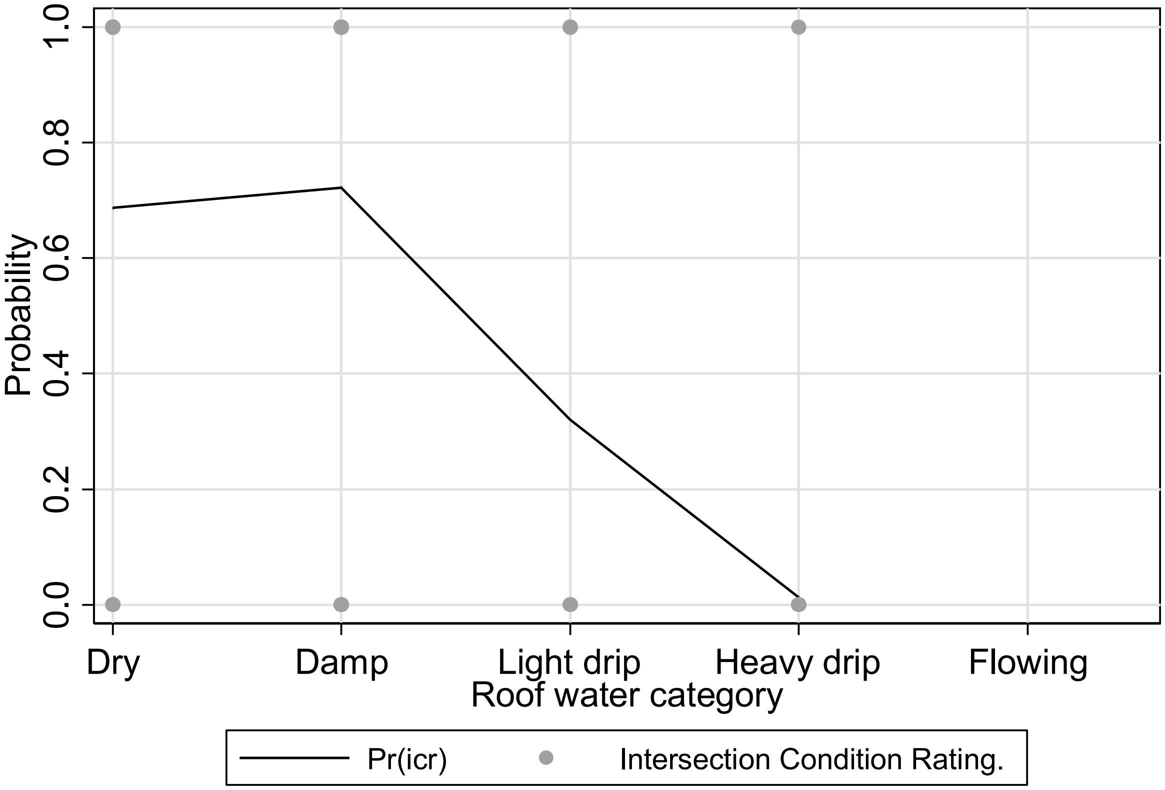


Figure 5.10 Probability of Satisfactory (Pr(*icr*)=1) intersection conditions based on predictor variable *rfwater* value.

Table 5.27 Frequency of roof dry condition categories.

Roof dry condition categories (value code)	Frequency Count	Frequency Percent	Cumulative Percent
No (0)	130	14.7	14.7
Yes (1)	754	85.3	100.0
Total	884	100.0	

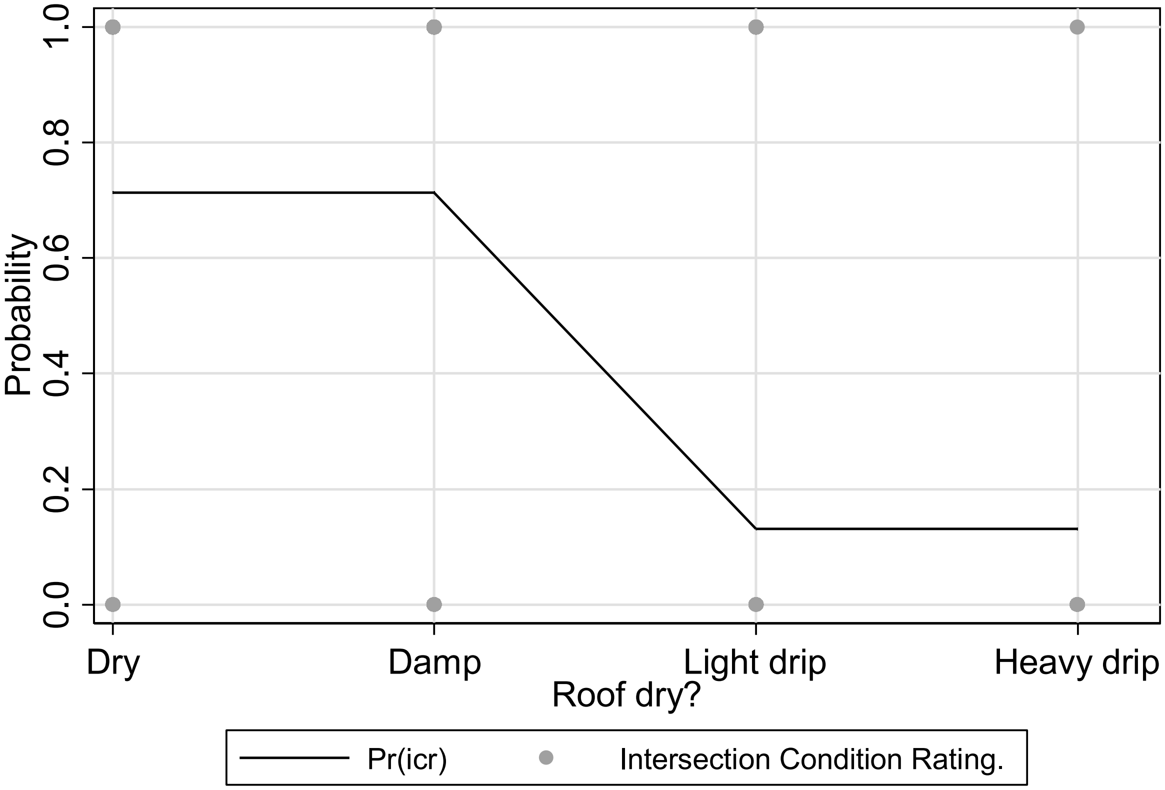


Figure 5.11 Probability of Satisfactory (Pr=1) intersection conditions based on predictor variable *rfdry* values.

Table 5.28 Frequency of floor water rating.

Floor water flow rating (Value code)	Frequency Count	Frequency Percent	Cumulative Percent
Dry (0)	448	50.68	50.68
Damp (1)	313	35.41	86.09
Wet (2)	70	7.92	94.00
Standing water (2)	41	4.64	98.64
Flooded (4)	12	1.36	100.00
Total	884	100.00	

The results of the one-way table test for randomness of the *flwater* variable (chi2(4)=843, Pr<0.001) allowed for rejection of the null hypothesis of randomly distributed data. The two-way table test of association results (chi2(3)=9.92, Pr=0.042, gamma= −0.166, somers'd= −0.103) and the logistic regression test for association between *flwater* and *icr* results (LRchi2(1)=9.32, Pr=0.002) allowed for rejection of the null hypothesis that *flwater* and *icr* are independent but indicated a weak level of association between the two variables. Re-categorization of the PV *flwater* as different combinations of categories confirmed the weak level of association between *icr* and *flwater*. The PV *flwater* was dropped from further analyses because the presence of floor water in any amount did not provide a statistically significant prediction of intersection condition.

The statistical analysis indicated that there was sufficient strength of the data to reject the null hypothesis of no association between *rfwater* and *icr*. The hypothesis that presence of roof water would have an impact on intersection condition was confirmed. The existence or evidence of water flow through the roof rock strata (i.e., *rfwater* database categories of light or heavy dripping), correlated well with Not satisfactory intersection conditions while dry or damp conditions correlated well with Satisfactory intersection conditions. The PV *rfwater* was re-categorized as the PV *rfdry*, indicating No (=0) for *rfwater* categories of dripping (flowing conditions also would be included in the No category) and Yes (=1) for *rfwater* categories of dry or damp. The PV *rfdry* was used as input into the logistic regression model development.

5.2.9 Pillar stability factors as a predictor of intersection condition.

The hypothesis was that the stability factors of pillars adjacent to an intersection were a significant predictor of the intersection condition rating. Pillar stability factors were calculated using the Mark-Bieniawski pillar strength formula (Mark et al. 1997) and tributary overburden loading. The theory was that a pillar that with a low stability factor resulting from its development geometry would be less stable and impact intersection conditions over time. Low stability factors also would be more impacted by any future mining-induced stresses. The PVs *plrnesf*, *plrsesf*, *plrswsf*, and *plrnwsf* were numeric variables that represented the calculated development stability factors for the pillars located to the northeast, southeast, southwest and northwest, respectively, of the intersection. Directions indicate compass direction relative to the intersection. Where an adjacent pillar was a barrier pillar, a stability factor of two was assigned to the barrier pillar. Development stability factors were calculated using the Mark-Bieniawski pillar strength formula (Mark et al. 1997) and overburden tributary area loading using depth and an overburden density of 150 lb/cu.ft. These PVs were used to create other PVs for statistical testing of the hypothesis. These created PVs were:

- *plrsum*. The sum of all the stability factors for pillars adjacent to an intersection.
- *plravg*. The average stability factor from the pillars adjacent to an intersection.
- *plrmin*. The minimum stability factor for the pillars adjacent to an intersection.

- *plrmax*. The maximum stability factor for the pillars adjacent to an intersection

All these PVs were continuous, numeric variables measured in units. Table 5.29 summarizes the descriptive statistics for these PVs.

Table 5.29 Descriptive statistics for pillar predictive variables.

Variable	**Obs**	**Unique**	**Mean**	**Std.Dev.**	**Min**	**Max**
plrnesf	884	30	1.3	0.6	0.6	4.1
plrsesf	884	32	1.2	0.5	0.6	4.6
plrswsf	884	32	1.2	0.6	0.6	4.6
plrnwsf	884	32	1.3	0.6	0.6	4.6
plrsum	884	164	4.9	2.1	2.6	17.7
plravg	884	164	1.2	0.5	0.6	4.4
plrmin	884	26	1.1	0.5	0.6	4.1
plrmax	884	31	1.4	0.6	0.7	4.6

The statistical analysis indicated that none of the PVs related to development stability factor was a randomly distributed variable. The logistic regression test results indicated moderate to moderately strong association between all the PVs and *icr*. The PV *plrmin* was the best fit PV with logistic regression results (LRchi2(1)=49.4, Pr<0.001, somers'd=0.204) indicated a moderately strong association between *icr* and *plrmin*. The statistical analysis indicated that there was sufficient strength of the data to reject the null hypothesis of no association between *plrmin* and *icr*. The hypothesis that the development stability factor had an impact on intersection condition was confirmed. The PV *plrmin* was retained as a PV for the logistic regression model development.

5.2.10 Hypothesis testing results.

The tests of the statistical validity of the nine hypotheses resulted in acceptance of five hypotheses as proposed and modification of three hypotheses. One hypothesis was dropped because there was insufficient variability in the data to statistically test and evaluate the hypothesis. Table 5.30 summarizes the results of the hypothesis tests.

Table 5.30 Summary of hypothesis testing results.

Hypothesis database predictor variables	**Status variables to test**
Depth of mining is a predictor of intersection condition. *depth*	Accepted hypothesis. Statistically significant; included in LR model development. *depth*
Geologic structures are predictors of intersection condition. 1. Discontinuities *delam*, *dome*, *fault*, *slicks* 2. Sandstone channels *ss1*, *ss2*, *sspc* 3. Channel margins *ss1margin*, *ss2margin*, *sspcmargin*	Modified significantly as follows for use in LR model development: 1. Geologic structures not statistically significant. Dropped from LR model analysis. 2. Sandstone channels weakly statistically significant and PVs *ss1*, *ss2*, and *sspc* included in LR model development. 3. Channel margins not statistically significant. Dropped from LR model analysis. *ss1*, *ss2*, *sspc*
CMRR of roof is a predictor of intersection condition. *cmrr*	Accepted hypothesis. Statistically significant; included in LR model development. *cmrr*
Top coal thickness is a predictor of intersection condition. *rfcoalthk*	Accepted hypothesis. Statistically significant; included in LR model development. *rfcoalthk*

Table 5.30 Continued

Hypothesis **database predictor variables**	**Status** **variables to test**
Intersection diagonal spans are a predictor of intersection condition. *diagnesw, diagnwse*, *diagsod*	Accepted hypothesis. Insufficient evidence to strongly accept the hypothesis as true. However, PV *diagsod* included in LR model development. *diagsod*
GRSUP (installed primary, in-roof support) is a predictor of intersection condition. *grsupact*	Dropped hypothesis. Insufficient evidence to accept the hypotheses due to insufficient range of available data. Included in initial LR model development for confirmation. *grsupact*
Longwall stresses are predictors of intersection condition. *lwstress*	Accepted hypothesis. Statistically significant, modified five-category *lwstress* to four-category PV, *lwstress2* for use LR model development. *lwstress2*
Water in roof or floor are predictors of intersection condition. *flwater, rfwater*	Modified hypothesis. Dropped *flwater*. Modified *rfwater* to a new PV *rfdry* for use in LR model development. *rfdry*
Pillar stability factors are predictors of intersection condition. *plrnesf, plrsesf, plrswsf, plrnwsf*	Modified hypothesis. Statistically significant with modified PV, *plrmin*

5.3 Logistic Model Development

This section describes the results of the logistic model (LR) development process. The LR model development process was described in Section 4.9 and the process was diagramed on Figure 4.5. The initial Full Model is defined in terms of the outcome variable and the PVs selected to populate the Full Model. The results of the iterative process used to derive the Main Model are tabulated. The resulting Main Model is presented. The results of the iterative process of testing the completeness of the Main Model are tabulated using the methods and recommendations of Hosmer et al. (2013)

and as described in Section 4.9. The resultant, derived, Predictive Model is presented. This section concludes with a discussion of the classification power of the Predictive Model using the AUC/ROC process and criteria presented in Section 4.9.

All models in this analysis used the Intersection Condition Rating, *icr*, as the model outcome variable. The *icr* was a binary categorical variable representing intersection condition as either Not satisfactory (*icr*=0) or Satisfactory (*icr*=1).

The PVs included in the Full Model were selected on the basis of the exploratory data analysis, the results of the hypothesis testing, experience at the WLM, and engineering judgement. Agresti (2007) presented a guideline for the number of PVs to be used in an analysis; there should be 10 outcomes of each type for every PV included in the model. Using the ratio of 1:10 and the total of 329 unsuccessful intersections out of a total of 884 intersections resulted in the need to limit the maximum allowable number of model PVs to 32 (=329/10). Eleven PVs were selected to populate the Full Model, Table 5.31. The Full Model was assigned the model ID, fullmodel00. Table 5.32 is a screen capture of the output of the Stata statistical software results for the logistic regression of fullmodel00. The Full Model was characterized by an AIC=903.9, a BIC=970.9, and an AUC/ROC=0.8149. Figure 5.12 illustrates the AUC/ROC graph for the Full Model.

Table 5.31 Predictor variables used in Full Model.

Model ID	**Notes**	**Model PVs**
fullmodel00	Full Model	*depth*, *cmrr*, *rfcoalthk*, *grsupact*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1*, *ss2*, *sspc*

Table 5.32 Logistic regression output for the Full Model.

```
. //fullmodel00 Logistic regression
. //FULL MODEL
. logit icr c.depth c.cmrr c.rfcoalthk c.grsupact c.diagsod c.plrmin ///
>         i.lwstress2 i.rfdry i.ss1 i.ss2 i.sspc, level(95) nolog allbase

Logistic regression                             Number of obs     =        884
                                                LR chi2(13)       =     291.16
                                                Prob > chi2       =     0.0000
Log likelihood = -437.94958                     Pseudo R2         =     0.2495

------------------------------------------------------------------------------
         icr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       depth |   .0022904   .0012908     1.77   0.076    -.0002394    .0048203
        cmrr |   .0581782   .0202846     2.87   0.004     .0184212    .0979352
   rfcoalthk |   .5582829   .2000955     2.79   0.005     .1661029    .9504628
    grsupact |  -.0570978   .0346437    -1.65   0.099    -.1249983    .0108026
     diagsod |  -.0670409   .0290257    -2.31   0.021    -.1239301   -.0101516
      plrmin |   2.043307   .5839841     3.50   0.000      .898719    3.187894
             |
   lwstress2 |
       None  |          0  (base)
        Low  |  -.6369337   .2209709    -2.88   0.004    -1.070029   -.2038386
   Moderate  |  -.6443387   .2570194    -2.51   0.012    -1.148088   -.1405898
       High  |  -1.004841    .461372    -2.18   0.029    -1.909113    -.100568
             |
       rfdry |
         No  |          0  (base)
        Yes  |   2.400081   .3333568     7.20   0.000     1.746713    3.053448
             |
         ss1 |
         No  |          0  (base)
        Yes  |    .716384   .2926539     2.45   0.014     .1427929    1.289975
             |
         ss2 |
         No  |          0  (base)
        Yes  |   .0957197   .2146009     0.45   0.656    -.3248904    .5163298
             |
        sspc |
         No  |          0  (base)
        Yes  |  -.2785262   .2551229    -1.09   0.275    -.7785579    .2215055
             |
       _cons |   -3.32526   1.649104    -2.02   0.044    -6.557444   -.0930758
------------------------------------------------------------------------------

. lroc, nograph

Logistic model for icr

number of observations =      884
area under ROC curve   =   0.8149
```

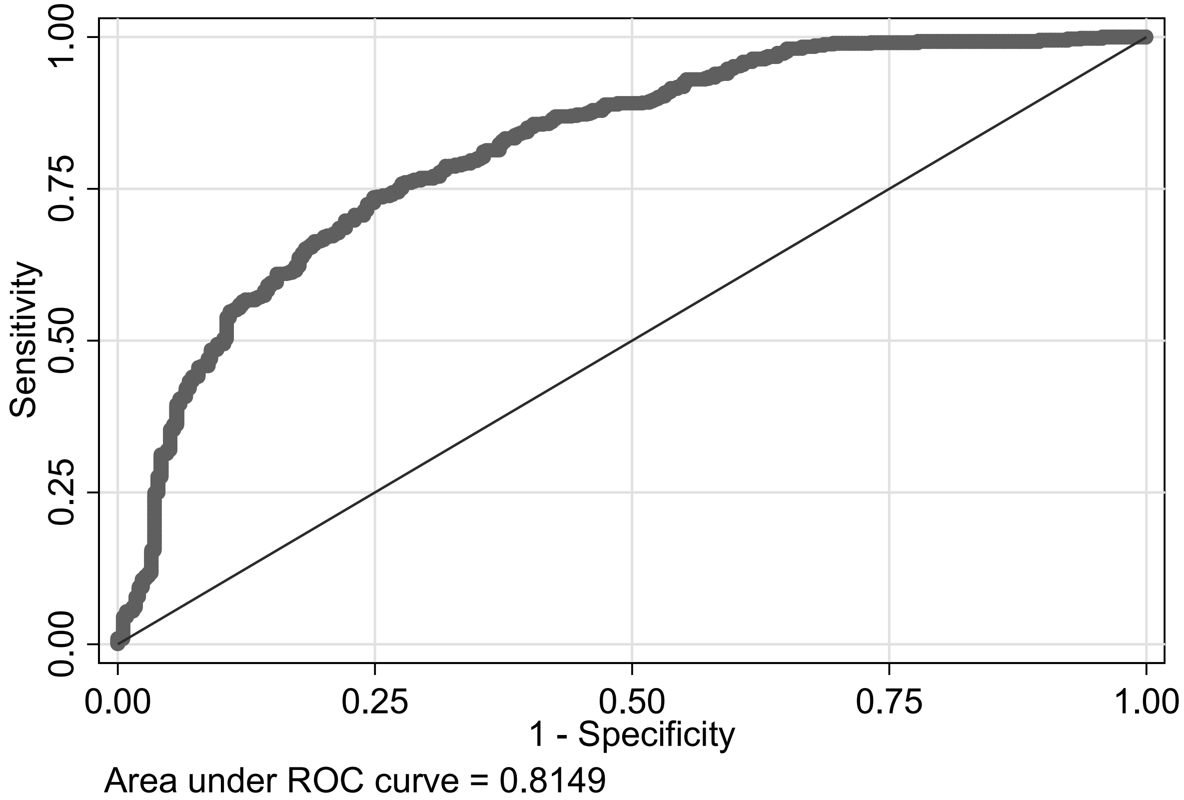


Figure 5.12 Logistic regression AUC/ROC output for the Full Model.

A review of the statistical software output presented in Table 5.32 (page 160) begins with the overall model results. The results (LRchi2(13)= 291, Pr<0.001) allow for the rejection of the null hypothesis that all the coefficients of all the PVs=0. The result (AUC/ROC=0.8149) indicated that the model, as specified, has "excellent" classification (Section 4.9) in terms of prediction of outcomes (Hosmer et al. 2013). Both results indicate that the model, as specified and populated with PVs, was a logical and statistically valid first effort.

The next step in the process was to review the individual PV results. An example of this reviewing process is described using the PV *depth* and resulted in the following observations:

- Coef is the coefficient of the variable. The coefficient represents the rate of change in *icr* due to a one-unit change in the PV value. Because depth is a variable with a range from approximately 100 to 1050 ft, a 1-ft change in depth has a very small impact in changing the value of *icr*.
- The sign of Coef is positive. This is counterintuitive as it was expected that increasing depth would result in a lower *icr* value.
- Std.Err is the standard error. It is used to test if the coefficient value is significantly different from zero. It is used to calculate the z-statistic and the resulting Pr value listed in the output. Added to and subtracted from the coefficient value, it defines the confidence limits listed in the output.
- The z value is obtained by dividing Coef by the Std.Err.
- P>|z| is the probability used to test the null hypothesis that the coefficient value is zero. At the 95% confidence level used in this study, a Pr<0.05 is required to reject the null hypothesis. That is not the case with this result (Pr=0.076). It is a statistical probability that, in this model, the value of the coefficient for the variable *depth* is equal to zero.
- 95% Conf. Interval represents the 95% confidence interval. The fact that the interval includes zero is cause for concern.

The PV *depth* is an important parameter so it was left in the model to see how it behaves with other PV changes. It was decided to delete the PV *sspc* to create the next model to be tested, model01. The PV *sspc* was dropped because its Pr=0.275 and, in the hypothesis testing, Section 5.2.2, Table 5.13 (page 134), *sspc* had only a weak association with *icr*.

Table 5.33 summarizes the five major LR models tested to arrive at the Main Model. The table shows the major steps in the iterative LR modeling process. There were many other LR model runs performed in developing each major model to test the impact of modifying or dropping a variable.

Table 5.33 Logistic regression model PVs.

Model ID	Notes	Model PVs
fullmodel00	Full Model	*depth*, *cmrr*, *rfcoalthk*, *grsupact*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1*, *ss2*, *sspc*
model01	Dropped *sspc*	*depth*, *cmrr*, *rfcoalthk*, *grsupact*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1*, *ss2*
model02	Dropped *ss2*	*depth*, *cmrr*, *rfcoalthk*, *grsupact*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1*
model03	Dropped *grsupact*	*depth*, *cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1*
model04	Dropped *depth*	cmrr, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1*
model05	Dropped *ss1*	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*

The results of the model runs used to develop the Main Model are tabulated in Table 5.34. All the models resulted in values of the model LRchi2, Pr<0.001 allowing for rejection of the null hypothesis that all the coefficients in each of the models were simultaneously zero.

Table 5.34 Logistic regression model output results.

Model ID	AIC	BIC	∆BICn−BIC00	AUC/ROC
fullmodel00 Full Model	903.9	970.9	NA	0.8149
model01	903.1	965.3	-5.6	0.8138
model02	901.7	959.1	-11.8	0.8138
model03	902.3	955.0	-15.9	0.8140
model04	901.5	949.3	-21.6	0.8124
model05 Main Model	906.2	949.2	-21.7	0.8051

The Main Model included five PVs, Table 5.35. Table 5.36 (page 165) is a screen capture of the output of the Stata statistical software results for model05. The Main Model was characterized by AIC=906.2 and BIC=949.2. The difference in the BIC values between the Full Model and the Main Model was −21.7, which provided very strong support for the Main Model (Table 4.7, page 104). The Main Model AUC/ROC=0.8051. Figure 5.13 (page 166) illustrates the AUC/ROC graph for the Main Model.

Table 5.35 Predictor variables used in Main Model.

Model ID	Notes	Model PVs
model05	Main Model	*cmrr*, *rfcoalthk*, *diagsod*, *lwstress2*, *rfdry*

Table 5.36 Logistic regression output for the Main Model.

```
. //model05
. //drop ss1
. logit icr c.cmrr c.rfcoalthk c.diagsod c.plrmin ///
>         i.lwstress2 i.rfdry, level(95) nolog allbase

Logistic regression                             Number of obs     =        884
                                                LR chi2(8)        =     278.89
                                                Prob > chi2       =     0.0000
Log likelihood =  -444.0855                     Pseudo R2         =     0.2390

------------------------------------------------------------------------------
         icr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        cmrr |   .0596914   .0196906     3.03   0.002     .0210985    .0982843
   rfcoalthk |   .7729611   .1519003     5.09   0.000      .475242     1.07068
     diagsod |  -.0605483   .0282879    -2.14   0.032    -.1159916   -.0051049
      plrmin |   1.627431   .3214741     5.06   0.000     .9973529    2.257508
             |
   lwstress2 |
       None  |          0  (base)
        Low  |  -.7267348   .2117033    -3.43   0.001    -1.141666   -.3118039
   Moderate  |  -.7790492   .2509351    -3.10   0.002    -1.270873   -.2872253
       High  |  -1.143801   .4398867    -2.60   0.009    -2.005963   -.2816386
             |
       rfdry |
         No  |          0  (base)
        Yes  |   2.305863   .3285775     7.02   0.000     1.661863    2.949863
             |
       _cons |  -2.935756   1.048673    -2.80   0.005    -4.991118   -.8803942
------------------------------------------------------------------------------

. lroc, nograph

Logistic model for icr

number of observations =      884
area under ROC curve   =   0.8051
```

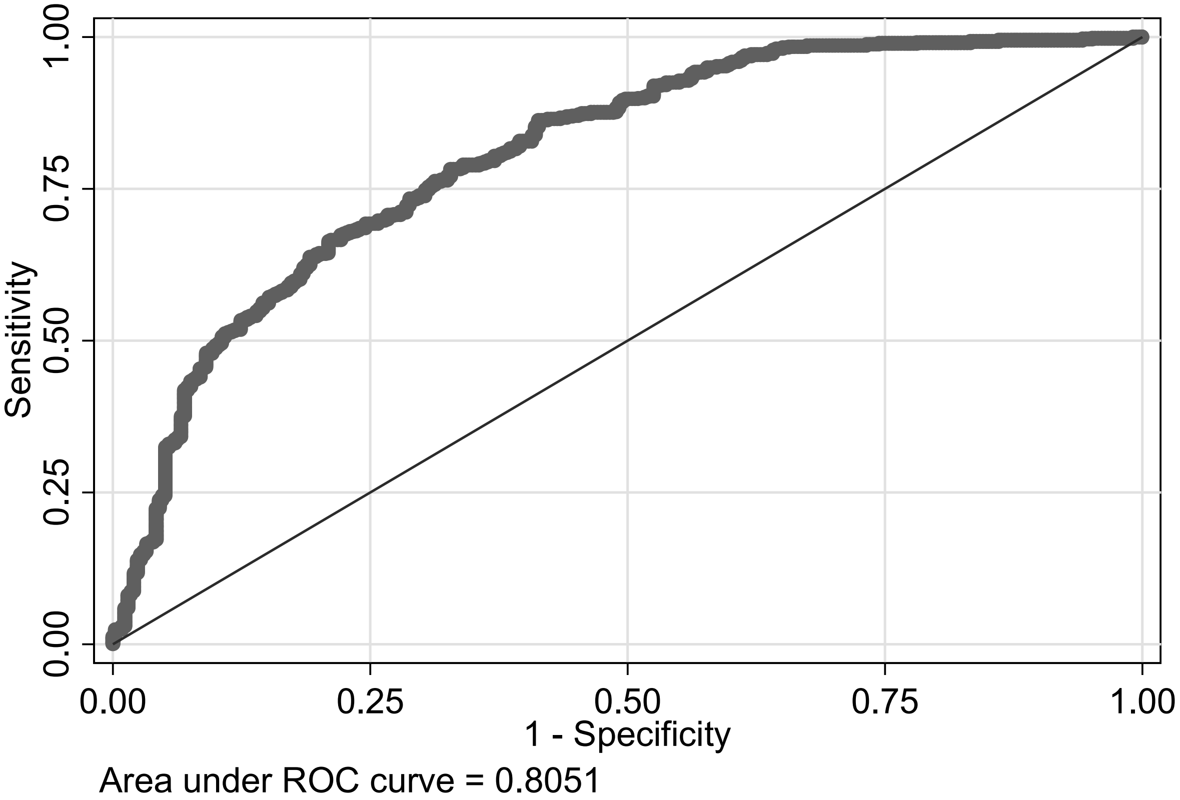


Figure 5.13 Logistic regression AUC/ROC output for the Main Model.

The derivation of the Main Model from the Full Model involved the steps outlined in Table 5.33 with respect to dropping PVs. Dropping the PVs <u>*sspc*</u> and <u>*ss2*</u> was based on model coefficient results (LRchi2, Pr>0.05) which did not allow for rejection of the null hypothesis that the variable coefficients were zero. As noted in Section 5.2.2, <u>*sspc*</u> had a very weak association with <u>*icr*</u>. The Pr>0.05 and the weak association resulted in the decision to drop PV <u>*sspc*</u>. The decision to drop PV <u>*ss2*</u> was based on the model01 result (LRchi2, Pr>0.05) and the decision that any contribution of <u>*ss2*</u> to the intersection condition rating was based on its contribution to intersection roof water. This relationship of <u>*ss2*</u> and roof water was confirmed by the results of a LR of the presence of dry roof and the *ss2* sandstone (LRchi2(1)=23.2, Pr<0.001) which showed that a dry roof and the presence of the *ss2* sandstone had a moderately strong negative strength of association (somers'd= -0.22, Pr<0.001). With respect to the predictive model, it was decided that *rfdry* contributed the same information to the model as *ss2*.

The decision to drop *grsupact* from model02 was based on the model02 result (LRchi2, Pr>0.05) and the reasons outlined in Section 5.2.6. With just two *grsupact* values, there was not enough variability in *grsupact* to establish any meaningful statistical relationship between *icr* and *grsupact*.

The decision to drop PV *depth* from model03 began with the observation that depth consistently had a positive coefficient (i.e., the probability of Satisfactory intersections increased with increasing depth), and a coefficient Pr=0.287, that did not allow for rejection of the null hypothesis of a value of zero for the depth coefficient. The LR results for model03 are presented in Table 5.37 (page 168). The calculated value of the *depth* coefficient was 0.0011. For the entire range of depths in the EMSA database, the contribution of *depth* to the value of logit(p) varied from 0.1 at depth=100 ft to 1.2 at depth-1000 ft; not a significant contribution. Various model runs showed that deleting *depth* resulted in better Pr values for PVs *diagsod*, *plrmin*, and *lwstress2*. Several model runs indicated a problem with collinearity between *depth*, and *plrmin* and *lwstress2*. Collinearity indicates that some of the PVs have high correlation with each other. One cause of collinearity is a variable that is computed using another variable in the model. In reviewing model PVs and results, it was noted that *depth* was highly correlated both with *plrmin* (linear regression, F(1,882)=3567, Pr(F)<0.001, R^2=0.81 and for *depth*, t=-59.7, P>|t|<0.001) and with *lwstress2* (logistic regression, LRchi2=84, Pr<0.001). In both cases, the PVs were calculated using *depth*. Because *plrmin*, *lwstress2*, and *diagsod* were variables of significant interest, *depth* was dropped from the Full Model with plans to retest *depth* in the completeness testing of the Main Model.

The decision to drop *ss1* as a PV was based on testing model fit with and without *ss1*. Comparison of the results for model04, with *ss1*, and model05, without *ss1*. The resulting values for AIC, BIC and AUC/ROC, Table 5.34, indicated that it was not a significant predictor of *icr*. A model without *ss1* fit the goal of a more parsimonious model; *ss1* was dropped from the Full Model.

