

# **A Methodology For The Development Of A Production Experience Database For Earthmoving Operations Using Automated Data Collection**

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## **Abstract**

Automated data acquisition has revolutionized the reliability of product design in recent years. A noteworthy example is the improvement in the design of aircrafts through field data. This research proposes a similar improvement in the reliability of process design of earthmoving operations through automated field data acquisition. The segment of earthmoving operations addressed in this research constitutes the truck-loader operation. Therefore, the applicability of this research extends to other industries involving truck-operation such as mining, agriculture and forest logging and is closely related to wheel-based earthmoving operations such as scrapers.

The context of this research is defined by data collection needed to increase the validity of the results obtained by analysis tools such as simulation, performance measures and graphical representation of variance in an activity's performance, and the relation between operating conditions and the variance in an activity's performance. The automated cycle time data collection is facilitated by instrumented trucks and the collection of information on operating conditions is facilitated by image database and paper forms. The cycle time data and the information on operating conditions are linked together to form the experience database.

This research developed methods to extract, quantify and understand the variation in each component of the earthmoving cycle namely, load, haul and return, and dump activities. For the load activity, the simultaneous variation in payload and load time is illustrated through the development of a PLT (PayLoad Time) Map. Among the operating conditions, material type, load area floor, space constraints and shift are investigated. A dynamic normalization process of determining the ratio of actual travel time to expected travel time is developed for the haul and return activities. The length of the haul road, sequence of gear downshifts and shift are investigated for their effect on the travel time. The discussion on the dump activity is presented in a qualitative form due to the lack of data.

Each component is integrated within the framework of the experience database. The implementation aspects with respect to developing and using the experience database are also described in detail. The practical relevance of this study is highlighted using an example.

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## Table of Contents

<b>CHAPTER 1:INTRODUCTION.....</b>	<b>1</b>
1.1 THESIS STATEMENT.....	1
1.2 CONTEXT.....	1
1.3 PLANNING AND MANAGING EARTHMOVING OPERATIONS.....	2
1.3.1 <i>Background</i> .....	2
1.3.2 <i>Data Recording</i> .....	4
1.3.3 <i>Operations Analysis</i> .....	5
1.3.4 <i>Recording and Analysis – The Balance</i> .....	6
1.3.5 <i>Informal Techniques in Methods Improvement</i> .....	7
1.3.6 <i>Historical Data in Planning</i> .....	8
1.4 RESEARCH OBJECTIVES.....	9
1.5 RESEARCH HYPOTHESES.....	10
1.6 RESEARCH OUTLINE.....	10
1.7 DATA AVAILABILITY.....	12
1.8 INDUSTRY RELEVANCE.....	12
1.9 ORGANIZATION OF THE DISSERTATION.....	13
<b>CHAPTER 2:LITERATURE REVIEW.....</b>	<b>17</b>
2.1 METHODS IMPROVEMENT FOR EARTHMOVING OPERATIONS.....	17
2.1.1 <i>Manual Data Collection Techniques for Deterministic Job Studies</i> .....	18
2.1.2 <i>Manual Data Collection Techniques for Simulation Models</i> .....	21
2.1.3 <i>Instrumented Vehicles for Deterministic Job Studies</i> .....	24
2.1.4 <i>Instrumented Vehicles for Simulation Models</i> .....	25
2.2 HISTORICAL DATA IN PLANNING AND ESTIMATING.....	26
2.3 GRAPHICAL FORMS OF PRODUCTION DATA.....	27
2.4 STATISTICAL PROCEDURES.....	28
2.5 SUMMARY.....	31
<b>CHAPTER 3:TECHNOLOGIES FOR COLLECTING PERFORMANCE DATA.....</b>	<b>33</b>
3.1 DESIRABLE FEATURES.....	33
3.1.1 <i>Desirable Properties of Production Data</i> .....	34
3.1.2 <i>Desirable Characteristics of Data Collection Systems</i> .....	34
3.2 ONBOARD INSTRUMENTATION SYSTEM (OBI).....	35
3.2.1 <i>Concept</i> .....	35
3.2.2 <i>Using OBI for Performance Data Collection</i> .....	36

3.2.3	<i>Benefits and Limitations of OBI</i> .....	37
3.2.4	<i>Suitability to Cycle Time Data Collection</i> .....	38
3.3	GLOBAL POSITIONING SYSTEMS (GPS).....	39
3.3.1	<i>Concept</i> .....	40
3.3.2	<i>Benefits and Limitations of GPS</i> .....	41
3.3.3	<i>Examples of Applications</i> .....	42
3.3.4	<i>Suitability to Performance Data Collection</i> .....	44
3.4	RADIO FREQUENCY IDENTIFICATION (RFID).....	44
3.4.1	<i>Concept</i> .....	44
3.4.2	<i>Equipment</i> .....	45
3.4.3	<i>Benefits and Limitations of RFID</i> .....	47
3.4.4	<i>Examples of Applications</i> .....	47
3.4.5	<i>Suitability to Performance Data Collection</i> .....	48
3.5	SUMMARY.....	49
3.6	RECOMMENDATION.....	52

**CHAPTER 4: TECHNOLOGIES FOR COLLECTING INFORMATION ON OPERATING CONDITIONS**

**54**

4.1	TOUCHPAD.....	54
4.1.1	<i>Sample Application: Fast food industry</i> .....	55
4.1.2	<i>Productivity Data Collection Using a Touchpad</i> .....	56
4.2	BAR CODES.....	59
4.2.1	<i>Equipment</i> .....	60
4.2.2	<i>Bar Code Symbologies</i> .....	60
4.2.3	<i>Bar Code Applications in Construction</i> .....	60
4.3	DIRECT DATA ENTRY.....	61
4.4	IMAGE DATABASE (IDB).....	62
4.4.1	<i>Concept</i> .....	62
4.4.2	<i>Creating the IDB Catalog</i> .....	64
4.4.3	<i>Using the IDB Catalog</i> .....	65
4.4.4	<i>Applications of Image Databases</i> .....	66
4.5	SUMMARY.....	67

**CHAPTER 5: FRAMEWORK OF RESEARCH: THE EXPERIENCE DATABASE ..... 68**

5.1	THE CONCEPT.....	68
5.2	THE PARADIGM SHIFT.....	69
5.2.1	<i>From Data Collection to Building Experience</i> .....	70

5.2.2	<i>From Generic to Specific Information</i> .....	70
5.2.3	<i>From a Static to a Dynamic Archive of Production Information</i> .....	72
5.2.4	<i>From a Non-Electronic To a Digital Format</i> .....	72
5.3	ROLE OF ONBOARD INSTRUMENTATION IN EXPERIENCE DATABASE .....	73
5.4	DATA FORMATS .....	74
5.4.1	<i>Performance Data</i> .....	74
5.4.2	<i>Information on Operating Conditions</i> .....	75
5.4.3	<i>Descriptors</i> .....	76
5.5	CHARACTERIZATION .....	76
5.6	NORMALIZATION .....	78
5.7	COMPONENTS OF THE EXPERIENCE DATABASE .....	78
5.7.1	<i>Production Statistics</i> .....	79
5.7.2	<i>Visual Representation</i> .....	81
5.8	ROLE OF THE EXPERIENCE DATABASE .....	84
5.8.1	<i>Planning and Estimating Earthmoving Operations</i> .....	84
5.8.2	<i>Methods Improvement of Ongoing Operations</i> .....	85
5.9	SUMMARY .....	85
<b>CHAPTER 6: PERFORMANCE MEASURES FOR THE LOAD ACTIVITY .....</b>		<b>87</b>
6.1	DEFINITION .....	88
6.2	PREDICTING LOAD TIME AND PAYLOAD OF A TRUCK .....	89
6.2.1	<i>Reference Value</i> .....	90
6.2.2	<i>Variance in Normalized Load Time and Normalized Payload</i> .....	91
6.3	VARIATION UNDER INDEPENDENCE ASSUMPTION .....	91
6.3.1	<i>Payload</i> .....	92
6.3.2	<i>Load Time</i> .....	95
6.3.3	<i>Payload and Time</i> .....	97
6.4	PLT MAP .....	99
6.4.1	<i>Creating a PLT Map</i> .....	100
6.4.2	<i>Using the PLT</i> .....	100
6.5	VARIATION UNDER DEPENDENCE ASSUMPTION .....	102
6.6	PRODUCTION OF THE LOADING OPERATION .....	106
6.7	THE ASSUMPTIONS ANALYZED .....	110
6.7.1	<i>Load-Growth Curves</i> .....	110
6.7.2	<i>Field Data and PLT Map</i> .....	111
6.8	MANAGING THE LOAD ACTIVITY .....	113
6.9	SUMMARY .....	115

<b>CHAPTER 7:PERFORMANCE MEASURES FOR THE HAUL &amp; RETURN ACTIVITIES .....</b>	<b>117</b>
7.1 DEFINITION OF HAUL AND RETURN TIMES.....	118
7.2 PREDICTING HAUL AND RETURN TIME .....	120
7.2.1 <i>Reference Value</i> .....	123
7.2.2 <i>Variance</i> .....	124
7.3 DETERMINING THE THEORETICAL TRAVEL TIME.....	125
7.4 THE RATIOS EXPLAINED.....	128
7.4.1 <i>Absolute Value of the Ratios</i> .....	130
7.4.2 <i>Variance of the Ratios</i> .....	131
7.5 PARAMETRIC DEFINITION OF HAUL TIME .....	131
7.6 USING PERFORMANCE MEASURES TO MANAGE HAUL AND RETURN TIMES .....	134
7.7 SUMMARY .....	134
<b>CHAPTER 8:PERFORMANCE MEASURES FOR THE DUMP ACTIVITY.....</b>	<b>136</b>
8.1 DEFINITION.....	136
8.2 PREDICTING DUMP TIME .....	137
8.2.1 <i>Estimating the Reference Value</i> .....	138
8.2.2 <i>Estimating the Variance</i> .....	138
8.3 MANAGING THE DUMP ACTIVITY .....	139
8.4 SUMMARY .....	139
<b>CHAPTER 9:DEFINING OPERATING CONDITIONS WHICH AFFECT THE LOAD ACTIVITY.....</b>	<b>140</b>
9.1 METHODOLOGY.....	141
9.2 SELECTION OF FACTORS WHICH DEFINE THE OPERATING CONDITIONS .....	142
9.3 EVALUATING GLOBAL FACTORS.....	144
9.3.1 <i>Projects</i> .....	144
9.3.2 <i>Loading Methods</i> .....	146
9.3.3 <i>Operator Efficiency</i> .....	149
9.4 EVALUATING PROJECT SPECIFIC FACTORS.....	150
9.4.1 <i>Material</i> .....	150
9.4.2 <i>Area Layout</i> .....	158
9.4.3 <i>Floor Conditions</i> .....	162
9.4.4 <i>Shift</i> .....	163
9.5 SUMMARY .....	167
<b>CHAPTER 10:DEFINING OPERATING CONDITIONS WHICH AFFECT THE HAUL &amp; RETURN ACTIVITIES</b>	<b>169</b>

10.1	METHODOLOGY .....	170
10.2	SELECTION OF FACTORS WHICH DEFINE THE OPERATING CONDITIONS.....	171
10.3	EVALUATING GLOBAL FACTORS .....	173
10.3.1	<i>Haul or Return</i> .....	173
10.3.2	<i>Machine Characteristics</i> .....	175
10.4	EVALUATING SPECIFIC FACTORS .....	178
10.4.1	<i>Length</i> .....	178
10.4.2	<i>Sequence of Downshifts</i> .....	181
10.4.3	<i>Shift</i> .....	189
10.4.4	<i>Miscellaneous Factors</i> .....	190
10.5	SUMMARY .....	192
<b>CHAPTER 11:DEFINING OPERATING CONDITIONS WHICH AFFECT THE DUMP ACTIVITY .....</b>		<b>194</b>
11.1	SELECTION OF FACTORS WHICH DEFINE THE OPERATING CONDITIONS.....	194
11.1.1	<i>Machine Characteristics</i> .....	195
11.1.2	<i>Material</i> .....	196
11.1.3	<i>Underfoot Conditions</i> .....	196
11.1.4	<i>Space Constraints</i> .....	197
11.2	SUMMARY .....	197
<b>CHAPTER 12:DEVELOPING THE EXPERIENCE DATABASE .....</b>		<b>198</b>
12.1	SYSTEM TO COLLECT PERFORMANCE RECORDS .....	200
12.1.1	<i>Downloading Data</i> .....	200
12.1.2	<i>Calibration</i> .....	200
12.1.3	<i>Data Format</i> .....	201
12.2	PROCESSING ADDITIONAL PERFORMANCE DATA .....	203
12.2.1	<i>Associating Material, Haul Name and Fleet to Each Performance Record</i> .....	203
12.2.2	<i>Night Shift Operations</i> .....	204
12.3	SYSTEM TO COLLECT INFORMATION ON OPERATING CONDITIONS.....	206
12.3.1	<i>Paper Forms</i> .....	206
12.3.2	<i>Image Catalog</i> .....	208
12.3.3	<i>Haul Road Profiles</i> .....	218
12.4	CREATING THE EXPERIENCE DATABASE .....	219
12.4.1	<i>Importing Performance Records</i> .....	221
12.4.2	<i>Inputting Information on Operating Conditions</i> .....	222
12.4.3	<i>Inputting Information of Haul Road Profiles</i> .....	223
12.4.4	<i>Linking Different Forms of Data</i> .....	224

12.5	SUMMARY .....	225
<b>CHAPTER 13:USING THE EXPERIENCE DATABASE .....</b>		<b>227</b>
13.1	USING THE EDB FOR THE LOAD ACTIVITY .....	228
13.1.1	<i>Filtering Records</i> .....	229
13.1.2	<i>Determining the PDF</i> .....	233
13.1.3	<i>Generating the Graphical Representation – PLT Map</i> .....	236
13.2	USING EDB FOR HAUL AND RETURN ACTIVITIES .....	238
13.2.1	<i>Filtering Records</i> .....	238
13.2.2	<i>Determining the PDF</i> .....	240
13.2.3	<i>Generating the Graphical Representation</i> .....	242
13.3	PREDICTING CYCLE TIME COMPONENTS.....	242
13.4	SUMMARY .....	244
<b>CHAPTER 14:CONCLUSIONS.....</b>		<b>245</b>
14.1	SUMMARY .....	245
14.2	CONTRIBUTIONS .....	248
14.3	PRACTICAL RELEVANCE OF THE RESEARCH.....	250
14.4	LIMITATIONS.....	255
14.5	DIRECTIONS FOR FUTURE RESEARCH.....	256
<b>REFERENCES.....</b>		<b>259</b>
<b>APPENDIX A: TRAVEL TIME CALCULATOR.....</b>		<b>272</b>
<b>APPENDIX B: PRODUCTION DATA COLLECTION USING GPS.....</b>		<b>275</b>

## List of Figures

Figure 1-1: Balance between data collection methods and operation analysis tools.....	2
Figure 1-2: Features of data recording methods.....	4
Figure 1-3: Features of operations analysis methods .....	6
Figure 1-4: States of balance between data recording and operations analysis methods .....	7
Figure 1-5: The document map of the dissertation.....	16
Figure 2-1: Methods improvement through data collection and analysis .....	18
Figure 3-1: Role of automated data collection systems in the development of an experience database .....	53
Figure 4-1: Sample screen showing a touchpad code .....	55
Figure 4-2: Sample application using a touchpad [ <a href="http://www.cedeq.com">http://www.cedeq.com</a> ] .....	56
Figure 4-3: Template for the load-area data collection .....	58
Figure 4-4: Sample application which interfaces with touchpad .....	58
Figure 4-5: Sample screen for a data entry program .....	62
Figure 4-6: Example of a catalog of baggage used by airline industry .....	67
Figure 5-1: Experience database for archiving and retrieving information.....	69
Figure 5-2: Process, location and technology aspects of the data collection system .....	73
Figure 5-3: Moments of a sample data set .....	80
Figure 5-4: An example of modeling payload for input to simulation.....	81
Figure 5-5: Histograms of payload and load time of a shovel-truck operation.....	82
Figure 5-6: Box plot representation of payload and load time.....	83
Figure 5-7: Histogram depicting a range of payload and the corresponding distribution of load time.....	84
Figure 6-1: Schematic representation of a data set.....	87
Figure 6-2: Definition of load time .....	88
Figure 6-3: Process diagram for developing performance measures for the load activity .....	92
Figure 6-4: Frequency distribution of payload .....	93
Figure 6-5: Distribution to model payload data .....	95
Figure 6-6: Frequency distribution of load time.....	96
Figure 6-7: Distribution to model load time data.....	97