The review of the statistical software output for the Main Model, Table 5.36, began with the overall model results. The result (LRchi2(13)= 286, Pr<0.001) allowed for the rejection of the null hypothesis that all the coefficients of all the PVs=0. The result (AUC/ROC=0.8083) indicated that the model, as specified, had “excellent” classification (Section 4.9, Table 4.8) in terms of prediction of outcomes (Hosmer et al. 2013). Both results indicated that the model, as specified and populated with PVs, was a logical and statistically valid result.

The next step in the process was to review the individual PV results. This review showed that the PVs populating the model were a logical and statistically valid set of PVs:

- Coefficient signs (+/−) were logical.
- P>|z| values all were significantly less than Pr<0.05 which allowed for rejection of the null hypothesis that the coefficient calculated for a PV was zero.
- 95% Conf. Intervals for any PV did not include a zero.

Table 5.37 Logistic regression output for model03 illustrating statistics for PV *depth*.

```
. //model03
. //drop grsupact
. logit icr c.depth c.cmrr c.rfcoalthk c.diagsod c.plrmin ///
>         i.lwstress2 i.rfdry i.ss1, level(95) nolog allbase

Logistic regression                             Number of obs     =        884
                                                LR chi2(10)       =     286.73
                                                Prob > chi2       =     0.0000
Log likelihood = -440.16293                     Pseudo R2         =     0.2457

------------------------------------------------------------------------------
         icr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
       depth |   .0011985   .0011261     1.06   0.287    -.0010086    .0034056
        cmrr |   .0574782   .0197675     2.91   0.004     .0187346    .0962217
   rfcoalthk |   .6467197   .1951817     3.31   0.001     .2641706    1.029269
     diagsod |  -.0618486   .0283163    -2.18   0.029    -.1173476   -.0063496
      plrmin |   2.002677   .5780387     3.46   0.001     .8697415    3.135612
             |
   lwstress2 |
        None |          0  (base)
         Low |  -.6438763   .2172431    -2.96   0.003    -1.069665   -.2180877
    Moderate |  -.7009205   .2537069    -2.76   0.006    -1.198177    -.203664
        High |  -1.040587   .4449665    -2.34   0.019    -1.912705   -.1684685
             |
       rfdry |
          No |          0  (base)
         Yes |   2.385849   .3334136     7.16   0.000     1.732371    3.039328
             |
         ss1 |
          No |          0  (base)
         Yes |   .7556212   .2915553     2.59   0.010     .1841834    1.327059
             |
       _cons |   -4.14642   1.546901    -2.68   0.007    -7.178291   -1.114549
------------------------------------------------------------------------------

. lroc, nograph

Logistic model for icr

number of observations =      884
area under ROC curve   =   0.8140
```

The conclusion was that the Main Model was a logical and statistically valid predictive model, ready for completeness testing. Completeness testing consisted of adding, one at a time, a PV considered as a potential predictor variable. Usually it was a PV dropped from the Full Model for lack of statistical significance that was considered a potentially important PV that was tested against the Main Model to determine statistical significance. Some PVs not included in the Full Model also were tested. Each LR and the Main Model were compared using the values of AIC, BIC and AUC/ROC. PV coefficients were evaluated both in terms of Pr<0.05 and the percent change between the common PVs in each model. Hosmer et al. (2013) described this step as designed to identify any PVs that were not individually statistically significant but made “an important contribution” to the model. The resulting model at the end of this step was the Predictive Model.

Table 5.38 summarizes the PVs that were selected for the evaluation completeness testing of the Main Model. The completeness testing method was described in Section 4.9 (page 100). Each variable tested during this phase of the analysis was selected based on the literature search results, the research hypotheses, or experience at the WLM. During the completeness testing, various combinations and re-coded values of these variables also were analyzed. APPENDIX A presents descriptions of these PVs. APPENDIX B presents descriptive notes for each of these PVs.

Table 5.38 Predictor variable selection for Main Model completeness testing.

sspc, *ss1margin*, *ss2margin*, *sspcmargin*, *flwater*, *flmoisenidx,* *flucs*, *ribms*, *grsupact*, *depth*, *venttype,* and *ventbelt*

Table 5.39 (page 172) summarizes the Main Model completeness testing sequence, the key model fit statistics, and the PVs populating the tested models. In reviewing the model results, three statistics were evaluated:

- The ∆BIC to the Main Model.
- The model AUC/ROC.
- The statistics calculated for the added PV.
- Changes to the PV statistics common both to the new model and the Main Model.

Negative values of the ∆BIC to the Main Model indicated an improved model fit. The new PV had to meet the Pr<0.05 test value and show reasonable values for coefficient sign (+/−), magnitude and confidence interval. The new PV could not have a significant negative impact on the existing PVs in the model. The Main Model variables in the new model were evaluated for the percent of change in the coefficient as well as the same criteria applied to reviewing the new PV statistics. The third objective was to maximize the value of the AUC/ROC. Because of this process, one additional variable, *ventbelt*, was added to the Main Model to develop the Predictive Model.

Table 5.39 Main Model completeness testing results.

Model ID Model Description PV Pr value(s)	AIC BIC ΔBIC to Main Model	AUC/ROC	Model PVs
Main Model model05	906.2 949.2 NA	0.8051	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry* Main Model
model06 Added sspc *sspc* P>|z|=0.221	906.7 954.5 +5.3	0.8072	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *sspc*
model07 Dropped *sspc* Added *ss1margin* *ss1margin* P>|z|=0.558	907.8 955.7 +6.4	0.8052	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ss1margin*
model08 Dropped *ss1margin* Added *ss2margin* *ss2margin* P>|z|=0.221	906.7 954.5 +5.3	0.8072	*cmrr*, *rfcoalthk*, *diagsod*, *lwstress2*, *rfdry*, *ss2margin*
model09 Dropped *ss2margin* Added *sspcmargin* *sspcmargin* P>|z|=0.232	906.7 954.5 +5.3	0.8069	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *sspcmargin*
model10 Dropped *sspcmargin* Added *fldry* *fldry* P>|z|=0.509	907.7 955.6 +6.3	0.8048	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *fldry*
model11 Dropped none Added *flmoisenidx* *flmoisenidx* P>|z|>0.05	912.8 974.3 +25.1	0.8062	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *fldry*, *flmoisenidx*
model12 Dropped *fldry* & *flmoisenidx* Added *flucs* *flucs* P>|z|=0.073	904.8 952.7 +3.5	0.8073	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *flucs*
model13 Dropped *flucs* Added *grsupact* *grsupact* P>|z|=0.167	906.3 954.1 +4.9	0.8057	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *grsupact*

Table 5.39 Continued

Model ID Model Description PV Pr value(s)	AIC BIC ΔBIC to Main Model	AUC/ROC	Model PVs
model14 Dropped *grsupact* Added *venttype* *venttype* P>|z| =0.001 (belt) =0.159 (return)	902.2 954.8 +5.6	0.8112	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *venttype*
model15 Replaced *venttype* With *ventbelt* *ventbelt* P>|z|=0.014	902.2 950.0 +0.8	0.8111	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ventbelt*
model16 Added *ribms* & *flucs* *ribms* P>|z|=0.034 *flucs* P>|z|=0.090	898.2 955.6 +6.4	0.8142	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ventbelt*, *ribms*, *flucs*
model17 Dropped *flucs*	899.2 951.8 +2.6	0.8183	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ventbelt*, *ribms*
model18 Added *depth* *depth* P>|z|=0.585	900.9 958.3 +9.1	0.8138	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ventbelt*, *ribms*, *depth*
model19 Dropped *ribms*&*depth* Predictive Model	902.2 950.0 +0.8	0.8111	*cmrr*, *rfcoalthk*, *diagsod*, *plrmin*, *lwstress2*, *rfdry*, *ventbelt* Predictive Model

The predictor variable *ventbelt* was added because of observations that the type of ventilation airway in which an intersection was located appeared to impact Satisfactory intersection conditions. The logistic regression analysis indicated that a location in the beltline entry was the statistically significant location. Thus, the predictor variable *ventbelt* was created to specify a beltline location as No (=0) or Yes (=1).

Both statistically and practically the Predictive Model was an incremental improvement over the Full Model and the Main Model. Table 5.40 summarizes model statistics and lists the PVs populating each of the three models. Model19 was selected as the Predictive Model because:

- All PVs had Pr values <0.05 with all PVs Pr<0.001 except for _cmrr_ (Pr=0.01).
- Acceptable value for the ∆BIC, and an improved AUC/ROC compared to the Full Model and the Main Model.
- It provided excellent predictive power, based on the AUC/ROC, with the fewest variables.

The final form of the Predictive Model equation is presented in Table 5.41 (page 175). Table 5.42 (page 176) presents a screen capture of the Stata program output for the Predictive Model. Figure 5.14 (page 177) shows the graph of the AUC/ROC for the Predictive Model.

Table 5.40 Comparison of model statistics, Full, Main and Predictive Models.

Model ID Model Description PV Pr value(s)	**AIC BIC ∆BIC to Full Model**	**AUC/ROC**	**Model PVs**
Full Model fullmodel00	903.9 970.9 NA	0.8149	_depth_, _cmrr_, _rfcoalthk_, _grsupact_, _diagsod_, _plrmin_, _lwstress2_, _rfdry_, _ss1_, _ss2_, _sspc_
Main Model model05	906.2 949.2 −21.7	0.8051	_cmrr_, _rfcoalthk_, _diagsod_, _plrmin_, _lwstress2_, _rfdry_
Predictive Model model19	902.2 950.0 −20.9	0.8111	_cmrr_, _rfcoalthk_, _diagsod_, _plrmin_, _lwstress2_, _rfdry_, _ventbelt_

Table 5.41 Predictive Model predictor variables, coefficients, and variable value measures.

Predictor Variable Description **PV *name***	**Coefficient (B)**	**Value measures**
Coal Mine Roof Rating (*cmrr*)	0.0545486	CMRR units
Thickness of coal in the intersection roof (*rfcoalthk*)	0.7752106	feet
Intersection diagonal length (*diagsod*)	-0.0549328	feet
Minimum stability factor of adjacent pillars (*plrmin*)	1.680431	Pillar Stability Factor
Longwall stress level from adjacent gobs (*lwstress*_None)	0	0 Base case
*lwstress*_Low	-0.6979015	0=No 1=Yes
*lwstress*_Moderate	-0.7522611	0=No 1=Yes
*lwstress*_High	-1.188414	0=No 1=Yes
Is roof dry? (*rfdry*_No)	0	0 Base case
*rfdry*_Yes	2.366076	0=No 1=Yes
Is intersection located in a beltline entry? (*ventbelt*_No)	0	0 Base case
*ventbelt*_Yes	-0.5813339	0=No 1=Yes
_cons	-3.040391	Constant

Table 5.42 Statistical software output for the Predictive Model.

```
. //model19
. //dropped ribms and depth
. logit icr c.cmrr c.rfcoalthk c.diagsod c.plrmin ///
>         i.lwstress2 i.rfdry i.ventbelt, level(95) nolog allbase

Logistic regression                             Number of obs     =        884
                                                LR chi2(9)        =     284.88
                                                Prob > chi2       =     0.0000
Log likelihood = -441.09154                     Pseudo R2         =     0.2441

------------------------------------------------------------------------------
         icr |      Coef.   Std. Err.      z    P>|z|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        cmrr |   .0545486   .0198045     2.75   0.006     .0157325    .0933646
   rfcoalthk |   .7752106   .1527906     5.07   0.000     .4757465    1.074675
     diagsod |  -.0549328   .0285933    -1.92   0.055    -.1109747    .0011091
      plrmin |   1.680431   .3241468     5.18   0.000     1.045115    2.315747
             |
   lwstress2 |
        None |          0  (base)
         Low |  -.6979015   .2132642    -3.27   0.001    -1.115892   -.2799114
    Moderate |  -.7522611   .2525417    -2.98   0.003    -1.247234   -.2572884
        High |  -1.188414   .4407558    -2.70   0.007     -2.05228   -.3245487
             |
       rfdry |
          No |          0  (base)
         Yes |   2.366076   .3326149     7.11   0.000     1.714163    3.017989
             |
    ventbelt |
          No |          0  (base)
         Yes |  -.5813339   .2359631    -2.46   0.014    -1.043813   -.1188548
             |
       _cons |  -3.040391   1.056525    -2.88   0.004    -5.111142   -.9696402
------------------------------------------------------------------------------

. lroc, nograph

Logistic model for icr

number of observations =      884
area under ROC curve   =   0.8111
```

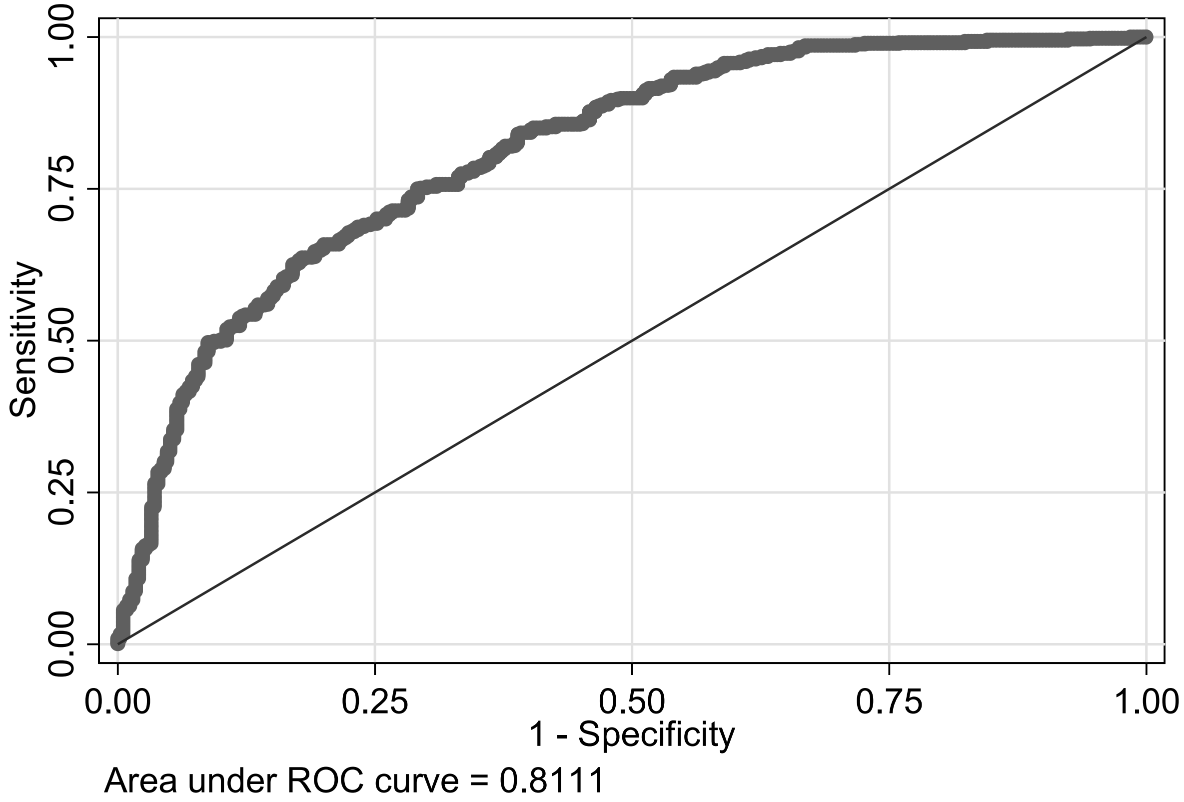


Figure 5.14 AUC/ROC for the Predictive Model.

5.4 Model Validation

The Predictive Model was tested using the 10-fold, cross-validation method described in Section 4.10. This validation test showed that the Predictive Model was statistically valid with excellent discrimination and predictive ability based on the AUC/ROC results. The Predictive Model was tested using the method of ideal types as suggested and described by Long et al. (2014) for testing of logistic regression models with a binary outcome variable. This method indicated good predictive ability for the Predictive Model. The classification strength of the Predictive Model was tested using the classification test method. This indicated good classification ability for the model at a cut point probability of 0.678. This section describes each of these testing methods, presents the results of testing Predictive Model with each method, and concludes that the Predictive Model performs with excellent discrimination and predictive ability based on the results of these tests.

Specific details of the 10-fold, cross-validation method were presented in Section 4.10. This method subdivided the EMSA database into 10 subsets of 88 to 89 intersections. A logistic regression model, populated with the same PVs from the Predictive Model, was run using nine of the ten subsets as a developmental data set. The LR model calculated and reported the coefficient value and statistics for each of the PVs. This LR model was then run against the validation data set and the AUC/ROC result was reported. This reported AUC/ROC reflects the ability of a fitted model (from the development data set) to accurately predict the results in an unrelated (validation) data set. This procedure was repeated 10 times so that each database subset, as well as each intersection in the database, served as part of a development data set nine times and as part of the validation set one time. The Stata software routine, Crossfold (Ben 2012), was used to perform the calculations. Table 5.43 presents the mean and summary statistics for the PVs coefficient values resulting from the 10-fold crossfold validation test and compares them to the coefficient values from the Predictive Model. These results show a high degree of equivalence between the coefficient values obtained by the Predictive Model and the 10-fold crossfold validation test results. Table 5.44 summarizes the AUC/ROC for each of the 10-fold cross validation test runs, labelled est1-est10, and compares them to the same statistic for the Predictive Model. The AUC/ROC is the key statistic defining model prediction ability (Hosmer et al. 2013).

The results of the 10-fold cross-validation test show very good agreement with the AUC/ROC result from the Predictive Model. Using the criteria of Hosmer et al. (2013), Table 4.8, these AUC/ROC values represent excellent model discrimination in predicting correct results.

Table 5.43 Mean predictor variable values from the 10-fold crossfold validation test.

Predictive Variable	Main Model Coefficient	10-fold crossfold validation results				
		mean	**Std.Dev.**	**Min**	**Max**	**Range**
cmrr	0.055	0.055	0.008	0.041	0.064	0.022
rfcoalthk	0.775	0.777	0.052	0.718	0.851	0.133
diagsod	-0.055	-0.055	0.008	-0.066	-0.046	0.02
plrmin	1.680	1.686	0.138	1.475	1.916	0.441
*lwstress*_None	0	0	0	0	0	0
*lwstress*_Low	-0.698	-0.699	0.061	-0.775	-0.602	0.173
*lwstress*_Moderate	-0.752	-0.754	0.078	-0.952	-0.659	0.292
*lwstress*_High	-1.188	-1.191	0.115	-1.365	-1.028	0.337
*rfdry*_No	0	0	0	0	0	0
*rfdry*_Yes	2.366	2.371	0.13	2.209	2.639	0.43
*ventbelt*_No	0	0	0	0	0	0
*ventbelt*_Yes	-0.581	-0.581	0.108	-0.741	-0.351	0.391
constant	-3.040	-3.048	0.465	-3.907	-2.464	1.443

Table 5.44 AUC/ROC values from the 10-fold crossfold validation test.

Model	Obs	AUC/ROC
est1	795	0.8046
est2	796	0.8141
est3	795	0.8137
est4	796	0.8152
est5	796	0.8055
est6	795	0.8035

Table 5.44 Continued

Model	Obs	AUC/ROC
est7	796	0.8168
est8	795	0.8141
est9	796	0.8136
est10	796	0.8154
Average est models	NA	0.8116
Predictive Model	884	0.8111

Long et al. (2014) suggested using ideal types to test logistic regression models with a binary outcome variable. An ideal type is a hypothetical observation of a case and its' associated PVs. If the Predictive Model is correctly specified and fit, the probability calculated from the model should match expectations. Five test cases were specified as described in Table 5.45 with the calculated logit(p) the probability of satisfactory intersection condition, Pr($\underline{icr}$). The results correlate well with observed conditions at the WLM.

A classification table can be used to summarize the predictive power of a fitted logistic regression model (Agresti 2007; Hosmer et al. 2013). Classification tables are sensitive to the selection of a parameter known as the cut point. The cut point is that probability value that splits the classification of an outcome between a Satisfactory condition rating and a Not satisfactory condition rating.

Table 5.45 Summary and results of ideal type test cases.

Ideal case description	logit(p)	Pr(*icr*)
test01. Intersection with fair roof (*cmrr*=35), topcoal (1.8 ft), sum-of-diagonal length (30 ft), pillar minimum SF (1.8), no lwstress (0), dry roof (Yes=1), located in a beltline (No=0)	4.007	0.982
test02. Intersection with fair roof (*cmrr*=35), topcoal (1.8 ft), sum-of-diagonal length (30 ft), pillar minimum SF (1.8), no lwstress (0), dry roof (No=0), located in a beltline (No=0)	1.641	0.838
test03. Intersection with poor roof (*cmrr*=15), topcoal (1.8 ft), sum-of-diagonal length (38 ft), pillar minimum SF (1.8), no lwstress (0), dry roof (Yes=1), located in a beltline (No=0)	0.111	0.528
test04. Intersection with poor roof (*cmrr*=15), topcoal (1.8 ft), sum-of-diagonal length (38 ft), pillar minimum SF (1.8), no lwstress (0), dry roof (Yes=1), located in a beltline (Yes=1)	-0.471	0.384
test05. Intersection with poor roof (*cmrr*=15), topcoal (1 ft), sum-of-diagonal length (38 ft), pillar minimum SF (1.1), no lwstress (0), dry roof (No=0), located in a beltline (Yes=1)	-2.267	0.094

Table 5.46 (page 182) presents the classification table developed from the Predictive Model and EMSA database at a cut point of 0.50. This cut point results in a classification of Satisfactory for any intersection with a probability estimate of greater than 0.50 from the Predictive Model. Those intersections equal to or less than the 0.50 probability threshold are classified as Not satisfactory. The data in Table 5.46 indicate that the model has a Satisfactory condition classification percentage (Sensitivity) of 89.9% (=499/555). The model Not satisfactory condition classification percentage (Specificity) is 50.2% (=165/ 329). The classification table indicates that 165 intersections with an actual Not satisfactory were classified by the model as Not satisfactory. The Predictive Model misclassified 164 intersections with actual Not satisfactory conditions as having Satisfactory conditions. This is not an uncommon result with assessing model fit based on a classification table. Hosmer et al. (2013) stated that, “Classification is sensitive to the relative sizes of the two component groups

and always favors classification into the larger group.” In the database, approximately 63% of the intersections were classified as Satisfactory conditions.

Table 5.46 Classification table for the fitted Predictive Model at probability cut point=0.5.

	Actual Observed		
Model Classification	**Satisfactory**	**Not Satisfactory**	**Total**
Satisfactory	499	164	663
Not Satisfactory	56	165	221
Total	555	329	884

The recommended method to determine the optimum cut point for classifying the outcome variable of a logistic regression model is to plot the sensitivity and specificity of the model outcome over a range of probability levels. Figure 5.15 plots these data for the Predictive Model.

Inspection of the intersection of the curves for sensitivity and specificity indicates an optimum probability cut point (Probability cutoff) of approximately 0.687. Performing a classification analysis of the Predictive Model with a cut point of 0.687 yields the results shown in Table 5.47 (page 184). The data in Table 5.47 indicate that the model has a Satisfactory condition classification percentage of 71.7% (=398/555). The model Not satisfactory condition classification (Specificity) percentage of 71.7% (=236/329).

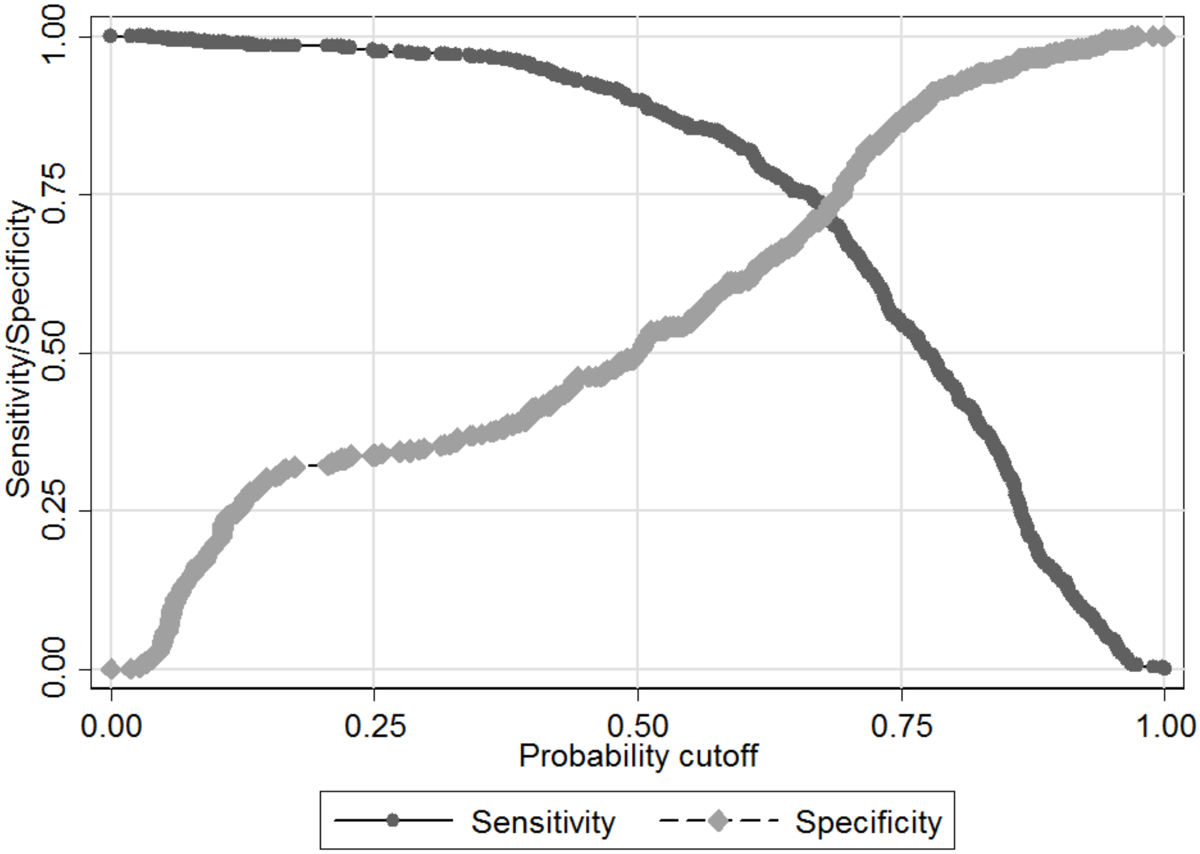


Figure 5.15 Predictive Model plot of sensitivity and specificity against probability cutoff values.

Table 5.47 Classification table for the fitted Predictive Model at probability cut point=0.678.

	Actual Observed		
Model Classification	**Satisfactory**	**Not Satisfactory**	**Total**
Satisfactory	398	93	491
Not Satisfactory	157	236	393
Total	555	329	884

This method of model validation indicates that the classification power of the Predictive Model is approximately 71% at the probability cut point of 0.678 for both Satisfactory and Not satisfactory intersections in the WLM database. Hosmer et al. (2013) cautioned using the classification table approach to model validation stating that, “a better and more complete description of classification accuracy is the area under the Receiver Operating Characteristic (ROC) curve.”

The Predictive Model was successfully validated using three methods, cross-validation, ideal type test cases, and a classification analysis. Johnson (2016) stated that the cross-validation method is a strong procedure for evaluating LR models as it uses one data set for fitting a model and a different data set for evaluating the model’s predictive accuracy. Long et al. (2014) recommended selecting ideal type test cases, predicting outcome probabilities, and verifying that the predicted outcomes matched expectations, WLM experience in this case. . Hosmer et al. (2013) stated that, “a better and more complete description of [model] classification accuracy is the area under the Receiver Operating Characteristic (ROC) curve.” All three methods indicated that the Predictive Model had good to excellent discrimination and predictive ability.

CHAPTER 6

DISCUSSION

This chapter discusses the results of this research into developing an equation for estimating the probability of Satisfactory intersection conditions using logistic regression. The applicability of logistic regression as the method for analyzing the data is described. The rationale for the selected study design is presented. The results of the research hypothesis testing are discussed. The development and validation of the Predictive Model are summarized. Anticipated uses of the Predictive Model are presented. This chapter concludes with a discussion of model limitations.

6.1 Applicability of Logistic Regression

The literature search showed that logistic regression has been used successfully to analyze and develop solutions for coal mining ground control problems. Table 6.1 summarizes some examples from the literature of the application of logistic regression to specific coal mine ground control problems.

Table 6.1 Some exampls of applications of logistic regression specific to coal mine ground control.

Application of logistic regression	Reference
South African pillar design based on collapsed and stable cases.	Salamon et al. (1967)
Pillar design in India.	Sheorey et al. (1987)
US multiple seam mine design.	Mark et al. (2007a, 2007b)
Longwall gateroad roof support design in Bowen Basin, Australia.	Lawrence (2007, 2009)
Severity of accident resulting from a roof fall in Indian coal mines.	Palei et al. (2009) and Das (2009)
Support of longwall gateroads in Australian coal mines.	Colwell et al. (2009)

Table 6.1 Continued

Application of logistic regression	Reference
Probability of stable coal pillars in Indonesian coal mines.	Wattimena et al. (2013)
Probability of stability in room and pillar retreat mining, West Virginia mines.	Ghasemi et al. (2014)
Empirical mine design.	Mark (2016)

The use of the logistic regression method for this research was appropriate because it:

- Allows for a binary outcome variable.
- Allows for the use of predictor variables of all types.
- Produces a probability of the outcome of a Satisfactory intersection condition.

The ability to use a binary outcome variable was critical to this research. The outcome variable developed for this research, the intersection condition rating, *icr*, was a binary variable, valued as either a Not satisfactory intersection condition rating (*icr*=0) or a Satisfactory intersection condition rating (*icr*=1).

The logistic regression method allows for the use of all types of predictor variables; continuous (numeric), interval (numeric), binary/dichotomous (categorical), nominal (categorical), and ordinal (categorical). This ability to incorporate all types of predictor variables into the data collection, database development, and statistical analysis allowed for flexibility, completeness, and accuracy in the variable measures used in this research. The ability to incorporate all types of predictor variables into the Predictive Model allowed for a more accurate model reflecting the complexity of the descriptive data for intersections developed in the deep/weak rock environment.

6.2 Study Design

It was determined that the collection of empirical data by observation and measurements underground at the intersection locations and from the related mine databases was the appropriate approach to address the research objectives. The specific study design was the analytic observational cross-sectional method.

An observational study is defined as a data collection method where the experimenter only collects empirical data. The experimenter does not manipulate any of the cases, or any of the case characteristics (Kleinbaum et al. 1982). An observational study like this one, designed to test specific hypotheses, to generate new hypotheses, to suggest mechanisms of causation, and to suggest probabilities for success is considered an analytic observational study (Kleinbaum et al. 1982).

The cross-section data collection method is defined by Kleinbaum et al. (1982) as the collection of “single observations at one hypothetical point in time”. The timing of the observations and collection of variable data were controlled by the availability of personnel to observe each intersection and record the data. Limited personnel availability dictated that the study was conducted based on an assessment of intersection conditions and success ratings during a period of months. The use of the cross-sectional study method was considered appropriate because of the generally slow rate of change of intersection conditions in the EMSA.

6.3 Intersection Condition Rating Method

The research Study Design included the development of a new intersection rating method. The literature review indicated that most intersection design methods were focused on the specific design of the roof support for the intersection. While this is a critical factor, this research was designed to consider the overall condition of the intersection floor, ribs, and roof as well as the ability of the intersection to satisfactorily perform its design and operational function. An intersection condition rating method was developed that expanded upon aspects of existing roof condition classification methods. The new condition rating method considered the overall conditions of the intersection, including the roof, ribs, floor, the immediately adjacent crosscuts and entries, and specifically included consideration of the current use of the intersection compared to the original design and functional requirements of the intersection. This new rating method was applied successfully in the field. Table 6.2 summarizes the field intersection condition rating categories developed and used in the research to assign a field intersection condition rating, *icrf*, to each intersection. This method proved easy to apply in the field and provided statistically significant results for use in the logistic regression analysis.

6.4 Statistically Significant Predictor Variables

The statistically significant predictor variables impacting Satisfactory intersection conditions were developed using the results of the hypothesis testing, Section 5.2, and the logistic regression model development results, Section 5.3. Initially, eleven variables were considered statistically significant, Table 6.3 (page 190). These eleven predictor variables were input into the Full Model as the initial logistic regression as described in Section 5.3. The final Predictive Model consisted of seven predictor variables as listed in Table 6.4 (page 190).