Figure 6-8: Joint frequency of payload and load time.....	98
Figure 6-9: An example of a PLT Map.....	101
Figure 6-10: Continuous distributions of payload for discrete intervals of load times.....	101
Figure 6-11: Parametric form of payload and load time.....	104
Figure 6-12: PLT Maps simulated from the PDFs.....	105
Figure 6-13: PLT Map showing iso-production lines.....	107
Figure 6-14: Frequency distribution of instantaneous production of the loading tool.....	109
Figure 6-15: Relation between the load growth curve and a PLT Map.....	111
Figure 6-16: A scatter plot of payload and load time.....	112
Figure 6-17: Target window on a PLT Map.....	114
Figure 6-18: PLT Map generated by uncharacterized data.....	116
Figure 7-1: Definition of haul time.....	118
Figure 7-2: Definition of return time.....	118
Figure 7-3: Procedures for performance measures for haul activity.....	120
Figure 7-4: Procedures of performance measures for the return activity.....	121
Figure 7-5: A histogram of haul times from a sample data set.....	122
Figure 7-6: A histogram and a PDF of ratios.....	125
Figure 7-7: An example of speed profile as generated by travel time calculator.....	127
Figure 7-8: Actual and theoretical speed profiles of a haul road.....	129
Figure 7-9: Procedure for developing the PDF of travel time ratios.....	131
Figure 7-10: Parametric definition of haul time in terms of payload.....	133
Figure 8-1: Different types of dump mechanisms in a truck.....	136
Figure 8-2: Definition of dump time.....	137
Figure 9-1: Methodology for characterizing performance data.....	141
Figure 9-2: Hierarchical order of factors that influence the load activity.....	143
Figure 9-3: Different types of loading methods.....	146
Figure 9-4: A comparison of PLT Maps for two different fleets.....	148
Figure 9-5: A comparison of PLT Maps for two different operators.....	149
Figure 9-6: Influence diagram for material.....	151
Figure 9-7: Influence diagram for fairness of shot.....	154

Figure 9-8: A comparison of PLT Maps for different types of material on Project A .....	155
Figure 9-9: A comparison of PLT Maps for different types of material for a loading method under Project C .....	157
Figure 9-10: Influence diagram for area layout .....	159
Figure 9-11: A comparison of PLT Maps for area layout for a loading method under Project C161	
Figure 9-12: Influence diagram for floor conditions .....	162
Figure 9-13: Influence diagram for shift .....	164
Figure 9-14: A comparison of PLT Maps for two shifts for a loading method for Project A.....	165
Figure 9-15: A comparison of PLT Maps for two shifts for a loading method for Project C (Fleet 2).....	166
Figure 10-1: Hierarchical order of factors which affect the haul and return activities.....	172
Figure 10-2: A comparison of haul and return ratios for various haul roads .....	174
Figure 10-3: A comparison of histograms for haul and return ratios for haul name HW .....	175
Figure 10-4: Power to weight ratio of various models of truck from one manufacturer.....	176
Figure 10-5: A comparison of histograms for machine characteristics for haul name HW .....	177
Figure 10-6: Influence diagram for length .....	179
Figure 10-7: A comparison of histograms for two different haul lengths for truck type = 'S' ...	180
Figure 10-8: Influence diagram for sequential downshift .....	181
Figure 10-9: An example of surface condition.....	182
Figure 10-10: Effect of payload on haul time .....	184
Figure 10-11: Force-Speed relationship .....	185
Figure 10-12: Results from statistical tests on the effect of payload and downshifts on haul ratios	188
Figure 10-13: Speed profile and gear position for a haul road.....	190
Figure 10-14: Effect of haul road width on haul time.....	191
Figure 10-15: An operator's visibility from the cab .....	191
Figure 11-1: Hierarchical order of factors that influence dump time.....	194
Figure 11-2: Different types of dump mechanisms in a truck.....	195
Figure 11-3: Different types of underfoot conditions in the dump area.....	196
Figure 11-4: Different types of space constraints in the dump area.....	197
Figure 12-1: The framework of the experience database .....	198

Figure 12-2: Procedures for developing the experience database .....	199
Figure 12-3: Procedures for processing additional information.....	204
Figure 12-4: Form for collecting information on operating conditions .....	207
Figure 12-5: The Material Catalog.....	210
Figure 12-6: The Load Area Catalog.....	212
Figure 12-7: The Haul Catalog.....	215
Figure 12-8: The Dump Catalog .....	216
Figure 12-9: The opening screen of the prototype for the experience database.....	220
Figure 12-10: Importing different forms of data into the experience database.....	220
Figure 12-11: Hierarchical format of the data import / input process.....	221
Figure 12-12: Details required to input performance records .....	222
Figure 12-13: Inputting information on operating conditions.....	223
Figure 12-14: Inputting information on haul roads .....	224
Figure 12-15: The logical relationship between various components of data within the experience database .....	225
Figure 13-1: Schematic representation of the experience database.....	227
Figure 13-2: Layout for using the experience database.....	228
Figure 13-3: The opening screen of the prototype for the experience database.....	229
Figure 13-4: Screen showing the different options for using the experience database .....	230
Figure 13-5: Options for filtering performance records for the load activity.....	230
Figure 13-6: A segment of the spreadsheet showing normalized payload and load time after filtering.....	232
Figure 13-7: Processes involved in deriving the PDF and generating the PLT Map .....	232
Figure 13-8: Determining the PDF for load time .....	234
Figure 13-9: Pivot table for parametric definition of payload in terms of load time .....	235
Figure 13-10: Plot of payload in terms of load time .....	235
Figure 13-11: A PLT Map generated from the filtered and normalized data.....	236
Figure 13-12: Pivot table showing the actual count of data points in each cell .....	237
Figure 13-13: Pivot table showing the normalized value for each cell.....	237
Figure 13-14: Filtering options for the haul and returning activities .....	239

Figure 13-15: Travel Time Calculator interface.....	239
Figure 13-16: Filtering records by choosing the appropriate haul name and truck model.....	240
Figure 13-17: PDF for haul ratios .....	241
Figure 13-18: PDF for return ratios.....	241
Figure 13-19: Haul and return ratios for the filtered haul name.....	242
Figure 13-20: A snippet of code from a model developed in STROBOSCOPE to implement payload distribution.....	243
Figure 14-1: Framework of research: Experience Database .....	246
Figure 14-2: Data from onboard instrumentation system.....	254
Figure 14-3: Transformation of data to information .....	254
Figure 14-4: Breadth and depth of knowledge in construction data .....	258

## List of Tables

Table 1-1: Data available for the study .....	12
Table 3-1: Comparison of candidate technologies .....	49
Table 5-1: Candidate factors for data characterization.....	77
Table 6-1: Spreadsheet showing a portion of the onboard instrumentation data and the corresponding values of instantaneous production .....	108
Table 9-1: Results from statistical tests on payload and load time for the different projects .....	145
Table 9-2: A multiple range comparison of fleet payload and load time .....	147
Table 9-3: Classification of material .....	151
Table 9-4: Results of statistical tests on Project A for characterizing factor- Material .....	155
Table 9-5: Results of statistical tests on Project C for characterizing factor- Material.....	156
Table 9-6: A multiple range comparison of material type for different loading methods.....	158
Table 9-7: Results of statistical tests for characterizing factor- Area Layout .....	161
Table 9-8: Results of statistical tests on Project A for characterizing factor- Shift .....	164
Table 9-9: Results of statistical tests on Project C for characterizing factor- Shift (Fleet 2).....	165
Table 9-10: Summary of analysis of factors which can be used for characterizing the load activity	168
Table 10-1: A comparison of statistical tests for characterizing factor – Truck Type .....	177
Table 10-2: Multiple range comparison of haul ratios for length for all truck type.....	179
Table 10-3: Multiple range comparison for haul ratios for length for truck type 'B' .....	180
Table 10-4: Effect of payload on haul ratio for truck type ‘B’ .....	186
Table 10-5: Multiple range comparison of haul ratios for payload for all trucks .....	187
Table 10-6: A comparison of statistical tests for characterizing factor - Shift.....	190
Table 10-7: Summary of analysis of operating conditions which affect the performance of the haul and return activities .....	193
Table 12-1: Sample data as obtained from onboard instrumentation.....	202
Table 12-2: Performance records after processing information on material, haul name, fleet ...	205
Table 12-3: Information on operating conditions collected using paper forms and image database	217
Table 13-1: Predicted duration of the activity.....	243
Table 14-1: A comparison of limited time-window and continuous data collection .....	251

## List of Symbols

$a$  is the lower bound of the distribution  
 $b$  is the higher bound of the distribution  
 $d_s$  is the downshifts  
 $E$  is the estimate for a future operation  
 $E_d$ , the estimate for a future project  
 $E_h$  is the estimate for haul time in a future operation  
 $E_r$  is the estimate for return time in a future operation  
 $f(p)$  is the PDF that describes the variation in payload for the entire range  
 $f(t)$  is the PDF that describes the variance in load time for the entire range  
 $f(t,p)$  is the surface represented by the joint frequency distribution of load time and payload  
 $f(v_a)$  is the PDF that describes the variation of the load time  
 $f(v_h)$  is the PDF that describes the variation of the haul time  
 $f(v_r)$  is the PDF that describes the variation of the return time  
 $H_{ah}$  is the actual haul time for each cycle as recorded by the onboard instruments  
 $H_{ar}$  is the actual return time for each cycle as recorded by the onboard instruments  
 $H_{th}$  is the theoretical estimate for haul time  
 $H_{tr}$  is the theoretical estimate for return time  
 $l_h$  is the haul length  
 $L$  is the total number of discrete locations on the haul road  
 $l, g, r$  are the length, grade and rolling resistance of each segment  
 $L_p$  and  $U_p$  are lower and upper limits of the range of payload  
 $L_t$  and  $U_t$  are lower and upper limits of the range of load time  
 $M_t$  is the mean of the Normal distribution  
 $n$  is the number and order of segments in the haul road  
 $p$  is the payload  
 $P(p)$  is the PDF that describes the payload  
 $P(t)$  is the PDF that describes the load time  
 $P(x)$  is the probability of a random variable  $x$   
 $R_h$  is the haul ratio  
 $R_i, R_j$  are the reference value for the  $i^{th}$  and  $j^{th}$  combination of descriptors  
 $R_r$  is the return ratio

$s_1$  and  $s_2$  are scale and shape factors respectively of a Beta distribution  
 $s_{ai}$  is the actual speed at the  $i^{\text{th}}$  location on the haul road  
 $Sd_t$  is the standard deviation of the Normal distribution  
 $s_{ti}$  is the theoretical speed at the  $i^{\text{th}}$  location on the haul road  
 $t_a$  is the load time for each cycle as recorded by the onboard instruments  
 $t_d$ , the actual duration of the dump time as recorded on the field  
 $v_a$  is the normalized load time for each cycle  
 $v_d$  is the normalized dump time for each cycle  
 $v_h$  is the normalized haul time for each cycle  
 $v_r$  is the normalized return time for each cycle  
 $\beta_1$  is square of the coefficient of skewness  
 $\beta_2$  is the coefficient of kurtosis  
 $\theta_1$  and  $\theta_2$  are the transformed parameters  
 $\theta_i$  is the ratio of actual to theoretical instantaneous speed at the  $i^{\text{th}}$  location on the haul road  
 $\bar{\theta}$  is the average value of  $\theta_i$   
 $\hat{\theta}_h$  is the estimator of  $\bar{\theta}$  for haul  
 $\hat{\theta}_r$  is the estimator of  $\bar{\theta}$  for return

### Errata

Equations on pages 92, 94, 98 have integral signs missing. The error in the software will be fixed as soon as possible and updated.

# **CHAPTER 1: INTRODUCTION**

## **1.1 THESIS STATEMENT**

The planning, estimating and management of earthmoving operations can be improved by developing a production experience database to retrieve and analyze production statistics by storing the performance data generated by vehicle instrumentation system and the corresponding operating conditions.

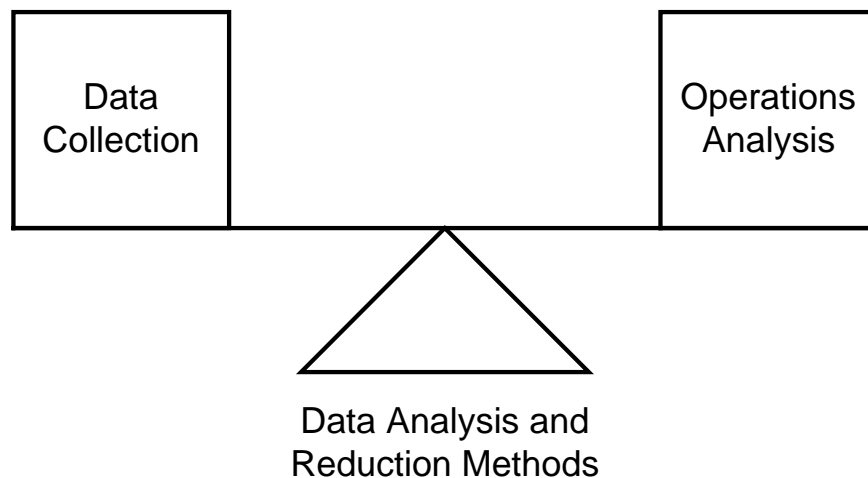
The development of the experience database will transform the field data collected by the vehicle instrumentation system into information which can then provide the basis for knowledge and application in earthmoving operations.

## **1.2 CONTEXT**

Planning and estimating of earthmoving operations rely on the ability to collect field data and analyze operations using formal techniques. Two recent developments have dramatically changed the methods and improved the results obtained in this process. The first of these developments involves data collection where instrumentation placed on the loading and hauling units can replace stopwatches as the primary source of data. The second development is changes in operations analysis where simulation techniques can replace deterministic job studies.

Figure 1-1 shows the balance between data collection methods and operations analysis tools. The use of stopwatches may satisfy the requirements of job studies but does not satisfy those of simulation. Simulation requires knowledge of the variance associated with the activity duration. Obtaining the variance from a few data points collected using stopwatches is frequently statistically incomplete. Simulation requires a continuous form of data collection to support its modeling process and hence, offers new challenges to the data collection methods. Vehicle instrumentation presents a viable opportunity to collect continuous field data. However, the data collected by vehicle instrumentation must be characterized in a way to reflect the actual operating conditions under which they were recorded.

Informal techniques such as data visualization achieve the goal of methods improvement through better communication at the site level. Powerful graphical techniques are required to depict the variance in an activity's performance, which is otherwise difficult to recognize among the details of data from vehicle instrumentation. Variance in an activity's performance, which is often the reason for reduced productivity, is an effect of variable operating conditions.



**Figure 1-1: Balance between data collection methods and operation analysis tools**

Therefore, the context of this research is defined by data collection needed to increase the validity of the results obtained by analysis tools such as simulation, performance measures and graphical representation of variance in an activity's performance, and the relation between operating conditions and the variance in an activity's performance.

## **1.3 PLANNING AND MANAGING EARTHMOVING OPERATIONS**

### **1.3.1 Background**

Planning and managing earthmoving operations pass through four distinct phases [Oglesby *et al.* 1989]. These phases are record, analyze, devise and implement. *Record* involves collecting data and other relevant information necessary for analysis. *Analyze* involves realistically modeling and reviewing construction operations. *Devise* involves making recommendations based on the output of the analysis. *Implement* involves executing the recommendations in the field.

The record and analyze phases are the foundations upon which the decisions and recommendations in the devise and implement phases are built. The fruits of the data recording phase will carry forward into the analysis phase which is, in itself, a well-tilled field of inquiry [Paulson *et al.* 1987, McCahill and Bernhold 1993, Ioannou and Martinez 1996]. Therefore, a thorough understanding and execution of the record and analyze phases has to be in place to facilitate informed decisions in the devise and implement phases. Better understanding of both of these phases has been fostered by technical advances and enhanced capabilities of tools that support the data recording and analysis domains.

The technology used in data collection for earthmoving operations has advanced from stopwatches to vehicle instrumentation [Oglesby *et al.* 1989, Sootodeh and Paulson 1989]. The knowledge in analysis of earthmoving operations has progressed from job studies to simulation models [Halpin and Riggs 1992, Paulson 1995]. There exists a balance between the requirements of job studies and data collected by stopwatches, time-lapse photography, and video taping [Touran 1981, Paulson *et al.* 1983, Paulson *et al.* 1987, Bjornsson and Sagert 1994]. Schexnayder *et al.* [1999] is one of the few reported instances of deterministic calculations on data collected using vehicle instrumentation. The increasing use of vehicle instrumentation in earthmoving operations will allow for a paradigm shift in data recording in order to support the changes which have occurred in the analysis methodologies.


Advances in vehicle instrumentation along with advances in database management and statistical methodologies can provide the construction industry with an abundance of both the data and technology needed to develop reliable production statistics. Vehicle instrumentation generates a continuous stream of indiscriminate data, and adapting it for use in planning and productivity improvement poses a new challenge.

The continuous stream of data from vehicle instrumentation extends the concept of recording data to a broader concept of building an *experience database*. This research methodology facilitates a structural change from generic (industry-wide), static and non-electronic standards and manuals such as those developed by equipment manufacturers [Caterpillar 1997] to company- or project-specific, dynamic and electronic archives of actual field experience.

### 1.3.2 Data Recording

Data recording is the process of collecting data and other relevant information for analysis. Figure 1-2 illustrates the advancement and features of data recording methodologies. The knowledge in earthmoving-equipment data recording has incrementally progressed from stopwatches to time-lapse photography, video cameras, and on-board instrumentation [Oglesby *et al.* 1989, Touran 1981, Stewart 1998]. Data collected by stopwatches is well defined because of the discretion used by the observer in selecting the data that is relevant to the study. The operating conditions under which the data are collected are explicitly recorded and characterized. Limitations to stopwatch studies include the restriction of the scope of information to the information that is recorded and the requirement of instantly distinguishing one event from another. On the other hand, techniques such as time-lapse or video photography require the extraction of data from the media.

Deterministic job studies require a single point estimate such as the average time required to load a truck. However, the variance in an activity's duration is necessary to describe the probabilistic information about the activity and to benefit from simulation analysis. Computing the variance in an activity's duration requires a statistically valid volume of data. Manually recording a large volume of data is tedious, costly and prone to error. Therefore automating the data recording process is vital to collecting a large and continuous volume of data.

STOP WATCHES	 <b>VEHICLE INSTRUMENTATION</b>
<ul style="list-style-type: none"> <li>• Few well defined data points</li> <li>• Operating conditions recorded during study</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Continuous stream</u> of data</li> <li>• Operating conditions not recorded by vehicle instruments</li> </ul>

**Figure 1-2: Features of data recording methods**

Vehicle instrumentation presents a viable opportunity for continuous productivity data collection. The vehicle instrumentation investigated as part of this research are machine health diagnostic systems, global positioning systems and radio frequency identification systems. Machine health diagnostic systems, henceforth termed as onboard instrumentation (OBI), were used in this research to collect performance records. Performance records refer to the activity durations of

different component of the earthmoving cycle. Different equipment manufacturers have their own proprietary onboard instrumentation systems. Examples of proprietary systems currently in use include VIMS<sup>®</sup> & TPMS<sup>®</sup> (Caterpillar [<http://www.cat.com>]), CONTRONICS<sup>®</sup> (Volvo [<http://www.vce.volvo.se>]) and HMS<sup>®</sup> (Komatsu [<http://www.komatsuamerica.com>]).


### 1.3.3 Operations Analysis

The analyze phase of a study attempts to realistically model a physical system and hence, facilitate decision making by presenting alternate scenarios. Analysis and methods improvement can be performed through simple analytical tools as well as mathematical models. Simple analytical tools include five-minute rating techniques, crew-balance charts, process and flow diagrams [Parker and Oglesby 1972]. Mathematical tools could include but are not limited to graphical models (e.g. load-growth curves), scheduling techniques, operations research (e.g. transportation problem) and simulation techniques [Parker and Oglesby 1972]. Simulation lends itself well to the analysis and methods improvement of earthmoving operations because the operations are cyclical in nature, they are prone to uncertainties in performance, and they involve resource interaction.

Figure 1-3 shows the progression of knowledge from job studies to simulation in the analysis of earthmoving operations [Halpin and Riggs 1992, Paulson 1995, Ioannou and Martinez 1996]. Job studies are characterized by single point estimates, deterministic calculations and a unique analysis. Resource interaction and uncertainty are seldom considered because of the complexities involved in modeling them. Job studies are well suited for small projects where the average values of productivity, duration and cost are sufficient. Deviation or variance from the average value is a critical factor [Martinez 1998]. Construction activities are prone to variations and uncertainties. Simulation lends itself well to the analysis of operations involving uncertainties.

Simulation models use probabilistic input data for activity duration and hence allow for the variations in the construction processes. Simulation models can provide meaningful and accurate results, not only with production rates for the overall process, but also detailed performance the of resources utilized [McCahill and Bernhold, 1993]. The most significant feature of simulation

models is in the ability to study different scenarios. Modeling physical systems for the purpose of quantitative analysis requires the abstraction of the process-flow as well as the data that support the processes. McCahill and Bernhold [1993] and Martinez [1996] have documented the enhancement of the modeling capability from CYCLONE [Halpin 1977] to STROBOSCOPE [Martinez 1996]. The data requirements implicit in any attempt to implement complex simulation models are however not addressed. Abourizk and Halpin [1992a, 1992b] have shown the importance of data requirements for simulation and the effects of using an inappropriate distribution on the output of simulation.

<b>JOB STUDIES</b> 	<ul style="list-style-type: none"> <li>• Deterministic approach</li> <li>• Single point estimates</li> <li>• Unique analysis</li> </ul>
<b>SIMULATION</b>	<ul style="list-style-type: none"> <li>• Stochastic approach</li> <li>• Probabilistic (Range) estimates</li> <li>• Range of scenarios</li> </ul>

**Figure 1-3: Features of operations analysis methods**



### 1.3.4 Recording and Analysis – The Balance

The discussions on data recording and the operations analysis suggest that there is a mutual interdependence between advances in data collection methodology and the requirements of the analysis methodology. The balance between the data recording methods and the operations analysis methods as illustrated in Figure 1-1 is critical. If the tool used for analysis is job studies, the data need is single point estimates for components of cycle time. The data reduction involves calculating the average value from a data set. If the job study needs to be performed under different conditions, such as day and night shifts, different data sets are required. It is clear that stopwatches present a viable opportunity to collect data for this purpose. A single point estimate is deceiving because it camouflages the variation in the operation and hence the value of information is restricted to the average value in output.

Operations analysis tools such as simulation are an order higher in terms of data requirements. The data must be in the form of statistically valid probabilistic distributions for the components

of cycle time. The data reduction involves fitting standard distributions to a data set which contains sufficient number of data points, or the population of the data itself. If the analysis includes differing site conditions such as day and night shifts or complex traffic patterns, the data set must be characterized in a way which reflects the actual conditions under which the data were recorded. Although the reduction process is well established, the data recording process to generate continuous data is still in its embryonic stage.

It is clear that a balance is necessary between the data recording capability and operations analysis methods. Figure 1-4 demonstrates the states of balance and imbalance between the data recording and analysis phases of productivity improvement. Using stopwatches for job studies presents a state of balance as the data requirements and data-collection methodology match one another. On the other hand, using vehicle instrumentation for job studies or using stopwatches for simulation create states of imbalance. In the former case, there is an overload of data and the benefit of a large data set is lost while in the latter case, the analysis process becomes seriously flawed without statistically sufficient data. The only other state capable of balance is through the deployment of a continuous stream of data collected by vehicle instrumentation for stochastic tools such as simulation.

	<b>STOP WATCHES</b>		<b>VEHICLE INSTRUMENTATION</b>
<b>JOB STUDIES</b> 	<ul style="list-style-type: none"> <li>• Balance between data recording and analysis tool</li> <li>• Suited for simple operations</li> </ul>		<ul style="list-style-type: none"> <li>• Balance is lost between data recording and analysis tool</li> <li>• Overload of data, lack of analysis capability</li> </ul>
<b>SIMULATION</b>	<ul style="list-style-type: none"> <li>• Balance is lost between data recording and analysis tool</li> <li>• Overload of analysis capability, lack of robust data</li> </ul>		<b>New Frontier</b>

**Figure 1-4: States of balance between data recording and operations analysis methods**

### 1.3.5 Informal Techniques in Methods Improvement

Managers as well as the work crew require an easy and intuitive mechanism to assess the performance of an activity and hence suggest means to improve it. The continuous stream of performance records from the vehicle instrumentation addresses the demand of data recording.

However, all the data collected by vehicle instruments is of no consequence to methods improvement if the information embedded in them is not extracted and presented in a clear format in a timely manner. Managers and site crews who are aware of the work face and understand the physical process require a mechanism to assess performance at regular intervals to make decisions [Schexnayder *et al.* 1999]. Information can be presented in the form of words, numbers and graphics [Oglesby *et al.* 1983]. Graphical display of information is easily understood by most people [Tuft 1983].

### **1.3.6 Historical Data in Planning**

Public standards and handbooks have been the de facto benchmark for data input to planning earthmoving [Paulson 1995]. These standards and handbooks are applicable to a wide range of projects but their relevancy to any one particular project is minimal because the values contained in them are averaged over a wide spectrum of projects under different conditions. Two types of difficulties are associated with using values provided by standards or handbooks [Knoke *et al.* 1993]. They are:

- [1] the values provided by these sources seldom represent the actual conditions of the project under consideration, and
- [2] it is difficult to derive the variability of the current project from the data in the sources.

It is possible to construct a company- or project-specific source of information using the performance records collected by vehicle instrumentation. However, the performance records need to be linked to the operating conditions under which they were collected. Linking the performance records to the operating conditions is termed “characterization.” The extension of historical data to plan future projects may also require a form of normalization where the relative variance in the performance data has to be extracted based on the operating conditions.

## 1.4 RESEARCH OBJECTIVES

The objective of this research was to develop a production experience database capable of providing production statistics for planning and estimating future operations and improving methods of ongoing operations.

1. The objectives in terms of developing the experience database are as follows:

- Design a system to collect performance records or cycle time data on earthmoving operations
- Design a system to collect information on operating conditions which affect performance
- Link the information on operating conditions to the corresponding performance records
- Develop a prototype to demonstrate the concepts embodied in the experience database

2. The objectives in terms of deriving production statistics are as follows:

- Develop methods to extract the relative variance in each component of the earthmoving operation
- Develop methods to quantify the variance so that it can be applied to future projects
- Develop methods to understand the variance based on the performance measures

3. The objectives in terms of evaluating the role of operating conditions on the performance are as follows:

- Develop a hierarchical order of factors that define the operating conditions
- Determine the effect of each factor on the different components of the cycle time based on statistical tests
- Suggest, and if necessary develop, metrics that can be used to extend historical data to future operations

4. The objectives in terms of monitoring and improving ongoing operations are as follows:

- Develop graphical techniques to present the large volume of data collected by vehicle instrumentation in an intuitive manner and hence contribute to informal techniques in productivity improvement
- Present probabilistic estimates for activity duration to be used in formal techniques in productivity improvement such as simulation

## 1.5 RESEARCH HYPOTHESES

Hypothesis #1: It is possible to construct and maintain a realistic experience database using data from instrumented vehicles.

The experience database will be company- or project-specific, dynamic and in an electronic format. The experience database will contain performance data linked to the corresponding operating conditions.

Hypothesis #2: It is possible to generate production statistics about activities' performance and hence quantify the variation in activities' performance.

The ability to provide reliable probabilistic data will increase the validity of results obtained using analysis tools such as simulation.

Hypothesis #3: It is possible to present a large volume of performance data in an intuitive graphical format and hence facilitate the transformation of data to information to knowledge and then to application.

The graphical representations will help in on-the-job communications and methods improvement on a daily basis.

## 1.6 RESEARCH OUTLINE

The following steps outline this research:

- Analyzed the need for data in planning and management aspects of earthmoving operations. This analysis was based on a thorough review of the literature and hands-on simulation of a variety of construction activities. The results of this analysis were instrumental in defining the objectives of this research.
- Reviewed technologies for collecting performance data and information on operating conditions. Existing technologies such as onboard instruments were evaluated while related applications were investigated in the case of proposed technologies such GPS or radio frequency identification (RFID) system. A data collection system based on image databases was created for each of the sites.
- Developed graphical techniques to transform a large volume of data into an intuitive format. The illustration of simultaneous variation in payload and load time and the development of joint probability function were the focal points in the design of graphical techniques.
- Designed and developed a standalone program called travel time calculator. The travel time calculator is used to calculate the travel time of a hauling equipment based on the equipment's specification and haul road segment details. It is used in the normalization of haul and return times.
- Designed a system architecture for the experience database. The processes involved in importing data, linking the performance data to the operating conditions, and automating the creation of the graphical representation were the main features. The modular design of the system facilitates the interface to external programs for input and output.
- Selected a programming environment to implement the design. MS Visual Basic<sup>®</sup> was selected due to its capability to rapidly develop a prototype and its ability to exchange data with MS Access<sup>®</sup> and MS Excel<sup>®</sup>. The database capability of MS Access<sup>®</sup> and the charting capability of MS Excel<sup>®</sup> formed integral parts of the system.
- Tested the prototype with actual field data. The prototype was installed on a laptop and taken to the different sites involved in this research. The user-interface, data requirements and

functionality of the output were evaluated. These evaluations were incorporated into the system design for the subsequent modifications to the prototype.

- Performed detailed statistical analysis on the effect of operating conditions on performance data. Standard hypothesis tests as well non-parametric tests were used. The statistical models were developed with assistance from the statistical consulting center at Virginia Tech.

## 1.7 DATA AVAILABILITY

Data available for this study was provided by three projects. A summary of the available data is shown in Table 1-1.

**Table 1-1: Data available for the study**

<b>Name</b>	<b>Time Period (Weeks)</b>	<b>Number / Models of Trucks</b>	<b>Number of Cycles</b>
Project A	18	8/1	21680
Project B	10	1/1	2655
Project C	14	5/2	10409

## 1.8 INDUSTRY RELEVANCE

Earthmoving and open cast mining activities share a common ground in the form of extensive use of similar equipment. Thus, the discussion presented in this dissertation is equally applicable to construction and mining activities. Construction projects, however, are relatively short in duration compared to mining operations and involve a continuous change of the work face. Therefore, there is an incentive to record the operating conditions as frequently as possible and understand the variance involved.

Mining activities are characterized by repetitive and long operations under virtually identical conditions and hence, average duration of activities is a good indicator of performance. However, variance in activity's performance has an impact on downstream activities. For example, a loader-truck production can have a substantial impact on a secondary production system such as crushing or transport by conveyor.

## 1.9 ORGANIZATION OF THE DISSERTATION

Figure 1-5 presents a document map of this dissertation. This dissertation is divided into four major divisions. The nature of discussion within a methodology is similar. The discussion on each component of the cycle such as load, haul & return, and dump in each division is inter-related. The four divisions are: understanding the challenge, developing the methodology, implementing the methodology, and review.

Understanding the challenge includes an analysis of the need for this research, a review of the literature, and an investigation of different technologies for data collection.

Developing the methodology involves describing, defining and testing each component of the cycle. The primary focus of this division is to transform the proposed concepts into procedures and statistically test the effect of operating conditions on each component of the cycle.

Implementing the methodology includes the integration of the different components into a system and developing methods to implement the procedures outlined in the previous division.

Review summarizes the contributions of this research to the body of knowledge and recommends future research based on the conclusions of this research.

This is a list of the chapters and their contents.

- Chapter 1: Introduction – The need for this research, its objectives and hypotheses, and industry relevance.
- Chapter 2: Literature Review – A review of previous research that support the need for this research and the opportunities to address this need.
- Chapter 3: Technologies for Collecting Performance Data – An investigation of technologies to collect performance data using onboard instruments (OBI), global positioning systems (GPS) and radio frequency identification (RFID).

- ❑ Chapter 4: Technologies for Collecting Information on Operating Conditions – An investigation of technologies such as touchpads, bar codes, and direct data entry; also includes a description of the concept of image database.
- ❑ Chapter 5: Framework of Research: Experience Database – The introduction to the concept of experience database.
- ❑ Chapter 6: Performance Measures for the Load Activity – The development of stochastic and graphical performance measures for the load activity.
- ❑ Chapter 7: Performance Measures for the Haul & Return Activities – The development of stochastic and graphical performance measures for the haul and return activities.
- ❑ Chapter 8: Performance Measures for the Dump Activity – A discussion on the performance measures for the dump activity.
- ❑ Chapter 9: Defining Operating Conditions which Affect the Load Activity – Identifying and testing operating conditions which affect the performance of the load activity.
- ❑ Chapter 10: Defining Operating Conditions which Affect the Haul & Return Activities – Identifying and testing operating conditions which affect the performance of the haul & return activities.
- ❑ Chapter 11: Defining Operating Conditions which Affect the Dump Activity – A discussion on the operating conditions which affect performance of the dump activity.
- ❑ Chapter 12: Developing an Experience Database – Integrating the components of the system through the development of a prototype, facilitating the import of data and linking operating conditions to the corresponding performance records.
- ❑ Chapter 13: Using the Experience Database – Implementing the experience database for each component of the cycle time, generating the graphical representation and probabilistic form of data.

- Chapter 14: Conclusions – A summary of the contributions made by the research and recommendations for future research.

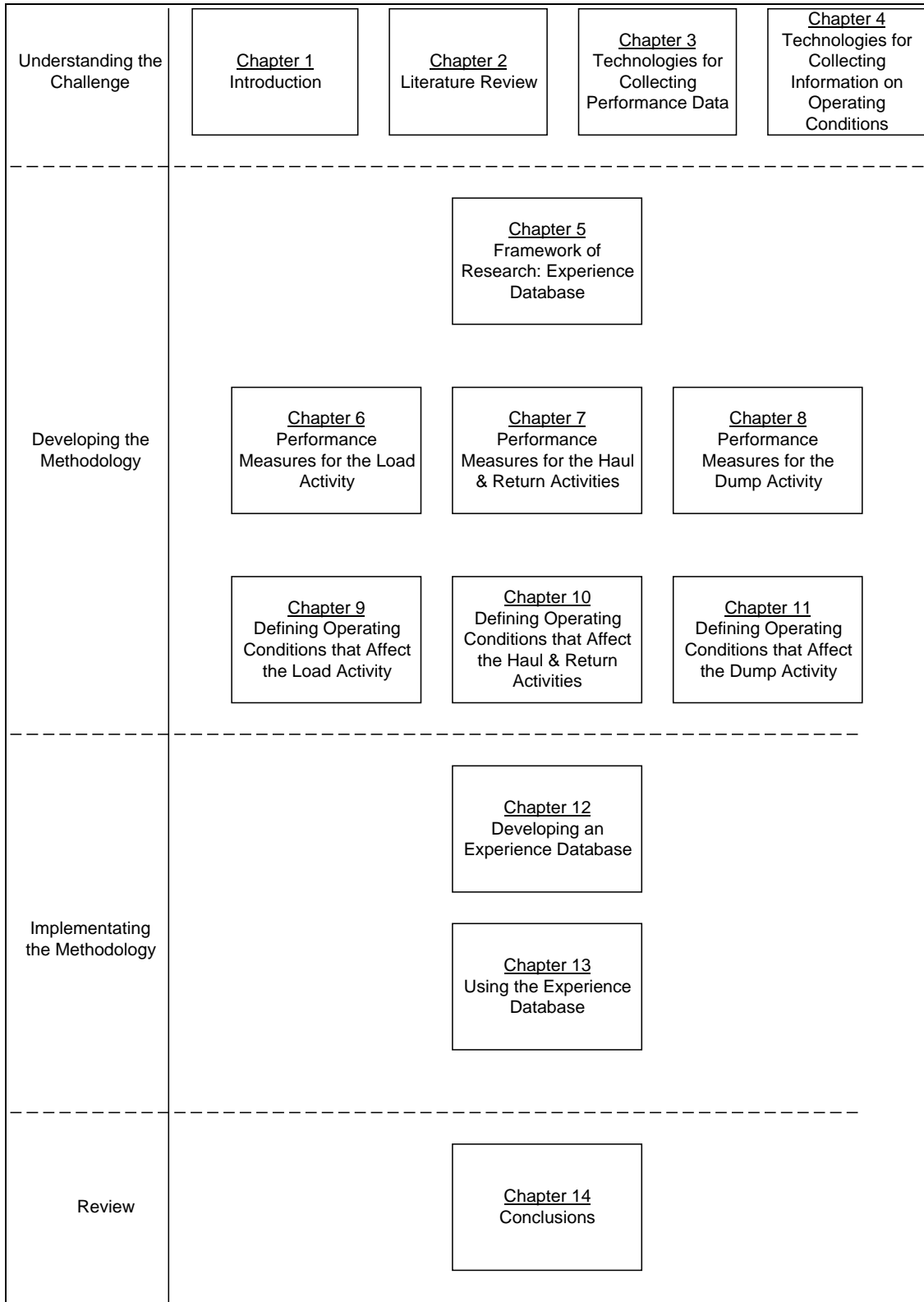


Figure 1-5: The document map of the dissertation

# CHAPTER 2: LITERATURE REVIEW

[Chapter 1](#) presented the context of this research and outlined the specific objectives that will be accomplished. The need for this research is developed based on the challenges posed by previous research and the thrust to develop best practices is provided by the opportunities in instrumentation and computation. This chapter will review the contributions of previous research to this study and provide a perspective of how this research will expand the existing structure of knowledge.