Table 6.2 Field Intersection Condition Rating (*icrf*), categories, and categorization criteria.

Numeric and Condition Rating	**Condition Category**	**Categorization Criteria**
1 Good	Satisfactory	All the following must be present: 1. Intersection has only original roof bolting. 2. No travel or ventilation restriction. 3. Intersection fully serves intended / functional design (intake, travelway, escapeway, return, belt line, overcast, etc.).
2 Fair	Satisfactory	Original functional design not currently compromised. And any of the following are present: 1. Intersection shows minor roof cracking or presence of water. 2. Original roof support supplemented with additional roof bolting, meshing, etc. 3. May include some minor standing support located at corners or for rib control.
3 Poor	Not satisfactory	Any of the following are present: 1. Significant additional standing support installed in the intersection or to either side of the intersection in the crosscuts. 2. Roof failure / fall below the top of the bolted interval. 3. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. 4. Belt maintenance operations compromised due to clearance issues with standing support.
4 Very poor	Not satisfactory	Any of the following area present: 1. Longwall tailgate blockage. 2. Escapeway routed around area. 3. Steel sets or equivalent installed to maintain access for underground mobile equipment. 4. Significant additional standing support installed in the crosscuts to either side of the intersection in the crosscuts.
5 MSHA Reportable	Not satisfactory	MSHA reportable roof fall. Roof failure above bolted horizon.

Table 6.3 Full Model input predictor variables.

Hypothesis	Predictor Variable
Depth of mining is a predictor of intersection condition.	*depth*
Geologic structures are predictors of intersection condition.	*ss1*, *ss2*, *sspc*
CMRR of roof is a predictor of intersection condition.	*cmrr*
Top coal thickness is a predictor of intersection condition.	*rfcoalthk*
Intersection diagonal spans are a predictor of intersection condition.	*diagsod*
Installed primary, in-roof support is a predictor of intersection condition.	Insufficient variability in data to perform statistical significance testing. *grsupact* retained for further testing in logistic regression model.
Longwall stresses are predictors of intersection condition.	*lwstress2*
Water in roof or floor are predictors of intersection condition.	*rfdry*
Pillar stability factors are predictors of intersection condition.	*plrmin*

Table 6.4 Predictive Model predictor variables.

Predictor Variable	Predictor Variable Description
cmrr	Coal Mine Roof Rating
rfcoalthk	Roof top coal thickness, feet
diagsod	Diagonal, Average, Sum-of-diagonals, feet.
plrmin	The minimum, or lowest value, of the stability factors of all the pillars adjacent to an intersection
lwstress2	The projected mining-induced stresses from one or two longwall panels adjacent to an intersection
rfdry	Presence of water in the roof.
ventbelt	Intersection is in a beltline entry.

The predictor variable *depth* was not specifically included in the Predictive Model. The variable *depth* was used directly to calculate both the predictor variable for longwall stress impacts, *lwstress2*, and the predictor variables for the stability factors of pillars adjacent to the intersection. Thus, the variable *depth* was mathematically highly correlated with both *lwstress2* and *plrmin*. In statistical terms, this is defined as collinearity between variables and results in significant model errors. Because various statistical tests showed that longwall stress and the minimum pillar stability factor were more significant as predictive variables of intersection Success, they were retained in the Predictive Model and *depth* was dropped.

The statistical analysis looked at three areas related to geologic structures: geologic discontinuities, sandstone channels, and channel margins. This was because the geologic structure data was based on in-mine observations while the sandstone channel and margin data were based on the geologic models.

The analysis of observed geologic structures indicated, in the case of observed slickensides in the intersection roof, that the sample sizes of n=5 resulted in too few occurrences of the geologic condition for statistical analysis. In the cases of observed faulting, bedding layer delamination, or doming:

- The sample sizes, while adequate, tended to be small, from 3% to 6% of intersections had identified geologic structures, Table 5.11.
- All one-way tests for variable randomness resulted in values for $Pr<0.001$ and $chi2>0$, allowing for rejection of null hypotheses that the variables were randomly distributed.

- All two-way tests for association of each geologic variable with *icr* resulted in all Pr>0.05 and chi2 values very close to zero, which did not allow for rejection of the null hypothesis that the variables were independent.

It was probable that the field teams did not pick up the subtler geologic discontinuities in their inspections. Both teams were composed of mining and geotechnical personnel. Detailed intersection geologic mapping and data did not exist to provide database input. It was interesting that the more obvious geologic discontinuities described by the field teams were not statistically correlated to the intersection condition rating. It is probable that top coal in the roof of an intersection obscured geologic structures in the roof rock. I concluded that the overall weak nature of the intersection roof rock, the moisture sensitivity of the roof mudstone units, and the presence of water were much greater negative factors than the impacts of geologic discontinuities on intersection condition rating in a weak rock environment. Any additional weakness in the intersection roof rock introduced by an observable geologic discontinuity was not statistically significant relative to the very weak nature of the rock units. The PVs *delam*, *dome*, *fault*, and *slick* all were dropped from further analysis.

Experience at the WLM indicated that problem intersections tended to be located under channel sandstone units. All but one of the nine MSHA-reportable roof falls were associated with one or more sandstone channels, Table 5.12 (page 133). Channel sandstones were projected to cause structural weakening of the surrounding rock mass due to differential compaction and to serve as a source of water from perched water zones within the channel sandstone units.

The sandstone channel PVs all were binary categorical variables. Table 5.11 (page 130) summarized the variable value measures, the value coding, and the frequency distribution of the variable value measures for the three sandstone channel variables. Table 5.13 (page 134) summarized the statistical test results for the sandstone channels and the correlations with *icr*.

The channel margin PVs all were binary categorical variables. Table 5.11 summarized the variable value measures, the value coding, and the frequency distribution of the variable value measures for the three sandstone channel variables. Table 5.14 (page 134) summarized the statistical test results for the channel margins and the correlations with *icr*.

The statistical analysis indicated that two of the three geologic components hypothesized to impact intersection conditions were not statistically significant:

- Geologic discontinuities.
- Channel margins.

Only the presence of sandstone channels provided correlations of sufficient strength to reject the null hypothesis of independence of sandstone channels and *icr*. Variables *ss1*, *ss2*, and *sspc* were retained as predictor variables for the logistic regression model development. However, based on the logistic modeling results, they were not significant predictors of Satisfactory intersection conditions were not included in the Predictive Model.

The results of the statistical tests of the Coal Mine Roof Rating, the *cmrr* variable, are presented in Section 5.2.3. The test results indicated that *cmrr* and *icr* are strongly associated. The variable *cmrr* was retained as a predictor variable for the logistic regression model development. The logistic modeling results indicated that *cmrr* was a predictor of Satisfactory intersection conditions, and *cmrr* was included as a predictor variable in the Predictive Model.

The results of the statistical tests of the top coal thickness, the *rfcoalthk* variable, are presented in Section 5.2.4. These test results indicated the *rfcoalthk* and *icr* are associated. The subsequent logistic model regression analysis indicated that they are strongly associated. The variable *rfcoalthk* was included as a predictor variable in the Predictive Model.

The variable *diagsod* represented the average intersection diagonal span. It is calculated as the average of the two intersection diagonal spans measured in the field, *diagnesw* and *diagnwse*. The results of the statistical tests of the intersection diagonal spans are presented in Section 5.2.5. The statistical analysis indicated a weak level of association between the predictor variables for intersection diagonal length and *icr*. The hypothesis that intersection diagonal lengths had an impact on intersection condition was conditionally accepted pending the development of the final logistic regression model. All five predictor variables related to intersection diagonal lengths were tested in the logistic regression model development. The predictor variable *diagsod* was included in the Predictive Model. However, it had a very limited impact on the probability of a Satisfactory intersection condition.

The results of the statistical tests of the intersection diagonal spans are presented in Section 5.2.5 . Primary roof support in the EMSA consisted of a 4-bolt per row, 4-ft truss spacing pattern up to intersection 334. Thereafter, a 6-bolt per row, 20 ft truss spacing pattern was adopted. This change occurred at a mining depth of approximately 550 feet and reflected a response to an increase in intersections with Not satisfactory condition ratings. The 4-bolt pattern was characterized by a $GRSUP_{ACT}$ value of 19.1 kips/ft (Std.Dev.=2.3 kips/ft), and the 6-bolt pattern was characterized by a $GRSUP_{ACT}$ value of 27.4 kips/ft (Std.Dev.=1.4 kips/ft). The hypothesis that roof support density, as measured by $GRSUP_{ACT}$ values, was an indicator of intersection conditions could not be statistically validated. However, because of the importance of roof support to intersection conditions, the PV *grsupact* was included in the logistic regression model development to confirm that, with interactions with other variables, it was not a statistically significant contributor to the multiple-PV model. The logistic model development indicated that there were no identifiable interactions with other variables tested in the model. Therefore, the roof support density was not included in the Predictive Model.

The results of the statistical tests of the impacts of stresses from adjacent longwall gobs are presented in Section 5.2.7. Table 5.22 (page 146) presents the longwall stress categories. Because of the low frequency count, 10 cases, for the *lwstress* level of Very high, Table 5.23 (page 147), the variable was recategorized by combining the High and Very high categories to create the variable *lwstress2*. The statistical analysis showed that there was a strong level of association between the two variables. The logistic regression model development confirmed this strong level of association, and the predictor variable *lwstress2* was included in the Predictive Model.

The results of the statistical tests of the impacts of water in the roof or floor are presented in Section 5.2.8. The presence of water in the immediate floor rock was not a predictor of a Satisfactory intersection condition. It was not used in the development of the Predictive Model. The absence of water in the roof was a statistically significant predictor of a Satisfactory intersection condition. The statistical analyses indicated that water conditions in the field categorized as dry or damp were equivalent to a dry roof condition. Water conditions in the field characterized as light or heavy drip were indicative of a “not dry” roof water condition. The variable, *rfdry* (No=0, Yes=1), was created and tested. A dry roof was a very significant indicator of a Satisfactory intersection condition. A ‘not dry” roof was a very significant indicator of a Not satisfactory intersection condition. Testing of this variable during development of the logistic regression model confirmed the statistical significance of this variable. It had the greatest impact on the probability of a Satisfactory intersection of all the variables in the Predictive Model.

Development of the Predictive Model resulted in the addition of the variable *ventbelt* as a predictor variable in the model. The variable *ventbelt* was categorized as Yes (=1) if the intersection was in a beltline entry and No (=0) if the intersection was in an intake or return ventilation entry.

The exploratory data analysis, statistical testing, and logistic regression modeling resulted in seven predictor variables in the Main Model:

- Coal Mine Roof Rating (CMRR), *cmrr*.
- Top coal thickness, *rfcoalthk*.
- Intersection average diagonal span, *diagsod*.
- Longwall stresses, *lwstress2*.
- Water present in the roof, *rfdry*.

- Minimum pillar stability factor of the pillars immediately adjacent to the intersection using the development tributary area load, ***plrmin***.
- Intersection location in a belt entry, ***ventbelt***.

6.5 Predictive Model

The results of the hypothesis testing, exploratory data analysis, experience at the WLM, and engineering judgement were used to develop the logistic regression model for estimating intersection conditions. Section 5.3 presents the details of the development of the Predictive Model using the logistic regression method. This Predictive Model took the form:

$$\text{logit}(p) = \text{cons}+(B_1 \bullet PV_1)+(B_2 \bullet PV_2)+(B_n \bullet PV_n) \qquad (6.1)$$

where:

p = The probability of the outcome of interest (e.g., a satisfactory intersection condition).
$\text{logit}(p)$ = Outcome as the logit transformation of the probability, or likelihood, of the outcome of interest (e.g., a satisfactory intersection condition).
cons = Constant value.
B_1–B_n = Coefficient values applied to the predictor variables PV_1–PV_n.
PV_1–PV_n = Predictor variables.

Probability, p, is calculated from the equation:

$$p= \frac{e^{\text{logit}(p)}}{1+e^{\text{logit}(p)}} \qquad (6.2)$$

Table 6.5 summarizes the predictor variables in the Predictive Model equation, the values of the predictor variable coefficients and the equation constant, and the measures used to input the predictor variable values.

Table 6.5 Predictive Model variables and variable coefficients.

PV#	**PV label**	**PV Coefficient (B_n)**
PV_1	*cmrr*	0.055
PV_2	*rfcoalthk*	0.775
PV_3	*diagsod*	-0.055
PV_4	*plrmin*	1.680
NA	*lwstress*_None	0
PV_5	*lwstress*_Low	-0.698
PV_6	*lwstress*_Moderate	-0.752
PV_7	*lwstress*_High	-1.188
NA	*rfdry*_No	0
PV_8	*rfdry*_Yes	2.366
NA	*ventbelt*_No	0
PV_9	*ventbelt*_Yes	-0.581
cons	constant	-3.040

The Predictive Model fit was 0.8111, measured using the receiver operating characteristic curve (AUC/ROC) method. This indicates excellent model fit (Hosmer et al. 2013) in predicting model outcomes. The area under the AUC/ROC method was developed by Hosmer et al. (2013) who provided criteria for assessing model fit as shown in Table 6.6.

Table 6.6 Model fit using AUC/ROC. After (Hosmer et al. 2013).

ROC value	**Model fit**
= 0.5	No discrimination, similar to a coin flip
0.5<ROC<0.7	Poor
0.7≤ROC<0.8	Acceptable
0.8≤ROC<0.9	Excellent
ROC≥0.9	Outstanding

6.6 Model Validation

The Predictive Model was tested using the 10-fold, cross-validation method described by Johnson (2016) as a strong procedure for evaluating logistic regression models as it uses one data set for fitting a model and a different data set for evaluating the model's predictive accuracy. This method was described in Section 4.10. This validation test showed that the Predictive Model was statistically valid and had excellent discrimination and predictive ability based on the AUC/ROC results with an average AUC/ROC for the ten tests of 0.8116.

A classification table can be used to summarize the predictive power of a fitted logistic regression model (Agresti 2007; Hosmer et al. 2013). Classification tables are sensitive to the selection of a parameter known as the cut point. The cut point is that probability value that splits the classification of an outcome between a Satisfactory condition rating and a Not satisfactory condition rating.

Table 6.7 presents the classification table developed from the Predictive Model and EMSA database at a cut point of 0.50. This cut point results in a classification of Satisfactory for any intersection with a probability estimate of greater than 0.50 from the Predictive Model. Those intersections equal to or less than the 0.50 probability threshold are classified as Not satisfactory. The data in Table 6.7 indicate that the model has a Satisfactory condition classification percentage of (499 / 555 =) 89.9% and a Not satisfactory condition classification percentage of (165 / 329 =) 50.2%.

Table 6.7 Classification table for the fitted Predictive Model at probability cut point=0.5.

	Actual Observed		
Model Classification	**Satisfactory**	**Not Satisfactory**	**Total**
Satisfactory	499	164	663
Not Satisfactory	56	165	221
Total	555	329	884

The recommended method to determine the optimum cut point for classifying the outcome variable of a logistic regression model is to plot the sensitivity and specificity of the model outcome over a range of probability levels. Figure 6.1 plots these data for the Predictive Model.

Inspection of the intersection of the curves for sensitivity and specificity indicates an optimum probability cut point (Probability cutoff) of approximately 0.687. Performing a classification analysis of the Predictive Model with a cut point of 0.687 yields the results shown in Table 6.8. The data in Table 6.8 indicate that the model has a Satisfactory condition classification percentage of (398 / 555 =) 71.7% and a Not satisfactory condition classification percentage of (236 / 329 =) 71.7%.

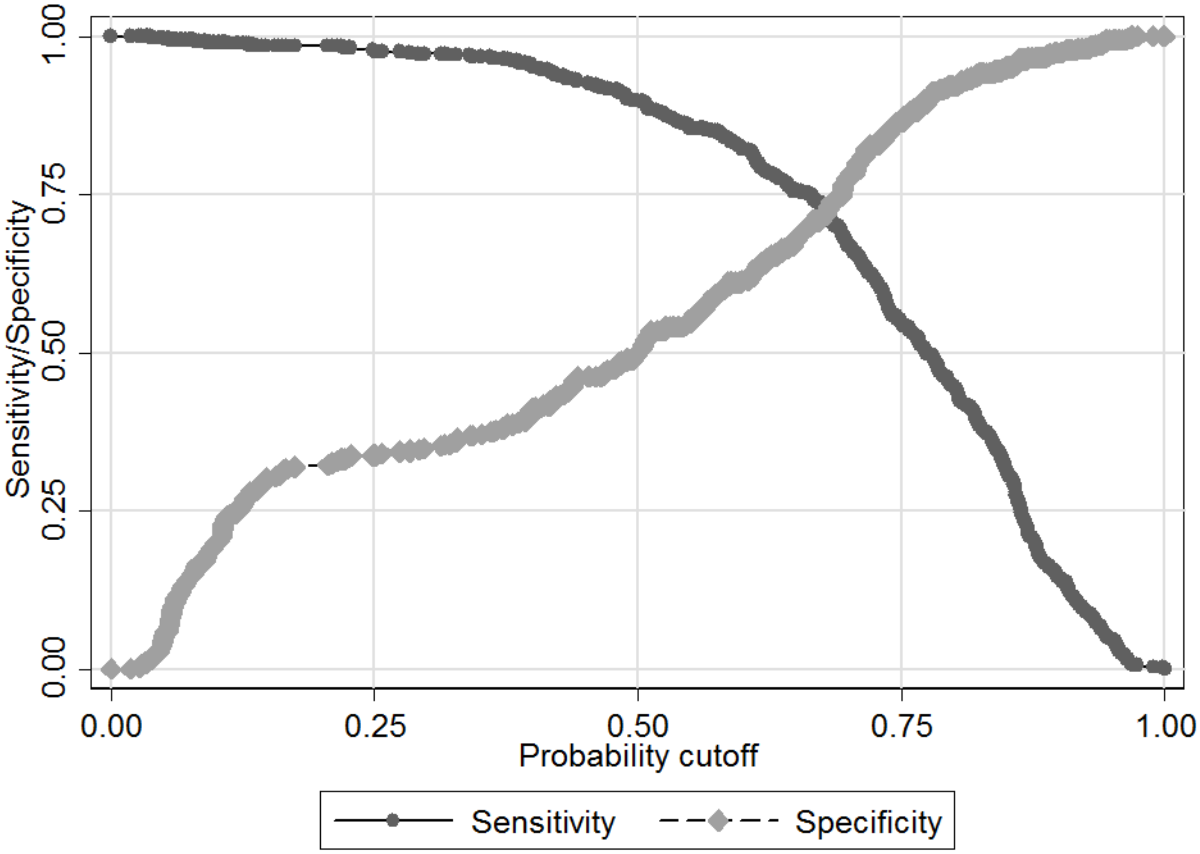


Figure 6.1 Predictive Model plot of sensitivity and specificity against probability cutoff values.

Table 6.8 Classification table for the fitted Predictive Model at probability cut point=0.678.

	Actual Observed		
Model Classification	**Satisfactory**	**Not Satisfactory**	**Total**
Satisfactory	398	93	491
Not Satisfactory	157	236	393
Total	555	329	884

This method of model validation indicates that the classification power of the Predictive Model is approximately 71% at the probability cut point of 0.678 for both Satisfactory and Not satisfactory intersections in the WLM database. Hosmer et al. (2013) stated that, “a better and more complete description of [model] classification accuracy is the area under the Receiver Operating Characteristic (ROC) curve.”

6.7 Predictive Model Applications

This section describes possible uses of the Predictive Model. Possible uses described include:

- Identification of significant predictor variables impacting intersection conditions in the deep/weak rock coal mine environment.
- Guidance for pre-mining drilling programs – what data to collect.
- Estimate of the probable intersection condition rating for a proposed design and anticipated conditions.
- Predictor variable sensitivity analysis.

The Predictive Model identifies statistically significant predictor variables impacting intersection conditions in the deep/weak rock coal mine environment. These statistically significant variables include:

- Rock moisture sensitivity.
- Geologic sources of water inflow into the roof rock strata.
- Pillar sizing.
- Mining-induced stresses.
- Top coal thickness.

The Predictive Model and listing of statistically significant predictor variables should be used to provide guidance on what data to collect for pre-mining exploration and drilling programs. The results of the analysis and Predictive Model indicate that knowledge of the amount and moisture sensitive characteristics of mudstones in the immediate floor and roof rock strata are important predictors of satisfactory intersection conditions. Collection of this information is not typically included in pre-mining coal exploration programs. It should be if the initial geologic models indicate the presence of mudstone rock units.

The Predictive Model was developed to allow a mine planner a method for estimating the probable intersection condition rating for a proposed design and anticipated conditions. Table 6.9 illustrates this use of the model. The data are from intersection 874 in the database. The intersection design data are presented in data items 1–4. Anticipated conditions impacting the intersection are presented in data items 5–7. The calculated estimate of the probability of a Satisfactory intersection condition is 0.84. This intersection design has a high probability that is will provide Satisfactory conditions and performance in the anticipated conditions. Intersection 874 was categorized as Satisfactory in the database.

The Predictive Model can be used to perform a sensitivity analysis of the equation predictor variables. Figure 6.2 illustrates the use to the Predictive Model to investigate the relationship between CMRR, roof top coal thickness, the presence of roof water, and the estimate of the probability of a Satisfactory intersection condition. In reviewing the figure, it should be noted that, typically, the higher CMRR values represent reduced amount of mudstone roof rock units. The figure indicates the importance of incorporating a thicker section of roof coal in the deep/weak rock environment, especially when water is anticipated in the roof strata.

Table 6.9 Intersection design analysis example.

Data Item	**Condition Description**	**Design Value**
1	Diagonal length (feet)	28.0
2	Roof coal thickness (feet)	2.1
3	Location in beltline?	No=0
4	Minimum stability factor for adjacent pillars.	0.7
5	Coal Mine Roof Rating	18.8
6	Longwall stress level–None	Yes, Base case=0
6	Longwall stress level–Low	No=0
6	Longwall stress level–Moderate	No=0
6	Longwall stress level–High	No=0
7	Roof dry (No water)?	Yes=1
Result	Probability of satisfactory intersection condition	0.84

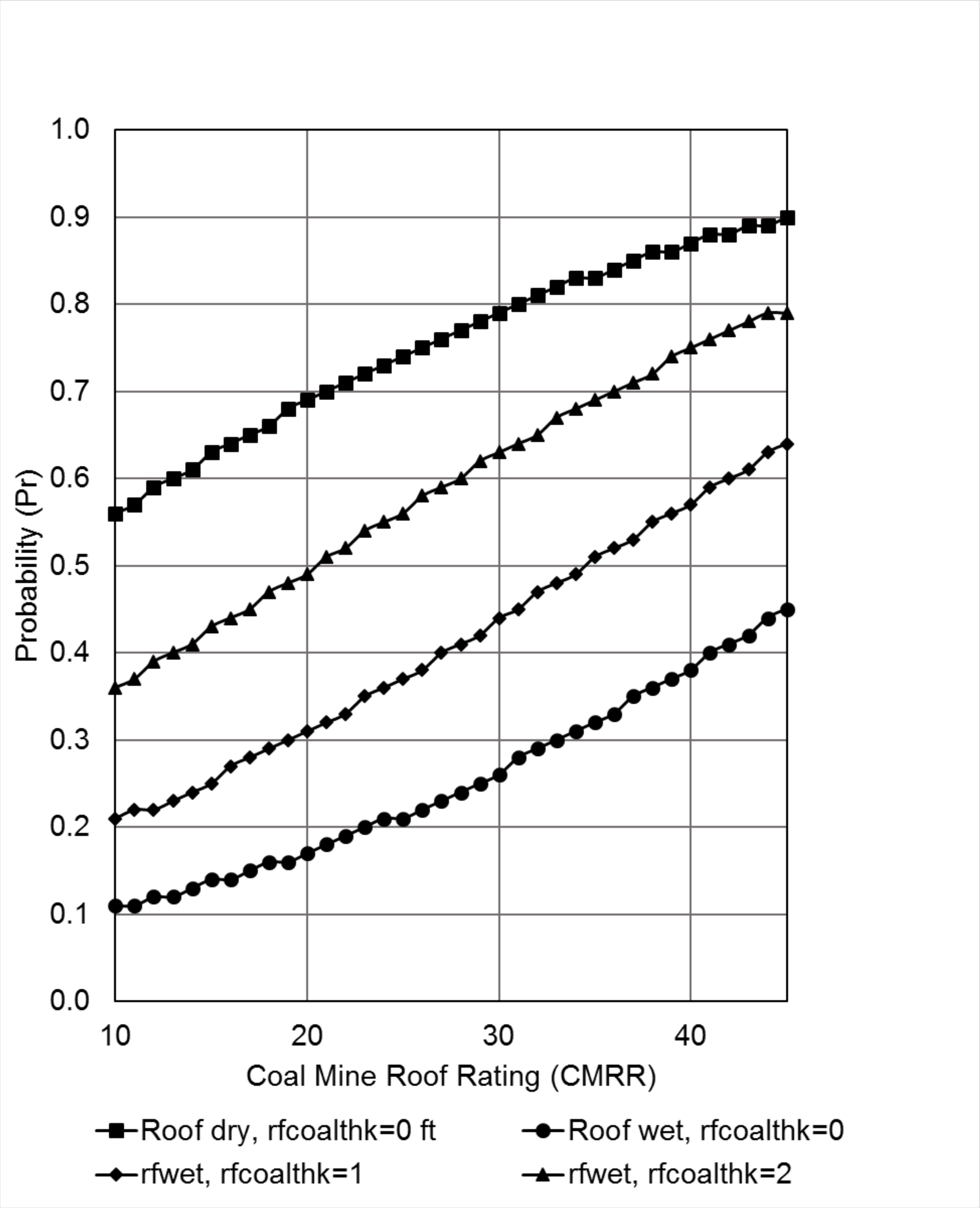


Figure 6.2 Impact of top coal thickness on estimate of satisfactory intersection condition.

6.8 Study Limitations

Mark (2016) in his paper titled *Science of empirical design in mining ground control* stated that one pitfall in empirical design,

> "is not making clear the limitations to the method. Empirical techniques are most reliable when they are interpolating within the boundaries of their case history database. It should be clear to users when a design problem falls outside those bounds."

The methodology, results, and Predictive Model represent data collected in the East Mains of the WLM. Key conditions in the East Mains included:

- The depth of mining from 104 ft to 1058 ft.
- Intersection geometry: 76% 4-way, 23% 3-way, and 1% 2-way.
- The number of entries across the East Mains was from 2 to 8.
- Average intersection diagonal length: mean 31.7 ft, Std.Dev=3.0 ft, range 24.4–47.6 ft.
- CMRR values: mean=22.5, Std.Dev.=5.2, range 0.9–40.8.
- Immediate floor and roof rock strata were generally very moisture sensitive, typically classified as moderately to severely moisture sensitive using the CMRR unit rating system (Mark and Molinda 1996).

While not specifically a predictor variable in my estimation equation, my model should not be applied where the primary in-roof support is less than that installed in the East Mains of the WLM:

- Mining depth up to 550 ft (Outby Xcut 334), 4 bolts per row, 4-ft row spacing, 4-ft truss spacing, mean=19.1 kips/ft, Std.Dev=2.3 kips/ft.

- Mining depth greater than 550 ft (Inby Xcut 334), 6 bolts per row, 4-ft row spacing, 2-ft truss spacing, mean=27.4 kips/ft, Std.Dev=1.4 kips/ft.

Applying this equation in a similar geologic and mining environment but with less roof support would not be appropriate.

The Predictive Model was developed using data from main entry intersections, and the results are not applicable to intersections longwall gateroads or retreat mining. While the database does include intersections impacted by stresses from longwall gobs adjacent to the main entries, it does not specifically include headgate or tailgate loading conditions and is not intended for the prediction of intersection conditions in any longwall gateroad. The data do not reflect stresses imposed by any type of retreat pillar mining. Multiple seam mining conditions are not represented in the database.

The fact that the final Predictive Model does not include depth of mining as a critical predictor variable is not intended to indicate or even imply that depth of mining is not a critical factor. One of the recommendations resulting from the research is to better define and understand the collinearity of depth with other key variables, particularly abutment stresses from adjacent longwall gobs and pillar stability factors. Developing this understanding would allow for the inclusion of depth and these collinear factors into a revised Predictive Model.

One area not explored during the development of the Predictive Model was the impact of changes in surface topography on intersection stability. Rapid changes in the depth of mining are not included in the Predictive Model. As indicated by the depth of mining contours shown on Figure 5.3 (page 126), the EMSA was transected by an escarpment around the 700-ft mining depth with an elevation change of approximately 160 feet.

Various authors (Adler et al. 1968; Peng et al. 1978; Patrick et al. 1979; Unal 1983, 1986, 1989; Gale et al. 1992) and methodologies defined estimates of the height of the relaxed zone above a mine opening as an important variable. This information was not available for EMSA intersections. WLM bulk rock mass model results (Applied Research Associates 2010) suggest an 18-ft to 20-ft relaxed zone may occur above the roof of a coal mine entry. This is consistent with the observation by Mark (2000) and Unal (1983) that as the CMRR value approaches zero, the height of the relaxed zone approaches the width of the entry or the intersection diagonal span (Unal 1983).

The actual time between mining an intersection and the installation of the primary intersection roof support, including trussing, was not available in the EMSA data set. WLM development mining used place-change mining with a separate miner and bolter. Mining practice at the WLM dictated that support was to be installed as soon as possible and that no roof was to be left unsupported for any idle shift. WLM engineering staff had defined this as a critical variable in satisfactory conditions and, at the time of this research, a miner-bolter was on order.

The Predictive Model provides a probability of Satisfactory intersection conditions intended to include roof, rib, and floor conditions as well as addressing the need for the intersection to meet specific functional requirements for safe access to travel, work, and for ventilation. It is up to the mining engineer to determine what probability level is acceptable for each specific intersection in terms of impacting predictor variables, functional requirements, and design life.

There is no opportunity for external validation of the Predictive Model due to the lack of coal mines operating in similar environments in the US and worldwide. Some have similarly weak immediate roof but not the depth of mining, or do not have the overall poor quality overburden rock mass, or do not have the regulatory, economic, or operating conditions of US coal mines. Still, this research has provided a methodology for developing a study design for data collection and analysis and the use of logistic regression as a modeling tool.

CHAPTER 7

CONCLUSIONS

Conclusion from my development of an equation for the estimation of the probability of Satisfactory intersection conditions in a deep/weak rock coal mine environment include:

- The use of the logistic regression method is appropriate for the analysis of coal mine ground control problems in a deep/weak rock coal mine environment.
- The analytic observational, cross-sectional method is an appropriate method for the collection of data to be applied to analyzing coal mine ground control issues.
- It is important to include the functional performance of an intersection as part of the rating criteria for a Satisfactory intersection.
- Depth of mining is considered a predictor of a Satisfactory intersection condition. However, it was not specifically included in the Predictive Model because it was directly used to calculate both the predictor variable for longwall stress impacts and the predictor variable for the stability factors of pillars adjacent to the intersection. This resulted in collinearity issues with these variables and instability in the logistic regression maximum likelihood calculation method.
- Geologic structures were not significant predictors of a Satisfactory intersection condition. It was hypothesized from the research that this was

the result of the very weak nature of the immediate roof and floor rock strata.

- Increasing Coal Mine Roof Rating values slightly increased the probability of a Satisfactory intersection condition.
- Increasing top coal thickness significantly increased the probability of a Satisfactory intersection condition.
- Increasing intersection diagonal length, measured as the average sum-of-the-diagonals, slightly decreased the probability of a Satisfactory intersection condition.
- Installed primary in-roof support was considered a highly significant predictor of a Satisfactory intersection condition. However, there was insufficient variability in the database to provide for a statistical analysis of this predictor variable.
- Longwall stresses transferred to an intersection from adjacent longwall gobs significantly reduced the probability of a Satisfactory intersection condition.
- Any water moving through the immediate roof rock strata (e.g., light or heavy drip) significantly reduced the probability of a Satisfactory intersection condition.
- Lower pillar stability factors moderately to significantly decreased the probability of a Satisfactory intersection condition.
- A belt entry location for an intersection moderately reduced the probability of a Satisfactory intersection condition.

- The Predictive Model provides a mine designer with a tool to test the probability of a Satisfactory intersection condition for a specific design against a set of anticipated conditions.

CHAPTER 8

RECOMMENDATIONS

The data set collected in the EMSA of the WLM and the resulting database provide a resource for both numerical and empirical modelers. Recommended future work includes:

- More detailed statistical analysis methods or numerical modeling should be applied to address the depth collinearity issue with those other predictor variables of interest that use depth as part of their input data for calculation.
- Statistical and numerical analyses of the impact of rapid changes in surface topography on intersection stability.
- While computerized mine maps provide a wealth of information, field data collection requires an intensive deployment of personnel. Remote sensing, data collection, and automated data process related to such items as intersection dimensions and measurements of geologic discontinuities in and around an intersection would provide valuable insights. Remote sensing of conditions immediately behind the surface of roof, ribs and floor would be invaluable. Such systems must be inexpensive to acquire and operate, require a minimum commitment of personnel, and meet US coal mine permissibility standards.
- Detailed numerical modeling including intersection immediate roof rock stratigraphy and geomechanical properties, intersection geometry, depth

of mining, any site-specific in situ stress information, and abrupt changes in surface topography are suggested to define a probable relaxed zone based on development mining. Changes in the stress regime resulting from mining induced stresses should be incorporated in the modeling to allow for assessment of the long-term satisfactory conditions of intersections in main entries.

- Continued development of the WLM Bulk Rock Mass Model to incorporate the findings of this research, to better define the height of the relaxed rock zone in the roof above intersections in the various types of environments present in the EMSA, and to address items presented in the preceding bullet point.

GLOSSARY AND ACRONYMS

AAMC. Anglo American Metallurgical Coal.

ACARP. Australian Coal Industry's Research Program.

AIC. Akaike's information criterion (Long et al. 2014) (statistics).

Air course. An entry or a set of entries separated from other entries by stoppings, overcasts, other ventilation control devices, or by solid blocks of coal or rock so that any mixing of air currents between each is limited to leakage. (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 75.301 Definitions, Air course.

ALTS. Analysis of Longwall Tailgate Serviceability design method for longwall tailgate support developed for the Australian underground coal mining industry (Colwell et al. 2009).

AMCMRR. Analytical Model for Coal Mine Roof Reinforcement (Frith et al. 2010).

Analytic observational study. A study designed to test specific hypotheses, to generate new hypotheses, to suggest mechanisms of causation and to suggest probabilities for success (Kleinbaum et al. 1982) (statistics).

ANOVA. Analysis of Variance (statistics).

ARBS. Analysis of Roof Bolt Systems (Mark 2000).

ARBSadjust. A suggested adjustment to the ARBSG value based in suggested and actual intersection span (Mark 2000).

ARBSG. Suggested value of ARBS based on CMRR and depth of cover (Mark 2000).

Association. The statistical relationship, whether causal or not, between two randomly distributed variables (statistics). See also **Independence**.

AUC/ROC. The area under the receiver operating characteristic curve (Hosmer et al. 2013) (statistics).

Beltline or belt line, also belt air course. A coal mine entry within which a conveyor belt line is installed and actively operated and any adjacent entries not separated from the belt entry by permanent ventilation controls. Requires a separate ventilation air course (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 75.301 Definitions, Belt air course.

BIC. Bayesian information criterion (Long et al. 2014) (statistics).

Binary logistic regression. A logistic regression model where the outcome variable is binary or dichotomous (Hosmer et al. 2013) (statistics).

Binary outcome variable. An outcome variable with only two values, typically 0 and 1. Also termed a dichotomous outcome variable. In this research the binary outcome variable is the Intersection Condition Rating: Not satisfactory (0) or Satisfactory (1) (statistics).

Binary. Having only two states or values.

BOM. Bureau of Mines (US).

Cable bolt. A high-strength cable installed in a bore hole drilled into the rock mass. Bolt may be fully-grouted or point-anchored; tensioned or untensioned.

Case. A case is the primary unit of analysis and may be measured on a variety of characteristics (Newton and Rudestam 2013) (statistics).

Categorical variable. A statistical variable with a measurement scale consisting of a set of categories (Agresti 2007). For example, roof conditions were measured and reported as “good”, “fair”, “poor”, “very poor”, and “MSHA reportable” (statistics).

CDC. Centers for Disease Control and Prevention, US Department of Health and Human Services.

chi2(#). Chi-square value. When present, # represents the degrees of freedom (statistics).

CMRR. Coal Mine Roof Rating (Molinda et al. 1994).

Coal reserves. See **Coal resources**.

Coal resources. Geological Survey Circular 891 (Wood et al. 1983) presents the following text describing the Coal Resource Classification System as,
“a concept by which coal is classified into resource/reserve base/reserve categories on the basis of the geologic assurance of the existence of those categories and on the economic feasibility of their recovery. Categories are also provided for resources/reserve base/reserves that are restricted because of legal, environmental, or technologic constraints. Geologic assurance is related to the distance from points where coal is measured or sampled; thicknesses of coal and overburden; knowledge of the rank, quality, depositional history, areal extent, and correlations of coal beds and enclosing strata; and knowledge of the geologic structure. Economic feasibility of recovery is affected not only by such physical and chemical factors as thicknesses of coal and overburden, quality of coal, and rank of coal, but also by economic variables--such as price of coal, cost of equipment, mining, labor, processing, transportation, taxes, and interest rates, demand for and supply of coal, and weather extremes--and by environmental laws, restrictions, and judicial rulings.

“The classification system is designed to quantify the total amounts of coal in the ground before mining began (original resources) and after any mining (remaining resources). It is also designed to quantify the amounts of coal that are known (identified resources) and the amounts of coal that remain to be discovered (undiscovered resources). The system also provides for recognizing amounts of coal that are (1) standard distances from points of thickness measurements --measured, indicated, inferred, and hypothetical; (2) similar to coal currently being mined (reserve base and inferred reserve base); (3) economically recoverable currently (reserves and inferred reserves); (4) potentially recoverable with a favorable change in economics (marginal reserves and inferred marginal reserves); and (5) subeconomic because of being too thin, too deeply buried, or lost-in-mining. Finally, the system allows tabulation of coal amounts that are restricted from mining by regulation, law, or judicial ruling."

Coal washout. A thinning or complete removal of the coal seam by an overlying rock channel, typically a sandstone channel with very weak to weak rock channel margin mudstone deposits

Combined support type. Combinations of Roc props with either J-channel or GT120 as follows:
1 – J-channel plus two Roc props
2 – J-channel plus three Roc props
3 – J-channel plus four Roc props
4 – GT 120 plus Roc props

Combo. See Combined support type.

Cons. Constant.

Coef. Coefficient.

Conf.Interval. Confidence interval (statistics).

Continuous variable. A numeric variable that is measured on a continuum [e.g., Coal Mine Roof Rating (CMRR)] (statistics).

Crosscut. A passageway mined between an entry and its parallel air course or air courses for ventilation, travel or escapeway purposes.

Cross-sectional study. An observational study that consists of measurements of the current characteristics of a series of cases (intersections) that differ with respect to the desired outcome variable (intersection condition rating) at a specific point in time (Agresti 2007). A study of "single observations at one hypothetical point in time" (Kleinbaum et al. 1982) (statistics).

Cutter. A linear fracturing of rock along the intersection of the roof and rib of an entry or crosscut. They generally propagate nearly vertical and the roof rock falls out along the cutter. See also Gutter.

Deep/weak coal mining environment. A coal mine environment characterized: (1) by mining depths greater than 800 ft, (2) by a poor to fair quality rock mass above the coal seam; and, (3) by very weak to weak rock strength conditions for the immediate rock strata above and below the coal seam.

Dependent variable. In a regression model, the dependent variable changes per the values of the independent variables (statistics).

Development Coal. That coal mined to provide access to a mining area that will subsequently have additional mining for development, pillaring or longwall mining.

Development Mining. That mining designed to provide access to a mining area that will subsequently have additional mining for development, pillaring or longwall mining.

df. Degrees of freedom (statistics).

Dichotomous variable. A categorical variable with only two categories (e.g., Intersection Condition Rating (*icr*) of either Satisfactory or Not satisfactory). Also, termed a binary variable (statistics).

Discrete variable. A numeric variable that can take only specific values, generally positive integers (e.g., number of roof bolts) (statistics).

Drivage. Opening in the coal seam developed by mining of the coal.

EM. East Mains of the WLM.

Empirical. Based or acting on observation and experiment, not on theory (Seedsman, Gordon and Aziz 2009).

EMSA. East Mains Study Area located at the Western Longwall Mine (WLM).

Entry, Intake. See **Intake entry**.

Entry, Return. See **Return entry**.

Entry. An entry is an opening excavated in the coal seam, oriented horizontal or nearly horizontal, used for ventilation, escape out of the mine (escapeway), transportation of men and materials or transport of coal via mechanized haulage equipment or a conveyor belt system.

EPV. Events per variable (Peduzzi et al. 1996) (statistics).

Escapeway. Generally, an escapeway is a distinct travelable passageway from each working section to the surface (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 75.380 Escapeways; bituminous and lignite mines.

Explanatory variable: In a regression model, the variables that are input data and influence the value of the response variable. The explanatory variable also is known as the independent variable or X variable (statistics).

F. F test statistic value (statistics).

Fair rock mass quality. A total rock mass rating of 41 to 60 out of 100 possible rating points (Bieniawski 1979).

Fall of face, rib, side or highwall. Falls of material (from in-place) while barring down or placing props; also, pressure bumps and bursts. Since pressure bumps and bursts which cause accidents are infrequent, they are not given a separate category. Not included are accidents in which the motion of machinery or haulage equipment caused the fall either directly or by knocking out support; such accidents are classified as machinery or haulage, whichever is appropriate.

Fall of roof or back. Falls of material while barring down or placing props; also, pressure bumps and bursts. Not included are accidents in which the motion of machinery or haulage equipment caused the fall either directly or by knocking out support; such falls are classified as machinery or haulage, whichever is appropriate.

FDV. Field descriptive variable (statistics).

gamma. Statistics. Goodman-Kruskal's gamma. A measure of association between two categorical variables. It is used with ordinal or binary nominal variables. The range is -1.0 to + 1.0 (statistics).

Good rock mass quality. A total rock mass rating of 80 to 61 out of 100 possible rating points (Bieniawski 1979).

Gob. Mined out and caved area of an extracted longwall panel.

Ground Control. The systems, processes, equipment and materials installed and in place in the rock mass adjacent to a mine opening to regulate and mitigate the closure of a mined opening due to gravity and in situ stresses.

Ground falls. See **Fall of face, rib side or highwall** and **Fall of roof or back**.

GRSUP. Ground Support Rating defined as "all bolt and longer tendon roof support installed within the roof" regardless of when it was installed and "includes all roof bolts, longer tendons, cables and trusses" (Colwell et al. 2009).

Gutter. Gutter is the resulting void space in the roof rock due to rock falling out of the fracture zone created by a developed cutter. Also, see **Cutter**.

Guttering. See **Gutter**.

Highwall. The unexcavated face of exposed overburden and coal in an open pit mine.

***icr*.** Intersection Condition Rating.

***icrf*.** Intersection Condition Rating, Field.

***icrp*.** Intersection Condition Rating, Preliminary.

Immediate roof. The roof rock strata that extends immediately upwards from the roof of the coal mine opening that is significantly impacted by changes to the original, in situ stress field resulting from the excavation of the coal mine opening (Peng 2008). At the WLM, this is the roof immediately above the entries, crosscuts and intersections excavated to construct the East Mains.

Independence. Given two variables, neither variable has an impact on the other variable (statistics).

Independent variable. A variable that isn't changed or influenced by other variables. In a regression model, the independent variables are input values used to determine the dependent variable (statistics).

Indicated reserves. See **Coal resources**.

Inferred reserve base. See **Coal resources.**

Intake entry. A coal mine entry or set of entries separated from other entries by permanent ventilation controls that carries intake air; e.g., air that has not yet ventilated the last working place on any split of any working section, or any worked-out area, whether pillared or nonpillared (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 75.301 Definitions, Intake air.

Intersection. An intersection is the intersection of two, infrequently more, entries or crosscuts, in the same horizontal plane, at some horizontal angle.

ISDM. Integrated Support Design Methodology (Gadde et al. 2007).

kN. kilonewtons

lb/cu.ft. Pound per cubic foot.

Longwall coal. Coal mined using the longwall mining method.

LR. Logistic Regression. In this research is specifically refers to binary logistic regression (statistics).

LRchi2(#). Likelihood ration chi-square value. When present, # represents the degrees of freedom (statistics).

m. meters

Main entry. A main entry is an entry used as the "main" access to a coal mine or a mining area within a coal mine. Uses of a main entry are the same as for an entry.

Main roof. Roof rock strata above the immediate roof that are self-supporting (Peng 2008)

Mains. A series of main entries and crosscuts. See **Main entry**.

Max. Maximum value of any variable in the data set for a single variable (statistics).

Measured reserves. See **Coal resources**.

Measurement value (statistics). The specific value(s) assigned to a characteristic of a thing, or case (Newton and Rudestam 2013) (statistics).

Measurement. The process of assigning numbers to a characteristic of a thing, or case (Newton and Rudestam 2013) (statistics).

Min. Minimum value of any variable in the data set for a single variable (statistics).

Mining depth. The distance from the roof of the intersection to the ground surface measured at approximately the center of the intersection.

MPa. Mega Pascal.

MSHA Reportable Roof Fall. The Code of Federal Regulations (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 50.10 requires immediate notification of MSHA of “an unplanned roof fall”. Section 50.20 (h) (8) defines an unplanned roof fall as, “An unplanned roof fall at or above the anchorage zone in active workings where roof bolts are in use; or, an unplanned roof or rib fall in active workings that impairs ventilation or impedes passage…”.

MSHA. Mine Safety and Health Administration, US Department of Labor.

N, also “n”. Sample size. See **Sample size** (statistics).

NIOSH. National Institute for Occupations Safety and Health, Centers for Disease Control and Prevention, US Department of Health and Human Services.

Nominal variable. A categorical variable with a measurement scale consisting of a set of categories without any significant meaning to the order of the categories (Agresti 2007). For example, the orientation of roof tension cracks, if present, were recorded as “east-west”, “north-south”, “northwest-southeast”, or “northeast-southwest”. The order of listing of these categories in a statistical analysis is irrelevant (statistics).

Null hypothesis. In this research, the null hypothesis is the hypothesis that the observations or associations occurred by chance (statistics).

Numeric variable. A variable that represents a quantity that is measurable and reportable as a number (statistics).

OBE. Optimum Beaming Effect (Stankus et al. 1996).

Obs. Observation or observations.

Observational study. A study using empirical data and where the experimenter does not manipulate any of the cases, or any of the case characteristics (Kleinbaum et al. 1982) (statistics).

OMSHR. Office of Mine Safety and Health Research, National Institute for Occupations Safety and Health, Centers for Disease Control and Prevention, US Department of Health and Human Services.

Ordinal categorical variable: A categorical variable with a measurement scale consisting of a set of categories with a natural ordering (Agresti 2007). For example, roof conditions measured and reported as “good”, “fair”, “poor”, “very poor”, and “MSHA reportable” have an order representing roof conditions from best to worst (statistics).

Ordinal variable. A categorical variable with two or more categories where the allowable categories are ordered, or ranked, and the order is important (e.g., overburden depth category as shallow, moderate or deep) (statistics).

Outcome variable. Outcome variable is a term equivalent to the term dependent variable in ANOVA and linear regression. In this research study, the outcome variable is the intersection condition rating (*icr*). The outcome variable is binary with only two values, Satisfactory or Not satisfactory (statistics).

Overburden cover. Overburden cover depth, depth of cover or cover depth, represent the vertical distance measured from the roof of the coal mine excavation to the ground surface at a specific point.

Overburden. The sequence of rock strata and surface soils that begins at the roof of the coal mine and extends to the ground surface.

***p*.** probability (statistics).

Permitted. Permitted means a permit to mine the specific block or area of the coal seam has been issued by the appropriate regulatory authority at the state or, in some cases, federal, level and that the permit is in an active status.

PIB. Program Information Bulletin published by the US Mine Safety and Health Administration.

Poor rock mass quality. A total rock mass rating of 21 to 40 out of 100 possible rating points (Bieniawski 1979).

Portal. The surface entrance to an entry starting at a rock face. Also, may apply to the structures constructed to provide ground control and safe travel into and out of the mine.

Pr. Statistical probability or p-value. Used in evaluating the null hypothesis. If the Pr is less than the significance level established for the test, the null hypothesis is rejected (statistics).

Predictor variable. Predictor variable is a term approximately equivalent to the term independent variable in ANOVA and linear regression; but, it specifically indicates that the variable was not changed by the researcher as a part of an active experiment; the variable was just “observed” by the researcher (Ellis 2004) (statistics).

Primary roof support. That support installed concurrent with and as a part of the coal excavation process Mark (Mark and Barczak 2000).

PRSUP. Primary Roof Support (Mark et al. 2001).

PRSUPALT. Primary Roof Support calculated as only that support installed off the miner (Colwell et al. 2009).

psi. pound per square inch.

PV. Predictor variable. See **Predictor variable** (statistics).

R^2. R squared, coefficient of determination (statistics).

Random variable. A random variable is a function that associates a unique numerical value with every outcome of a random experiment. The value of the random variable will vary from trial to trial as the experiment is repeated. A random variable has either an associated probability distribution (discrete random variable) or probability density function (continuous random variable). (Easton et al. 1997)

Randomly distributed variable. A distribution of probability which is uniform in the range concerned (i.e. a rectangular distribution in a histogram plot). The frequency of occurrence of the results tend to be approximately equal.

Reportable roof fall. See **MSHA Reportable roof fall**.

Reserve base. See **Coal resources**.

Response variable: In a regression model, the response variable changes per the levels of the input explanatory variables. The response variable also is known as the dependent variable or Y variable (statistics).

Return entry. A coal mine entry or set of entries separated from other entries by permanent ventilation controls that carries return air; e.g., air that has ventilated the last working place on any split of any working section or any worked-out area whether pillared or nonpillared. If air mixes with air that has ventilated the last working place on any split of any working section or any worked-out area, whether pillared or nonpillared, it is considered return air. For the purposes of §75.507-1, air that has been used to ventilate any working place in a coal producing section or pillared area, or air that has been used to ventilate any working face if such air is directed away from the immediate return is return air. Notwithstanding the definition of intake air, for the purpose of ventilation of structures, areas or installations that are required by this subpart D to be ventilated to return air courses, and for ventilation of seals, other air courses may be designated as return air courses by the operator only when the air in these air courses will not be used to ventilate working places or other locations, structures, installations or areas required to be ventilated with intake air. (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 75.301 Definitions, Return air.

Rib sloughing. The process and result where unmined coal pieces and slabs fall away from and off a solid coal rib in an underground coal mine opening.

RMR. Geomechanics Classification Rock Mass Rating (Bieniawski 1973, 1979)

ROC. Receiver Operating Characteristic curve (Hosmer et al. 2013) (statistics).

Rock Mass Quality, Fair. See **Fair rock mass quality**.

Rock Mass Quality, Good. See **Good rock mass quality**.

Rock Mass Quality, Poor. See **Poor rock mass quality**.

Roof potting. A process where rock detaches and falls out from the roof a coal mine leaving holes in the roof rock like potholes in a roadway.

Sample size. The number of cases in a study is the sample size, N (Newton and Rudestam 2013) (statistics).

Secondary roof support. That support installed after primary roof support in anticipation of additional loading at a future point in time (Mark and Barczak 2000).

Sensitivity. The proportion of true positives or the proportion of intersections correctly identified by the model as meeting a Satisfactory intersection condition (statistics).

SGSSM. Stress, Geologic and Support Design System (Stankus et al. 2008).

Significance level. The probability of rejecting the null hypothesis when it is true. In this research, a significance level of 0.05 is used. This is equivalent to a 95% chance that the result is correct (statistics).

Specificity. The proportion of true negatives or the proportion of intersections correctly identified by the model as not meeting a Satisfactory intersection condition (statistics).

SOD. Sum-of-diagonals; the average length of the two diagonals measured across an intersection from diagonal corners.

somers'd. Somers' D; an ordinal measure of association between predictor variables (Newson 2014) (statistics).

Stack rock. A sequence of coal mine roof rock strata composed of interbedded sandstone and shale layers, varying from 0.1 in to several inches in layer thickness (Molinda et al. 2010).

Standing supplemental roof support. That support installed such that the supporting members extend from the roof to the floor in a crosscut, an entry, an intersection or a working face, at a later point in time, because the primary and secondary, if any, support has been shown to be inadequate.

Standing support. Support that is installed such that the supporting members extend from the roof to the floor of the crosscut, entry, intersection or working face.

Std.Dev. Standard deviation (statistics).

Std.Err. Standard Error (statistics).

Supplemental roof support. That support installed in an area a later point in time when the primary and secondary, if any, support has been shown to be inadequate (Mark and Barczak 2000).

Tendon. Australian term for a cable bolt. See **Cable bolt**.

Tension crack. Any open crack in a coal mine roof, rib, or floor.

Travelway. In a coal mine, an entry or crosscut used for travel by men or equipment.

Truss. A roof support system consisting of a roof bolt installed into the roof rock on either side of an entry or crosscut and an assemblage of crossbars and connects across the roof between the roof bolts placed in tension.

UCS or ucs. Unconfined compression strength, units as noted. Typically expresses as psi in the US.

Univariable model. A model with a single predictor variable (statistics).

Unplanned roof fall. The Code of Federal Regulations (Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration 2015), Section 50.20 (h) (8) defines an unplanned roof fall as a fall of roof rock that occurs and meets any one of the following conditions or results:
Any roof fall that resulted in death, injury with potential to cause death, or entrapment for 30 minutes or with the potential to cause death.
•Any unplanned roof fall at or above the anchorage zone in active workings where roof bolts are in use.
•Any unplanned roof or rib fall in active workings that impairs ventilation or impedes passage.
•Any coal or rock outburst that causes withdrawal of miners or which disrupts regular mining activity for more than one hour.
at or above the anchorage zone in active workings where roof bolts are in use; or an unplanned roof or rib fall in active workings where the fall impairs ventilation or impedes passage.

UTS. Ultimate tensile strength.

Variable value. A variable is assigned a value or several values, based on the measurements (Newton and Rudestam 2013) (statistics).

Variable. The term used to describe a particular characteristic of a case (Newton and Rudestam 2013) (statistics). Examples of variables from the EMSA database that describe specific characteristics of an individual case, or intersection, are intersection condition rating, height, diagonal span, coal mine roof rating, roof sag, roof tension cracking, etc.

Ventilation airway. See **Air course**.

Very weak rock. The International Society of Rock Mechanics defines a very weak rock as Grade R1 and as a rock that “crumbles under firm blows with point of geological hammer, can be peeled by a pocket knife”, and has an “approximate range of uniaxial compressive strength of from 1.0 MPa to 5.0 MPa” (Brown 1981).

Weak rock. The International Society of Rock Mechanics defines a weak rock as Grade R2 and as a rock that “can be peeled by a pocket knife with difficult, shallow indentations made by firm blow with point of geological hammer” and has an “approximate range of uniaxial compressive strength of from 5.0 MPa to 25.0 MPa” (Brown 1981).

WLM. Western Longwall Mine.

Working face. The Code of Federal Regulations (CFR) Title 30-Mineral Resources:
§75.2 Definitions
“Working face. Any place in a coal mine in which work of extracting coal from its natural deposit in the earth is performed during the mining cycle.”

Workings. The system of portals, shafts, entries, crosscuts and other underground openings constructed for exploitation and extraction of the coal.

Xcut. Crosscut.

z. z test statistic (statistics).

REFERENCES CITED

Abbasi, Behrooz. 2010. "A numerical analysis of mine intersections and support systems for stability." 1488835 Master of Science, Mining Engineering, Southern Illinois University at Carbondale.

Adler, Lawrence, and Meng-Cherng Sun. 1968. *Ground control in bedded formations: Research Division Bulletin 28*. Blacksburg: Virginia Polytechnic Institute.

Agresti, Alan. 2007. *An introduction to categorical data analysis*. Second ed, *Wiley Series in probability and statistics*. Hoboken, NJ: John Wiley & Sons, Inc.

Agresti, Alan. 2010. *Analysis of ordinal categorical data*. 2nd ed. ed. Hoboken, N.J.: Hoboken, N.J. : Wiley.

Applied Research Associates, Inc. 2008. Bulk rock mass modeling proof of concept. In *ARA-TR-18683*. Albuquerque, New Mexico.

Applied Research Associates, Inc. 2010. Bulk rock mass modeling phase 2: analysis of additional 3-d geometry (2 entry). In *ARA-TR-18683-5*. Albuquerque, New Mexico.

Applied Research Associates, Inc. 2011. Constitutive properties characterization for bulk rock mass modelingof the San Juan Mine. In *ARA Project #: 00974*. Albuquerque, New Mexico.

Barton, N., R. Lien, and J. Lunde. 1974. "Engineering Classification of Rock Masses for the Design of Tunnel Support." *Rock Mechanics. Supplementum = Felsmechanik. Supplementum = Mecanique des Roches. Supplementum* 6 (4):189-236.

CROSSFOLD: Stata module to perform k-fold cross-validation S457426. Boston College Department of Economics.

Bieniawski, Z. T. 1973. "Engineering classification of jointed rock masses." *Trans. S. Afr. Instn. Civ. Engrs.* 15:335-344.

Bieniawski, Z. T. 1979. "The Geomechanics Classification in rock engineering applications." 1979/1/1/.

Brown, E. T., ed. 1981. *Rock characterization, testing & monitoring : ISRM suggested methods*. Edited by International Society for Rock Mechanics. Commission on Testing Methods. Oxford ; New York: Pergamon Press

Published for the Commission on Testing Methods, International Society for Rock Mechanics by Pergamon Press.

Burkhard, David R. 2012. Summary of East Mains mapping project. Waterflow, NM: Western Longwall Mine.

Canbulat, I., and J.N. van der Merwe. 2009. "Design of optimum roof support systems in South African collieries using a probabilistic design approach." *Journal of the Southern African Institute of Mining and Metallurgy* 109:71-88.

Canbulat, Ismet. 2010. "Roadway roof support design in critical areas at anglo american metallurgical coal’s underground operations." The 29th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, July 27-29, 2010.

Carlberg, Conrad 2012. "Predictive Analytics: Microsoft Excel." In *Kindle Edition*. QUE / Pearson Education: Indianapolis, IN.

Colwell, Mark, and Russell C. Frith. 2009. "ALTS 2009 - A ten year journey." Coal 2009: 9th Underground Coal Operators' Conference, University of Wollongong, 12-13 February 2009.

Colwell, Mark, and Russell C. Frith. 2013. "Analysis and design of faceroad roof support." Coal 2013: 13th Underground Coal Operators' Conference, University of Wollongong, 14-15 February 2013.

Colwell, Mark, Russell C. Frith, and G. Reed. 2008. "Tailgate 802 -Grasstree Mine: a case study in prgmatic roof support design." Coal 2008: Coal Operators' Conference, University of Wollongong.

Conover, David P., and Kanaan Hanna. 1989. "Improved design techniques for coal mine entry intersections." Prc. 8th International Strata Control Conference, Dusseldorf, West Germany.

Conover, David P., Kanaan Hanna, Khamis Y. Haramy, and R. Kneisley. 1986. "Structural stability of coal mine entry intersections – case studies." Proceedings of the 27th US Symposium on Rock Mechanics, Rock Mecanics, Key to Energy Production, Tuscaloosa, AL, USA.

Cox, Robert M. 1973. "Why some bolted mine roofs fail, SME Preprint Number 73-F-319." Annual Meeting 1973 Society of Mining Engineers of AIME (SME), Pittsburgh, Pennsylvania, September 19-21, 1973.

Davis, John C. 2002. *Statistics and data analysis in geology*. New York: J. Wiley.

Demidenko, Eugene. 2007. "Sample size determination for logistic regression revisited." *Statistics in Medicine* 26 (18):3385-3397. doi: 10.1002/sim.2771.

Dolinar, Dennis R., and Suresh K. Bhatt. 2000. "Trends in roof bolt application." Information Circular 9453, Proceedings: new technology for coal mine roof support, Pittsburgh, PA, 1/20/2014.

Dunham, R. K. 1976. "Anchorage tests on strain-gauged resin bonded bolts." *Tunnels and Tunnelling* 8 (6):73-76.

Easton, Valerie J., and John H. McColl. 1997. "Statistics glossary v1.1." accessed October 20, 2016. http://www.stats.gla.ac.uk/steps/glossary/probability_distribu.

Electronic Code of Federal Regulations. Title 30. Mineral Resources. Chapter 1 - Mine Safety and Health Administration. 2015. U.S. Government Publishing Office.

Ellis, Charles H. 2004. *Predictor Variable. The SAGE Encyclopedia of Social Science Research Methods. Sage Publications, Inc*. Thousand Oaks, CA: Sage Publications, Inc.

Fabjanczyk, Mike W., and Winton J. Gale. 1999. Reinforcement techniques for weak rock, final report, Report No ACA844/1, ACARP Project No. C5023. In *Australian Coal Assoication Research Program*. Riverside Centre, QLD 4001.

Fairhurst, C., and B. Singh. 1974. "Roofbolting in horizontally laminated rock." *Engineering and Mining Journal* 175 (2):80-88.

Forbes, J. J., and H. J. Sloman. 1948. Information Circular 7461, Control of roof and prevention of accidents from falls of rock and coal. U.S. Bureau of Mines, U.S. Department of the Interior.

Frith, Russell C., and Mark Colwell. 2010. "AMCMRR - an analytical model for coal mine roof reinforcement." Coal 2010: 10th Underground Coal Operators' Conference, University of Wollongong, 11-12 February 2010.

Frith, Russell C., and Mark Colwell. 2011. "Why dead load suspension design for roadway roof support is fundamentally flawed within a pro-active strata management system." The 30th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, July 26-28, 2011.

Gadde, Murali Mohan, John A. Rusnak, and Christopher Mark. 2007. "An integrated approach to support design in underground coal mines." Information Circular 9498 Proceedings of the International Workshop on Rock Mass Classification in Underground Mining, Pittsburgh, PA, May 2007.

Gale, Winton J., Mike W. Fabjanczyk, G. C. Tarrant, and R. J. Guy. 1992. "Optimisation of reinforcement design of coal mine roadways." The 11th International Conference on Ground Control in Mining, University of Wollongong, New South Wales, Australia, July 7-10, 1992.

Galvin, J.M., Bruce K. Hebblewhite, and M.D.G. Salamon. 1999. "University of New South Wales coal pillar strength determinations for Australian and South African mining conditions." Information Circular 9448, Proceedings of the second international workshop on coal pillar mechanics and design, Pittsburgh, PA.

Gercek, Hasan. 1982. "Stability of intersections in room-and-pillar coal mining." PhD Dissertation, Department of Mineral Engineering, The Pennsylvania State University.

Gerdeen, J. C., Snyder V. W., Viegelahn G. L., and J. Parker. 1979. Design critgeria for roof bolting plans using fully resin-grouted nontensioned bolts to reinforce bedded mine roof. Volume III: Experimental models studies; Volume IV:Theoretical analysis. Bureau of Mines contract No. J036604. Houghton, MI: Michigan Technological University.

Ghasemi, Ebrahim, Mohammad Ataei, and Kourosh Shahriar. 2014. "Prediction of global stability in room and pillar coal mines." *Natural Hazards* 72 (2):405-422. doi: http://dx.doi.org/10.1007/s11069-013-1014-2.

Hanna, Kanaan. 1986. "Effect of High Horizontal Stress on Coal Mine Entry Intersection Stability." Proceeding of the Fifth Conference on Ground Control in Mining (ICGCM).

Hanna, Kanaan, and David P. Conover. 1988. "Design of coal mine entry intersections, SME Preprint Number 88-39." Annual Meeting 1988 Society for Mining, Metallurgy, and Exploration, Inc. (SME), Phoenix, AZ USA, January 25-28, 1988.

Hanna, Kanaan, David P. Conover, and Khamis Y. Haramy. 1991a. Report of Investigation 9337, Coal mine entry intersection behavior study. Denver, Colorado: U.S. Department of the Interior, Bureau of Mines.

Hanna, Kanann, David P. Conover, and Khamis Y. Haramy. 1991b. Coal mine entry intersection behavior study. U.S. Dept, of the Interior, Bureau of Mines.

Hoek, Evert , and Edwin T. Brown. 1980. *Underground Excavations in Rock*. London: Institution of Mining and Metallurgy.

Hosmer, David W., Jr., Stanley Lemeshow, and Rodney X. Sturdivant. 2013. *Applied Logistic Regression, Third Edition*, *Wiley Series in Probability and Statistics*. Hoboken, NJ: John Wiley & Sons.

Johnson, Elizabeth. 2016. "Topic2 - Logistic Regression." accessed August 10, 2016. http://www.biostat.jhsph.edu/~ejohnson/regression/topic2.pdf.