This chapter is organized into the following four areas. They are:

1. methods improvement for earthmoving operations,
2. historical data in planning and estimating earthmoving operations,
3. graphical forms of production data, and
4. statistical procedures for data analysis.

The section on methods improvement for earthmoving operations studies the literature with a focus on the balance between data collection techniques and analysis methods. The section on historical data reviews previous studies relating to the use of databases in planning and estimating. Data mining concepts of visualization is the focus of the subsequent section. The section on statistical analysis is different from the other sections. The purpose of this section is not to review research in statistical methods but to provide an understanding of procedures that is used in identifying and testing operating conditions which affect the performance. [Chapters 9, 10 and 11](#) discuss the role of operating conditions on load, haul & return, and dump activities.

## 2.1 METHODS IMPROVEMENT FOR EARTHMOVING OPERATIONS

Figure 2-1 is based on [Figure 1-4](#) from [Chapter 1](#). The fundamental steps in methods improvement are data collection and analysis. The progress and advancements in data collection

and analysis methodology will be established through appropriate references in literature. The balance between the data collection techniques and the analysis methods will be highlighted.

	<b>MANUAL TECHNIQUES</b>	<b>INSTRUMENTED VEHICLES</b>
<b>JOB STUDIES</b>	<ul style="list-style-type: none"> <li>• Balance between data collection and analysis tool</li> <li>• Suited for simple operations</li> </ul>	<ul style="list-style-type: none"> <li>• Balance is lost between data collection and analysis tool</li> <li>• Overload of data, lack of analysis capability</li> </ul>
<b>SIMULATION MODELS</b>	<ul style="list-style-type: none"> <li>• Balance is lost between data collection and analysis tool</li> <li>• Overload of analysis capability, lack of robust data</li> </ul>	<b>New Frontier</b>

**Figure 2-1: Methods improvement through data collection and analysis**

### 2.1.1 Manual Data Collection Techniques for Deterministic Job Studies

Manual data collection techniques are so called because of the need for human interaction in at least one step of the process. Techniques that will be reviewed under this section are stopwatches, time lapse photography and video tape-based analysis.

#### 2.1.1.1 Stopwatches

Stopwatches or interval timers are the simplest tools for data collection since they require the minimum equipment [Parker and Oglesby 1972]. This technique is the cheapest and fastest way to record duration of activities involving men or machines. Efficiency of the operations can be evaluated in terms of delays or idleness. However, there are some limitations with this technique. The results are limited by the proficiency and training of the operator. An observer can concentrate only on a small area of the operation, typically a machine. Parker and Oglesby [1972] note that

*“...the observer must decide instantly when one phase or cycle stops and another begins. He can have no “second guesses”; there is no chance for hindsight. ...A further limitation to a stopwatch study is that the scope of information is strictly limited to the information that is recorded.”*

They also add that the varying interrelationships among the components under observation result in a significant error in the observations.

### ***2.1.1.2 Time Lapse Photography***

Parker and Oglesby [1972] note that the time lapse photography has the advantages of being relatively inexpensive, able to record the activities of a large number of components at one time, able to record interrelationships among these components, and useful as a permanent, easily understandable record. They also note that applications such as methods improvement through on-the-job communication, teaching and safety studies have been equally effective in addition to collecting data on production.

Touran [1981] presented an advanced system of interfacing time lapse photography with a computer. The motivation behind this research was the lack of a convenient method to extract the pertinent data from the films and reduce them to a format usable by analytical systems. A computer was used in the expedition of data extraction from a time lapse film and hence, accomplish the statistical analysis of the data.

Everest *et al.* [1998] revived the interest in time lapse photography as a tool for documentation and analysis of construction operations. They presented an in-depth description of the present day equipment used in time lapse photography. The research discussed the important role played by technology in the format of data that can be collected by automating the process. The article also pointed out that time-lapse video allows the analyst to compress the information so that lengthy operations can be viewed in a much shorter time. However, the research did not address the extraction of data from the media.

### ***2.1.1.3 Video Tape-based Motion Pictures***

Oglesby *et al.* [1983] point out that using video can be used to record continuous movements of machine and can be viewed over and again in real time. They point out that the major disadvantage is that the period required for each viewing equals that of the initial operation. This approach is seldom practical or cost-effective. However, since then the cost of instruments and

media for recording video has been considerably reduced. The major advantage of the video based data collection is the elimination of observer-related difficulties.

Research at Stanford University was focussed on integrating three powerful analytical tools [Paulson 1978, Paulson *et al.* 1983]. They were low-cost field-portable time-lapse motion picture photography, computer-based simulation modeling and interactive man-computer graphics systems. In one of the modules of this system, the film is mounted on a video player that has a synchronizing electrical interface to the computer. An analyst could build files of raw data that essentially contains frame counts, and the times of significant events corresponding to the various activities and cycles using a computer program. This research made a significant advancement towards the extraction of data.

PAVIC+ was developed at Chalmers University in Sweden to gather data from video source [Bjornsson and Sagert 1994]. The precursor to PAVIC+ was PAVIC, a computer based system that was developed in 1987 for traditional time lapse photography. PAVIC+ has the capability of building large relational databases using standard VHS and PC with a user-friendly graphical interface. PAVIC+ creates a time stamp on the audio channel and hence it makes it possible to review the tape from the same reference point. PAVIC+ also provides an interface to spreadsheet programs for data analysis.

Senior and Swanberg-Mee [1997] described the creation of time lapse photography from videotape. The analog video signals are fed into a computer program that records a frame for every pre-specified time interval. A time stamp is placed on each frame and the digital form is converted back to an analog video. This approach is essentially useful in methods improvement; the time lapse video can be used for on-the-job communication with the crew.

All the techniques discussed in this section are a form of data collection or data sampling. Thomas *et al.* [1982] add that the data sampling process is a statistical procedure wherein it is important that the data remain unbiased as possible. They also add that samples should be collected throughout the entire day or shift and a common error is that windows in the shift are established when no data is collected. All of the above techniques require sufficient amount of resource and human interaction for generating a statistically significant amount of data. It is

almost impractical to use these techniques for collecting data in a continuous form. However, data collected from these techniques can serve the requirements of deterministic job studies.

#### **2.1.1.4 Deterministic Job Studies**

Oglesby *et al.* [1983] note that with the deterministic approach to planning and analysis, single values of time are assigned to each operation and delay in each cycle. Halpin and Riggs [1992] explain that deterministic models for earthmoving operations are based on rated equipment characteristics, equivalent grade and haul distances. These models use fixed or constant values for duration of work tasks. Any variability in the work task duration is assumed to be small or insignificant. Drevdahl [1961] notes that two hours or ten individual unit times are sometimes considered the basic minimum for a study. The average, the most probable value, or values corresponding to an appropriate percentile can be used for activity durations in job studies. Data collected using manual techniques provide the necessary and sufficient condition for deterministic job studies.

#### **2.1.2 Manual Data Collection Techniques for Simulation Models**

The deterministic studies are not well suited for systems involving resource interaction such as earthmoving environments. Halpin and Riggs [1982] add that

*“...The imbalance or mismatch between units in dual-cycle system resulting from deterministic times associated with unit activities is called interference. It is due only to the time imbalance between the interacting cycles. It does not consider idleness or loss of productivity because of random variation in the system activity durations.”*

Hajjar and AbouRizk [1997] state that simulation studies are well suited for earthmoving operations for three reasons. First, projects involve some form of resource interactions wherein certain equipment must obtain certain resources before proceeding to a subsequent task. Second, the activity durations are fraught with uncertainties and thus suited for stochastic modeling. Third, projects are effected by external processes such as weather, traffic etc.

System simulations are characterized by two forms of requirements — ability to model and ability to provide probabilistic data for the model.

### **2.1.2.1 Modeling**

A significant body of research was the development of CYCLONE [Halpin 1977]. CYCLONE can model and simulate repetitive construction processes that are cyclical. A number of researchers have extended the capability of CYCLONE since then, the notable ones being the development of MicroCYCLONE — a microcomputer edition [Lluch and Halpin 1982] and UMCYCLONE [Ioannou 1990]. INSIGHT [Kalk 1980] is based on CYCLONE and includes time-lapse photography for data acquisition, graphics support and an interactive environment [Paulson *et al.* 1987]. Since then, there have been several other simulation programs. The recent addition to this list is the development of STROBOSCOPE [Martinez 1996], a comprehensive and sophisticated tool that incorporates end-user programmability and extensibility. Martinez and Ioannou [1995], and, Ioannou and Martinez [1996] illustrate the principles of construction simulation and capabilities of STROBOSCOPE.

The above account suggests that the body of knowledge in modeling has progressed extensively. Current knowledge in modeling is capable of realistically replicating construction activities. The implicit assumption made by various researchers in formulating their problem is that sufficient data is readily available.

### **2.1.2.2 Input Data**

In their textbook on simulation, Banks and Carson sum up the simulation environment from a data collection perspective [Banks and Carson 1984].

*“...Problems are found at the end chapter, as exercise for the reader, in mathematics, physics, chemistry and other technical subject texts. Years and years of working these problems may give the student the impression that data are readily available. Nothing could be further from the truth. Data collection is one of the biggest tasks in solving a real problem. It is one of the most important and difficult problems in simulation.”*

AbouRizk *et al.* [1989] found that random input tends to propagate to the output of the simulation experiments. The research demonstrated the dangers of using improper modeling of input data. Output parameters as well as resource utilization were sensitive to the input model utilized, a potential mine that could mislead to bad decisions.

AbouRizk and Halpin [1992a] record that

*“...Simulation in all of its form is greatly dependent on the quality of the input provided. This area is frequently neglected because the simulator is not familiar with the statistical methods required or because he/she underestimates the effect input modeling will have on simulation output.”*

AbouRizk and Halpin [1992b] analyzed the properties of construction duration data with regard to adequacy of using various statistical distributions. The aim of this research was to develop an efficient, accurate and easy-to-use statistical and numerical methods for modeling input data. An empirical study on the effect of input model selection was conducted using seventy-one sets of activity duration.

Other commercially available programs can perform the function of determining a distribution to model the data. STAT:FIT [Stat:Fit 1996] is one such example. The main issue with determining the distribution is the sample size. Oglesby *et al.* [1983] point out that when gathering data for productivity improvement studies, the aim is to have the observation reflect reality, which is accomplished by data sampling. Data collection or sampling must adhere to certain statistical principles and rules. The sample size is a function of the confidence limit and the error in the mean.

Benjamin and Cornell [1970] emphasize the need for sufficient data size.

*“...We cannot stress frequently enough the variation inherent in samples of small size and hence the small confidence one can have in conclusions based on an observation of such a sample.”*

It is not that collecting data using manual techniques cannot serve the needs of simulation models. It may not be possible for a human to collect all the different forms of data simultaneously. The difficulty is that collecting statistically significant data will require many man-hours to observe and extract the data. The cost involved in collecting the data may be very high. Therefore, the only way to accept data from manual techniques is to accept a lower level of confidence in the input model and hence, a lesser reliability of the simulation results.

### 2.1.3 Instrumented Vehicles for Deterministic Job Studies

Instrumented vehicles refer to the process of placing instruments onboard the vehicles to automatically and continuously collect data. The introduction of instruments to earthmoving equipment is relatively new and they are economically feasible only on the large equipment, which are not very common in construction. The mining industry has taken the lead role in using instrumented vehicles to monitor production.

#### 2.1.3.1 Instrumented Vehicles

One of the first uses of onboard microprocessor-based data collection in construction application was reported in Sotoodeh-Khoo [1987] and Sotoodeh-Khoo and Paulson [1989]. Sensors were used on a scraper to implement a non-linear production optimization of the load-growth curve. Data acquisition and data analysis were performed in real time to help in the decision-making of the load time of a scraper. With known haul and return road lengths, grades and rolling resistances, a theoretical time for the balance of the cycle was determined. The system was designed to select a load time for the scraper by using logic and information about the fleet.

The mining industry has been in the forefront of capitalizing on the prowess of instrumentation. There are several articles, which refer to various forms of instrumentation [Chironis 1985, Chironis 1987, Kenney 1981, Jaliwala 1990, Grimes 1990, Stewart 1998]. The present day technology can provide health-related information such as fuel left in the tank, average miles per gallon, engine temperature as well productivity data such as load time, payload, haul time. Schaidle [1994] notes that

*“...I see the day when the service truck pulls up to the machine with the mechanic already knowing what the problem is and how to fix it.”*

Truck Payload Monitoring System (TPMS<sup>®</sup>) and Vital Information Management System (VIMS<sup>®</sup>), both proprietary products of Caterpillar Company [Caterpillar, <http://www.cat.com>], DISPATCHER<sup>®</sup> [Modular Mining Systems Inc., <http://www.mmsi.com>], CONTRONICS<sup>®</sup> [VOLVO, <http://www.vce.volvo.se>] are examples of some vehicle instrumentation systems. While not specifically oriented towards production data collection, it is clear that vehicle instrumentation can be used as an economical way to collect large volumes of production data.

Production totals or averages are reported for load or tonnage, load per truck, per shovel or per dump point. Time accounting can be reported in terms of average activity time or idle time, which in turn can be used to calculate the utilization of the equipment. Dispatching trucks to different loading and points is another application based on the instrumented data [Chironis 1985].

### ***2.1.3.2 Deterministic Analysis***

Schexnayder *et al.* [1999] reported a study on the effect of payload weight on production. They reported that there was a diminished productivity increase when the load weight exceeded the truck's gravimetric capacity. Several other interesting observations were made based on the data. The data was examined to determine if there was any relationship between the time to load the trucks and payload. The results indicate a decrease in load time as the load range increased. The study also points out that there is a good match between volumetric load and "full" shovel buckets. In the concluding section of the article, they note that

*"...data in the computer is of no value; it must be extracted and presented in a clear format so that earthmoving professionals who understand the physical processes can discern the effects of their decisions."*

This study was a straightforward analysis of data generated by the onboard instruments. It did not emphasize the variance in payload or any other parameter such as load time, haul time etc. Although conclusions based on average values provide partially useful information, their value could have been enhanced by the inclusion of an understanding of the variance.

### **2.1.4 Instrumented Vehicles for Simulation Models**

Schexnayder *et al.* [1999] allude to the usefulness of instrumented data in describing the stochastic nature of the data. They present a histogram of a part of the data; however, the discussion on the effect of factors is focussed on the average values. They note that the data set was from an 8-month study period consisting of two 10-h shifts, five days a week and one 8-h shift on Saturday, 54,300 cycles of data approximately equal to 14,419 operating hours. The order of these numbers suggests that it is the first opportunity to collect a large volume of data sufficient to derive statistical properties.

## 2.2 HISTORICAL DATA IN PLANNING AND ESTIMATING

Howard [1991] presents a case for developing project-specific knowledge bases. Capturing and communicating project-specific knowledge can facilitate design, reduce errors, and provide a basis for future projects. In order to make effective use of project-specific knowledge bases, formidable problems in knowledge acquisition and automated explanation need to be solved. However, the lack of a formal structure to capture the as-built production data has prompted estimators to use past experience, books, records and even intuition as data source for the analysis [Paulson 1995, pp502]. Two forms of historical data — cost and production — are required for planning and estimating. This section will review some established facts related to these two forms of data.

### 2.2.1.1 Cost Databases

Prior to 1980s, many companies used estimator's manual, a guide to methods and resource inputs to estimate construction operations [Harris and McCaffer 1995]. These manuals essentially served as a standard for a company to be used by the estimating team. An estimator would refer to the information abstracted from previous records and notes in the estimator's personal manual.