Justice, Amy C., and Kenneth E. Covinsky. 1999. "Assessing the generalizability of prognostic information." *Annals of Internal Medicine* 130 (6):515.

Karabin, George J., and James P. Evans. 1998. "Experience with the Boundary-element method of numerical modeling to resolve complex ground control problems." In *Information Circular 9448, Proceedings of the Second International Workshop on Coal Pillar Mechanics and Design*, edited by Christopher Mark, Keith A. Heasley, Anthony T. Iannacchione and Robert J. Tuchman, 89-113. Pittsburgh, PA: Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Insitute for Occupations Safety and Health, Pittburgh Research Laboratory.

Karabin, George J., and Michael A. Evanto. 1994. "Experience with the boundary element method of numerical modeling as a tool to resolve complex ground control problems." The 13th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 2-4, 1994.

Kelly, L. W. 1952. Information Circular 7637, successful use of wooden roof bolts in Stony Point Mine, Stony Point Coal Co., Hopkins County, KY. U.S. Bureau of Mines, U.S. Department of the Interior.

Kleinbaum, David G. 2010. *Logistic Regression A Self-Learning Text*. Edited by Mitchel Klein, *Statistics for Biology and Health*. New York: New York : Springer New York.

Kleinbaum, David G., Lawrence L. Kupper, and Hal Morgenstern. 1982. *Epidemiologic research*. Belmon, California: Wadsworth, Inc.

Lang, Thomas A. 1962. "Theory and practice of rock bolting." In *Transactions of the American Institute of Mining, Metallurgical, and Petroleum Engineers*. New York: Society of Mining Engineerins of AIME.

Lawrence, W.J.C. 2007. "A method for the design of longwall gateroad roof support." PhD PhD, Julius Kruttschitt Mineral Research Centre, The University of Queensland.

Lawrence, W.J.C. 2009. "A method for the design of longwall gateroad roof support." *International Journal of Rock Mechanics and Mining Sciences* 46 (4):789-795. doi: http://dx.doi.org/10.1016/j.ijrmms.2008.11.012.

Lawson, J., E. Zahl, and J. Whyatt. 2012. "Ground condition mapping: a case study." SME Annual Meeting and Exhibit 2012, February 19 - 22, 2012, Seattle, WA, US.

Long, J. Scott, and Jeremy Freese. 2014. *Regression Models for Categorical Dependent Variables Using Stata, Third Edition*. Third ed. College Station, TX: Stata Press.

Maleki, Hamid N. 1992. "Significance of bolt tension in ground control." Proceedings of the International Symposium on Rock Support in Mining and Underground Construction, Jun 16 - 19 1992, Sudbury, Ontario, Canada.

Mangelsdorf, C. P. 1982. "Current trends in roof truss hardware." The 2nd International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, July 19-21, 1982.

Mangelsdorf, C. P. 1985. "Design of a roof truss bolting plan for bear mine." The 4th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, July 22-24, 1985.

Mark, Christopher. 2000. "Design of roof bolt systems." In *Information Circular 9453, Proceedings: new technology for coal mine roof support*, edited by Christopher Mark, Dennis R. Dolinar, Robert J. Tuchman, Thomas M. Barczak and Priscilla F. Wopat, 111-131. Pittsburgh, PA: U.S. Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory.

Mark, Christopher. 2016. "Science of empirical design in mining ground control." *International Journal of Mining Science and Technology* 26 (3):461-470. doi: http://dx.doi.org/10.1016/j.ijmst.2016.02.015.

Mark, Christopher, and Thomas M. Barczak. 2000. "Fundamentals of coal mine roof support." Information Circular 9453, Proceedings: new technology for coal mine roof support, Pittsburgh, PA, 1/20/2014.

Mark, Christopher, and Frank E. Chase. 1997. "Analysis of retreat mining pillar stability (ARMPS)." Information Circular 9446, Proceedings: new technology for ground control in retreat mining, Pittsburgh, PA.

Mark, Christopher, Frank E. Chase, and Deno M. Pappas. 2007a. "Analysis of multiple seam stability." The 26th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, July 31-August 2, 2007.

Mark, Christopher, Frank E. Chase, and Deno M. Pappas, eds. 2007b. *Multiple-seam mining in the United States: design based on case histories*. Edited by Christopher Mark and Robert J. Tuchman, *Information Circular 9495, Proceedings: new technology for ground contrl in multiple-seam mining, DHHS (NIOSH) Publication No. 97-122*. Pittsburgh, PA: U.S Department of Health and Human Services, Public Health Service, Centers for Disease Control and

Prevention, National Insitute for Occupations Safety and Health, Pittburgh Research Laboratory.

Mark, Christopher, Dennis R. Dolinar, and Thomas P. Mucho. 2000. "Summary of field measurements of roof bolt performance." Information Circular 9453, Proceedings: new technology for coal mine roof support, Pittsburgh, PA, 1/20/2014.

Mark, Christopher, Gregory M. Molinda, and Timothy Barton. 2002. "New developments with the coal mine roof rating." The 21st International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 6-8, 2002.

Mark, Christopher, Gregory M. Molinda, Lisa M. Burke, and Penny Padgett. 2004. "Preventing falls of ground in coal mines with exceptionally low-strength roof: two case studies." The 23rd International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 3-5, 2004.

Mark, Christopher, Gregory M. Molinda, and Dennis R. Dolinar. 2001. "Analysis of roof bolt systems." The 20th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 7-9, 2001.

McKillup, Steve, and Melinda Darby Dyar. 2010. *Geostatistics explained; an introductory guide for earth scientists*: Cambridge University Press, Cambridge.

Molinda, Gregory M. 2003. Information Circular 9466, Geologic hazards and roof stability in coal mines. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH).

Molinda, Gregory M., and Ted M. Klemetti. 2008. Diagnosing and controlling moisture-sensitive roof in coal mines. *Electron J Geotech Eng* 13 (A): 1-20. Accessed January 15, 2014.

Molinda, Gregory M., and Christopher Mark. 1994. Information Circular 9387, Coal mine roof rating (CMRR): a practical rock mass classification for coal mines. Pittsburgh, PA: United States Department of the Interior, Bureau of Mines.

Molinda, Gregory M., and Christopher Mark. 2010. Ground failures in coal mines with weak roof. *Electron J Geotech Eng* 13 (F): 547-588. Accessed January 15, 2014.

Molinda, Gregory M., Christopher Mark, Eric Bauer, Daniel Babich, and Deno M. Pappas. 1998. "Factors influencing intersection stability in U.S. coal mines." Proceedings of the 17th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 4-6, 1998.

Molinda, Gregory M., Christopher Mark, and Dennis R. Dolinar. 2000. "Assessing coal mine roof stability through roof fall analysis." In *Information Circular 9453, Proceedings: new technology for coal mine roof support*, edited by Christopher Mark, Dennis R. Dolinar, Robert J. Tuchman, Thomas M. Barczak and Priscilla F. Wopat, iii, 280 p. Pittsburgh, PA: U.S. Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, Pittsburgh Research Laboratory.

Newson, Roger B. 2014. Interpretation of Somers' D under four simple models.

Newton, Rae R., and Kjel Erik Rudestam. 2013. *Your statistical consultant*. Second ed. Thousand Oaks, California: SAGE Publications, Inc.

ARBS - Analysis of roof bolt systems 2..5.02. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA.

CMRR - Coal mine roof rating 2.1.03. U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health (NIOSH), Pittsburgh, PA.

NIOSH. 2014. "CDC NIOSH Program Portfolio, Mining, Projects." accessed 4/29/2014. http://www.cdc.gov/niosh/programs/mining/projects.html.

NIST. 2016. "Runs test for detecting non-randomness." The U.S. Department of Commerce, The National Institute of Standards and Technology (NIST), accessed July 27, 2016. http://itl.nist.gov/div898/handbook/eda/section3/eda35d.htm.

Obert, Leonard, and Wilbur I. Duvall. 1967. *Rock mechanics and the design of structures in rock*. New York: John Wiley & Sons, Inc.

Office of Mine Safety and Health Research (OMSHR). 2013. Mining product: CMRR - Coal mine roof rating. edited by Office of Mine Safety and Health Research. Pittsburgh, PA: U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Osouli, A., A. Shafii, B. Moradi Bajestani, S. Zamiran, and K. S. Singh. 2014. "Rock Mass Characterization for Roof Control Design." 2014 48th US Rock Mechanics/Geomechanics Symposium, Minneapolis, MN USA, 2014/8/18/.

Palei, Sanjay Kumar, and Samir Kumar Das. 2009. "Logistic regression model for prediction of roof fall risks in bord and pillar workings in coal mines: An approach." *Safety Science* 47 (1):88-96. doi: http://dx.doi.org/10.1016/j.ssci.2008.01.002.

Panek, Louis A. 1956a. U.S. Bureau of Mines Report of Investigation 5154, Theory of model testing as applied to roof bolting. Bureau of Mines, U.S. Department of the Interior.

Panek, Louis A. 1956b. U.S. Bureau of Mines Report of Investigation 5155, Design of bolting systems to reinforce bedded mine roof. Bureau of Mines, U.S. Department of the Interior.

Panek, Louis A. 1956c. U.S. Bureau of Mines Report of Investigation 5156, Principles of reinforcing bedded mine roof with bolts. Bureau of Mines, U.S. Department of the Interior.

Panek, Louis A. 1957. "Anchorage characteristics of roof bolts." *Mining Congress Journal* 43 (11):62-64.

Panek, Louis A. 1962a. U.S. Bureau of Mines Report of Investigation 6138, The effects of suspension in bolting bedded mine roof. Bureau of Mines, U.S. Department of the Interior.

Panek, Louis A. 1962b. U.S. Bureau of Mines Report of Investigation 6139, The combined effects of friction and suspension in bolting bedded mine roof. Bureau of Mines, U.S. Department of the Interior.

Panek, Louis A. 1964a. "Design for bolting stratfied roof, SME Preprint Number 64FM37." Annual Meeting 1964 Society of Mining Engineers of AIME (SME), New York, New York, February 16-20, 1964.

Panek, Louis A. 1964b. "Rock mechanics - design for bolting stratified roof." In *AIME Transactions*. Denver: SME-AIME.

Pappas, Deno M., and Christopher Mark. 2011. *Roof and rib fall incident trends: a 10-year profile*. Vol. 330, *Transactions of the Society for Mining, Metallurgy, and Exploration, Inc.* Englewood, CO 80112: Society for Mining, Metallurgy, and Exploration, Inc.

Patrick, W. C., and N. B. Aughenbaugh. 1979. "Classification of roof falls in coal mines." In *AIME Transactions*, 279-283. Denver: SME-AIME.

Peduzzi, Peter, John Concato, Elizabeth Kemper, Theodore R. Holford, and Alvan R. Feinstein. 1996. "A simulation study of the number of events per variable in logistic regression analysis." *Journal of Clinical Epidemiology* 49 (12):1373-1379. doi: http://dx.doi.org/10.1016/S0895-4356(96)00236-3.

Peng, Syd S. 2008. *Coal mine ground control*. 3rd ed. Morgantown, WV: Dept. of Mining Engineering/College of Engineering and Mineral Resources/ West Virginia University.

Peng, Syd S. 2015. "Topical areas of research needs in ground control – A state of the art review on coal mine ground control." *International Journal of Mining Science and Technology* 25 (1):1-6. doi: http://dx.doi.org/10.1016/j.ijmst.2014.12.006.

Peng, Syd S., and L. B. Guo. 1991. "Design criteria for resin bolting." In *AIME Transactions*, 5. Denver: SME-AIME.

Peng, Syd S., L. B. Guo, and C. T. Holland. 1989. "Design criteria for resin bolting, SME Preprint Number 89-166." Annual Meeting 1989 Society for Mining, Metallurgy, and Exploration, Inc. (SME), Las Vegas, NM USA, February 27 - March 2, 1989.

Peng, Syd S., and S. Okubo. 1978. "Roof bolting patterns at the four-way entry intersections, SME Preprint Number 78-AM-5." Annual Meeting 1978 Society of Mining Engineers of AIME (SME), Denver, Colorado, February 28 - March 2, 1978.

Platt, D. H. 1952. Information Circular 7652, roof bolting the Delaware Aqueduct. U.S. Bureau of Mines, U.S. Department of the Interior.

Salamon, M. D. G. 1999. "Strength of coal pillars from back-calculation." 37th US rock mechanics symposium, Vail, Colorado.

Salamon, M.D.G., and A.H. Munroe. 1967. "A study of the strength of coal pillars." *J. S. Afr. Inst. Min. Metall.* (September 1967):55-67.

Seedsman, Ross W., Nick Gordon, and Naj Aziz. 2009. Analytical tools for managing rock fall hazards in Australian coal mine roadways. Australian Coal Association Research Program (ACAPR).

Sheorey, P. R., M. N. Das, D. Barat, R. K. Prasad, and B. Singh. 1987. "Coal pillar strength estimation from failed and stable cases." *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts* 24 (6):347-355. doi: http://dx.doi.org/10.1016/0148-9062(87)92256-X.

Skiles, Mark E., and Kevin G. Stricklin. 2009. Program Information Bulletin No. P09-03, General guidelines for the use of numerical modeling to evaluate ground control aspects of proposed coal mining plans. edited by Coal Mine Safety and Health. Arlington, VA.

Stahl, R. W. 1962. Information Circular 8113, Survey of practices in controlling roof at intersections and junctions in underground coal mines. Bureau of Mines, U.S. Department of the Interior.

Stankus, John C., and Song Guo. 1997. "New design criteria for roof bolt systems." The 16th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 5-7, 1997.

Stankus, John C., K. J. Ma, H. Chen, and X. Li. 2008. Stress, geologic, and support analysis methodology for underground openings. US Patent Application 20100042381. Filed on August 18, 2008. United States.

Stankus, John C., and Syd S. Peng. 1996. "A new concept for roof support." *Coal Age*, 67.

Stankus, John, Kevin Jinrong Ma, Hanjie Chen, and Xiaoting Li. 2011. "Application of Stress, Geologic, and Support Design System (SGSSM) to Ground Control for Mine Slope Entries." The 30th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, July 26-28, 2011.

smallStata statistical analysis and graphics software. StataCorp LP, College Station, TX, USA.

Stone, Ry. 2016. "Design of primary ground support during roadway development using empirical databases." *International Journal of Mining Science and Technology* 26 (1):131-137. doi: http://dx.doi.org/10.1016/j.ijmst.2015.11.021.

Systat 13 Statistical analysis and graphics software. Systat Software, a division of Cranes Software International, San Jose, CA.

Tadolini, Stephen C., and Raymond A. Mazzoni. 2006. "Twenty-four conferences; more than one-hundred and seventy papers; understanding roof bolt selection and design still remains priceless." The 25th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, August 1-3, 2006.

Terzaghi, Karl. 1946. "Section I - Rock defects and loads on tunnel supports." In *Rock tunneling with steel supports*, edited by Robert V. Proctor and While Thomas L., 296. Youngstown, Ohio: Commercial Shearing, Inc.

Thomas, Edward. 1950. Information Circular 7583, Roof bolting in the United States. U.S. Bureau of Mines, U.S. Department of the Interior.

Thomas, Edward. 1954. "Rock bolting finds wide application." *Mining Engineering* 6 (11):1080-1085.

Thomas, Edward. 1962. "Stabilization of rock by bolting." *Reviews in Engineering Geology* 1:257-280. doi: 10.1130/REG1-p257.

Thomas, Edward, A. J. Barry, and A. Metcalfe. 1949. Information Circular 7533, suspension roof support, progress report I. U.S. Bureau of Mines, U.S. Department of the Interior.

Thomas, Edward, C. H Seeling, F. Perz, and M. V. Hansen. 1948. Information Circular 7471, control of roof and prevention of accidents from falls of rock and coal: suggested roof supports for use at faces in conjunction with mechanical loading. U.S. Bureau of Mines, U.S. Department of the Interior.

Unal, Erdal. 1983. "Development of design guidelines and roof-control standards for coal-mine roofs." 8327564 Ph.D., Department of Mineral Engineering, The Pennsylvania State University.

Unal, Erdal. 1986. "Empirical approach to calculate rock loads in coal mine roadways." The 5th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, June 11-13, 1986.

Unal, Erdal. 1989. "Support selection of mine roadways by means of a computer program." The 8th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, June 19-22, 1989.

van Kempen, C. J. H. Brest. 1986. "How to design an efficient roof bolting plan based on simple in-mine measurements." The 5th International Conference on Ground Control in Mining, Lakeview Scanticon Resort & Conference Center, Morgantown, West Virginia, June 11-13, 1986.

Vittinghoff, E., and C. E. McCulloch. 2007. "Relaxing the rule of ten events per variable in logistic and Cox regression." *American Journal of Epidemiology* 165 (6):710-718. doi: 10.1093/aje/kwk052.

Voegele, Michael D. 1979. Rational design of tunnel supports: an interactive graphics based analysis of the support requirements of excavations in jointed rock masses. Vicksburg, Mississippi: Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station.

Wattimena, R. K., S. Kramadibrata, I. D. Sidi, and M. A. Azizi. 2013. "Developing coal pillar stability chart using logistic regression." *International Journal of Rock Mechanics and Mining Sciences (1997)* 58:55-60. doi: http://dx.doi.org/10.1016/j.ijrmms.2012.09.004.

Wood, Jr., Gordon H., Thomas M. Kehn, M. Devereux Carter, and William C. Culbertson. 1983. "Coal Resource Classification System of the U.S. Geological Survey." US Geological Survey, US Department of Interior, Last Modified 16-Mar-2015, accessed June 16. http://pubs.usgs.gov/circ/c891/intro.htm.

Young, H. C. 1954. Informational Circular 7678, Roof bolting in Alabama coal mines and iron-ore mines. Pittsburgh, PA: Bureau of Mines.

APPENDIX A

EAST MAINS STUDY AREA DATABASE CODEBOOK

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
agemo	Age of intersection in months.	Numeric Variable Range: 13–134
arbs	Analysis of Roof Bolt Systems, actual.	Numeric Variable Range: 9–47 kips/ft
arbsniosh	Analysis of Roof Bolt Systems, NIOSH program calculation.	Numeric Variable Range: 3–33 kips/ft
can	Standing, supplemental roof support, pumpable crib or can type.	0 = None 1 = Pumpable cribs 2 = Cuttable cribs 3 = Burrell cans
cmrr	Coal Mine Roof Rating, with roof water.	Numeric Variable Range: 0–40
cmrrdry	Coal Mine Roof Rating, dry conditions.	Numeric Variable Range: 23–41
combo	Standing, supplemental roof support, combined support type.	0 = None 1 = J-channel plus two Roc props 2 = J-channel plus three Roc props 3 = J-channel plus four Roc props 4 = GT 120 plus Roc props
coordeast	Intersection east coordinate.	Numeric Variable
coordnorth	Intersection north coordinate.	Numeric Variable
crib	Standing, supplemental roof support, wood crib type.	0 = None 1 = 4-point wood cribs 2 = 6-point wood cribs 3 = 9-point wood cribs
ctr_cnrne	Cutter-gutter, corner, northeast.	0 = No 1 = Yes

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
ctr_cnrneamt	Cutter-gutter, corner, northeast, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
ctr_cnrnw	Cutter-gutter, corner, northwest.	0 = No 1 = Yes
ctr_cnrnwamt	Cutter-gutter, corner, northwest, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
ctr_cnrse	Cutter-gutter, corner, southeast.	0 = No 1 = Yes
ctr_cnrseamt	Cutter-gutter, corner, southeast, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
ctr_cnrsw	Cutter-gutter, corner, southwest.	0 = No 1 = Yes
ctr_cnrswamt	Cutter-gutter, corner, southwest, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
ctr_ribe	Cutter-gutter, rib, east.	0 = No 1 = Yes
ctr_ribeamt	Cutter-gutter, rib, east, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
ctr_ribn	Cutter-gutter, rib, north.	0 = No 1 = Yes
ctr_ribnamt	Cutter-gutter, rib, north, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
ctr_ribs	Cutter-gutter, rib, south.	0 = No 1 = Yes
ctr_ribsamt	Cutter-gutter, rib, south, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
ctr_ribw	Cutter-gutter, rib, west.	0 = No 1 = Yes
ctr_ribwamt	Cutter-gutter, rib, west, amount.	0 = None 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
delam	Visible delamination of intersection roof rock.	0 = No 1 = Yes
depth	Mining depth.	Numeric Variable Range: 100–1200 feet
devldate	Development mining date.	Numeric Variable yyyy.mm Range: 2001.08–2010.07
diagmax	Diagonal, single maximum, length.	Numeric Variable Range: 22–47 feet
diagmin	Diagonal, single minimum, length.	Numeric Variable Range: 0–47 feet
diagnesw	Diagonal, NE-SW, length.	Numeric Variable Range: 0–47 feet
diagnwse	Diagonal, NW-SE, length.	Numeric Variable Range: 0–46 feet
diagsod	Diagonal, Average, Sum-of-diagonals.	Numeric Variable Range: 11–47 feet
dome	Visible doming of roof in intersection.	0 = No 1 = Yes
entcndinby	Entry roof condition, inby from intersection.	1 = Good 2 = Fair 3 = Poor 4 = Very poor 5 = MSHA Reportable fall

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
entcndoutby	Entry roof condition, outby from intersection.	1 = Good 2 = Fair 3 = Poor 4 = Very poor 5 = MSHA Reportable fall
entwid	Average entry width.	Numeric Variable Range: 17–33 feet
fault	Visible fault anywhere in the intersection.	0 = No 1 = Yes
flhvht	Floor heave height.	Numeric Variable Range: 0–3 feet, 0.5-ft increments
flmoisendata	Immediate floor rock moisture sensitivity data.	Numeric Variable Range: 0.9–4.1
flmoisenidx	Immediate floor rock moisture sensitivity index.	1 = Not sensitive 2 = Slightly sensitive 3 = Moderately sensitive 4 = Severely sensitive
flpltdia	Immediate floor rock point load diameter strength.	Numeric Variable Range: 19–147 psi
flrqd	Immediate floor rock RQD.	Numeric Variable 0–100
flthk	Immediate floor rock unit thickness.	Numeric Variable 1–44 feet
flucs	Immediate floor rock unconfined compressive strength.	Numeric Variable Range: 487–7450 psi
flwater	Floor water flow rating.	1 = Dry 2 = Damp 3 = Wet 4 = Standing water 5 = Flooded
fptb	Roof Fall prior to bolting.	0 = No 1 = Yes
grsupact	Ground Support Rating, actual.	Numeric Variable Range: 14–32 kips/ft
grsupcal	Ground Support Rating, recommended.	Numeric Variable Range: 14–32 kips/ft
icr	Intersection Condition Rating.	0 = Not satisfactory 1 = Satisfactory

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
icrf	Intersection Condition Rating, Field, Team 2.	1 = Good 2 = Fair 3 = Poor 4 = Very poor 5 = MSHA reportable roof fall
icrp	Intersection Condition Rating, Preliminary	0 = Not satisfactory 1 = Satisfactory
icrss	Intersection Condition Rating, East Mains standing support mine map.	1 = Good 2 = Fair 3 = Poor
inroof	In-roof secondary or supplemental roof support.	0 = None 1 = Thread bar 7 = Monster mat plus Hi-Ten 35’ cable bolts 8 = J-channel + thread bar 9 = J-channel + thread bar + trussing 10 = J-channel + thread bar
intgm	Intersection geometry.	2 = 2-way intersection 3 = 3-way intersection 4 = 4-way intersection
intht	Intersection height, feet.	Numeric Variable Range: 6–24 feet
intno	Intersection database number.	Numeric Variable Range: 1–884
lwstress	Longwall stress level.	0 = None 1 = Low 2 = Moderate 3 = High 4 = Very high
lwstress2	Longwall stress level.	0 = None 1 = Low 2 = Moderate 3 = High
mainwide	Number of entries across the mains.	Numeric Variable Range: 3, 4, 5, 6, or 7
msha	MSHA reportable roof fall.	0 = No 1 = Yes

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
plravg	Intersection average pillar stability factor.	Numeric Variable Range 0–5
plrmax	Maximum pillar development stability factor.	Numeric Variable Range: 0.7 – 4.6
plrmin	Minimum pillar development stability factor.	Numeric Variable Range: 0.6 – 4.1
plrnesf	Pillar NE, development stability factor.	Numeric Variable Range: 0.6 – 4.1
plrnwsf	Pillar NW, development stability factor.	Numeric Variable Range: 0.6 – 4.6
plrsesf	Pillar SE, development stability factor.	Numeric Variable Range: 0.6 – 4.6
plrsum	Sum of all pillar development stability factors.	Numeric Variable Range: 2.6 – 17.7
plrswsf	Pillar SW, development stability factor.	Numeric Variable Range: 0.6 – 4.6
prop	Standing, supplemental roof support, prop type.	0 = None 1 = Wood timbers 2 = Spider props 3 = Ball busters 4 = Roc props
rfbltdia	Roof bolt diameter.	1 = #7 (0.875 inch) 2 = #8 (1.000 inch) 3 = 0.804 (0.804 inch)
rfbltgrd	Roof bolt grade.	1 = 60 grade 2 = 75 grade
rfbltlen	Roof bolt length.	1 = 7 ft 2 = 8 ft
rfbltmfg	Roof bolt manufacturer.	1 = Dywidag 2 = Excel 3 = Jennmar 4 = Locotos
rfbltrow	Roof bolts per row.	4, 5, or 6
rfbltspc	Roof bolt row spacing.	4 or 5 ft
rfblttype	Roof bolt type.	1 = Torque-tension 2 = Rebar 3 = D-dome 4 = Mechanical 5 = DSI thread bar

Variable Name	**Variable Label**	**Categorical Variable Value Code and Value Label, or Numeric Variable Range**
rfcoal	Top coal thickness categories.	0 = None 0 ft to <= 0.5 ft 1 = Thin >0.5 ft to <=1.8 ft 2 = Moderate > 1.8 ft
rfcoalthk	Roof top coal thickness, feet.	Numeric Variable Range 0.0–2.1 feet
rfcorr1	Roof corrosion amount, Team 1.	0 = No 1 = Yes
rfcorr2	Roof corrosion amount, Team 2.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
rfdry	Is the roof dry?	0 = No 1 = Yes
rfgeo	Roof stratigraphic location.	1 = P3 location 2 = P3½ location 3 = P4 location 4 = Sandstone
rfmat	Presence and type of steel sheeting as part of in-roof support.	0 = none present 1 = monster mat 2 = bacon strips 99 = Missing data
rfmesh	Type of mesh installed as part of in-roof support.	1 = 4x4 2 = 6x6 3 = EM 4 = Hy4x4 5 = Hy6x6 6 = SL 99 = Missing data
rfsag	Roof sag present.	0 = No 1 = Yes
rfsagamt	Roof sag amount, feet.	Numeric Variable 0–1.5 ft. 0.25-ft increments
rfsagcat	Roof sag amount ≤ 0.25 ft.	0 = No 1 = Yes
rfucs	Immediate roof rock ucs.	Numeric Variable 600–2773 psi

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
rfwater	Roof water flow rating.	0 = Dry 1 = Damp 2 = Light drip 3 = Heavy drip 4 = Flowing
rfwater1	Roof water flow, Team 1.	0 = Dry 1 = Damp 2 = Wet 3 = Dripping 4 = Running
rfwater2	Roof water flow, Team 2.	0 = Dry 1 = Damp 2 = Light drip 3 = Heavy drip 4 = Flowing
ribbltlen	Rib bolt length.	0 = no rib bolts, 4, 6, 7, 8, 10-ft bolt lengths, and 99 = Missing data
ribblttype	Rib bolt type.	0 = no rib bolts present 1 = torque-tension 2 = rebar 3 = D-dome 4 = mechanical 5 = DSI thread bar 99 = Missing data
ribmesh	Rib mesh type.	0 = no rib mesh present 1 = welded wire 2 = chain link 3 = Tensar 4 = Huesker 99 = Missing data
ribms	Mudstone in lower rib.	0 = No mudstone is present in the rib. Intersection floor is comprised of coal. 1 = Mudstone present in the rib. Intersection floor is comprised of mudstone.

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
ribmsthk	Thickness of mudstone in lower rib.	Numeric Variable Range: 0–9 feet
ribplatetype	Rib bolt plate type.	0 = no rib plates present 1 = 6x6 2 = 8x8 3 = 6x16 4 = 11x12 5 = 11x18 6 = 18x18 99 = Missing data
set	Standing, supplemental roof support, steel set type.	0 = None 1 = Square 2 = Cambered 3 = Gazebo-style
slfcnrne	Sloughage, corner, NE, present.	0 = No 1 = Yes
slfcnrneamt	Sloughage, corner, NE, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfcnrneloc	Sloughage, corner, NE, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfcnrnw	Sloughage, corner, NW, present.	0 = No 1 = Yes
slfcnrnwamt	Sloughage, corner, NW, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfcnrnwloc	Sloughage, corner, NW, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfcnrse	Sloughage, corner, SE, present.	0 = No 1 = Yes
slfcnrseamt	Sloughage, corner, SE, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
slfcnrseloc	Sloughage, corner, SE, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfcnrsw	Sloughage, corner, SW, present.	0 = No 1 = Yes
slfcnrswamt	Sloughage, corner, SW, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfcnrswloc	Sloughage, corner, SW, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfe	Sloughage, rib, E, present.	0 = No 1 = Yes
slfeamt	Sloughage, rib, E, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfeloc	Sloughage, rib, E, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfn	Sloughage, rib, N, present.	0 = No 1 = Yes
slfnamt	Sloughage, rib, N, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfnloc	Sloughage, rib, N, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfs	Sloughage, rib, S, present.	0 = No 1 = Yes
slfsamt	Sloughage, rib, S, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfsloc	Sloughage, rib, S, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slfw	Sloughage, west side, present.	0 = No 1 = Yes

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
slfwamt	Sloughage, rib, W, amount.	0 = None observed 1 = Very minor 2 = Minor 3 = Moderate 4 = Major
slfwloc	Sloughage, rib, W, location.	1 = from mid-rib to roof 2 = from mid-rib to floor
slick	Slickensides in intersection?	0 = No 1 = Yes
ss1	SS1 present.	0 = No 1 = Yes
ss1margin	SS1 margin deposit present.	0 = No 1 = Yes
ss2	SS2 present.	0 = No 1 = Yes
ss2margin	SS2 margin deposit present.	0 = No 1 = Yes
sspc	PCSS Present.	0 = No 1 = Yes
sspcmargin	PCSS margin deposit present.	0 = No 1 = Yes
tanylarge	Any large tension crack.	0 = No 1 = Yes
tn	Tension crack in intersection roof.	0 = No tension cracks observed 1 = Tension cracks observed

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
tnc	Tension crack, center, size.	0 = No tension crack running through center of intersection. 1 = Hairline tension crack running through center of intersection. 2 = Small (~1/8 inch) tension crack running through center of intersection. 3 = Medium (~1/4 inch) tension crack running through center of intersection. 4 = Large (>1/4 inch) tension crack running through center of intersection.
tncdir	Tension crack, center, orientation.	1 = East-west 2 = North-south 3 = Northwest-southeast 4 = Northeast-southwest
tne	Tension crack, E side, size.	0 = No tension crack running along east side of intersection. 1 = Hairline tension crack running along east side of intersection. 2 = Small (~1/8 inch) tension crack running along east side of intersection. 3 = Medium (~1/4 inch) tension crack running along east side of intersection. 4 = Large (>1/4 inch) tension crack running along east side of intersection.
tnedir	Tension crack, E side, orientation.	1 = East-west 2 = North-south 3 = Northwest-southeast 4 = Northeast-southwest

Variable Name	**Variable Label**	**Categorical Variable Value Code and Value Label, or Numeric Variable Range**
tnn	Tension crack, N side, size.	0 = No tension crack running through center of intersection. 1 = Hairline tension crack running through center of intersection. 2 = Small (~1/8 inch) tension crack running through center of intersection. 3 = Medium (~1/4 inch) tension crack running through center of intersection. 4 = Large (>1/4 inch) tension crack running through center of intersection.
tnndir	Tension crack, N side, orientation.	1 = East-west 2 = North-south 3 = Northwest-southeast 4 = Northeast-southwest
tns	Tension crack, S side, size.	0 = No tension crack running through center of intersection. 1 = Hairline tension crack running through center of intersection. 2 = Small (~1/8 inch) tension crack running through center of intersection. 3 = Medium (~1/4 inch) tension crack running through center of intersection. 4 = Large (>1/4 inch) tension crack running through center of intersection.

Variable Name	**Variable Label**	**Categorical Variable Value Code and Value Label, or Numeric Variable Range**
tnsdir	Tension crack, S side, orientation.	1 = East-west 2 = North-south 3 = Northwest-southeast 4 = Northeast-southwest
tnw	Tension crack, W side, size.	0 = No tension crack running through center of intersection. 1 = Hairline tension crack running through center of intersection. 2 = Small (~1/8 inch) tension crack running through center of intersection. 3 = Medium (~1/4 inch) tension crack running through center of intersection. 4 = Large (>1/4 inch) tension crack running through center of intersection.
tnwdir	Tension crack, W side, orientation.	1 = East-west 2 = North-south 3 = Northwest-southeast 4 = Northeast-southwest
trsbltlen	Truss anchor bolt length.	Numeric Variable Range: 8 or 10 feet
trscare	Number of carrier trusses, E side of intersection.	Numeric Variable Range: 0 – 3
trscarn	Number of carrier trusses, N side of intersection.	Numeric Variable Range: 0 – 3
trscars	Number of carrier trusses, S side of intersection.	Numeric Variable Range: 0 – 3
trscarw	Number of carrier trusses, W side of intersection.	Numeric Variable Range: 0 – 3
trsdbl	Intersection double trussed.	0 = No 1 = Yes

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
trsdir	Truss orientation.	0 = No trusses in intersection 1 = North-south 2 = East-west
trsload	Truss shoe load amount.	Numeric Variable Range: 0–1.5 feet
trsloadcat	Truss shoe loading ≤ 2 in.	0 = No 1 = Yes
trsspc	Truss spacing.	Numeric Variable Range: 2 or 4 feet
trstype	Truss type.	1 = Jennmar 2 = DSI Mark IV 3 = DSI Mark VI 4 = DSI Mark VII 5 = DSI Mark VIII 6 = Minova In-roof 7 = Jennmar Bytm 7
tsum	Total tension crack magnitude sum.	Numeric Variable Range: 0 – 12 in
ventbelt	Intersection is located in a beltline entry.	0 = No 1 = Yes
venttype	Intersection ventilation type.	1 = Return or Seal 2 = Belt line 3 = Intake
widentavg	Average width of entries and crosscuts forming the intersection, feet.	Numeric Variable Range: 15–23 feet
widente	Width of entry to E of intersection, feet.	Numeric Variable Range: 15–29 feet
widentw	Width of entry to W of intersection, feet.	Numeric Variable Range: 16–30 feet
widxcn	Width of crosscut to N of intersection, feet.	Numeric Variable Range: 14–25 feet
widxcs	Width of crosscut to S of intersection, feet.	Numeric Variable Range: 12–29 feet
xcutcondn	Crosscut roof condition, N side of intersection.	1 = Good 2 = Fair 3 = Poor 4 = Very poor 5 = MSHA Reportable fall

Variable Name	Variable Label	Categorical Variable Value Code and Value Label, or Numeric Variable Range
<u>xcutconds</u>	Crosscut roof condition, S side of intersection.	1 = Good 2 = Fair 3 = Poor 4 = Very poor 5 = MSHA Reportable fall

APPENDIX B

EAST MAINS STUDY AREA DATABASE VARIABLE NOTES

Variable Name	Variable Notes
agemo	Age is calculated as the number of months elapsed between the mining month, based on survey maps and data, and October 2012, the approximate end date of field data collection by Team 2.
arbs	Calculated using actual field data and the ARBS method (Mark et al. 2001).
arbsniosh	Calculated using the NIOSH ARBS Method (Mark, Molinda and Dolinar, 2001) equations (6 and 7). ARBSNIOSH = 1.2 • (ARBSG - ARBSadjust)
can	Denotes the presence and type of pumpable crib or can, if present. There is no information on support size, load carrying capacity, installed location or installed pattern.
cmrr	Calculations from Excel spreadsheet cmrr_calcs.xlsx.
cmrrdry	Calculations from Excel spreadsheet cmrr_calcs.xlsx.
combo	Denotes the presence and type, if present, of combinations of Roc Props with either J-channel or GT 120 used to create supplemental standing support. Combos are typically used were continued clearance for access is needed. There is no information on support size, load carrying capacity, installed location or installed pattern.
coordeast	Easting coordinate of the approximate center of the intersection based on New Mexico State Plane Coordinate System, NAD27 datum. Measurement is feet.
coordnorth	Northing coordinate of the approximate center of the intersection based on New Mexico State Plane Coordinate System. NAD 27 datum. Measurement is feet.
crib	Denotes the presence and type of wood crib, if present. There is no information on support size, load carrying capacity, installed location or installed pattern.
ctr_cnrne	Denotes the presence or absence of cutter or gutter on the northeast corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection.

Variable Name	Variable Notes
	Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_cnrneamt	Degree of cutter or gutter observed on the northeast corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_cnrnw	Denotes the presence or absence of cutter or gutter on the northwest corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_cnrnwamt	Degree of cutter or gutter observed on the northwest corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_cnrse	Denotes the presence or absence of cutter or gutter on the southeast corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_cnrseamt	Degree of cutter or gutter observed on the southeast corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
*ctr_*cnrsw	Denotes the presence or absence of cutter-gutter on the southwest corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_cnrswamt	Degree of cutter-gutter observed on the southwest corner of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection.

Variable Name	Variable Notes
	Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribe	Denotes the presence or absence of cutter or gutter along ribs immediately to the east of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribeamt	Denotes the presence or absence of cutter or gutter along ribs immediately to the east of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribn	Denotes the presence or absence of cutter or gutter along ribs immediately to the north of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribnamt	Degree of cutter or gutter observed along ribs immediately to the north of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribs	Denotes the presence or absence of cutter or gutter along ribs immediately to the south of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribsamt	Degree of cutter or gutter observed along ribs immediately to the south of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribw	Denotes the presence or absence of cutter-gutter along ribs immediately to the west of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection.

Variable Name	Variable Notes
	Gutter is the resulting void space due to rock falling out of the fracture zone.
ctr_ribwamt	Degree of cutter-gutter observed along ribs immediately to the west of the intersection. Cutter is a linear fracturing of rock along the roof-rib intersection. Gutter is the resulting void space due to rock falling out of the fracture zone.
delam	Is delamination of roof rock strata visible in the intersection roof?
depth	Depth from the ground surface to the mine roof of the intersection at the approximate center of the intersection determined from the geology overburden map. Measurement is in feet.
devldate	Approximate year and month the intersection was developed for mine survey progress maps.
diagmax	Intersection diagonal length of longest of the two diagonal measurements, actual, feet.
diagmin	Intersection diagonal length of shortest of the two diagonal measurements, actual, feet.
diagnesw	Intersection diagonal length measurement from NE corner to SW corner of the intersection, actual, feet.
diagnwse	Intersection diagonal length measurement from NW corner to SE corner of the intersection, actual, feet.
diagsod	diagsod = (diagnesw + diagnwse) / 2. Very small values represent 2-way intersection geometry.
dome	Is there visible doming of the intersection roof?
entcndinby	The average condition of the roof of the entry for approximately 30 ft inby from the intersection. Condition rating is based on the field intersection success rating measurement scale. Good (=1). All of the following must be present: Intersection has only original roof bolting. No travel or ventilation restriction. Intersection fully serves intended / functional design (intake, travelway, escapeway, return, belt line, overcast, etc.). Fair (=2). Any of the following may be present: Intersection shows minor roof cracking or presence of water. Original roof support supplemented with additional roof bolting, meshing, etc.

Variable Name	Variable Notes
	May include some minor standing support located at corners or for rib control. Original functional design not currently compromised. Poor (=3). Any of the following may be present: Significant additional standing support installed in the intersection or to either side of the intersection in the crosscuts. Roof failure / fall below the top of the bolted interval. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. Belt maintenance operations compromised due to clearance issues with standing support. Very poor (=4). Any of the following may be present: Longwall tailgate blockage. Escapeway routed around area. Steel sets or equivalent installed to maintain access for underground mobile equipment. Significant additional standing support installed in the crosscuts to either side of the intersection in the crosscuts. MSHA Reportable Roof Fall (=5). Roof failure and caving occurred above the bolted horizon. 30 CFR § 50.10 requires immediate reporting to MSHA of a roof fall with failure and caving above the bolted horizon.
entcndoutby	The average condition of the roof of the entry for approximately 30 ft outby from the intersection. Condition rating is based on the field intersection success rating measurement scale. Good (=1). All of the following must be present: Intersection has only original roof bolting. No travel or ventilation restriction. Intersection fully serves intended / functional design (intake, travelway, escapeway, return, belt line, overcast, etc.). Fair (=2). Any of the following may be present: Intersection shows minor roof cracking or presence of water. Original roof support supplemented with additional roof bolting, meshing, etc. May include some minor standing support located at corners or for rib control.

Variable Name	Variable Notes
	Original functional design not currently compromised. Poor (=3). Any of the following may be present: Significant additional standing support installed in the intersection or to either side of the intersection in the crosscuts. Roof failure / fall below the top of the bolted interval. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. Belt maintenance operations compromised due to clearance issues with standing support. Very poor (=4). Any of the following may be present: Longwall tailgate blockage. Escapeway routed around area. Steel sets or equivalent installed to maintain access for underground mobile equipment. Significant additional standing support installed in the crosscuts to either side of the intersection in the crosscuts. MSHA Reportable Roof Fall (=5). Roof failure and caving occurred above the bolted horizon. 30 CFR § 50.10 requires immediate reporting to MSHA of a roof fall with failure and caving above the bolted horizon.
entwid	Average entry width calculated as [diagnesw+diagnwse] / [2 • sqrt(2)]. This is equivalent to the ARBS variable, We, Entry width.
fault	Is a fault visible anywhere in the intersection, roof, rib, or floor?
faultfl	Visible faults in the floor and, if present, vertical extent of the fault.
faultrf	Visible faults in the roof and, if present, vertical extent of the fault.
flhvht	Measured height of observed floor heave, nearest 0.5-foot. 0 - 3.0 in 0.5-ft increments
flmoisendata	Immediate floor moisture sensitivity data from contours developed from drill hole data using Golden Software Surfer ® 12.
flmoisenidx	Immediate floor moisture sensitivity rating based on CMRR moisture sensitivity index and created by rounding flgeo01moisendata contour data to the nearest integer with the Excel ROUND function.

Variable Name	Variable Notes
flpltdia	Immediate floor point load diameter strength, psi, created by rounding flgeo01pltdata contour data to the nearest integer with the Excel ROUND function.
flrqd	Immediate floor RQD data from contours developed from drill hole data using Golden Software Surfer ® 12. Immediate floor RQD created by rounding Surfer ® 12 contour data to the nearest integer with the Excel ROUND function.
flthk	Thickness of the geologic unit that comprises the immediate floor of the intersection from contours developed from drill hole data using Golden Software Surfer ® 12.
flucs	The unconfined compressive strength of the floor unit from contours developed from drill hole data using Golden Software Surfer ® 12.
flwater	Degree of moisture or water visible on the intersection floor.
fptb	Did a roof fall occur prior to bolting?
grsup	Calculated using the GRSUP method (Colwell et al. 2009) and field data.
icr	The final categorization of intersection success was made utilizing the following criteria for a successful intersection. SUCC equals "Successful" (1) when: Intersection geometry of 3-way or 4-way. WLM East Mains standing support rating of 1. Field Team 2 intersection success rating of 1 or 2. No secondary or supplemental in-roof support installed. No supplemental standing support installed. No large (>0.25 in) tension crack present anywhere in the intersection. Total number of tension cracks less than or equal to 3. Roof sag less than or equal to 75 mm (3 inch). Truss shoe deformation less than or equal to 52 mm (2 inch).
icrf	The intersection success rating assigned in the field to each intersection by Team 2 during their inspection of each intersection and adjacent workings. Good (=1). All of the following must be present: Intersection has only original roof bolting. No travel or ventilation restriction. Intersection fully serves intended / functional design (intake, travelway, escapeway, return, belt line, overcast, etc.).

Variable Name	Variable Notes
	Fair (=2). Any of the following may be present: Intersection shows minor roof cracking or presence of water. Original roof support supplemented with additional roof bolting, meshing, etc. May include some minor standing support located at corners or for rib control. Original functional design not currently compromised. Poor (=3). Any of the following may be present: Significant additional standing support installed in the intersection or to either side of the intersection in the crosscuts. Roof failure / fall below the top of the bolted interval. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. Belt maintenance operations compromised due to clearance issues with standing support. Very poor (=4). Any of the following may be present: Longwall tailgate blockage. Escapeway routed around area. Steel sets or equivalent installed to maintain access for underground mobile equipment. Significant additional standing support installed in the crosscuts to either side of the intersection in the crosscuts. MSHA Reportable Roof Fall (=5). Roof failure and caving occurred above the bolted horizon. 30 CFR § 50.10 requires immediate reporting to MSHA of a roof fall with failure and caving above the bolted horizon.
icrp	This is the intersection condition rating, preliminary. Values and value labels are as follows: 0 = Not satisfactory 1 = Satisfactory It is based on the following criteria for a rating of satisfactory intersection condition: • icrf rating of Good (1) or Fair (2), icrf<=2. • icrss (EMSA standing support map) rating of Good (1), icrss=1. • inroof = 0. No secondary or supplemental in-roof support installed in intersection, Team 1.

Variable Name	Variable Notes
	• No supplemental standing support installed in intersection. The following variables all equal zero: can, combo, crib, prop, and set.
icrss	This data comes from an AutoCAD drawing map titled, Jordans Working Map - Standard.zip 1 = Good. Intersection has no to very little standing support shown on map. Intersection travelway not impacted by the installed supplemental standing support. This is categorized as a successful intersection. 2 = Fair. Intersection has some standing support shown on the map, either in the intersection or in the adjacent crosscuts. Intersection travelway function somewhat impacted by the installed supplemental standing support. This is categorized as an unsuccessful intersection. 3 = Poor. Significant supplemental standing support installed in the intersection or to either side of the intersection in the crosscuts. Intersection travelway function either significantly impacted or routed around intersection. Escapeway routed around intersection. Also, includes MSHA-reportable roof fall. This is categorized as an unsuccessful intersection.
inroof	Secondary or supplemental in-roof support installation data collected by Team 1. There is no information on support installed location or installed pattern.
intgm	Intersection geometry as 2-way, 3-way or 4-way.
intht	Intersection height. The distance from the floor to the roof, measured at the approximate center of each intersection. Reported values are in feet to the nearest 0.1-ft.
intno	Arbitrary, unique number assigned to each of the 884 intersections in the East Mains for variable identification purposes.
lwstress	lwstress, Longwall Stress Impact Categorization Method. The categorization method is based on additive stresses for adjacent longwalls impacting an intersection and the pillars adjacent to that intersection. The maximum distance of a high lwstress impact was calculated as a radius equal to 0.5•depth; but, was capped at a maximum of 500 ft. This 500-ft distance is a subjective determination based on the EMSA data and observations. The maximum value for radius based on depth was capped at 1000 ft. These distances reflect

Variable Name	Variable Notes
	the observed front abutment data that indicates 1000 ft as a reasonable maximum front abutment distance. The process included consideration of impacts on an intersection from two longwall gobs. None (=0). All longwall gobs at a horizontal distance from the intersection of the lessor of: 1000 ft, or >depth of the intersection Low (=1). One longwall gob at a horizontal distance from the intersection of the lessor of: 1000 ft, or ≤depth of the intersection. Moderate (=2). Two longwall gobs, both at horizontal distances from the intersection of the lessor of: 1000 ft, or ≤depth of the intersection. High (=3). Two longwall gobs. One at a horizontal distance from the intersection of the lessor of: 500 ft, or ≤0.5•depth of the intersection. One at a horizontal distance from the intersection of the lessor of: 1000 ft, or ≤depth of the intersection. Very high (=4). Two longwall gobs, both at a horizontal distance from the intersection of the lessor of: 500 ft, or ≤0.5•depth of the intersection.
<u>*lwstress2*</u>	Recoding of the variable lwstress into only four categories: 0 = None

Variable Name	Variable Notes
	1 = Low 2 = Moderate 3 = High
mainwide	Total number of entries counted across the mains. Coded as 3, 4, 5, 6, 7 or 8.
msha	Roof reported to MSHA. A MSHA Reportable Roof Fall is required with roof failure and caving occur above the bolted horizon. 30 CFR § 50.10 requires immediate reporting to MSHA of a roof fall with failure and caving above the bolted horizon.
plravg	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. This is the average value of the stability factors of all the pillars adjacent to an intersection.
plrmax	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. This is the maximum, or highest value, of the stability factors of all the pillars adjacent to an intersection.
plrmin	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. This is the minimum, or lowest value, of the stability factors of all the pillars adjacent to an intersection.
plrnesf	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. Pillar to NE corner of the intersection. Pillars classified as solid, unmined coal, are assigned a SF of 1.99. Pillars classified as longwall barrier pillars are assigned a SF of 0.99.
plrnwsf	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. Pillar to NW corner of the intersection. Pillars classified as solid, unmined coal, are assigned a SF of 1.99. Pillars classified as longwall barrier pillars are assigned a SF of 0.99.
plrsesf	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. Pillar to SE corner of the intersection. Pillars classified as solid, unmined coal, are assigned a SF of 1.99. Pillars classified as longwall barrier pillars are assigned a SF of 0.99.
plrsum	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading

Variable Name	Variable Notes
	only. This is the sum of the stability factors of all the pillars adjacent to an intersection.
plrswsf	Pillar stability factor calculated using the Mark-Bieniawski formula. Tributary area development loading only. Pillar to SW corner of the intersection. Pillars classified as solid, unmined coal, are assigned a SF of 1.99. Pillars classified as longwall barrier pillars are assigned a SF of 0.99.
prop	Denotes the presence and type of prop, if present. Team 1 Props field data. There is no information on support size, load carrying capacity, installed location or installed pattern.
rfbltdia	Roof bolt diameter.
rfbltgrd	Roof bolt steel grade.
rfbltlen	Length of roof bolt, feet. This is equivalent to the ARBS variable, Lb, Length of bolt.
rfbltmfg	Roof bolt manufacturer.
rfbltrow	Number of roof bolts per row. This is equivalent to the ARBS variable, Nb, Number of bolts per row.
rfbltspc	Spacing between consecutive rows of bolts, feet. This is equivalent to the ARBS variable, Sb, Spacing between rows of bolts.
rfblttype	Roof bolt type.
rfcoal	Ordinal classification of top coal thickness based on field variable, rfgeo, immediate roof stratigraphic position. Variable is based on assumption used in CMRR calculation that did not include an estimated coal layer 0.5 ft thick or less as part of the roof CMRR calculation.
rfcoalthk	Estimated top coal thickness based on reported roof stratigraphic location and general stratigraphy and unit thicknesses for p3, S84, p4 and S85 units.
rfcorr1	Visible corrosion observed on the intersection in-roof support?
rfcorr2	Degree of visible corrosion observed on the intersection in-roof support.
rfdry	Presence of water in the roof. Based on the predictor variable rfwater. A rfwater rating of Dry or Damp was categorized as dry roof (rfdry=1). A rfwater rating of Light or Heavy Drip was categorized as wet roof (rfdry=0).
rfgeo	The location in the mined coal seam where ribs (sides) of the entry or crosscut intersect the roof of the

Variable Name	Variable Notes
	intersection. A "p" represents a parting in the coal seam. A "S" represents a coal split. See the general coal seam stratigraphy figure for more information on coal seam splits and partings. Nomenclature and explanations are as follows. 1 = p3 location, coal thickness category = thick, roof coal thickness > 1.8 ft; p3 parting is visible in the rib immediately below roof line. S84, p4 and S85 fully present in the immediate roof. 2 = p3-1/2 location, coal thickness category, thin, roof coal thickness >0.5 ft to <=1.8 ft; roof line within the S84 coal split. Estimated thickness of S84 in the immediate roof as 0.3 ft and all of p4 and all of S85 present in the immediate roof. 3 = p4 location, coal thickness category, very thin, roof coal thickness >0 ft to <= 0.5 ft; p4 visible in the rib immediately below the roof line. S85 present in the immediate roof. 4 = none (0 ft), rock visible as the immediate roof. Mapping noted this as "sandstone" which may or may not be the case. There was no notation of the amount of rock in the rib below the roof line. The assumption is made that no roof rock was deliberately mined so all of the immediate roof rock layer thickness is present.
rfmat	Presence and type of steel sheeting as part of in-roof support.
rfmesh	Type of mesh as part of in-roof support. Number values represent opening size, inches.
rfsag	Denotes the presence or absence of roof sag in the intersection.
rfsagamt	Approximate amount of visible roof sag, feet.
rfsagcat	Categorization of roof sag amount on the basis of: 0 = roof sag > 0.25 ft. 1 = roof sag ≤ 0.25 ft.
rfucs	Calculated thickness of the first rock layer above the s85 coal rider seam. This is the value used in the CMRR calculation.
rfwater	Roof ground water flow rating used in CMRR calculations. The value is based on an assessment of field observations of roof groundwater flow by the two field teams, on indications of roof bolt corrosion due to past ground water flow, and on the type of ventilation present in the intersection. It is estimated from these five variables, rfcorr1, rfcorr2, rfwater1, rfwater2 and

Variable Name	Variable Notes
	venttype. Generally, an intake entry is rated a zero because of the dry conditions in the western US. Beltlines and returns are rated at least a 1 because of conditions and moisture in the ventilation air. The coding method follows that used in the NIOSH CMRR calculation procedure -1; *rfwtrcmrr* coded as 0 is input into the CMRR program as a 1.
rfwater1	Degree of moisture or water flow visible on the intersection roof. Original Team 1 coding was as follows: 1 = roof is dry 2 = damp 3 = wet 4 = roof is dripping 5 = running water from roof
rfwater2	Degree of moisture or water flow visible on the intersection roof as reported by field Team 2.
ribbltlen	Length of rib bolts. Values are in feet. A value of zero indicates no rib bolts present. A value of 999 indicates no data.
ribblttype	Rib bolt type
ribmesh	Rib mesh type
ribms	Presences of mudstone in the ribs adjacent to the intersection.
ribmsthk	A measure of the amount of mudstone, if any, comprising the lower portion of the entry ribs. A value of zero indicates that no mudstone is present in the entry rib and that, therefore, the immediate surface of the entry floor is comprised of coal. A value greater than zero: (1) indicates that mudstone is present in the entry rib; (2) represents the thickness of mudstone in the entry rib measured in feet; and, (3) that, therefore, the immediate surface of the entry floor is comprised of mudstone.
ribplatetype	Rib plate type. Dimensions are inches.
set	Denotes the presence and type of steel set, if present. Team 1 Steel-Sets field data. There is no information on support size, load carrying capacity, installed location or installed pattern.
slfcnrne	Denotes the presence or absence of sloughage on the northeast corner of the intersection.

Variable Name	Variable Notes
slfcnrneamt	Degree of sloughage observed on the northeast corner of the intersection.
slfcnrneloc	Location on rib where sloughage occurs on the northeast corner of the intersection.
slfcnrnw	Denotes the presence or absence of sloughage on the northwest corner of the intersection.
slfcnrnwamt	Degree of sloughage observed on the northwest corner of the intersection.
slfcnrnwloc	Location on rib where sloughage occurs on the northwest corner of the intersection.
slfcnrse	Denotes the presence or absence of sloughage on the southeast corner of the intersection.
slfcnrseamt	Degree of sloughage observed on the southeast corner of the intersection.
slfcnrseloc	Location on rib where sloughage occurs on the southeast corner of the intersection.
slfcnrsw	Denotes the presence or absence of sloughage on the southwest corner of the intersection.
slfcnrswamt	Degree of sloughage observed on the southwest corner of the intersection.
slfcnrswloc	Location on rib where sloughage occurs on the southwest corner of the intersection.
slfe	Denotes the presence or absence of sloughage along ribs immediately to the east of the intersection.
slfeamt	Degree of sloughage observed along ribs immediately to the east of the intersection.
slfeloc	Location on rib where sloughage occurs along ribs immediately to the east of the intersection.
slfn	Denotes the presence or absence of sloughage along ribs immediately to the north of the intersection. Note: Sloughage is spalling of coal off the rib.
slfnamt	Degree of sloughage observed along ribs immediately to the north of the intersection.
slfnloc	Location on rib where sloughage occurs along ribs immediately to the north of the intersection.
slfs	Denotes the presence or absence of sloughage along ribs immediately to the south of the intersection.
slfsamt	Degree of sloughage observed along ribs immediately to the south of the intersection.
slfsloc	Location on rib where sloughage occurs along ribs immediately to the south of the intersection.

Variable Name	**Variable Notes**
slfw	Denotes the presence or absence of sloughage along ribs immediately to the west of the intersection.
slfwamt	Degree of sloughage observed along ribs immediately to the west of the intersection.
slfwloc	Location on rib where sloughage occurs along ribs immediately to the west of the intersection.
slick	Slickensides visible in the intersection.
ss1	Is the SS1 Sandstone channel located in the roof at any distance above the intersection location?
ss1margin	Is a channel margin deposition environment, adjacent to the SS1 Sandstone channel, located in the roof at any distance above the intersection?
ss2	Is the SS2 Sandstone channel located in the roof at any distance above the intersection location?
ss2margin	Is a channel margin deposition environment, adjacent to the SS2 Sandstone channel, located in the roof at any distance above the intersection?
sspc	Is the Picture Cliffs Sandstone present in the floor at any depth below the intersection location?
sspcmargin	Is a channel margin deposition environment, adjacent to the Picture Cliffs Sandstone channel, located in the floor at any depth below the intersection?
tanylarge	Any tension crack equal to or greater than 0.25-in, located anywhere in the intersection. Based on any value of *tnc*, *tne*, *tnn*, or *tns* coded as a value of “4”.
tn	The presence or absence of visible tension cracks in the intersection roof.
tnc	Size of tension crack running through center of intersection.
tncdir	Approximate longitudinal direction of center tension crack.
tne	Size of tension crack running along east side of intersection.
tnedir	Approximate longitudinal direction of east side tension crack.
tnn	Size of tension crack running along north side of intersection.
tnndir	Approximate longitudinal direction of north side tension crack.
tns	Size of tension crack running along south side of intersection.

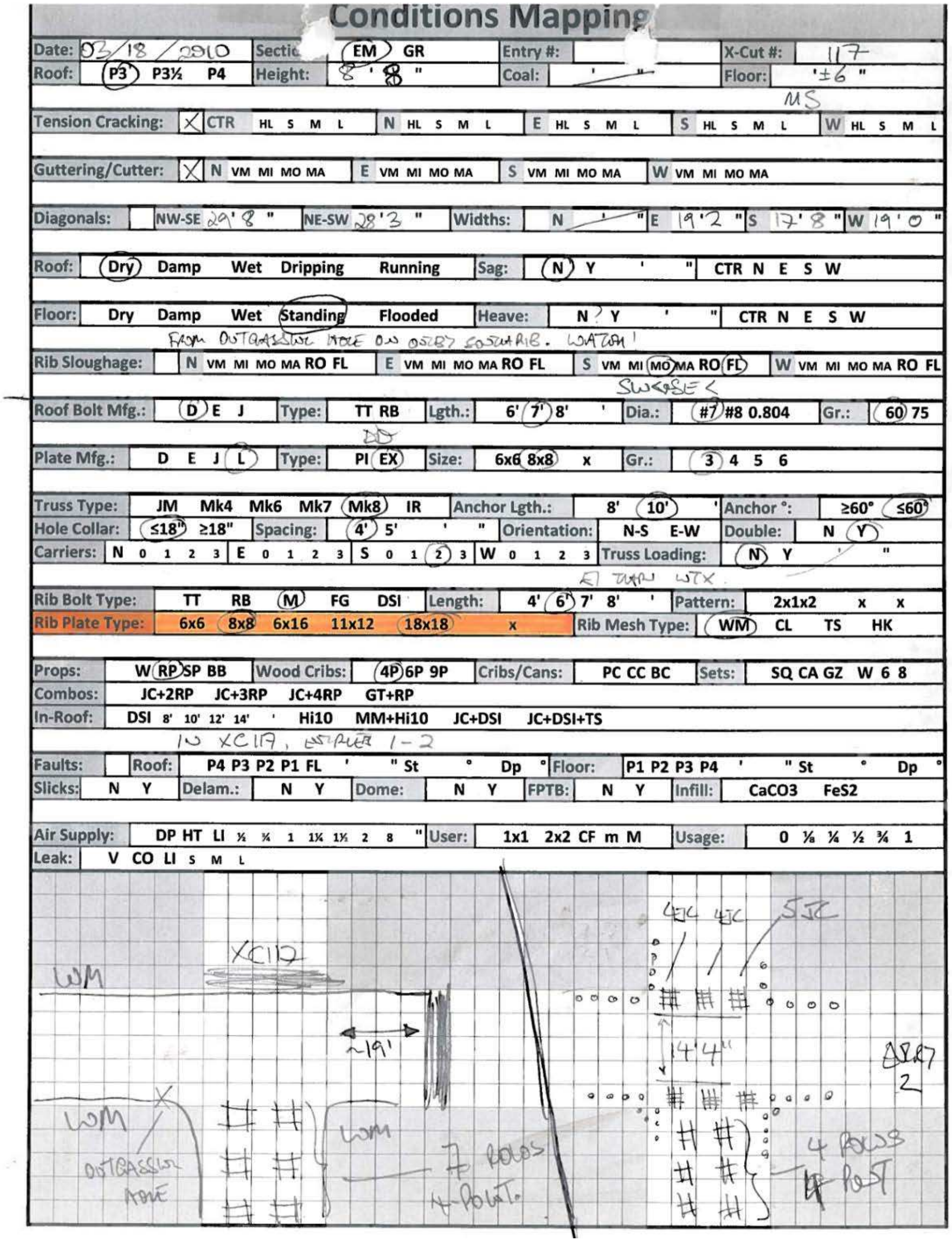
Variable Name	Variable Notes
tnsdir	Approximate longitudinal direction of south side tension crack.
tnw	Size of tension crack running along west side of intersection.
tnwdir	Approximate longitudinal direction of west side tension crack.
trsbltlen	Truss anchor bolt length, feet.
trscare	Number of carrier trusses east of intersection. When trusses are oriented north-south, carrier trusses will only be present to the north and south. When trusses are oriented east-west, carrier trusses will only be present to the east and west.
trscarn	Number of carrier trusses north of intersection. When trusses are oriented north-south, carrier trusses will only be present to the north and south. When trusses are oriented east-west, carrier trusses will only be present to the east and west.
trscars	Number of carrier trusses south of intersection. When trusses are oriented north-south, carrier trusses will only be present to the north and south. When trusses are oriented east-west, carrier trusses will only be present to the east and west.
trscarw	Number of carrier trusses west of intersection. When trusses are oriented north-south, carrier trusses will only be present to the north and south. When trusses are oriented east-west, carrier trusses will only be present to the east and west.
trsdbl	Is the intersection double trussed (i.e., truss spacing of 2 ft rather than the plan truss spacing of 4-ft).
trsdir	Orientation of the intersection trusses.
trsload	Presence and, if present, approximate amount of truss shoe loading, feet. Truss shoe loading was the approximate amount of roof movement downward at the location of the truss shoe.
trsloadcat	Truss load amount categorization bases on: 0 = > 2 in. 1 = ≤ 2 in.
trsspc	Spacing between trusses, feet.
trstype	Type of truss shoe.
tsum	Sum of the tension crack variables. *tnc*+*tne*+*tnn*+*tns*+*tnw*
ventbelt	Location of an intersection is in a beltline.