During the 80s, the cost data were transferred to databases in the estimating systems [Harris and McCaffer 1995]. The use of computers significantly improved the management of data through improved processing speed, fast access and retrieval. A significant step was to define and populate the database. One method of populating the database is to use public standards (R.S. Means, Richardson's etc.). Two types of difficulties are associated with using values provided by standard manuals or handbooks [Knoke *et al.* 1993]: a) the values provided in the manuals seldom represented the actual conditions of the project under consideration; and b) difficult to derive the variability of the current project from the ones in the manuals. Hence, there arose a need for creating and maintaining company-specific databases. Larger companies involved in competitive bidding built their data libraries from their own estimating manuals or work-study exercises [Harris and McCaffer 1995, pp229]. The data libraries are well structured — the cost of an activity could be easily built up from smaller units of work elements.

### **2.2.1.2 Production Databases**

Public standards such as Means [1997] and Richardson [1992] serve as generic database for both cost and productivity. Productivity values used in these standards are either an instantaneous value arrived based on theoretical calculations or a sustainable average rate based on physical observations [Gransberg 1998]. Since no two construction jobs are alike, data archived from different projects need not necessarily match the project to be estimated. Hence, the estimator is given the freedom of factoring the productivity values [Smith 1997]. The situation is complicated when a standard group of resources is changed. The error in judgement in production rate can permeate to the computation of unit cost of work.

Researchers have suggested the use of performance manuals and handbooks in the absence of a proficient database [Paulson 1995]. The degree of variability in productivity under different environments is more pronounced than the cost values — cost mollifies the variation in production. The concept of a dynamic productivity databases is not as mature as the dynamic nature of cost databases. Burton [1991] notes that one of the reason for the lack of productivity database is

*“...construction productivity requires the collection and processing of an enormous amount of data. This is a substantial investment which our industry has not seen fit to make.”*

However, the introduction of vehicle instrumentation may change that perspective for the earthmoving sector of the construction industry.

## **2.3 GRAPHICAL FORMS OF PRODUCTION DATA**

Data in a table format is the simplest form of presenting productivity information. The tables are accompanied by a statistical analysis such as mean, mode, deviation etc. Marakas [1999] notes that the data in a raw table form is difficult to interpret because of the overwhelming quantity and complexity of information and the embedded patterns. The human brain is capable of processing significant amount of visual information — recognizing patterns and trends. Tufte [1983] explains that graphics help in communication of complex ideas with clarity, precision, and efficiency.

Oglesby *et al.* [1983] have suggested the use of line graphs, pie charts, histograms for representing productivity data. Schexnayder *et al.* [1999] used line graphs to depict trends such as a learning curve and the effect on a factor on production. Pie charts are useful in showing the relative components of an aggregate operation. A pie chart of average load time, haul time, return time and dump time will indicate the relative time a truck spends on each activity. It must be noted that neither the line graph nor the pie charts can indicate the variation in the operation. Histograms are the simplest tools that depict the frequency of occurrence. A histogram was used by Schexnayder *et al.* [1999] in describing the range of payload placed on the truck.

Drevdahl [1961] states that besides simple averages, a visual picture presents important aspects of the operation. One such representation is the graph of percentile curve. The curve is constructed by arranging in ascending order all times recorded for one task and the percentage of points that lie in the interval. This curve can be used to determine the percentage of field data that lie in a required range.

A load-growth curve is a visual representation of payload and load time for a scraper [Day 1973]. The payload is recorded for small increments of time. The curve can be used to determine the optimum load time of scrapers by using the balance cycle time. The curve also presents a relationship between payload and load time.

Oglesby *et al.* [1983] offer the crew-balance chart as an effective way to show the interrelationship among the activities of the individual members of the crew or equipment. They also add that before the chart can be made, the time devoted to each element of the activity must be observed and recorded. They record that often much can be learned by studying the best among the cycles or examining the reasons for variations.

## **2.4 STATISTICAL PROCEDURES**

The intent of this section of literature is not to review the state of knowledge in statistical methods but to document some background information on statistical procedures that will be used in [Chapters 9 – 10](#).

The objective of statistics is to make inferences about a population based on information contained in the sample [Ott 1993]. Typical population parameters are the mean and standard deviation and the area under the probability distribution to the right or left of some random variable. In this research, it is critical to address the homogeneity of data sets corresponding to each characterizing factor. The test for homogeneity among different data sets, with a viewpoint of finding out any differences in their distribution, may be influenced by at least four different situations.

1. The models used to represent the data set may be different. For example, one data set can be modeled by a *Normal* distribution while another can be modeled by a *Lognormal* distribution.
2. The model representing the data sets may be the same but the parameters may be different. For example, a *Normal* distribution can be used to model the data sets but their means and standard deviations can be different.
3. For the same form of model, say a *Normal*, the means may be the same but the standard deviation may be different and vice versa. For higher order distributions, the mean and standard deviation may be replaced by other parameters.
4. For the same form of model, for a given mean and standard deviation, the skewness and kurtosis may be different.

Testing the homogeneity of distribution is not straightforward considering the complexities of the situation. AbouRizk and Halpin [1992b] presented a transformation method to detect the type of distribution that can model the data set. Given that modeling the distribution and estimating the parameters are significant by themselves, this methodology, however, is not very useful in determining the homogeneity of two or more data sets. After extensive research, four statistical tests were identified as suitable for addressing the complexity of the scenario.

1. **Analysis of Variance (ANOVA):** In ANOVA, all differences in sample means are judged for statistical significance by comparing both the within sample and among samples variation [Ott 1993]. The test on equality of means is not very important when comparing two different fleets or two different projects because of the inherent differences in the two

operations. However, in comparing the cycle times for two different types of material, a test for equality of means may be very significant. The research hypothesis, that the effect of an operating condition is significant within a project, can be analyzed using the means.

2. **The General Linear Model (GLM) – Levene’s Test:** The GLM procedure is also used to test the equality of means [Ott 1993 pp564]. The Levene’s test is part of the GLM procedure to detect the homogeneity of the variance. This is especially useful in comparing cycle time data for different levels of an operating condition. For example, the mean load time of common earth and well-shot rock may be the same while the variation may be significantly different. Similarly, the variations in operation between two projects may be used as an indicator of the management style and the set of instructions given to the crew. Duncan’s grouping is also part of the GLM procedure wherein data sets are grouped together if their means are not significantly different.
3. **Kruskal-Wallis Test:** Law and Kelton [1991, pp409] recommend the use of Kruskal-Wallis test for studying the homogeneity of different data sets. It is a non-parametric test and does not make any assumption about the underlying distribution of the data set. This test also determines if there is a shift in the means.
4. **The Kolmogorov-Smirnov Test:** Benjamin and Cornell [1970, pp466] suggest the Kolmogorov-Smirnov (KS) test, which measures the deviation between the hypothesized cumulative distribution function and the observed cumulative histogram, as a test for goodness-of-fit. The test statistic is the maximum deviation of the observed histogram from a hypothesized distribution. The test can be applied to detect any differences in the homogeneity in two or more data sets. The KS test has several advantages such as no grouping of data, validity for any size of sample ( $n$ ) and applicability to a wide range of distribution. However, the KS test can easily detect small differences in the homogeneity of two samples and may not be able to support the reason for the differences.

In the discussion of the various statistical procedures, skewness and kurtosis in particular are conspicuous by their absence. The reasons are two folds:

1. standard tests for skewness and kurtosis are not very common, and
2. Law and Kelton [1991] note that many distributions encountered in practice are skewed to the right and kurtosis may not be very useful in discriminating among distributions.

SAS<sup>®</sup>, which is the statistical package used for analysis in this research, accommodates ANOVA, GLM-Levene's test, the Kruskal-Wallis test and the Kolmogrov-Smirnov test. Therefore, wherever applicable, all these tests will be used to test the null hypothesis that the different data sets are homogenous.

## 2.5 SUMMARY

This chapter presented a review of previous research that contribute to the development of the objectives of this research and opportunities available to address the challenges. The discussion focussed primarily on the balance between data collection techniques and analysis methods. The role of historical data on planning and estimating, and graphical forms of production were also reviewed. The final section of this chapter was devoted to the description of statistical procedures that will be used in [Chapters 9-10](#).

The next two chapters will describe in further detail the candidate technologies which can be used for collecting performance data and information on operating conditions. The discussion in these two chapters is necessarily rather academic at times. While it is believed that it is necessary to provide background information on this subject, it is possible to skip to [Chapter 5](#) without loss of continuity. For those readers who prefer to make this leap, the contents of the next two chapters are summarized here.

Details of onboard instrumentation (OBI), global positioning systems (GPS) and radio frequency identification (RFID) are presented in [Chapter 3](#). The conceptual framework of each system, the equipment used, the suitability to production data collection and related applications are discussed. OBI is adopted for this research because it is fully functional and readily available in the market.

Details of touchpad, bar codes, direct data entry using paper forms and computer programs, and image databases are presented in [Chapter 4](#). A brief outline of the concept, a description of the equipment and some sample applications that were developed as part of the investigation process are presented. Paper forms and image databases are adopted for this research because of their simplicity, convenience and connectivity to an existing system such as the foreman's daily report.

# **CHAPTER 3: TECHNOLOGIES FOR COLLECTING PERFORMANCE DATA**

Chapter 2 presented a brief survey of the literature that provided the motivation as well as the opportunity for this research as outlined in Chapter 1. Previous investigations on various techniques for collecting performance data on earthmoving operations were discussed. The literature search points to several emerging technologies that can be adapted to collect data on earthmoving operations in an autonomous and continuous manner. Although most of these technologies' primary purpose is something other than production data collection, the challenge lies in harnessing their capability and adapting them to collect production data. This chapter will review three technologies, namely, onboard instrumentation system (OBI), global positioning system (GPS) and radio frequency identification system (RFID) as potential candidates. OBI and GPS are located on the equipment and hence, commonly referred to as vehicle instrumentation. This chapter will address the features and issues relating to each form of technology and will recommend an appropriate technology for the purpose of this research.

## **3.1 DESIRABLE FEATURES**

The development of any data collection system has to be based on the match between the form of data required and the format of data collectible. For example, if the technology used for analysis is job studies, the data need is single point estimates for components of cycle time. It is clear that stopwatches present a viable opportunity to collect data for this purpose. Analysis tools such as simulation require the data to be in the form of probabilistic distributions, which require an automated process to collect a large volume of data. This section briefly outlines some the desirable properties of the data and the corresponding desirable characteristics of the data collection system.

### 3.1.1 Desirable Properties of Production Data

Field data can be used for both formal and informal techniques for methods improvement as well as planning and estimating future projects. The following are some of the desirable features of production data:

a) Extraction of idle time from activity time

Construction simulation consists of queues and combis [Halpin 1977, Martinez and Ioannou, 1995]. Queues are model elements where idle resources wait while combis are activities which consume resources and time. Various data collection methods — for example, manual methods using stopwatches — find it difficult to keep track of activity time and idle time. Even a large set of such data will not help the cause of simulation.

b) A large of volume of statistically sufficient data to obtain probabilistic distributions

An integral part of any simulation system is to model the probability density function of the activity duration. Modeling the probability distribution of an activity's duration requires a sufficiently large volume of data.

c) Well represented in terms of operating conditions as well as time-periods.

Data representing only a window of operation does not provide a good knowledge of the operation. The data should be well represented in terms of the time of the day as well as the calendar period. The desirable property would be to have a continuous form of data.

### 3.1.2 Desirable Characteristics of Data Collection Systems

The desirable characteristics of production data-collection systems should provide for most, if not all the desirable properties of data. They are:

(a) Autonomous function

Only an autonomous mode of data collection will facilitate a large volume of data, free of judgmental-error and bias. Data collection and data extraction should be integrated — a major drawback with systems such as time-lapse photography and video taping.

(b) Cost-effectiveness

Cost effectiveness is an important criterion because the value of information is non-tangible and accrues over a period. The instruments are typically a small portion of the cost when big construction equipment are used and hence, most applicable in such situations.

(c) Electronic format

Data in an electronic format presents an excellent opportunity for analysis and storage. Methods using stopwatches often produced data on paper, which further needs the services of a human to convert it to electronic format.

(d) Mobile — independent of the vehicle

Mobility of the system is often related to the cost of the system. A company would find it cost-effective to have a mobile system independent of the vehicle so that it can be transferred to equipment on an as-needed basis.

The subsequent sections in this chapter will describe each of the candidate technology with a focus on the concept, the beneficial features and limitations, other applications and the suitability to cycle time data collection.

## **3.2 ONBOARD INSTRUMENTATION SYSTEM (OBI)**

The two forms of OBI investigated as part of this research are TPMS<sup>®</sup> and VIMS<sup>®</sup>, which are both proprietary systems from Caterpillar, Inc. The intent of this section is to provide a general understanding of the OBI although most information may be pertinent to the functioning of these two systems.

### **3.2.1 Concept**

Construction equipment is increasingly being equipped with onboard instrumentation and microprocessors to measure and record selected mechanical parameters. Sotoodeh [1987] showed that productivity can be improved by combining output from sensors placed on a model-

scraper and some predefined rules. Chironis [1985, 1987] described the use of instrumentation and microprocessor onboard mining trucks for monitoring as well as increasing productivity.

The principal purpose of OBI is to aid in the diagnosis of a machine health — reduce downtime and improve component life. These systems are designed to help the mechanic identify malfunctions and perform the role of a “mechanic in the cab.” The challenge and the opportunity lies in using selected mechanical outputs and a system clock, to collect productivity data on a continuous basis.

OBI relies on sensors placed at various locations on the vehicle. The sensors measure physical parameters, such as temperatures, pressures, strains, and control lever positions. These parameters can be used to determine the time needed for various cycle time components such as loading, hauling and dumping by applying domain specific rules.

Understanding and using the OBI can provide a cost-effective mechanism to collect production data, in addition to measuring the mechanical performance of the equipment. Such a mechanism would be instrumental in the creation and maintenance of the experience database. OBI data would be able to provide cost effective and statistically reliable stochastic data for simulation. The data from these systems would be in an electronic format and so, can be exchanged with other programs without any difficulty.

### **3.2.2 Using OBI for Performance Data Collection**

This section will present an example illustrating how the suspension strut pressure, gear control lever position, bed raise switch position and speed can be used to derive haul truck cycle time components. Change in strut pressure arises out of an increase in load or while traveling along a bumpy haul road. Travelling along a bumpy haul road also indicates that the transmission is in gear (very rarely in neutral) and the speed is greater than zero. If the bed-raise switch indicates that the body is raised, then definitely the truck is dumping its load in the dump area. Although trucks leave the dump area while their bed comes down, the speed is very low and hence such a state exists only for a short duration of time. Productivity data can be extracted from these mechanisms through the development of the following rules.

## **Rules**

**Loading:** *The truck is loading when the sensors register an increase in pressure (pressure greater than tare weight), the gear is in neutral, the bed-raise switch is not active and the speed is zero.*

**Hauling:** *The truck is hauling when the sensors register an increase in pressure (pressure greater than tare weight), the gear is not in neutral, bed-raise switch is not active and the speed is greater zero.*

**Waiting on the haul road:** *The truck is waiting on the haul road when the sensors register an increase in pressure (pressure greater than tare weight), the gear is not in neutral, bed-raise switch is not active and the speed is zero.*

**Dumping:** *When the bed-raise switch is active.*

**Returning:** *The truck is returning when the sensors do not register an increase in pressure (pressure equal to tare weight), the gear is not in neutral, bed-raise switch is not active and the speed is not zero.*

**Waiting on return:** *The truck is waiting on return when the sensors do not register an increase in pressure (pressure equal to tare weight), the gear is not in neutral, bed-raise switch is not active and the speed is zero.*

Since the OBI is oriented towards health diagnostics, these systems seldom have the capability to record the other half of productivity information — operating conditions such as haul road surface, weather, visibility etc. These details are essential in qualifying the cycle time data collected by OBI. These details need to be collected independently by site supervisors and linked to cycle time data collected through OBI.

### **3.2.3 Benefits and Limitations of OBI**

The electronic instrumentation is part of the vehicle mechanics and hence, it is the most accurate form of measurement of change of state. Since change in pressure are observed through physical

sensors, the calculation of payload is possible — the only form of data collection mechanism to record payload. Derivation of activities is based on physically sensed parameters such as strut pressure, gear position, speed etc. making it possible to collect productivity-related data very much suited for the purpose of this research.

Some of the limitations in the use of OBI are:

- The cost of the system — high proportion of cost especially for smaller trucks,
- Fixed — integral part of the vehicle and is not transferable between different vehicles, and
- Need for training — requires substantial training for operators to understand the role of the instruments and the routine calibration required on a daily basis.

#### **3.2.4 Suitability to Cycle Time Data Collection**

These systems present a viable and practical solution to collect production data. They can function autonomously except for the calibration required at the beginning of a shift. It is possible to extract the activity time and idle time. The activity time is a function of vehicle mechanics and derived based on physically observed values. The activity time is highly functional – duration for activities in the same format as used in analysis methods. Although haul time for each individual segment of the haul road may not be available, this system provides an accurate measure of the haul distance and the total time between load and dump activities (with waiting times separated). The biggest advantage is that the technology is readily available and well tested.

The principal drawback of this system is the mobility. The modules of this system are built into the body of the vehicle and are not easily transferable among vehicles. The cost of the system may be considerably high in comparison to other equipment such as time lapse or video camera. However, these systems are meant to perform vehicle health monitoring. Therefore, apportioning the total cost of the system to data collection may be misleading.