Variable Name	Variable Notes
venttype	Type of ventilation in an intersection based on the ventilation map current at the time of Team 2 field inspections.
widentavg	Calculated as the sum of all intersecting entries and crosscuts around the intersection divided by the intersection geometry, intgm.
widente	Width of the crosscut immediately to the east of the intersection, feet.
widentw	Width of the crosscut immediately to the west of the intersection, feet.
widxcn	Width of the crosscut immediately to the north of the intersection, feet.
widxcs	Width of the crosscut immediately to the south of the intersection, feet.
xcutcondn	The average condition of the roof in the crosscut north of the intersection for approximately 30 ft into the crosscut from the intersection. Condition rating is based on the field intersection success rating measurement scale. 1 = Good. Crosscut roof has only original roof bolting. No travel or ventilation restriction. Crosscut fully serves intended / design function (intake, travelway, escapeway, return, belt line, overcast, etc.). 2 = Fair. Crosscut roof shows minor roof cracking or presence of water. Original roof support supplemented with additional roof bolting, meshing, etc., May include some additional standing support. Original functional design not currently compromised. Pillar rib spall has increased the current crosscut width by up to 10% versus the design crosscut width of 18 ft. 3 = Poor. Additional supplemental and / or standing support installed in the crosscut. Roof failure / fall below the top of the bolted interval. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. Belt maintenance operations compromised due to clearance issues with standing support. Pillar rib spall has increased the current effective span width >10% to <=15% versus the design crosscut width of 18 ft. 4 = Very Poor. Escapeway routed around area. Steel sets or equivalent installed to maintain access for underground mobile equipment. Significant additional standing support installed in the crosscut. Pillar rib spall

Variable Name	Variable Notes
	has increased the current effective span width >15% versus the design crosscut width of 18 ft. 5 = MSHA Reportable Roof Fall. Roof failure and caving occurred above the bolted horizon. 30 CFR § 50.10 requires immediate reporting to MSHA of a roof fall with failure and caving above the bolted horizon.
xcutconds	The average condition of the roof in the crosscut south of the intersection for approximately 30 ft into the crosscut from the intersection. Condition rating is based on the field intersection success rating measurement scale. 1 = Good. Crosscut roof has only original roof bolting. No travel or ventilation restriction. Crosscut fully serves intended / design function (intake, travelway, escapeway, return, belt line, overcast, etc.). 2 = Fair. Crosscut roof shows minor roof cracking or presence of water. Original roof support supplemented with additional roof bolting, meshing, etc., May include some additional standing support. Original functional design not currently compromised. Pillar rib spall has increased the current crosscut width by up to 10% versus the design crosscut width of 18 ft. 3 = Poor. Additional supplemental and / or standing support installed in the crosscut. Roof failure / fall below the top of the bolted interval. Original functional design partially compromised (not passable to normal-sized underground mobile equipment. Belt maintenance operations compromised due to clearance issues with standing support. Pillar rib spall has increased the current effective span width >10% to <=15% versus the design crosscut width of 18 ft. 4 = Very Poor. Escapeway routed around area. Steel sets or equivalent installed to maintain access for underground mobile equipment. Significant additional standing support installed in the crosscut. Pillar rib spall has increased the current effective span width >15% versus the design crosscut width of 18 ft. 5 = MSHA Reportable Roof Fall. Roof failure and caving occurred above the bolted horizon. 30 CFR § 50.10 requires immediate reporting to MSHA of a roof fall with failure and caving above the bolted horizon.

APPENDIX C

COMPLETED EXAMPLE OF TEAM 1 FIELD DATA COLLECTION SHEET



Conditions Mapping

Date:	03/18/2010	Sectio	[✓ EM] GR	Entry #:		X-Cut #:	117
Roof:	[✓ P3] P3½ P4	Height:	8 ' 8 "	Coal:	' "	Floor:	'±6 " MS

Tension Cracking: ☒ CTR HL S M L | N HL S M L | E HL S M L | S HL S M L | W HL S M L

Guttering/Cutter: ☒ N VM MI MO MA | E VM MI MO MA | S VM MI MO MA | W VM MI MO MA

Diagonals: ☐ NW-SE 29' 8 " | NE-SW 28' 3 " | Widths: N ' " | E 19' 2 " | S 17' 8 " | W 19' 0 "

Roof: [✓ Dry] Damp Wet Dripping Running | Sag: [✓ N] Y ' " | CTR N E S W

Floor: Dry Damp Wet [✓ Standing] Flooded | Heave: N ? Y ' " | CTR N E S W

FROM OUTGASSING HOLE ON [illegible] SOUTH RIB. WATCH!

Rib Sloughage: ☐ N VM MI MO MA RO FL | E VM MI MO MA RO FL | S VM MI [✓ MO] MA RO [✓ FL] | W VM MI MO MA RO FL

SW&SE<

Roof Bolt Mfg.: [✓ D] E J | Type: TT RB | Lgth.: 6' [✓ 7'] 8' ' | Dia.: [✓ #7] #8 0.804 | Gr.: [✓ 60] 75

DD

Plate Mfg.: D E J [✓ L] | Type: PI [✓ EX] | Size: 6x6 [✓ 8x8] x | Gr.: [✓ 3] 4 5 6

Truss Type: JM Mk4 Mk6 Mk7 [✓ Mk8] IR | Anchor Lgth.: 8' [✓ 10'] ' | Anchor °: ≥60° [✓ ≤60°]

Hole Collar: [✓ ≤18"] ≥18" | Spacing: [✓ 4'] 5' ' " | Orientation: N-S E-W | Double: N [✓ Y]

Carriers: N 0 1 2 3 | E 0 1 2 3 | S 0 1 [✓ 2] 3 | W 0 1 2 3 | Truss Loading: [✓ N] Y ' "

[illegible]

Rib Bolt Type: TT RB [✓ M] FG DSI | Length: 4' [✓ 6'] 7' 8' ' | Pattern: 2x1x2 x x

Rib Plate Type: 6x6 [✓ 8x8] 6x16 11x12 [✓ 18x18] x | Rib Mesh Type: [✓ WM] CL TS HK

Props: W [✓ RP] SP BB | Wood Cribs: [✓ 4P] 6P 9P | Cribs/Cans: PC CC BC | Sets: SQ CA GZ W 6 8

Combos: JC+2RP JC+3RP JC+4RP GT+RP

In-Roof: DSI 8' 10' 12' 14' ' Hi10 MM+Hi10 JC+DSI JC+DSI+TS

IN XC117, [illegible] 1-2

Faults: ☐ Roof: P4 P3 P2 P1 FL ' " St ° Dp ° | Floor: P1 P2 P3 P4 ' " St ° Dp °

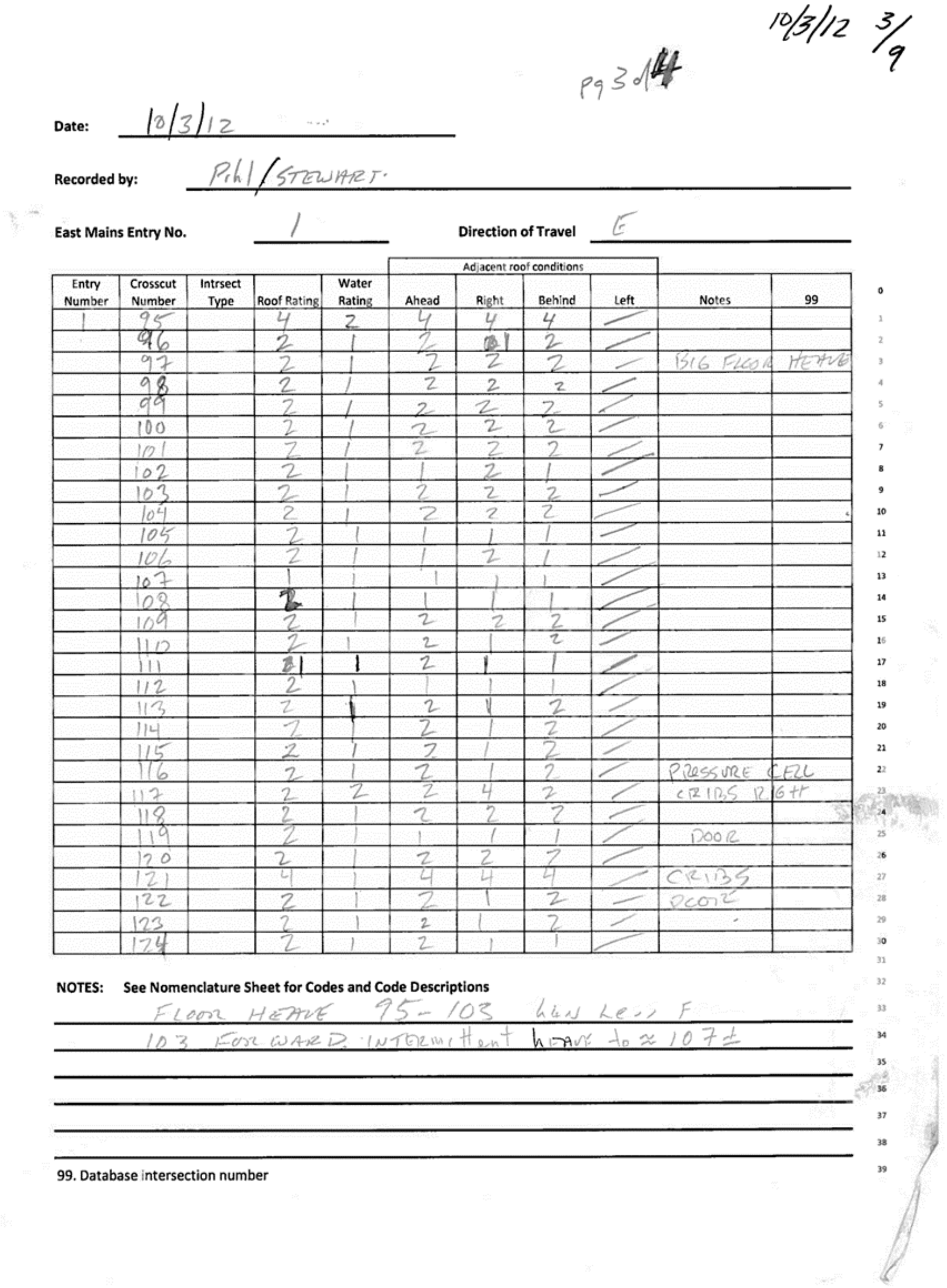
Slicks: N Y | Delam.: N Y | Dome: N Y | FPTB: N Y | Infill: CaCO3 FeS2

Air Supply: DP HT LI ½ ¾ 1 1¼ 1½ 2 8 " | User: 1x1 2x2 CF m M | Usage: 0 ⅛ ¼ ½ ¾ 1

Leak: V CO LI S M L

APPENDIX D

COMPLETED EXAMPLE OF TEAM 1 FIELD DATA COLLECTION SHEET



10/3/12 3/9

Pg 3 of 4

Date: 10/3/12

Recorded by: Pihl / STEWART.

East Mains Entry No. 1 **Direction of Travel** E

Entry Number	Crosscut Number	Intrsect Type	Roof Rating	Water Rating	Adjacent roof conditions Ahead	Right	Behind	Left	Notes	99
1	95		4	2	4	4	4	/		
	96		2	1	2	1	2	/		
	97		2	1	2	2	2	/	BIG FLOOR HEAVE	
	98		2	1	2	2	2	/		
	99		2	1	2	2	2	/		
	100		2	1	2	2	2	/		
	101		2	1	2	2	2	/		
	102		2	1	1	2	1	/		
	103		2	1	2	2	2	/		
	104		2	1	2	2	2	/		
	105		2	1	1	1	1	/		
	106		2	1	1	2	1	/		
	107		1	1	1	1	1	/		
	108		2	1	1	1	1	/		
	109		2	1	2	2	2	/		
	110		2	1	2	1	2	/		
	111		1	1	2	1	1	/		
	112		2	1	1	1	1	/		
	113		2	1	2	1	2	/		
	114		2	1	2	1	2	/		
	115		2	1	2	1	2	/		
	116		2	1	2	1	2	/	PRESSURE CELL	
	117		2	2	2	4	2	/	CRIBS RIGHT	
	118		2	1	2	2	2	/		
	119		2	1	1	1	1	/	DOOR	
	120		2	1	2	2	2	/		
	121		4	1	4	4	4	/	CRIBS	
	122		2	1	2	1	2	/	DOOR	
	123		2	1	2	1	2	/		
	124		2	1	2	1	1	/		

NOTES: **See Nomenclature Sheet for Codes and Code Descriptions**

FLOOR HEAVE 95 - 103 [illegible]

103 FORWARD INTERMittent heave to ≈ 107±

99. Database intersection number

APPENDIX E

INTERSECTION CMRR VALUES AND CONDITION RATINGS

FOR THE 884 EMSA INTERSECTIONS

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
1	331709.4	2108120.5	34.3	2	1	1	1
2	331709.4	2108217.3	19.8	2	1	1	1
3	331807.3	2108042.8	40.8	2	1	1	1
4	331812.3	2108118.4	17.6	2	1	1	1
5	331927.6	2107962.5	21.3	2	1	1	1
6	331929.0	2108041.4	33.8	2	1	1	1
7	331929.0	2108120.5	20.3	2	1	1	1
8	331931.2	2108219.8	25.3	2	1	1	1
9	331974.8	2108299.6	35.8	2	1	1	0
10	332098.6	2107958.2	20.5	2	1	1	1
11	332098.6	2108039.0	16.4	2	1	1	1
12	332100.8	2108118.0	21.2	2	1	1	1
13	332098.6	2108217.3	29.8	2	1	1	1
14	332102.9	2108297.5	35.9	2	1	1	1
15	332270.4	2107958.2	14.2	2	1	1	1
16	332267.3	2108035.6	14.9	2	1	1	1
17	332270.4	2108117.2	24.4	2	1	1	1
18	332270.4	2108217.3	31.9	2	1	1	1
19	332270.4	2108299.6	35.9	2	1	1	1
20	332433.5	2108120.5	23.0	2	1	1	1
21	332437.8	2108299.6	35.1	2	1	1	1
22	332439.9	2108035.7	18.7	2	1	1	1
23	332442.8	2108217.3	31.8	2	1	1	1
24	332447.1	2107958.9	15.3	2	1	1	1
25	332635.8	2108115.8	20.8	2	1	1	1
26	332636.5	2107960.3	19.0	2	1	1	1
27	332638.6	2108041.4	17.6	2	1	1	1
28	332638.7	2108214.2	27.0	2	2	0	0
29	332641.2	2108295.7	30.7	2	1	1	1
30	332824.8	2107958.2	18.8	2	1	1	1
31	332825.5	2108039.3	17.7	2	1	1	1
32	332825.5	2108118.4	21.2	2	1	1	1
33	332824.8	2108217.3	24.1	2	2	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
34	332824.8	2108299.6	31.2	2	1	1	1
35	333009.6	2107958.2	23.8	2	1	1	1
36	333009.6	2108041.4	23.9	2	1	1	1
37	333009.6	2108120.5	25.5	2	1	1	1
38	333009.6	2108217.3	23.0	2	1	1	1
39	333009.6	2108299.6	30.5	2	1	1	1
40	333212.1	2107958.2	29.0	1	1	1	1
41	333212.1	2108041.4	28.3	1	1	1	1
42	333212.1	2108120.5	27.7	1	1	0	0
43	333212.1	2108217.3	27.1	2	1	1	1
44	333212.1	2108299.6	30.0	1	1	1	1
45	333404.3	2107958.2	28.0	1	1	1	1
46	333404.3	2108041.4	27.6	1	1	1	1
47	333404.3	2108120.5	22.1	1	1	1	1
48	333404.3	2108217.3	20.8	2	2	0	0
49	333404.3	2108299.6	29.8	1	1	1	1
50	333605.8	2107958.2	31.4	1	1	1	1
51	333605.8	2108041.4	23.8	1	1	1	1
52	333605.8	2108120.5	19.8	1	1	1	1
53	333605.8	2108217.3	19.0	2	2	0	0
54	333605.8	2108299.6	27.2	1	1	1	1
55	333746.1	2107958.2	19.5	3	3	0	0
56	333746.1	2108041.4	26.9	1	1	1	1
57	333746.1	2108120.5	26.8	1	1	1	1
58	333746.1	2108217.3	16.5	2	1	1	0
59	333746.1	2108299.6	17.2	1	1	1	1
60	333782.3	2108374.3	27.2	1	1	1	0
61	333877.4	2107958.2	19.6	1	1	0	0
62	333877.4	2108041.4	19.2	1	1	1	1
63	333877.4	2108120.5	17.2	1	1	1	1
64	333877.4	2108217.3	16.8	2	1	1	1
65	333877.4	2108299.6	26.8	2	1	1	1
66	333877.4	2108381.3	26.8	1	1	1	1
67	334002.5	2107958.2	30.8	1	1	0	0
68	334002.5	2108041.4	22.5	1	1	1	1
69	334002.5	2108120.5	20.3	1	1	1	1
70	334002.5	2108217.3	20.1	1	1	1	1
71	334002.5	2108299.6	29.9	1	1	1	1
72	334002.5	2108381.3	29.7	1	1	1	1
73	334091.0	2107958.2	31.1	1	1	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
74	334091.0	2108041.4	20.8	1	1	1	1
75	334091.0	2108120.5	20.7	1	1	1	1
76	334091.0	2108217.3	20.4	4	3	0	0
77	334091.0	2108299.6	30.2	2	1	1	1
78	334091.0	2108381.3	29.9	1	1	1	1
79	334261.4	2107958.2	31.4	1	1	0	0
80	334261.4	2108041.4	19.9	1	1	1	1
81	334261.4	2108120.5	19.9	1	1	1	1
82	334261.4	2108217.3	21.0	2	1	1	1
83	334261.4	2108299.6	30.9	1	1	1	1
84	334261.4	2108381.3	30.5	1	1	1	1
85	334432.8	2107958.2	31.4	1	1	0	0
86	334432.8	2108041.4	19.8	1	1	1	1
87	334432.8	2108120.5	22.2	1	1	1	1
88	334432.8	2108217.3	23.5	2	2	0	0
89	334432.8	2108299.6	31.6	1	1	1	1
90	334432.8	2108381.3	31.5	1	1	1	1
91	334503.8	2108119.8	23.7	1	1	1	1
92	334510.9	2108217.3	23.5	2	1	1	1
93	334510.9	2108299.6	31.9	1	1	1	1
94	334568.4	2108381.9	32.3	1	1	1	1
95	334584.8	2107958.2	31.3	1	1	0	0
96	334584.8	2108041.4	22.1	1	1	1	1
97	334584.8	2108120.5	23.7	1	1	1	1
98	334584.8	2108217.3	23.5	1	1	1	1
99	334584.8	2108299.6	32.3	1	1	1	1
100	334730.5	2108041.4	23.5	1	1	1	1
101	334730.5	2108120.5	23.6	1	1	1	1
102	334730.5	2108217.3	23.5	1	1	1	1
103	334730.5	2108299.6	32.8	1	1	1	1
104	334730.5	2108381.3	30.4	1	1	1	1
105	334740.2	2107958.2	31.3	1	1	1	1
106	334891.1	2107958.2	30.4	1	1	1	1
107	334891.1	2108041.4	22.4	2	1	1	1
108	334891.1	2108120.5	22.4	1	1	1	1
109	334891.1	2108217.3	22.6	2	1	1	1
110	334891.1	2108299.6	30.6	2	1	1	1
111	334891.1	2108381.3	30.6	1	1	1	1
112	335052.8	2107957.5	30.8	1	1	0	0
113	335052.8	2108040.7	22.7	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
114	335057.1	2108120.5	25.0	1	1	1	1
115	335057.1	2108299.6	30.9	1	1	1	1
116	335057.1	2108381.3	30.9	1	1	1	1
117	335061.4	2108217.3	24.9	2	1	1	1
118	335166.3	2107958.2	31.0	1	1	1	1
119	335166.3	2108120.5	25.1	1	1	1	1
120	335166.3	2108217.3	24.9	2	1	1	1
121	335166.3	2108299.6	31.0	1	1	1	1
122	335166.3	2108381.3	31.0	1	1	1	1
123	335173.0	2108042.0	25.0	1	1	1	1
124	335279.8	2107958.2	25.2	3	3	0	0
125	335279.8	2108041.4	23.2	1	1	1	1
126	335279.8	2108120.5	25.2	1	1	1	1
127	335279.8	2108217.3	25.2	2	1	1	1
128	335279.8	2108299.6	31.1	1	1	1	1
129	335279.8	2108381.3	31.1	1	1	1	1
130	335455.1	2107958.2	25.7	1	1	1	1
131	335455.1	2108041.4	25.6	1	1	1	1
132	335455.1	2108120.5	31.3	1	1	1	1
133	335455.1	2108217.3	25.7	1	1	0	0
134	335455.1	2108299.6	31.3	1	1	1	1
135	335455.1	2108381.3	31.2	1	1	1	1
136	335622.9	2108120.5	26.5	1	1	1	1
137	335622.9	2108216.6	26.5	1	1	1	1
138	335623.6	2108380.6	31.3	1	1	1	1
139	335624.3	2107958.2	26.4	1	1	0	0
140	335624.3	2108041.4	26.5	1	1	1	1
141	335625.0	2108299.6	31.3	1	1	1	1
142	335710.8	2108381.0	31.3	1	1	1	1
143	335788.6	2108041.4	26.4	1	1	1	1
144	335793.5	2108120.5	31.2	1	1	1	1
145	335793.5	2108217.3	26.3	2	1	1	1
146	335793.5	2108299.6	31.2	1	1	1	1
147	335793.5	2108381.3	31.1	1	1	1	1
148	335800.8	2107958.8	26.4	1	1	0	0
149	335960.6	2108041.4	26.3	1	1	1	1
150	335960.6	2108120.5	26.3	1	1	1	1
151	335960.6	2108217.3	26.3	1	1	1	1
152	335964.2	2107958.2	26.3	1	1	1	1
153	335964.2	2108299.6	31.0	1	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
154	335964.2	2108381.3	31.0	1	1	1	0
155	336095.3	2108381.3	26.1	1	1	1	1
156	336150.1	2107958.2	30.0	1	1	1	1
157	336150.1	2108041.4	26.2	2	1	1	1
158	336150.1	2108120.5	26.2	1	1	1	1
159	336150.1	2108217.3	26.2	1	1	1	1
160	336150.1	2108299.6	30.9	1	1	1	1
161	336150.1	2108381.3	26.1	1	1	1	1
162	336197.9	2108381.3	26.0	1	1	1	1
163	336272.6	2107958.2	26.0	1	1	0	0
164	336272.6	2108041.4	26.1	1	1	1	1
165	336272.6	2108120.5	26.0	2	1	1	1
166	336272.6	2108217.3	26.1	1	1	1	1
167	336272.6	2108299.6	30.8	1	1	1	1
168	336272.6	2108381.3	25.3	1	1	1	1
169	336336.4	2108381.3	24.0	1	1	1	1
170	336365.7	2108458.0	24.0	1	1	1	0
171	336394.3	2108120.5	23.6	1	1	1	1
172	336394.9	2108040.8	23.5	1	1	1	1
173	336397.9	2107958.2	23.8	1	1	1	1
174	336397.9	2108217.3	21.7	1	1	0	0
175	336397.9	2108299.6	30.9	1	1	1	1
176	336397.9	2108381.3	24.5	1	1	1	1
177	336482.5	2108041.4	23.7	1	1	1	0
178	336482.5	2108120.5	23.9	1	1	1	0
179	336482.5	2108217.3	24.1	4	3	0	0
180	336482.5	2108299.6	30.9	1	1	1	1
181	336482.5	2108381.3	24.4	1	1	1	1
182	336488.2	2107959.6	23.1	2	1	1	1
183	336491.0	2108461.0	24.5	1	1	1	1
184	336569.9	2108119.8	23.7	1	1	1	1
185	336572.8	2108040.7	23.6	1	1	1	1
186	336573.5	2108299.6	30.7	1	1	1	1
187	336573.5	2108461.0	24.4	1	1	1	1
188	336574.2	2108381.3	24.2	1	1	1	1
189	336577.8	2107958.2	21.4	1	1	1	1
190	336577.8	2108217.3	23.9	1	1	0	0
191	336668.8	2108119.8	23.5	1	1	1	1
192	336670.3	2108298.9	30.7	1	1	1	1
193	336671.0	2108381.3	24.1	1	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
194	336673.8	2108461.0	24.3	1	1	1	1
195	336677.4	2107958.2	23.1	1	1	1	1
196	336677.4	2108041.4	23.3	1	1	1	1
197	336677.4	2108217.3	23.7	1	1	0	0
198	336758.7	2107958.2	22.9	1	1	0	0
199	336758.7	2108041.4	23.1	1	1	1	1
200	336758.7	2108120.5	23.2	1	1	1	1
201	336758.7	2108217.3	23.6	1	1	1	1
202	336758.7	2108299.6	30.6	1	1	1	1
203	336758.7	2108381.3	23.9	1	1	1	1
204	336758.7	2108461.0	24.1	1	1	1	1
205	336918.8	2107958.2	29.9	1	1	1	1
206	336918.8	2108041.4	22.8	1	1	1	1
207	336918.8	2108120.5	23.1	1	1	1	1
208	336918.8	2108217.3	30.2	2	2	0	0
209	336918.8	2108299.6	30.3	1	1	1	1
210	336918.8	2108381.3	20.5	1	1	1	1
211	336918.8	2108461.0	20.9	1	1	1	1
212	336922.3	2108554.0	21.4	2	1	1	0
213	337040.9	2107958.2	29.7	1	1	0	0
214	337040.9	2108041.4	18.6	1	1	1	1
215	337040.9	2108120.5	18.8	1	1	1	1
216	337040.9	2108217.3	19.7	2	1	1	0
217	337040.9	2108299.6	30.1	1	1	1	1
218	337040.9	2108381.3	20.4	1	1	1	1
219	337040.9	2108461.0	20.7	1	1	1	1
220	337042.9	2108554.0	21.4	2	1	1	1
221	337153.3	2107958.2	29.5	1	1	1	1
222	337153.3	2108041.4	18.3	2	1	1	1
223	337153.3	2108120.5	18.2	1	1	1	1
224	337153.3	2108217.3	29.7	2	1	1	0
225	337153.3	2108299.6	29.7	1	1	1	1
226	337153.3	2108381.3	19.9	1	1	1	1
227	337153.3	2108461.0	20.4	1	1	1	1
228	337159.1	2108554.0	20.8	2	1	1	0
229	337275.4	2107958.2	29.3	1	1	1	1
230	337275.4	2108041.4	18.0	1	1	1	1
231	337275.4	2108120.5	17.9	1	1	1	1
232	337275.4	2108217.3	18.1	2	1	1	1
233	337275.4	2108299.6	29.0	1	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
234	337275.4	2108381.3	19.5	2	1	1	1
235	337275.4	2108461.0	20.0	1	1	1	1
236	337401.8	2107958.2	29.0	2	1	1	1
237	337401.8	2108041.4	17.8	1	1	1	1
238	337401.8	2108120.5	16.1	1	1	1	1
239	337401.8	2108217.3	18.3	1	1	1	1
240	337401.8	2108381.3	18.6	2	1	1	1
241	337401.8	2108461.0	19.3	1	1	1	1
242	337509.7	2107960.2	28.8	2	1	0	0
243	337568.4	2107965.4	15.1	2	1	0	0
244	337568.8	2108381.3	18.6	1	1	1	1
245	337568.8	2108461.0	19.1	1	1	1	1
246	337570.2	2108042.1	17.6	1	1	1	1
247	337570.2	2108121.2	17.6	1	1	1	0
248	337570.9	2108299.6	18.2	1	1	1	1
249	337572.2	2108216.6	17.9	1	1	1	1
250	337638.0	2107965.0	17.1	2	1	0	0
251	337636.8	2108379.6	18.7	1	1	1	1
252	337645.2	2108460.2	19.2	1	1	1	1
253	337741.2	2107958.2	14.1	2	1	0	0
254	337741.2	2108041.4	28.7	2	1	1	0
255	337741.2	2108120.5	28.7	1	1	0	0
256	337741.2	2108217.3	17.9	1	1	1	1
257	337741.2	2108299.6	18.3	1	1	1	1
258	337741.2	2108381.3	18.8	1	1	1	1
259	337741.2	2108461.0	19.1	1	1	1	1
260	337849.4	2107958.2	14.4	2	1	0	0
261	337849.4	2108041.4	14.3	1	1	1	1
262	337849.4	2108120.5	17.5	1	1	1	1
263	337849.4	2108217.3	17.9	1	1	1	1
264	337849.4	2108299.6	18.3	1	1	1	1
265	337849.4	2108381.3	18.8	1	1	1	1
266	337849.4	2108461.0	19.1	1	1	1	1
267	337953.3	2107958.2	12.1	2	1	0	0
268	337953.3	2108041.4	11.8	1	2	0	0
269	337953.3	2108120.5	12.5	3	2	0	0
270	337953.3	2108217.3	15.8	2	2	0	0
271	337953.3	2108299.6	18.2	1	1	1	1
272	337953.3	2108381.3	18.7	2	1	1	1
273	337953.3	2108461.0	19.1	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
274	338124.7	2107958.2	20.6	4	3	0	0
275	338124.7	2108041.4	25.3	2	2	0	0
276	338124.7	2108120.5	14.2	3	2	0	0
277	338124.7	2108217.3	14.8	4	3	0	0
278	338124.7	2108299.6	18.2	2	2	0	0
279	338124.7	2108381.3	18.7	1	1	1	1
280	338124.7	2108461.0	18.7	1	1	1	1
281	338280.8	2107958.2	20.4	4	3	0	0
282	338280.8	2108041.4	20.7	1	1	1	1
283	338280.8	2108120.5	17.9	1	1	1	1
284	338280.8	2108217.3	14.7	2	2	0	0
285	338280.8	2108299.6	15.2	2	1	1	1
286	338280.8	2108381.3	15.5	1	1	1	1
287	338280.8	2108461.0	18.8	2	1	1	1
288	338440.0	2107958.2	18.2	2	1	0	0
289	338440.0	2108041.4	20.6	2	1	1	1
290	338440.0	2108120.5	17.9	1	1	1	1
291	338440.0	2108217.3	18.2	2	2	0	0
292	338440.0	2108299.6	15.2	2	1	1	1
293	338440.0	2108381.3	15.3	2	1	1	1
294	338440.0	2108461.0	16.0	2	1	0	0
295	338595.3	2107958.2	19.7	2	1	1	1
296	338595.3	2108041.4	20.1	1	1	1	1
297	338600.7	2108120.5	20.3	1	1	1	1
298	338600.7	2108217.3	17.7	3	2	0	0
299	338600.7	2108299.6	14.5	2	2	0	0
300	338600.7	2108381.3	15.0	2	1	0	0
301	338600.7	2108461.0	15.2	2	1	1	1
302	338761.5	2107958.2	18.2	2	1	1	1
303	338761.5	2108041.4	28.1	1	1	1	1
304	338761.5	2108120.5	28.5	1	1	1	1
305	338761.5	2108217.3	17.9	2	2	0	0
306	338761.5	2108299.6	18.1	2	1	1	1
307	338761.5	2108381.3	15.0	3	1	0	0
308	338761.5	2108461.0	15.1	4	3	0	0
309	338900.5	2108120.5	28.8	1	1	1	1
310	338900.5	2108217.3	21.1	1	1	1	1
311	338900.5	2108461.0	15.3	2	1	1	0
312	338905.3	2108299.6	18.3	2	1	1	1
313	338905.3	2108381.3	14.9	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
314	338909.3	2108041.4	28.3	1	1	1	1
315	338911.4	2107958.9	27.9	2	1	1	1
316	339027.9	2107958.2	28.1	2	1	1	1
317	339027.9	2108041.4	28.6	1	1	1	1
318	339027.9	2108217.3	21.1	1	2	0	0
319	339027.9	2108381.3	15.0	2	1	1	1
320	339027.9	2108461.0	14.9	2	1	0	0
321	339032.0	2108117.1	29.3	1	2	0	0
322	339034.7	2108299.6	21.0	2	1	1	1
323	339153.2	2107958.2	18.5	4	1	0	0
324	339153.2	2108041.4	20.6	5	3	0	0
325	339153.2	2108120.5	18.0	5	3	0	0
326	339153.2	2108217.3	20.8	1	2	0	0
327	339153.2	2108299.6	19.1	2	1	0	0
328	339153.2	2108381.3	17.7	2	1	0	0
329	339153.2	2108461.0	15.1	2	1	0	0
330	339216.9	2107957.5	20.1	4	3	0	0
331	339309.2	2107959.4	19.5	4	3	0	0
332	339309.2	2108042.6	18.0	5	3	0	0
333	339309.2	2108121.7	16.6	5	3	0	0
334	339306.8	2108215.3	13.3	3	2	0	0
335	339348.3	2108220.3	16.2	4	3	0	0
336	339350.7	2108299.6	18.2	2	1	1	1
337	339350.7	2108381.3	13.2	2	1	1	0
338	339350.7	2108461.0	18.7	2	1	1	1
339	339386.7	2107961.8	30.4	4	3	0	0
340	339396.6	2108042.5	15.1	2	2	0	0
341	339396.6	2108216.3	12.7	4	3	0	0
342	339398.6	2108122.5	14.6	4	3	0	0
343	339486.1	2107962.3	28.3	4	1	0	0
344	339486.7	2108038.1	15.1	1	1	1	1
345	339577.7	2107956.8	26.1	2	1	1	1
346	339578.4	2108041.4	26.3	1	1	1	1
347	339578.4	2108120.5	26.3	1	1	1	1
348	339582.0	2108217.3	20.1	2	1	0	0
349	339582.0	2108299.6	18.2	2	1	1	1
350	339582.0	2108381.3	18.2	2	1	1	1
351	339582.0	2108461.0	18.7	2	1	1	1
352	339773.7	2107958.2	18.1	2	1	1	1
353	339773.7	2108041.4	29.4	1	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
354	339773.7	2108120.5	29.3	1	1	1	1
355	339773.7	2108217.3	14.1	1	1	1	0
356	339773.7	2108299.6	20.6	2	1	1	1
357	339773.7	2108381.3	18.4	1	1	1	1
358	339773.7	2108461.0	18.8	1	1	1	1
359	339937.9	2108460.3	20.9	1	1	1	1
360	339943.6	2108381.3	16.5	3	1	0	0
361	339964.3	2108299.6	16.4	2	1	1	1
362	339977.2	2108120.5	16.3	1	1	1	0
363	339977.2	2108217.3	15.9	1	2	0	0
364	339982.2	2108041.4	26.4	1	1	1	1
365	339983.6	2107957.5	26.3	2	1	0	0
366	340172.1	2107958.2	13.3	2	1	1	1
367	340172.1	2108041.4	15.6	4	3	0	0
368	340173.5	2108120.5	14.1	2	2	0	0
369	340173.5	2108381.3	16.7	4	3	0	0
370	340177.1	2108217.3	16.4	1	1	1	1
371	340177.1	2108299.6	14.2	4	1	0	0
372	340177.1	2108461.0	16.7	1	1	1	1
373	340293.8	2107958.2	12.7	5	2	0	0
374	340293.8	2108041.4	26.4	1	1	0	0
375	340293.8	2108120.5	26.4	1	1	0	0
376	340293.8	2108217.3	16.3	1	1	1	1
377	340293.8	2108299.6	16.8	4	1	0	0
378	340293.8	2108381.3	16.6	2	1	1	1
379	340293.8	2108461.0	16.6	1	1	1	1
380	340397.2	2108217.3	17.8	1	1	1	1
381	340403.0	2108041.4	17.7	3	3	0	0
382	340411.6	2107958.2	26.4	3	3	0	0
383	340411.6	2108120.5	17.7	1	1	1	1
384	340411.6	2108217.3	17.7	1	1	1	1
385	340411.6	2108299.6	11.7	4	1	0	0
386	340411.6	2108381.3	16.5	2	1	1	1
387	340411.6	2108461.0	16.5	1	1	0	0
388	340609.7	2107958.2	29.4	3	2	0	0
389	340609.7	2108041.4	15.6	5	3	0	0
390	340609.7	2108120.5	29.5	1	1	1	1
391	340609.7	2108217.3	20.6	3	3	0	0
392	340609.7	2108299.6	20.8	2	1	1	1
393	340609.7	2108381.3	16.0	5	1	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
394	340609.7	2108461.0	21.0	1	1	0	0
395	340703.7	2108298.6	20.8	2	1	1	1
396	340706.0	2108221.6	20.6	1	1	1	1
397	340800.3	2107958.2	15.3	4	3	0	0
398	340800.3	2108041.4	15.5	4	3	0	0
399	340800.3	2108120.5	29.5	1	2	0	0
400	340800.3	2108217.3	20.5	1	1	1	1
401	340800.3	2108381.3	20.9	1	1	1	1
402	340800.3	2108461.0	21.0	1	1	0	0
403	340806.7	2108299.6	20.8	2	1	1	1
404	340881.2	2108038.9	29.5	4	1	0	0
405	340881.8	2107963.1	20.1	4	3	0	0
406	340988.8	2108120.5	29.5	1	1	1	0
407	340988.8	2108217.3	21.9	1	1	0	0
408	340988.8	2108299.6	21.9	2	1	1	0
409	340988.8	2108381.3	21.7	1	1	1	1
410	340988.8	2108461.0	21.8	1	1	1	0
411	340997.4	2108042.1	29.5	1	1	1	1
412	341005.2	2107958.9	17.1	4	3	0	0
413	341175.1	2107958.2	20.1	4	3	0	0
414	341175.1	2108041.4	29.5	4	3	0	0
415	341175.1	2108120.5	29.5	4	3	0	0
416	341175.1	2108217.3	21.9	1	1	1	1
417	341175.1	2108299.6	21.9	2	1	1	1
418	341175.1	2108381.3	21.7	1	1	1	1
419	341175.1	2108461.0	21.7	4	3	0	0
420	341361.1	2107958.2	17.0	4	3	0	0
421	341361.1	2108041.4	17.1	1	1	0	0
422	341361.1	2108120.5	21.9	1	1	1	1
423	341361.1	2108217.3	22.0	3	2	0	0
424	341361.1	2108299.6	22.0	2	1	1	1
425	341361.1	2108381.3	21.9	1	1	1	1
426	341361.1	2108461.0	21.7	4	3	0	0
427	341481.0	2107958.2	16.9	4	3	0	0
428	341481.0	2108041.4	17.0	4	3	0	0
429	341481.0	2108120.5	29.6	1	2	0	0
430	341481.0	2108217.3	24.3	1	1	0	0
431	341481.0	2108299.6	16.9	4	3	0	0
432	341481.0	2108381.3	21.7	4	3	0	0
433	341481.0	2108461.0	21.5	4	3	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
434	341586.0	2107958.2	17.0	4	3	0	0
435	341586.0	2108041.4	21.9	3	1	0	0
436	341586.0	2108120.5	29.7	1	1	0	0
437	341586.0	2108217.3	24.9	1	1	1	1
438	341586.0	2108299.6	21.7	2	1	1	1
439	341586.0	2108381.3	21.5	1	1	1	1
440	341586.0	2108461.0	16.4	3	1	0	0
441	341735.9	2107958.2	29.7	2	2	0	0
442	341735.9	2108041.4	29.7	1	2	0	0
443	341735.9	2108120.5	29.7	4	3	0	0
444	341735.9	2108217.3	24.7	2	2	0	0
445	341735.9	2108299.6	20.7	2	1	1	1
446	341735.9	2108381.3	15.9	2	1	0	0
447	341735.9	2108461.0	20.7	1	1	1	0
448	341880.5	2107958.2	29.6	4	3	0	0
449	341880.5	2108041.4	18.8	3	3	0	0
450	341880.5	2108120.5	29.6	2	2	0	0
451	341880.5	2108217.3	24.7	2	2	0	0
452	341880.5	2108299.6	20.5	2	1	1	1
453	341880.5	2108381.3	20.5	1	1	1	1
454	341880.5	2108461.0	20.5	2	1	1	1
455	342020.7	2107958.2	29.6	4	3	0	0
456	342020.7	2108041.4	29.6	1	1	1	1
457	342020.7	2108120.5	29.6	1	1	1	1
458	342020.7	2108217.3	24.4	1	1	1	1
459	342020.7	2108299.6	20.2	2	1	1	1
460	342020.7	2108381.3	20.1	1	1	1	1
461	342020.7	2108461.0	20.2	1	1	1	1
462	342208.7	2107958.2	29.5	1	1	0	0
463	342208.7	2108041.4	29.5	1	1	1	1
464	342208.7	2108120.5	29.7	1	1	0	0
465	342208.7	2108217.3	21.5	1	1	1	1
466	342208.7	2108299.6	18.8	2	1	1	1
467	342208.7	2108381.3	18.5	1	1	1	1
468	342208.7	2108461.0	18.8	1	1	1	1
469	342377.2	2108041.4	29.6	1	2	0	0
470	342378.6	2108299.6	18.5	2	1	0	0
471	342380.8	2108120.5	29.8	1	1	1	1
472	342382.2	2108217.3	21.2	1	1	1	1
473	342382.2	2108381.3	18.3	1	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
474	342382.2	2108461.0	21.3	1	1	1	1
475	342407.2	2107958.2	28.7	3	2	0	0
476	342548.2	2107958.2	22.1	2	1	1	1
477	342548.2	2108041.4	21.0	1	1	0	0
478	342548.2	2108120.5	17.0	1	1	1	1
479	342548.2	2108217.3	18.6	1	1	1	1
480	342548.2	2108299.6	18.6	2	1	1	1
481	342548.2	2108381.3	18.7	1	1	1	1
482	342548.2	2108461.0	18.7	2	1	1	1
483	342687.4	2107958.2	24.1	2	1	1	1
484	342687.4	2108041.4	28.6	1	1	1	1
485	342687.4	2108120.5	29.6	1	1	1	1
486	342687.4	2108217.3	20.7	1	1	1	1
487	342687.4	2108299.6	20.3	2	1	1	1
488	342687.4	2108381.3	20.1	1	1	1	1
489	342687.4	2108461.0	17.1	1	1	1	1
490	342825.6	2107958.2	17.3	4	3	0	0
491	342825.6	2108041.4	29.5	2	1	1	0
492	342825.6	2108120.5	29.6	1	1	0	0
493	342825.6	2108217.3	22.3	1	1	1	1
494	342825.6	2108299.6	22.0	2	1	1	1
495	342825.6	2108381.3	18.9	2	1	1	1
496	342825.6	2108461.0	21.2	1	1	1	1
497	342828.7	2108554.0	21.4	1	1	1	0
498	342925.2	2108554.0	21.5	1	1	1	0
499	342927.6	2108459.6	21.3	1	1	0	0
500	342947.6	2108381.3	21.5	2	1	0	0
501	342962.7	2108120.5	22.6	2	2	0	0
502	342963.4	2108299.6	23.0	1	1	0	0
503	342964.8	2107958.2	23.0	2	2	0	0
504	342964.8	2108041.4	17.8	4	3	0	0
505	342964.8	2108217.3	22.2	1	1	1	1
506	343106.1	2107958.2	22.9	2	1	1	1
507	343106.1	2108041.4	29.1	2	1	0	0
508	343106.1	2108120.5	28.8	1	1	1	1
509	343106.1	2108217.3	23.7	1	1	1	1
510	343106.1	2108299.6	23.3	2	1	1	1
511	343106.1	2108381.3	22.0	1	1	1	1
512	343106.1	2108461.0	21.7	1	1	1	1
513	343249.6	2107877.9	24.2	2	1	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
514	343249.6	2108041.4	29.4	2	1	0	0
515	343249.6	2108120.5	29.2	1	1	1	1
516	343249.6	2108217.3	22.4	1	1	1	1
517	343249.6	2108299.6	23.3	1	1	1	1
518	343249.6	2108381.3	22.9	2	1	1	1
519	343249.6	2108461.0	22.1	1	1	1	1
520	343256.0	2107962.5	23.9	2	1	1	1
521	343398.8	2107958.2	27.5	2	1	1	1
522	343401.7	2107877.9	28.0	2	1	0	0
523	343401.7	2108041.4	33.3	2	1	1	1
524	343401.7	2108120.5	32.8	1	1	1	1
525	343401.7	2108217.3	25.9	1	1	0	0
526	343401.7	2108299.6	25.4	1	1	1	1
527	343406.0	2108379.2	24.9	2	1	1	1
528	343408.1	2108461.7	22.0	1	1	1	0
529	343549.1	2107958.2	28.0	2	1	1	1
530	343549.1	2108041.4	33.9	2	1	0	0
531	343549.1	2108120.5	33.4	1	1	1	1
532	343552.7	2107877.9	28.5	2	1	0	0
533	343552.7	2108217.3	24.2	5	3	0	0
534	343552.7	2108299.6	20.6	4	3	0	0
535	343552.7	2108381.3	25.1	3	3	0	0
536	343552.7	2108461.0	17.1	4	3	0	0
537	343732.8	2108379.9	22.1	3	3	0	0
538	343734.9	2107958.2	28.0	2	1	1	1
539	343734.9	2108041.4	34.3	1	1	1	0
540	343734.9	2108120.5	21.8	4	3	0	0
541	343736.3	2108299.6	23.6	3	1	0	0
542	343737.8	2108217.3	22.7	4	3	0	0
543	343739.9	2107877.9	28.6	2	1	1	1
544	343739.9	2108461.0	17.0	4	3	0	0
545	343843.1	2107958.2	27.8	2	1	1	1
546	343843.1	2108041.4	34.3	2	1	1	1
547	343843.1	2108120.5	26.7	1	1	1	1
548	343854.5	2107877.9	28.4	2	1	1	1
549	343854.5	2108217.3	26.0	4	3	0	0
550	343854.5	2108381.3	21.9	3	3	0	0
551	343854.5	2108461.0	21.9	3	3	0	0
552	343857.4	2108299.6	21.9	4	3	0	0
553	343954.0	2107877.9	28.2	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
554	343954.0	2107958.2	27.6	3	2	0	0
555	343954.0	2108041.4	22.1	4	3	0	0
556	343954.0	2108120.5	21.4	4	3	0	0
557	343954.0	2108217.3	21.9	4	3	0	0
558	343954.0	2108299.6	21.8	2	1	1	0
559	343954.0	2108381.3	21.9	4	3	0	0
560	343954.0	2108461.0	21.7	3	3	0	0
561	344049.9	2107884.5	27.7	2	1	1	1
562	344071.8	2107958.2	22.2	4	3	0	0
563	344071.8	2108041.4	20.0	4	3	0	0
564	344071.8	2108120.5	19.9	3	2	0	0
565	344071.8	2108217.3	21.7	4	3	0	0
566	344071.8	2108299.6	21.6	2	1	0	0
567	344071.8	2108381.3	19.7	4	3	0	0
568	344071.8	2108461.0	16.6	4	3	0	0
569	344228.2	2107958.2	16.8	4	3	0	0
570	344228.2	2108041.4	19.8	5	3	0	0
571	344228.2	2108120.5	16.8	4	3	0	0
572	344228.2	2108217.3	16.6	4	3	0	0
573	344228.2	2108299.6	16.4	3	2	0	0
574	344228.2	2108381.3	16.3	4	3	0	0
575	344228.2	2108461.0	16.4	4	3	0	0
576	344319.7	2107958.2	21.7	2	1	1	1
577	344319.7	2108041.4	13.6	4	3	0	0
578	344319.7	2108120.5	29.1	1	1	1	1
579	344369.6	2108299.6	22.0	2	1	1	1
580	344369.6	2108381.3	22.7	3	1	0	0
581	344369.6	2108461.0	18.0	4	3	0	0
582	344373.0	2108218.5	20.0	4	3	0	0
583	344448.9	2108215.5	16.7	4	3	0	0
584	344450.4	2107882.4	21.9	4	3	0	0
585	344451.6	2107958.2	16.6	4	3	0	0
586	344451.6	2108041.4	16.6	4	3	0	0
587	344451.6	2108120.5	21.7	2	2	0	0
588	344580.5	2107877.9	21.8	4	3	0	0
589	344580.5	2107958.2	16.2	4	3	0	0
590	344580.5	2108041.4	28.4	2	1	1	1
591	344580.5	2108120.5	28.5	2	2	0	0
592	344580.5	2108217.3	16.7	4	3	0	0
593	344580.5	2108299.6	21.7	3	2	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
594	344580.5	2108381.3	17.6	4	3	0	0
595	344580.5	2108461.0	20.0	4	3	0	0
596	344772.2	2107877.9	21.4	4	3	0	0
597	344772.2	2107958.2	16.1	4	3	0	0
598	344772.2	2108041.4	19.8	4	3	0	0
599	344772.2	2108120.5	19.9	1	1	0	0
600	344772.2	2108217.3	22.3	2	2	0	0
601	344772.2	2108299.6	21.6	2	2	0	0
602	344772.2	2108381.3	17.6	4	3	0	0
603	344772.2	2108461.0	20.5	4	3	0	0
604	344947.8	2107877.9	16.2	4	3	0	0
605	344947.8	2107958.2	20.6	4	3	0	0
606	344947.8	2108041.4	16.3	4	3	0	0
607	344947.8	2108120.5	16.3	4	3	0	0
608	344947.8	2108217.3	20.8	1	1	1	1
609	344947.8	2108299.6	12.8	2	1	1	0
610	344947.8	2108381.3	13.5	4	3	0	0
611	344947.8	2108461.0	13.6	4	3	0	0
612	345042.0	2107877.9	20.5	2	1	1	1
613	345055.5	2107957.5	18.1	2	1	1	1
614	345064.1	2108041.4	27.3	2	1	1	1
615	345064.1	2108120.5	24.3	1	1	1	1
616	345064.1	2108217.3	17.8	2	1	1	1
617	345064.1	2108299.6	12.6	2	1	1	0
618	345064.1	2108381.3	18.1	2	1	1	1
619	345064.1	2108461.0	18.5	2	1	1	0
620	345145.0	2107877.9	17.0	2	1	1	1
621	345151.3	2107958.2	14.6	4	3	0	0
622	345159.1	2108120.5	27.2	2	1	1	0
623	345160.6	2108041.4	26.5	3	2	0	0
624	345162.7	2108217.3	17.5	2	1	1	1
625	345162.7	2108299.6	12.1	2	1	1	0
626	345162.7	2108381.3	12.9	2	1	1	0
627	345162.7	2108461.0	18.0	2	1	1	1
628	345255.0	2107877.9	16.9	1	1	0	0
629	345277.2	2107958.2	9.1	2	1	1	1
630	345277.2	2108041.4	16.6	1	1	0	0
631	345277.2	2108120.5	11.5	4	3	0	0
632	345277.2	2108217.3	12.0	3	3	0	0
633	345277.2	2108299.6	16.9	2	2	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
634	345277.2	2108381.3	12.4	4	3	0	0
635	345277.2	2108461.0	17.8	2	1	0	0
636	345411.1	2108217.3	17.0	2	1	1	1
637	345412.0	2107877.9	15.9	1	1	1	1
638	345416.1	2107958.2	16.6	2	1	1	0
639	345416.1	2108041.4	23.8	1	1	1	1
640	345416.1	2108120.5	14.6	1	1	1	1
641	345416.1	2108300.3	11.6	2	1	1	0
642	345416.1	2108382.0	17.5	2	1	1	1
643	345416.1	2108461.7	17.5	2	1	1	1
644	345546.6	2107882.1	16.2	1	1	1	1
645	345550.3	2108217.3	16.2	2	1	1	1
646	345556.0	2107958.2	16.5	2	1	1	0
647	345556.0	2108041.4	23.9	2	1	0	0
648	345556.0	2108120.5	12.1	3	3	0	0
649	345557.5	2108461.0	11.2	4	3	0	0
650	345558.2	2108381.3	17.0	2	1	1	0
651	345561.0	2108299.6	17.1	2	1	1	1
652	345755.9	2107877.9	19.3	1	1	1	1
653	345755.9	2107958.2	16.2	3	2	0	0
654	345755.9	2108041.4	23.7	2	1	1	1
655	345755.9	2108120.5	14.4	4	3	0	0
656	345755.9	2108217.3	17.0	2	1	1	1
657	345755.9	2108299.6	16.7	2	1	1	1
658	345755.9	2108381.3	16.8	2	1	1	1
659	345755.9	2108461.0	12.1	4	3	0	0
660	345957.8	2107877.9	19.3	1	1	1	1
661	345957.8	2107958.2	20.2	2	2	0	0
662	345957.8	2108041.4	14.4	4	3	0	0
663	345957.8	2108120.5	19.6	3	2	0	0
664	345957.8	2108217.3	18.3	4	3	0	0
665	345957.8	2108299.6	19.9	3	2	0	0
666	345957.8	2108381.3	12.0	4	3	0	0
667	345957.8	2108461.0	17.3	2	1	1	0
668	346188.1	2107877.9	19.5	2	2	0	0
669	346188.1	2107958.2	16.0	2	1	0	0
670	346188.1	2108041.4	19.6	2	1	0	0
671	346188.1	2108120.5	14.5	3	3	0	0
672	346188.1	2108217.3	14.9	4	3	0	0
673	346188.1	2108299.6	19.9	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
674	346188.1	2108381.3	20.2	2	1	1	1
675	346188.1	2108461.0	20.3	2	1	1	0
676	346321.9	2107877.9	19.7	1	1	1	1
677	346321.9	2107958.2	20.3	2	1	1	1
678	346321.9	2108041.4	14.7	3	3	0	0
679	346321.9	2108120.5	14.8	3	3	0	0
680	346321.9	2108217.3	15.0	4	3	0	0
681	346321.9	2108299.6	20.1	4	3	0	0
682	346321.9	2108381.3	20.5	2	1	1	1
683	346321.9	2108461.0	20.5	2	1	1	1
684	346416.2	2107877.9	21.6	1	1	1	0
685	346416.2	2107958.2	14.6	4	3	0	0
686	346416.2	2108041.4	17.8	3	2	0	0
687	346416.2	2108120.5	20.0	4	3	0	0
688	346416.2	2108217.3	20.3	2	1	1	1
689	346416.2	2108299.6	20.4	2	1	1	1
690	346416.2	2108381.3	20.8	2	1	1	1
691	346416.2	2108461.0	20.9	2	1	1	1
692	346525.4	2107877.9	22.0	1	1	1	1
693	346525.4	2107958.2	21.9	2	1	1	1
694	346525.4	2108041.4	15.5	3	2	0	0
695	346525.4	2108120.5	20.6	2	1	1	0
696	346525.4	2108217.3	20.9	2	2	0	0
697	346525.4	2108299.6	21.0	4	1	0	0
698	346525.4	2108381.3	0.9	2	1	0	0
699	346525.4	2108461.0	21.5	2	1	0	0
700	346679.2	2108218.0	20.8	3	2	0	0
701	346679.2	2108300.3	16.2	4	3	0	0
702	346682.1	2108382.0	16.3	4	3	0	0
703	346687.8	2107878.6	22.0	1	1	1	0
704	346687.8	2107958.9	22.0	2	1	1	1
705	346687.8	2108042.1	18.5	4	3	0	0
706	346687.8	2108121.2	15.7	4	3	0	0
707	346687.8	2108461.7	21.6	2	1	0	0
708	346850.9	2108041.4	28.4	2	2	0	0
709	346850.9	2108120.5	28.5	3	2	0	0
710	346850.9	2108217.3	21.0	3	2	0	0
711	346850.9	2108299.6	21.3	3	2	0	0
712	346850.9	2108381.3	21.4	2	1	1	1
713	346850.9	2108461.0	21.7	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
714	346852.3	2107958.9	22.1	4	3	0	0
715	346858.1	2107878.6	22.0	4	3	0	0
716	346962.0	2108120.5	28.6	1	1	1	1
717	346962.0	2108217.3	21.8	3	2	0	0
718	346962.0	2108299.6	21.4	3	2	0	0
719	347060.7	2107877.9	22.1	1	1	1	1
720	347060.7	2107958.2	22.2	2	1	1	1
721	347060.7	2108041.4	28.6	2	1	1	1
722	347060.7	2108120.5	28.7	1	1	1	1
723	347060.7	2108217.3	21.2	1	1	1	1
724	347060.7	2108299.6	21.2	2	1	1	1
725	347060.7	2108381.3	21.5	1	1	1	0
726	347060.7	2108461.0	21.6	2	1	1	1
727	347271.3	2107877.9	22.4	1	1	1	1
728	347271.3	2107958.2	22.5	2	1	1	1
729	347271.3	2108041.4	28.9	2	1	0	0
730	347271.3	2108120.5	28.9	1	1	0	0
731	347271.3	2108217.3	21.6	2	1	0	0
732	347271.3	2108299.6	21.7	2	1	0	0
733	347271.3	2108381.3	21.7	2	1	1	0
734	347271.3	2108461.0	21.7	2	1	1	1
735	347439.4	2107877.9	22.5	1	1	1	1
736	347439.4	2107958.2	21.2	2	1	1	1
737	347439.4	2108041.4	29.0	2	1	1	1
738	347439.4	2108120.5	21.5	1	1	1	1
739	347439.4	2108217.3	21.7	1	2	0	0
740	347439.4	2108299.6	21.7	2	1	1	1
741	347439.4	2108381.3	22.0	2	1	0	0
742	347439.4	2108461.0	22.0	2	1	1	1
743	347602.2	2107877.9	23.1	1	1	1	1
744	347602.2	2107958.2	19.3	1	1	1	1
745	347602.2	2108041.4	29.1	2	1	1	1
746	347602.2	2108120.5	29.1	1	1	1	1
747	347602.2	2108217.3	21.6	2	1	1	1
748	347602.2	2108299.6	21.9	2	1	1	1
749	347602.2	2108381.3	21.9	1	1	1	1
750	347602.2	2108461.0	22.1	2	1	1	1
751	347756.4	2107877.9	22.5	1	1	1	1
752	347756.4	2107958.2	21.4	2	1	1	1
753	347756.4	2108041.4	28.8	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
754	347756.4	2108120.5	31.1	1	1	1	1
755	347756.4	2108217.3	21.7	2	1	1	1
756	347756.4	2108299.6	22.0	2	1	1	1
757	347756.4	2108381.3	22.0	1	1	1	1
758	347756.4	2108461.0	22.2	1	1	1	1
759	347907.4	2107877.9	22.6	1	1	1	1
760	347907.4	2107958.2	21.6	2	1	1	1
761	347907.4	2108041.4	21.6	2	1	1	1
762	347907.4	2108120.5	21.9	1	1	1	1
763	347907.4	2108217.3	21.9	2	1	1	1
764	347907.4	2108299.6	22.1	2	1	1	1
765	347907.4	2108381.3	22.1	2	1	1	1
766	347907.4	2108461.0	22.4	2	1	1	1
767	348106.6	2107877.9	22.9	1	1	1	1
768	348106.6	2107958.2	21.9	2	1	1	1
769	348106.6	2108041.4	29.7	2	1	1	1
770	348106.6	2108120.5	29.7	1	1	1	1
771	348106.6	2108217.3	22.1	1	1	1	1
772	348106.6	2108299.6	22.3	1	1	1	1
773	348106.6	2108381.3	22.3	2	1	1	1
774	348106.6	2108461.0	22.3	2	1	1	1
775	348315.4	2107877.9	25.2	1	1	1	1
776	348315.4	2107958.2	25.3	2	1	1	1
777	348315.4	2108041.4	30.1	2	1	1	1
778	348315.4	2108120.5	30.0	1	1	1	1
779	348315.4	2108217.3	25.4	2	1	1	1
780	348315.4	2108299.6	25.3	2	1	1	1
781	348315.4	2108381.3	25.2	2	1	1	1
782	348315.4	2108461.0	25.3	2	1	1	1
783	348525.8	2107877.9	27.1	1	1	1	1
784	348525.8	2107958.2	27.1	2	1	1	1
785	348525.8	2108040.7	30.4	1	1	1	1
786	348525.8	2108120.5	30.4	1	1	1	1
787	348525.8	2108217.3	25.5	1	1	1	1
788	348525.8	2108299.6	25.5	2	1	1	1
789	348525.8	2108381.3	25.5	2	1	1	1
790	348525.8	2108461.0	25.4	1	1	1	1
791	348692.5	2107877.9	27.4	1	1	1	1
792	348692.5	2107958.2	27.4	2	1	1	1
793	348692.5	2108041.7	30.6	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
794	348692.5	2108120.5	30.5	1	1	1	1
795	348692.5	2108217.3	27.1	1	1	1	1
796	348692.5	2108299.6	25.6	2	1	1	1
797	348692.5	2108381.3	25.5	2	1	1	1
798	348692.5	2108461.0	25.4	2	1	1	1
799	348852.3	2107877.9	27.3	1	1	1	1
800	348852.3	2107958.2	27.3	2	1	1	1
801	348852.3	2108042.7	30.6	2	1	1	1
802	348852.3	2108120.5	30.5	1	1	1	1
803	348852.3	2108217.3	27.0	2	1	1	1
804	348852.3	2108299.6	25.5	2	1	1	1
805	348852.3	2108381.3	25.4	2	1	1	1
806	348852.3	2108461.0	25.4	2	1	1	1
807	349011.2	2107877.9	27.0	1	1	1	1
808	349011.2	2107958.2	27.0	2	1	1	1
809	349011.2	2108043.7	30.4	2	1	1	1
810	349011.2	2108120.5	30.4	1	1	1	1
811	349011.2	2108217.3	25.4	2	1	1	1
812	349011.2	2108299.6	25.3	2	1	1	1
813	349011.2	2108381.3	25.2	2	1	1	1
814	349011.2	2108461.0	25.3	2	1	1	1
815	349160.3	2107877.9	25.0	1	1	1	1
816	349160.3	2107958.2	25.0	2	1	1	1
817	349160.3	2108044.7	25.0	2	1	1	1
818	349160.3	2108120.5	25.0	1	1	1	1
819	349160.3	2108217.3	25.0	1	1	1	1
820	349160.3	2108299.6	25.1	2	1	1	1
821	349160.3	2108381.3	25.0	2	1	1	1
822	349160.3	2108461.0	25.1	2	1	1	1
823	349360.3	2107877.9	24.3	1	1	1	1
824	349360.3	2107958.2	24.4	2	1	1	1
825	349360.3	2108045.7	29.8	2	1	1	1
826	349360.3	2108120.5	29.8	1	1	1	1
827	349360.3	2108217.3	24.6	2	1	1	1
828	349360.3	2108299.6	24.6	2	1	1	1
829	349360.3	2108381.3	24.6	2	1	0	0
830	349360.3	2108461.0	24.8	2	1	1	1
831	349570.9	2107877.9	31.5	1	1	1	1
832	349570.9	2107958.2	29.1	2	1	1	1
833	349570.9	2108046.7	20.7	4	3	0	0

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
834	349570.9	2108120.5	18.6	4	3	0	0
835	349570.9	2108217.3	20.9	2	2	0	0
836	349570.9	2108299.6	21.0	2	1	1	1
837	349570.9	2108381.3	16.3	4	3	0	0
838	349570.9	2108461.0	21.2	3	1	0	0
839	349783.2	2107877.9	27.7	1	1	1	1
840	349783.2	2107958.2	26.9	2	1	1	1
841	349783.2	2108047.7	20.3	2	1	1	1
842	349783.2	2108120.5	20.4	1	1	1	1
843	349783.2	2108217.3	20.7	2	1	1	1
844	349783.2	2108299.6	20.8	2	1	1	1
845	349783.2	2108381.3	21.1	2	1	1	1
846	349783.2	2108461.0	21.0	1	1	1	1
847	349943.5	2107877.9	21.3	1	1	1	1
848	349943.5	2107958.2	20.3	2	1	1	1
849	349943.5	2108048.7	20.3	1	1	1	1
850	349943.5	2108120.5	20.5	1	1	1	1
851	349943.5	2108217.3	20.5	2	1	1	1
852	349943.5	2108299.6	21.0	1	1	1	1
853	349943.5	2108381.3	21.1	1	1	1	1
854	349943.5	2108461.0	21.1	1	1	1	1
855	350106.0	2108299.6	21.0	1	1	1	1
856	350106.0	2108381.3	21.0	1	1	1	1
857	350106.0	2108461.0	21.3	1	1	1	1
858	350266.2	2108299.6	21.2	1	1	1	1
859	350266.2	2108381.3	21.2	2	1	1	1
860	350266.2	2108461.0	21.4	4	3	0	0
861	350417.0	2108299.6	20.9	1	1	1	1
862	350417.0	2108381.3	21.3	1	1	1	1
863	350417.0	2108461.0	21.2	1	1	1	1
864	350615.6	2108299.6	19.8	1	1	1	1
865	350615.6	2108381.3	20.2	1	1	1	1
866	350615.6	2108461.0	20.2	1	1	1	1
867	350824.0	2108299.6	19.2	1	1	1	1
868	350824.0	2108381.3	19.6	1	1	1	1
869	350824.0	2108461.0	19.7	1	1	1	1
870	351024.2	2108311.5	19.1	1	1	1	1
871	351025.5	2108396.5	19.2	1	1	1	1
872	351026.4	2108479.2	19.4	1	1	1	1
873	351207.2	2108501.2	19.2	2	1	1	1

intno	coordeast	coordnorth	cmrr	icrf	icrss	icrp	icr
874	351211.5	2108317.0	18.8	1	1	1	1
875	351216.1	2108409.7	17.0	4	3	0	0
876	351361.5	2108321.0	18.8	1	1	1	1
877	351367.8	2108419.5	18.8	1	1	1	1
878	351369.1	2108516.8	17.0	4	3	0	0
879	351511.3	2108321.0	18.2	1	1	1	1
880	351517.6	2108419.5	18.6	1	1	1	1
881	351518.9	2108516.8	19.0	1	1	1	1
882	351663.1	2108416.1	18.8	1	1	1	1
883	351663.5	2108317.7	18.4	1	1	1	0
884	351664.3	2108513.5	18.6	1	1	1	0