### 3.3 GLOBAL POSITIONING SYSTEMS (GPS)

GPS is a tracking system, essentially developed by the US military to provide navigation for vessels and aircraft, consists of satellites, ground antennas (control stations) and user-receivers. The tracking information consists of position, time and velocity information [Hofmann-Wellenhof *et al.* 1994]. The GPS constellation consists of 24 satellites a fixed distance and inclination to the earth [GPS 1995]. Each satellite passes over the same location on earth every 23h 56m. This particular configuration and number of satellites allow a user to have a link with at least four satellites at point during a 24-hour period.

The GPS signals are broadcast by each satellite and carry data to both user equipment and the ground control facilities. The user equipment is in the form of a receiver that can be either handheld or mounted on a vehicle. The master control station is located in Colorado Springs, Colorado and four remote monitors are located across the country. Land-based and space-based communications are used to connect the remote stations with the master station. The four remote monitor stations contribute to satellite control by tracking each GPS satellite in orbit, monitoring its navigation signal, and relaying this information to the master control station. All the stations can collectively track and monitor the position of each satellite in orbit, monitoring its signal, and relaying this information to the master station. The master control station is responsible for maintaining the exact orbits of each satellite and determining any timing errors.

GPS receivers vary from small handheld units to complex systems that can be mounted on vehicles. A GPS receiver will house an antenna, which receives the GPS signal; a processor, which converts the signal to usable information; and a control/ display unit, which is the user-interface for providing the positioning information. A GPS receiver can track one or more signals depending upon its capability. The ranging data is extracted once a signal is received and passed on to the processor, where computer software converts the information for the user (position in terms of latitude, longitude, and altitude).

### 3.3.1 Concept

Each satellite continuously transmits a radio signal with a unique code, which includes data about the satellite's position and the exact time that the coded transmission is initiated on the satellite. A powerful and accurate atomic clock keeps track of time on the satellite. The x, y, z coordinates of a user can be determined through a simple computation based on the time it takes the electromagnetic signal to reach the user from the satellite [GPS 1995].

$$(X_1 - U_x)^2 + (Y_1 - U_y)^2 + (Z_1 - U_z)^2 = R_1^2 \quad (1)$$

$$(X_2 - U_x)^2 + (Y_2 - U_y)^2 + (Z_2 - U_z)^2 = R_2^2 \quad (2)$$

$$(X_3 - U_x)^2 + (Y_3 - U_y)^2 + (Z_3 - U_z)^2 = R_3^2 \quad (3)$$

where

$$R_1 = C * \Delta T_1; R_2 = C * \Delta T_2; R_3 = C * \Delta T_3 \quad (4)$$

and where

$C$  is the speed of light,

$X_n, Y_n, Z_n$  are the  $XYZ$  co-ordinates of the  $n^{\text{th}}$  satellite,

$U_x, U_y, U_z$  are the co-ordinates of the user,

$T_n$  is the time taken by the signal from the  $n^{\text{th}}$  satellite to reach the user.

It is clear that at least three satellite signals are required to solve the system of equations. A fourth signal is required to correct a clock bias, discussion of which is beyond the scope of this document. The coded signal is transmitted in two frequency spectrums for security purposes [Leick 1990]. The Coarse Acquisition (C/A) code is transmitted around 1500MHz and is 1 ms long. The length of the signal is 1KB making the speed of transfer about 1Mbps. This carrier frequency is called  $L_1$ . The C/A code provides free positioning and timing information to users all over the world and is known as the standard positioning service (SPS). The typical accuracy

of the C/A code is to the order of 100m. The second frequency spectrum is called the Precision (P) code. It is generated mathematically by mixing two codes and operates at 10.23MHz. The accuracy of P-code is within 10m. This carrier is called  $L_2$  and provides precise positioning and anti-jamming functions.  $L_1$  and  $L_2$  together provide the navigation information.

There are several types of errors that can be induced in a GPS measurement, namely, atmospheric error, clock error, multi-path error, and receiver-error [Leick 1990]. These errors can be corrected on the receiver through appropriate routines in the processor. A differential GPS (DGPS) is a corrective method used to increase the accuracy and reliability of GPS data. DGPS uses the knowledge of highly accurate, geodetically surveyed location of a reference point, which observes GPS signal in real time and compares the ranging information to the ranges expected to be observed at that point [GPS 1995]. These differential corrections are then transmitted to GPS users, who then apply the correction to their data. A DGPS base station can be a permanent or a mobile station depending on the application; the only requirement being that the station is surveyed accurately.

At least three government agencies assist with DGPS services — FAA (Federal Aviation Administration), US Coast Guard, NOAA (National Oceanic and Atmospheric Administration) [GPS 1995]. The FAA proposes to have a ground-based network of several stations in the near future. Corrections derived from this network of station are broadcast to users on a unique frequency. The coast guard beacons are specially meant for marine navigators in the harbor and harbor-approach areas. The typical range of a coast guard beacon is 500km and the accuracy can be as good as 1.5m. The NOAA DGPS functions very much like the one described under FAA DGPS. The correction information is usually archived on a server, which can be accessed by users. There are several other public and private DGPS services around the country.

### 3.3.2 Benefits and Limitations of GPS

Earthmoving being an open-air outdoor operation is conveniently suited for data collection using GPS. GPS provides a complete hands-off system thereby promoting the vision of an autonomous system. The numerical values involved in terms of space coordinates and time stamp are very accurate. The GPS signals are provided free or a very nominal cost by the government and

therefore there is almost no maintenance cost except for the cellular transmissions. GPS can be use a variety of applications related to earthwork and so may become very cost effective.

There are however certain limitations with the technology. Although GPS has been used in military operations for more than 10 years, it has surfaced in construction only in the form of survey instruments. There is a lack of industry-wide standard protocol and format making it difficult for instruments from different vendors to communicate with one another. Weather is a deterrent to smooth functioning of the GPS receiver.

### 3.3.3 Examples of Applications

GPS is used in a variety of applications ranging from avionics, military, combat warfare to land survey, mapping, mining, and construction. It is not within the interest of this document to report all possible applications; instead, applications that provide support to this research or those that can augment this research will be discussed briefly. A survey of different applications can be obtained from GPS [1995], Leick [1990] and the web-site [<http://www.utexas.edu/depts/grg/gcraft/notes/gps/gps.html>].

#### 1. Avionics

Air navigation services use ground-based radio-navigation systems that utilize radar, voice position reporting and visual sightings for aircraft surveillance. GPS is being considered as a replacement for the ground-based navigation systems. Currently, GPS is being by civilian pilots in uncontrolled airspace for aerial photography and surveying, search and rescue operations. The essential requirement in all the above application is the exact position in space at any point in time (x, y, z, and t co-ordinates).

#### 2. Earthmoving and road construction

Centimeter-level guidance of cut and fill surfaces can be achieved by installing GPS onboard the earthmoving machine [<http://www.trimble.com>]. The operator can view the topography in real time. GPS allows three-dimensional models of work in progress, updating in real

time, and thereby assisting the operator to move earth more efficiently. Cost reduction is achieved through the elimination of staking.

### 3. Guard rail maintenance in Minnesota

Minnesota Department of Transportation (MNDOT) initiated a guard rail maintenance system in 1997 [Gorg and Zenk 1998]. A brief discussion on the application is as follows. A MNDOT appointed person drives around on the highways in Minnesota with a hand held GPS receiver, a computer and a digital camera. The person would stop at the beginning and end of each guardrail, get the position using the GPS receiver, take a digital photograph and enter any additional information on the computer. All the information is compiled on a server in the main office after completing the tour of highways. The data is updated when any incident or a change is reported. MNDOT then has a clear idea of priority for replacing guardrail. The other important application is in insurance claims. The photograph and GPS data is used as evidence in insurance claims when automobiles collide into a guardrail.

### 4. Vehicle tracking and machine guidance

GPS can be used to locate vehicles to improve operational efficiencies as well as machine scheduling. Naresh and Jahren [1997] explain a messaging system wherein a mechanic, a dealer and an operator work in tandem using GPS to solve a mechanical problem. The result is reduced downtime and increased productivity of all entities involved.

### 5. Trucking and railroad industries

Trucking and rail industries are characterized by a common need — meeting the needs of just-in-time manufacturers and goods distributors. The increasing emphasis on on-time delivery has prompted trucking and railroad operators not only to locate their carriers (vehicles) but also to locate the components of the cargo that need to be delivered. The need to achieve this with good accuracy and in real time mandates a superior tracking technology such as GPS. Currently, trucking as well as car rental agencies are trying to employ GPS and CD-ROM maps to provide real time guidance to drivers.

### 3.3.4 Suitability to Performance Data Collection

The potentials of global positioning systems have been illustrated by a variety of applications. If used in this research, the global positioning receivers are used as passive position-time collector. Most features of the system would depend on the computer program that can manipulate the position-time data. The features that are essential for the receiver are the buffer and communication capability. Activity and idle times can be extracted if speed is also available as input. It is not possible to determine load time of a truck but time in load area and time to maneuver into position can be extracted. The noteworthy feature is the ability to determine speed on every segment of the haul and thereby create a velocity profile. GPS receivers are mobile and can be transferred between trucks with ease. Global positioning also opens door to numerous related applications.

Among the drawbacks, GPS is contingent on an unobstructed view to the sky. The technology as such is emerging and so, the cost of equipment and software are high at present. Buffer on the receiver and communications to the base station require further advancement to make the data collection process economical.

## 3.4 RADIO FREQUENCY IDENTIFICATION (RFID)

Identification or detection is the process wherein a mobile tag is identified or detected when it passes through the zone of influence of a reader. Different types of technologies have been used for the detection process. Among them, radio frequency (RF), ultrasonic waves, microwaves, acoustic waves, lasers and image detection have been used in commercial applications [<http://www.aimi.org>, <http://www.micron.com>]. Radio frequency applications are better suited for construction environment and applications developed using RFID are very closely related to the objectives of the proposed research. The following section will briefly describe RFID technology, the equipment used, benefits of using RFID and some applications using RFID.

### 3.4.1 Concept

The basics of RF technology are well illustrated in Jaselskis *et al* [1995] as well as in AIM [<http://www.aimi.org>]. The technology uses low frequency FM transmission to transmit data

between a RF tag and a receiver. The RF technology can be compared to the bar code technology wherein the tag corresponds to the bar code on an item and the receiver, to the wand. The principal difference is that the identification process is almost autonomous in the case of RFID. RFID applications are well-suited in applications where components are not physical visible or move from place to place. Hence, RFID presents an ideal case for auto-identification and data collection.

A RFID system consists of tags, receivers and antennas communicating on radio frequency. A tag, also called as transponder, is mounted on the moving unit (vehicle) and can store data such as identification number as well as additional properties such as weight, fuel left etc. A receiver is placed at convenient locations and facilitates the interrogation of the tags. The receiver can store data temporarily in its buffer before it can be communicated to a host computer. Tags come with ability to be programmed, for example, the identification number can be set by the user. A two-way communication is required in such cases. The range of tags varies according to manufacturer's specifications but a common factor is that the antennas on both tags and receivers improve range as well as accuracy.

The RF receiver sends out a power burst through its antenna [<http://www.micron.com>]. The power pulse is absorbed by the tag's antenna and stored in a capacitor. When the receiver's power pulse is over, the tag starts to transmit its data back to the receiver. The data transmitted can be as long as 64 bits and could include information such as identification number and any other coded information (the coded information is part of the binary string). It is also possible to link the data on the tag to a database located elsewhere. The duration of a complete cycle is approximately 70ms.

### **3.4.2 Equipment**

A brief overview of the different components of RFID is presented here. The purpose of this discussion is essentially to provide a background on the requirements and the functionality of the instruments.

### Tags

Tags or transponders are the identifying units. Tags can carry alphanumeric messages in addition to a unique identification number. The alphanumeric message can be used to store properties or information about the item to which they are tagged. For example, in an assembly line, each component of a machine can be tagged, monitored from arrival to shipping from the plant. As for Civil Engineering applications, transponders can be mounted on major structural components, which can be tagged by inspectors as well as maintenance personnel [Jaselskis *et al* 1995].

At a high level of hierarchy, RFID tags can be divided into two groups: active and passive tags. Active tags are usually powered by an internal battery and can transmit energy on their own. Since they can transmit energy on their own, they can identify themselves to any number of receivers placed in the vicinity. The combined energy of the tags as well as the receivers increases the performance through greater range and acceptable noise level. If driven by an internal battery, then the transponder has to be decommissioned at regular intervals, battery replaced and commissioned again. Passive tags derive their power to operate from the field generated by the receiver, guaranteeing almost an unlimited life. The trade-off to this feature is the short range and the requirement of a high-powered reader.

### Receivers

Receivers perform the function of detecting the presence of a tag. Receivers can be mobile or stationary. The size, reading ranges and scanning capabilities vary widely. The reading range and scanning ability is the deciding factor in choosing a particular reader for an application. Most receivers require power although some of the modern instruments can function with lithium batteries or solar power. Receivers have a buffer that can hold data transmitted from the tags. Either in real time or in batch mode, data from the receiver can be transferred to a base computer.

### Antennae

Antennae collect and transmit the RF signal between the tag and the receiver. Among other purposes, antennae improve the reading range and the accuracy of information.

### 3.4.3 Benefits and Limitations of RFID

RFID technology aids in automatic data collection — it does not involve human interaction. It is not restricted by harsh environment due to contactless identification and data transmission. Majority of the transponders can withstand temperature ranges of -40C to +85C [Jaselskis *et al* 1995]. A very important consideration is that RFID does not require line of sight — a major constraint in manual data collection in construction sites.

One of the principal concerns using RFID is the lack of a common protocol — the receiver and the tag must be from the same manufacturer [Jaselskis *et al* 1995]. RFID are well suited for identification-only applications — any other data such as payload weight, location of a vehicle in real time, is not obtained directly. A receiver is required at every point where data needs to be collected; these receivers have to be manually setup each time the operation is changed. The cost of equipment is a big factor — a tag may cost as little as \$20, the cost of a receiver is usually in the range of \$4000 - \$5000 per unit. Although RFID works well in most harsh environment, metallic surfaces or other RF sources in the vicinity may induce noise in the system.

### 3.4.4 Examples of Applications

Jaselskis *et al* [1995], TI Web site [<http://www.ti.com>] present a variety of RFID applications.

#### 1. Automatic Toll Collection

Toll collection involves collecting a specified amount from each individual vehicle that passes a lane. Automatic toll collection includes a card-like transponder placed on the windshield or the bumper of the vehicle. When a car passes through the toll lane, typically within 15 kmph speed, a reader placed about it detects the card and deducts the appropriate amount from the card. In this case, the card contains information about the car as well as the balance amount. During the period when the car is within the range of the reader, the data transmission takes place in both the directions.

## 2. Railroad industries

Tags are typically mounted on the sides of the railroad cars and receivers are placed at the starting, ending and intermediate stations. This allows a real-time update on the status of the vehicle as well as the cargo. Additional parametric data such as temperature change can be transmitted through the transponder.

## 3. Car Race Track - timing and scoring

Keeping track on lap counts and speed for individual cars in a racetrack with precision is a task that requires real time identification and data transmission. Tags are placed at the identical location on each car — on the right side floor. Receivers in the form of cylinders with diameter 0.3m and height 0.5m are placed on side of the tracks. Antennae in the form of inductive loops are placed on the ground in such a form that the width car is always greater than a loop. Antennae are placed on various locations of the racetrack, pit lanes, exit lanes etc. All receivers are connected in the form of a network. When a car passes over the field of a loop, it is detected by the receiver and the information is immediately sent from the receiver to a main computer at the steward's office. Information such as lap count, time between two points on the track etc are calculated at the steward's office. Two adjacent antennae located at a fixed distance and connected to the same receiver can be used to detect speed as well as direction.

### 3.4.5 Suitability to Performance Data Collection

Radio frequency identification is essentially an identification tool wherein a presence of a coded transponder is detected by a receiver. Although this feature serves well in mines, concrete dispatch applications, it falls short of providing the necessary features for the production data collection system. Detection range and directionality are two primary concerns. In order to determine time in load area, at least two receivers are required at the entrance and the exit of the load area. Every segment of the haul requires at least one receiver. This system does not present a very economical way to collect productivity data because of the relatively high cost of the receivers. RFID could become a part of the performance data-collection mechanism, especially,

in conjunction with GPS as improvements are made in this field. A tag on the (back of) loader could be detected by a receiver on the truck and fed into a GPS system as input. This may help in identifying trucks that are loading, maneuvering or waiting to load. The only features favorable to this system are the readiness of technology and proven test under harsh environment.

### 3.5 SUMMARY

Data collectible varies according to the technology used for data collection. For example, if OBI is used, then the load time of a truck can be measured accurately. The time spent in the load area is only possible if GPS is used. Determining load time requires physical sensors on the truck. OBI can record only the aggregate time to haul whereas a global positioning system will be able to calculate the time for each segment. This discussion is not only important from the point of view of technology feature but also for the design of the experience database. Although the experience database is theoretically independent of the methodology of data collection, its design, contents and functionality are governed by the technology used for data collection.

Details of OBI, GPS and RFID systems were presented in this chapter. The features of each system and its applicability to collect cycle time data were discussed. Table 3-1 summarizes the features and presents a comparison of the three candidate technologies.

**Table 3-1: Comparison of candidate technologies**

<b>Feature</b>	<b>On-board Instrumentation (OBI)</b>	<b>Global Positioning Systems (GPS)</b>	<b>Radio Frequency Identification (RFID)</b>
<b>Data</b>			
1) Extent of Automation	Almost complete automation; calibration required on daily basis	Full automation possible	Partial automation is possible; continuous monitoring not feasible

Continued.

<b>Feature</b>	<b>On-board Instrumentation (OBI)</b>	<b>Global Positioning Systems (GPS)</b>	<b>Radio Frequency Identification (RFID)</b>
2) Activity time	Directly available	Can be calculated based on proximity rules	Can be calculated based on presence
3) Load time	Yes; sensors are available	No; only time in load area is possible	No; only time in load area is possible
4) Load time from each pass	Not with the systems investigated; possible by others	No; physical sensors are needed to collect this data	No; physical sensors are needed to collect this data
5) Waiting time	Yes; using speed as a criterion, waiting time can be separated from activity time	Yes; if speed is used as an input, waiting time can be incorporated into the rules	No; requires continuous monitoring along a path
6) Dump time	Not with the systems investigated; possible by others	No; time in dump area	No; time in dump area
7) Individual haul segments	No; only aggregate information is available	Yes; can be computed on the server	No; requires continuous monitoring along a path
<b><u>Communication</u></b>			
1) Individual unit to base	Cell phone / radio link possible; one-way in most instances	Cell phone / radio link possible; two-way in most instances	Cell phone possible in advanced applications; two-way in some instances
2) Individual unit	Integrated with machine instruments; almost all internal	Communication with satellites depend on weather	Proximity is a factor; tested under harsh environments
3) Buffer	Can store records temporarily until refreshed	Can store records temporarily until refreshed	Can store records temporarily until refreshed

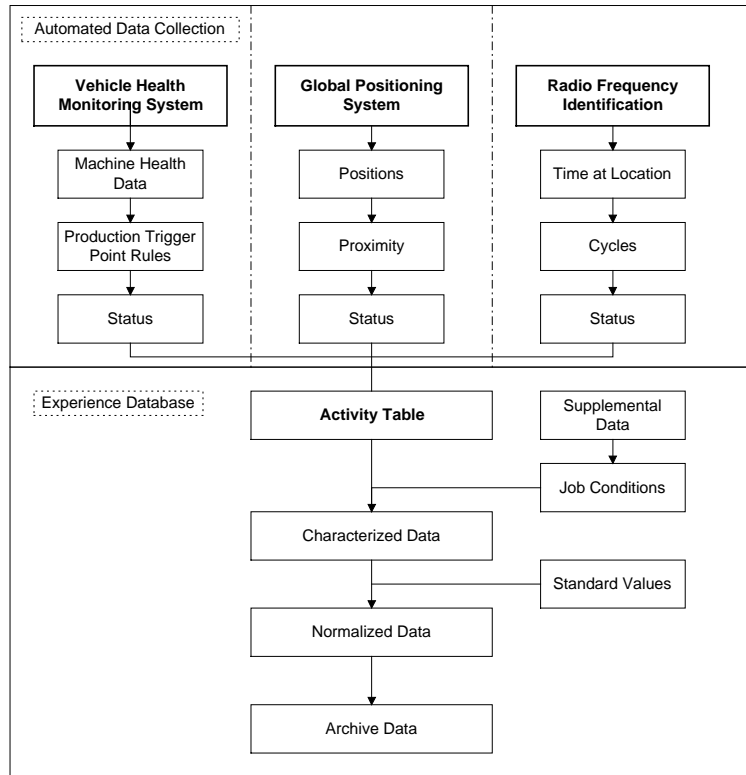
Continued.

<b>Feature</b>	<b>On-board Instrumentation (OBI)</b>	<b>Global Positioning Systems (GPS)</b>	<b>Radio Frequency Identification (RFID)</b>
<b><u>Availability</u></b> : Types of machines	Available only from some manufacturers on selected trucks	Independent of truck manufacturers	Independent of truck manufacturers
<b><u>Mobility</u></b> : Fixed or portable	Fixed; completely integrated with machine electronics	Portable; can be easily detached and mounted on any machine	Portable; readers and tags can be moved around; power is a constraint for readers
<b><u>Other Features and Applications</u></b>	Load as a output	(a) Haul road profile (actual vs. theoretical speed) (b) Haul road maintenance (accelerometer) (c) Load counting (d) Actual-built-simulation (e) Machine health monitoring (through tire pressure, temperature etc.)	Partial machine health monitoring
<b><u>Cost</u></b> <sup>1</sup>			
1) Equipment	Varies with manufacturer; usually ranging from \$40000 to \$50000 per truck; software extra.	Receiver = \$1000 / Truck Base station = \$20000 or can be substituted with coast guard beacon or community base station; software extra.	Tags = \$25 / Truck Readers = \$4000 / unit Communication through cable or wireless extra
2) Training	Operator training required	No form of training is required for operation	No form of training is required for operation

<sup>1</sup> Cost information was based on various sources – newsletters, web pages, personal communications. Therefore, the amounts do not reflect any one system available in the market rather gives an idea about the order of magnitude.

### 3.6 RECOMMENDATION

Figure 3-1 shows the role of an automated data collection system in the development of an experience database. The common ground between the data collection system and the experience database is the activity table. An activity table consists of the performance data in terms of each component of the earthmoving cycle. Therefore, a row in the activity table can be imagined to contain a date & time stamp, load time, haul time, return time and dump time. The direct output of an OBI produce an activity table. A system can be designed using GPS to generate the activity table. It is possible that a futuristic technology can generate this activity table with more proficiency. However, it is emphasized that the purpose of this research is to develop a methodology to use field data for improving planning, estimating and management of earthmoving operations. The intent is not to develop multiple technologies to produce the same form of data although such a requirement may be the focus of a future research. OBI, in particular TPMS<sup>®</sup> and VIMS<sup>®</sup>, will be used for developing this methodology. The actual implementations of the concepts relating to GPS and RFID presented in this chapter are left as a challenge for future research. [Appendix B](#) presents a proposal for a system using GPS. The next chapter investigates technologies for collecting information on operating conditions.



**Figure 3-1: Role of automated data collection systems in the development of an experience database**

# CHAPTER 4: TECHNOLOGIES FOR COLLECTING INFORMATION ON OPERATING CONDITIONS

[Chapter 3](#) reviewed candidate technologies for performance data collection. This chapter will review some technologies for collecting information on operating conditions. Performance data together with information on operating conditions form the two basic components of experience database. [Chapter 5](#) will discuss the role of these two forms of data within the framework of the experience database.

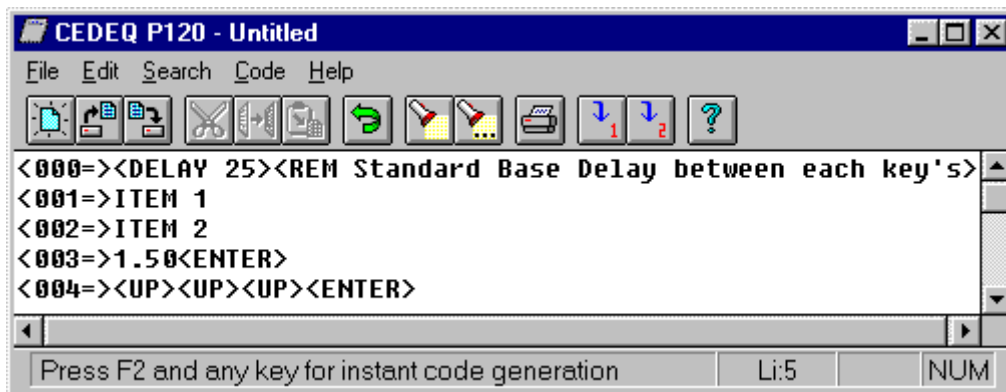
The technologies investigated in this chapter are touchpad, barcodes and direct data entry. Image database (IDB) is a concept that can be applied to all these technologies. This chapter will briefly introduce the concept of image database while [Chapter 12](#) will take up the implementation of the image database in detail.

## 4.1 TOUCHPAD

A touchpad is essentially a programmable keyboard. The touchpad investigated for this research was manufactured by CEDEQ [<http://www.cedeq.com>]. A touchpad consists of hotkeys arranged in a grid-like fashion. On a normal keyboard, each key corresponds to particular character only. Each hotkey on a touchpad can be programmed to emulate a set of events, which in turn may correspond to multiple keystrokes. A touchpad typically has 100 to 120 such hot keys and measure about 25cm x 30cm x 3cm. A shift key may be used in tandem to produce additional hotkeys. The touchpad also has a limited memory to store the programmed code. The most functional aspect of a touchpad is that it is based on a domain specific language. For example, a fast food application may have a hotkey labeled “value meal 1,” which in turn could correspond to a set of individual items.

Each key on a touchpad is labeled sequentially from 1 to say, 100. A simple ASCII editor can be used to program each key, a sample snippet of code is shown in Figure 4-1. The code for each

key can represent anything from a single character to a complete sentence or even a macro. The string corresponding to this code is transmitted each time the key is pressed. Once the code for each key is programmed on a desktop computer, a software program is used to upload the code to the memory of the touchpad. The memory of the touchpad is temporary and so the code is deleted from memory when the touchpad is switched off. When the touchpad is active – code uploaded and connected to a desktop computer, any key pressed will send the appropriate code to the active program on the desktop.



**Figure 4-1: Sample screen showing a touchpad code**

#### 4.1.1 Sample Application: Fast food industry

The point of sales application in the fast food industry is interesting and closely related to collecting information on operating conditions. A typical touchpad for the fast food industry is shown in Figure 4-2. The application has a display unit in addition to the touchpad. Since the menu items seldom change on a regular basis, the program code is uploaded automatically each time the keypad is switched on. Some of the hotkeys are not assigned any actions — these keys provide for new items. A hotkey can be re-assigned to new actions if necessary, the important criterion being that the code is uploaded each time it is changed. When an operator presses a hotkey, the code is used to translate into events such as a “value meal 1” could correspond to a “burger, fries and a drink.” The price of the meal as a whole or the individual items can be stored in a database independent of the touchpad and is retrieved each time to prepare the check. If during a promotion, the description of the value meal is changed to “two burgers, fries and a drink,” then the code is altered accordingly and uploaded. This modularity provides a constant

environment for the operator — the touchpad looks the same in both the scenarios; the processing details can be maintained on the main computer by an individual conversant with programming. The significant features of this application are the elimination of a mouse, detailed description of the item or the need to remember identification code.



Figure 4-2: Sample application using a touchpad [<http://www.cedeq.com>]

#### 4.1.2 Productivity Data Collection Using a Touchpad

As part of reviewing and investigating the technology, a sample application was developed using the touchpad. This section briefly describes the application and functioning of the technology with the viewpoint of production data collection. Touchpad can be used in two different ways for productivity data collection: a) collect information on operating conditions, and b) collect components of a loader cycle time manually. Both the applications are described below briefly.

a) Collecting information on operating conditions

Operating conditions involve load area characteristics such as material being loaded, floor conditions, swing angle, loading pattern, and haul road characteristics such as slope, floor conditions, turning radius etc. Natural language description can make the design of the user interface very simple. The touchpad can be divided into four regions, namely, load, haul, dump and return details. Each area can be differentiated with a different color. Description such as floor conditions is hard and even can be augmented with pictures. In case the space occupied by such description or an equivalent picture is larger than the area of a key, then more than one key can be assigned the same action. The active program to which the touchpad is linked can be incorporated with intelligence such as obtaining the current date and time from the system date and time or the top row of the touchpad can be devoted to numbers, which can then be used to build a particular date.

b) Collecting detail performance records manually

Onboard instrumentation systems are fully geared to collect performance data automatically. Not all form of data can be collected using these systems. For example, the management may realize that the load times collected during a period are sufficiently greater than expected. The management might be interested in investigating the issue further by determining the components of the cycle time for each loader pass. The touchpad can be used to collect such production data with relative ease.

The touchpad does not have the capability to generate time by itself; instead, a keystroke can be used to generate a macro that will create a time stamp. A data collection system was designed as shown in Figure 4-3 taking advantage of this capability. The important details for this form of data collection are the truck number and events such as enter load area, start first pass, start subsequent pass and leave load area. These details can be assigned to individual hotkeys or if necessary, to multiple keys. The active program that will be interfaced with the touchpad entry is shown in Figure 4-4. Simple processing logic can be used to collect cycle time for each pass, the load time for a truck and time spent in the load area. The processing algorithm is executed in a Visual Basic<sup>®</sup> environment.

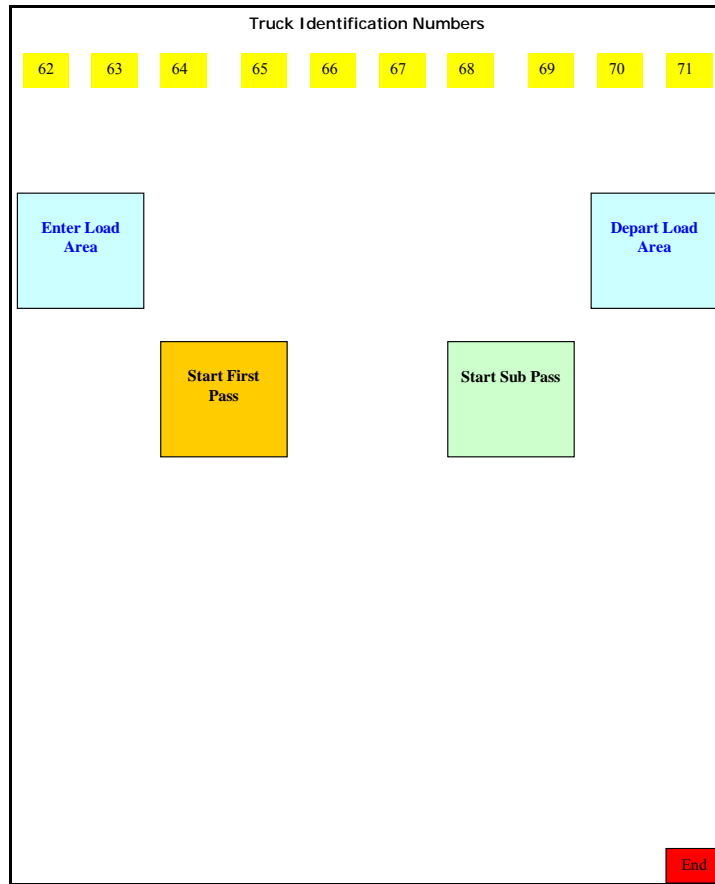


Figure 4-3: Template for the load-area data collection

The screenshot shows a window titled 'Form1' with a standard Windows-style title bar. The window contains three text input fields arranged vertically. The first field is labeled 'Truck Number', the second is labeled 'Event', and the third is labeled 'Time'. At the bottom right of the window, there is a button labeled 'End'.

Figure 4-4: Sample application which interfaces with touchpad

## 4.2 BAR CODES

Bar code is another example of an automatic identification technology. Bar codes are being implemented by most industries to efficiently log data by reducing keyboard entries, thereby reducing errors at the entry of a system. Bar codes help to process transactions about an item in a faster — almost 50% faster than keyboard entry, and in a more accurate manner — almost 100% accuracy [Lee 1997]. Bar codes are currently being used for inventory management wherein each item is tagged with a bar code representing its unique identification number. A database located on the central server helps to identify the properties of the item based on the identification number.

Bar code technology is analogous to the radio frequency identification (RFID) technology discussed in [Chapter 3](#). A code corresponding to the identification number is tagged on to the item, which is detected by a reader. Nevertheless, there are significant differences between the two technologies, some of which are listed below.

- The bar code label should appear on the external surface of the item because the reader usually relies on infrared or laser technology for detection. Readers relying on radio frequency can permit the tag to be located within the item; the main consideration is that metallic surface impede radio transmission.
- A bar code tags just the identification number only — a combination of alphanumeric characters. It is always static — the code does not necessarily reflect any dynamic properties of the item. RFID supports input from other sources in real time, such as fuel level, temperature etc. These dynamically changing properties can be included as a part of or in addition to the identification number.
- Some bar code readers rely on physical contact or close proximity to the bar code label. Most RFID systems can function without physical contact. In fact, some RFID application supports up to range of 30m.

### 4.2.1 Equipment

**Scanner:** The scanner, sometimes referred to as a wand when hand-held, is the external device that is used to read the bar code label. Scanners also come in the form of a fixed light-emitting source on a transparent surface, such as the ones used in a grocery store. Typically, the wands are connected to the serial port of a computer and require very close proximity to the label.

**Decoder:** The principal purpose of the decoder is to decode the bars into simple ASCII information. Decoders can be "wedged" in between the keyboard and the computer or could be part of the software that is active on the host computer.

**Bar code labels:** Bar codes are essentially series of bars and spaces grouped together. Any word processing or a bar code program can generate bar codes, which can be printed out from laser or inkjet printers on adhesive labels. The adhesive labels are usually mounted on the surface of the item, which is tagged.

### 4.2.2 Bar Code Symbologies

As discussed under RFID technology, a significant drawback is a common protocol among various manufacturers and users. Each industry uses a domain-specific interpretation protocol. The interpretation of a group of bars and spaces is referred to as symbologies. Each bar code consists of four zones: quiet zone, the start code, the data, the stop code, and a trailing quiet zone. Density is the resolution of the bars and is a trade-off between space used versus the capability of the scanner. One of the more widely used symbology is the Code39, the description of which is beyond the scope of this discussion. Although the concept of symbology is not a required criterion for a system design, knowledge of the symbology will help in developing a suitable and a user-friendly system.

### 4.2.3 Bar Code Applications in Construction

Bar code applications in construction are aimed at providing improved accuracy, productivity and timeliness. Bernhold [1990a, 1990b] provides a background on the technical details, suitability of bar codes for construction and field testing of bar codes in the construction site environment.

Blakey [1990] demonstrated the use of bar codes in parts inventory and scheduling maintenance for military facilities. Rasdorf and Herbert [1990a, 1990b] presented a construction information management system (CIMS), which integrates scheduling, inventory cost, and document control applications. Bar code vendors have leveraged on advances in computing and incorporated essential computing facilities such as time stamp and programming logic into the bar code reader.

### **4.3 DIRECT DATA ENTRY**

Direct data entry refers to the mode of data entry wherein the parametric values are entered on a paper form directly on the site or using a computer program as shown in Figure 4-5.

Questionnaire in a paper form is one of the best organized methods to extract information regarding the operating conditions. Oglesby *et al* [1983] note that questionnaires must be carefully designed to fit each situation. The customized form or simply, the paper form must include options that reflect the operating conditions on each site. The criteria for designing a questionnaire should include their general purpose, the time that can be devoted to filling them out, and the attitudes and verbal abilities of the respondents. One of the drawbacks involved using the paper form is the need to enter the information into a computer manually.

There are several advantages as well as drawbacks to computer-based data entry. The principal advantage is the simplicity of the process and the accuracy of the data. An intuitive and friendly user-interface as shown in Figure 4-5 can aid the process of data entry. A discussion on the design of a user-interface is beyond the scope of this document. The major drawback about using a computer program to collect information on operating conditions is that it requires the data collector to be computer literate. Lighting conditions and dusty environment may be two reasons why using a laptop on the field has not yet become very widespread.

The screenshot shows a software window titled "Conditions Data for Earthmoving Operations". It contains the following fields and options:

- Date:** 1/01/97
- Shift:** Day
- Weather:** Clear and Hot
- Fleet:** CAT 5230 + 785
- Material:** Good common earth
- Haul Length (in Feet):** 1000
- Load Area Details:**
  - Space: Adequate space
  - Floor: Muck
  - Pattern: Back Loading
- Fill Area details:**
  - Space: Adequate space
  - Floor: Muck
  - Pattern: Back in, Dump and Go
- Haul Road Characteristics:**
  - Surface: Hard and Even
  - Curves: None
  - Other: (empty text box)

At the bottom of the window, there are two buttons: "Update" and "Exit", and a long empty text input field.

**Figure 4-5: Sample screen for a data entry program**

## 4.4 IMAGE DATABASE (IDB)

The concept of image database involves creating a database with image as a key field. Each image is linked to a set of characteristics details. The database can be queried based on the image field or any other field. The advantage of using images helps to catalog and categorize a large database. Images also help in the communication and interpretation aspects of a user interface. The concept of IDB can be used along with touchpad, bar codes and the direct data entry methods. An image which defines a particular operating condition can be placed over a keystroke and when the user presses the key, the characteristic details of the image can be transferred to the active program. The same principle can be adopted while using a bar code or the direct entry method.

### 4.4.1 Concept

The use of IDB standardizes and improves communication and interpretation in the collection of information on operating conditions thereby improving the reliability of the data. The other purpose is to make the data collection process intuitive and less burdensome for the data collector. An IDB contains photographs from the site which typically concentrate on a small area such as the load area, haul roads and dumpsite. Each photograph is characterized by a set of

conditions by one individual, who will be addressed as the *critic* for illustrative purpose. The implementation of IDB can be one of the three following ways:

1. A catalog of images can be created based on the photographs from the site. The foreman on the site identifies the photograph that closely matches the operating conditions and makes a record on the foreman's daily report or the questionnaire.
2. The foreman on the site takes photographs of the different areas on the site typically at least once a day and then sends it to the *critic* who then characterizes the operating conditions based on the photographs.
3. A foreman can enter keywords in a computer program, which then retrieves photographs that match the required criteria. The foreman then chooses the photograph that has the best match to the operating conditions.

The role of IDB in recording operating conditions in any one of the three approaches has the following advantages:

- (a) the process of data collection is intuitive and less burdensome,
- (b) images along with text help in standardizing and improving communication, and
- (c) there is only one point of interpretation, namely, the *critic*.

The first approach appears to be suited to collecting information on operating conditions. Most site management feel that their foremen should not be burdened with an overload of additional tasks such as taking photographs of operations and filling out additional forms. The use of digital cameras is still not a common place on most construction sites. Taking photographs in the traditional manner involves additional cost. Finally, not many foremen were computer literate to handle a laptop to record operating conditions.

Application of IDB can be viewed as a two-step approach. The first step is the creation of an image catalog, which contains representative photographs of the different aspects of the site. The

second step is the application of this catalog in collecting the information on operating conditions.

#### 4.4.2 Creating the IDB Catalog

Although the technology of recording digital images has substantially improved and the cost of such technology has made it affordable, the use of digital cameras on a construction project is still in its nascent stage. Taking pictures using a normal camera and then scanning them subsequently provides a viable option. Both digital images as well as digital formats of scanned images can be used in the development of the image catalog.

Image recording is the first step in the creation of the catalog. Several different photographs of the different areas on the site are taken. For example, photographs from the load area indicate the configuration of load area, the material being loaded, the floor conditions, and any other information such as the slope of the toe, whenever applicable. The photographs about the haul road indicate the overall layout if possible, the typical surface condition, width of the road, and any other information such as curves. The photographs from the dump area indicate the dump pattern, the floor conditions, and additional information such as dumping over a berm. Examples of such photographs are presented in [Chapter 12](#).

Each photograph is then be placed under one of the three areas — load, haul and dump. This is the process of sorting the photographs. There is a possibility that some photographs better depict the operating conditions than others. There is also a possibility that a photograph depicts more than one operating condition. In either case, the best set of photograph should be selected. Heuristics can be used to decide the number of photographs or the granularity of information.

Each image is given a unique identification number (ID). The identification number can include a smart coding system, where the first one or two characters are used to identify the related area and the next two digits the sub-category of the area. For example, a leading ‘L’ can indicate load area. A textual description of each image is also included to help the user distinguish two images based on discriminating characteristics while creating the catalog. If custom designed paper forms are used for collecting information on operating conditions, the selection and

categorization is linked to the form. All descriptions included in the form should be represented by an image wherever possible.

Six categorized images are placed on two sheets paper, which gives twelve images to elicit information on operating conditions. The two sheets of paper are placed back to back and laminated for durability. This serves as the reference for the foreman on the site. Although it is possible to envision the creation of a catalog to be a one-time process, it is also possible that work face is constantly changing. The material could change from well-shot rock to good common earth. It is also possible that the equipment could change in the course of operation. In order to prevent the catalog from being irrelevant, it should be possible to add, delete, or modify the catalog. As with any database, key fields such as ID should not be reused.

#### **4.4.3 Using the IDB Catalog**

The advantage of applying the concepts of IDB to collecting information on operating conditions is that it can be used with a customized system or can be augmented to an existing system. An IDB can be used along with a customized system such as paper form, touch pad or computer program based tools. The IDB can also be as part of a foreman's daily reporting system.

The paper form is created based on the operating conditions in the shape of a multiple-choice questionnaire. The questions progressively change from general to particular areas. Questions under particular area such as load area involved sub-divisions such as material, floor conditions and space constraints. Similar terms are used in the textual description of the images in the IDB. A foreman is required to check the alternative that closely matches the operating conditions or include the ID number of the image that closely match the operating conditions.

An existing method is a reference to the foreman's daily report. The daily report is filled out by foremen as part their routine and includes information on the location of cut and fill, type of material and load count. The biggest difficulty with using a foreman's daily report is that it is open-ended — it does not contain information on all aspects of the site and the discretion of words to describe the site conditions. On most occasions information on floor conditions, space

constraints are not included as part of the report. The terminology for describing the type of material varies among foremen.

The foremen can be instructed to use the comments column on the daily report to note the ID number of the picture. The foremen can be given the option of using the image ID and/ or the textual description with the only requisite that all aspects of the site are included. Since the foreman's daily report is produced once a shift, the information provided can be taken as the representation of the operation during the entire shift.

#### **4.4.4 Applications of Image Databases**

##### ***4.4.4.1 Airline Industry***

The airline industry has successfully used the IDB to extract information from customers who have lost their baggage [<http://www.nwa.com>]. The information required to trace a lost baggage can be partitioned into two groups: subjective and objective. Subjective information refers to relative terms such as big or small, heavy or light etc., while objective information refers to constant-reference terms such as color, name tag etc. Among the two, the extraction of the subjective information poses the tougher challenge. In order to address this issue, the airline hands out to the customer a catalog containing the images of different types and sizes of baggage as shown in Figure 4-6. The customer is asked to identify the image of the bag that closely matches the customer's bag. Characterizing subjective information as described above and using objective information such as color helps to communicate the request to various airports without the fear of misinterpretation. This is similar to the knowledge required to capture operating conditions on a construction site.

##### ***4.4.4.2 Picture Queries***

There is a requirement in several different industries to query a picture database for information retrieval. The art industry [Cawkell 1993] uses picture-based queries to retrieve information from a large collection of paintings, artwork, manuscripts, photographs, and drawings. The images from such sources are classified, cataloged and digitized. A registration form for each image containing fields such the creator, the photographer, the caption, the place, the era and the

sub-category. Queries can be either in the form of “17<sup>th</sup> Century pictures which include animal pets” or “a selection of cartoons by Leonardo da Vinci.” A well-designed IDB can accommodate both information discovery, as in the former example, or information recovery, as in the case of the latter example [Cawkell 1993].



**Figure 4-6: Example of a catalog of baggage used by airline industry**

## 4.5 SUMMARY

Operating conditions are an important part of the production data. Operating conditions are required to characterize the performance data. The technologies described in this section include touchpad, bar codes, and direct data entry methods. The concept of image database was presented as a method to organize a large database of qualitative information.

The paper form is the simplest mechanism to collect information on operating conditions. The image database along with customized paper form or foreman’s report presents the best opportunity to collect information on operating conditions.

# CHAPTER 5: FRAMEWORK OF RESEARCH: THE EXPERIENCE DATABASE

Chapters 3 & 4 described the opportunities available to address the challenges raised in Chapter 1. Chapter 2 outlined previous research in the related areas. This chapter outlines the concepts involved in the framework of this research – the experience database. Chapters 6-8 develop the performance measures for the load, haul & return, and dump activities. Chapters 9-11 define a range of possible operating conditions and using statistical tests, identify those which affect the performance.

Webster’s dictionary describes *experience* as “a direct observation of or participation in events as a basis of knowledge,” and *database* as “usually a large collection of data organized specially for rapid search and retrieval.” Thus, the phrase *experience database*, in this context, refers to a large collection of directly observed field data, which will be employed to retrieve production statistics about the performance. This production statistics expands the knowledge about earthmoving operations and serves as input to applications such as simulation.

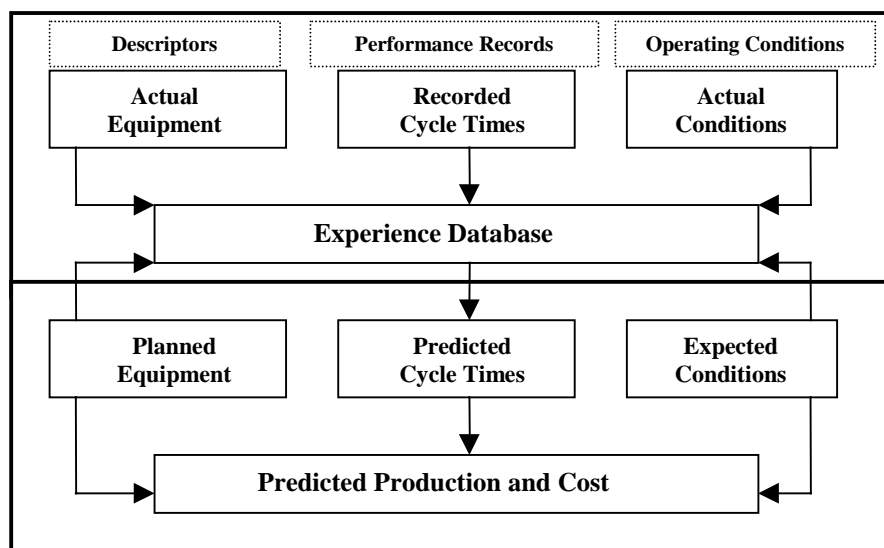
The agenda for this Chapter is:

- to define the concept of experience database,
- to describe characterization and normalization within the experience database, and
- to define the roles of various forms of data.

## 5.1 THE CONCEPT

An experience database is a repository of as-built information whose structures is shown in Figure 5-1. It is a data warehouse that is company- or project-specific, dynamic and in an electronic format. It links performance data such as components of cycle times and information on operating conditions such as material type, haul road surface characteristics which affect performance. The performance data is discriminated based on characterizing factors which

define the operating conditions and normalized for application to future projects. The primary purpose of the experience database is to provide production statistics in the form of a distribution, which forms the input to a process analysis model. An important component of the experience database is a bivariate frequency plot or a PLT Map, a visual tool to present the performance of the load activity. Target window is an enhancement to the PLT Map which provides a project management tool for both construction and mining industries. This chapter will present a general perspective on these features while [Chapters 6 to 8](#) will provide specific information regarding each activity.



**Figure 5-1: Experience database for archiving and retrieving information**

## 5.2 THE PARADIGM SHIFT

The framework for managing production data is both need-driven and opportunity-induced. The need for an experience database is driven by the lack of a methodology to electronically archive company- or project-specific information in a dynamic manner. The opportunity in terms of vehicle instrumentation is the ability to collect performance data in an autonomous and continuous mode. The confluence of the needs with the opportunity provides the impetus for this paradigm shift.

### **5.2.1 From Data Collection to Building Experience**

Stopwatches and other manual data-collection methods are useful in collecting small samples of data whose averages are the input to deterministic job studies. The data samples are well selected and the operating conditions are recorded as an integral part of the data. However, process analysis using simulation requires the knowledge of variance and the effect of operating conditions on the variance in operation. The main concern about using data collected by stopwatches as input to simulation models is the relatively small volume of data. Statistically significant volume of data is required to measure both the central tendency and variance.

On the other hand, vehicle instrumentation generates a continuous and indiscriminate stream of production data. Data is collected as long as the equipment is in operation. The sample size is not a concern anymore; in fact, data on the whole population is available. The principal challenge is to understand and process the data to derive useful information so as to improve the knowledge about earthmoving activities. The underlying experience is captured by extracting the relative variance in the operation and characterizing this variance. The experience database serves as the basis for planning and estimating future projects.

### **5.2.2 From Generic to Specific Information**

There are public standards and handbooks as well as equipment manufacturer's manuals that serve as a good starting point in production estimating. R. S. Means [Means 1997] and Richardson's [1992] are two examples of public standards. The information provided by these standards are very generic — encompassing a wide spectrum of projects, and at a high hierarchical level — daily or hourly production. These values could either reflect an instantaneous (maximum possible theoretically) or sustainable (average realistic production achievable throughout project) production [Gransberg 1998]. Important factors such as variance in activities, nature of the project, and operating conditions are either left out or seldom emphasized.

Equipment manufacturers provide an estimate of each of the task — load, haul, dump and return — of an earthmoving operation. For example, Caterpillar's performance handbook suggests the use of a range for the loading time of a shovel [Caterpillar 1997]. Sometimes the width of the

range, such as 0.04-0.20 minute per loader pass, does not provide very useful information. Volvo uses a single point estimate for each loader pass [Volvo 1995]. These single point estimates are a measure of the average of averages, i.e., the average load time for a particular operation is determined over a period and averages from different projects are then averaged. The data may include day and shifts, different weather conditions, different periods of the year in one aggregate form. Although such averages provide a solution for a wide breadth of operations, they lack the depth to provide good information for any one operation.

Standards, manuals and handbooks are being used as the basis for data input to analysis tools for the lack of a better practice. Two types of difficulties are associated with using values provided by standard manuals or handbooks [Knoke *et al.* 1993]:

- a) the values provided in the manuals seldom represented the actual conditions of the project under consideration, and
- b) it is difficult to derive the variability of the current project from the data in the manuals.

The experience database offers for the first time a method to archive company- or project-specific data. An experience database is built using a continuous stream of field data from the instrumented vehicles. The stream of data typically consists of load, haul, dump and return times. Operating conditions on the site are recorded manually and are linked to the cycle time data. The experience database addresses the first difficulty by recording the actual cycle times and the actual conditions as observed on the site, thereby providing a realistic basis for comparison to the expected conditions on a future project. On the second difficulty, it is difficult to precisely measure the variability of one project from another, especially if the basis is an aggregate of different types of projects. The basis provided by the experience database is derived from actually observed performance for a single company or project.

The important consideration is that the data is collected continuously within the framework of the experience database. For example, the on-board instrumentation collects data as long as the equipment is active. The continuous form enables the collection of data under different scenarios such as day and night shifts, during rain or sunny weather, during different parts of the year etc. The advantage of recording data under such varying conditions is the flexibility to use the entire set (similar to public standards or performance manuals) or a subset based on required

conditions. Some of these conditions will be used in a process called characterization, which is the basis of associating performance data with operating conditions.

### **5.2.3 From a Static to a Dynamic Archive of Production Information**

The information provided by standards, handbooks and manuals are static — does not include the latest production achieved. There is a lack of a feedback mechanism to update the information in these manuals. An error in terms of under- or over-estimates always stays in the system and is never corrected over time based on directly observed values. The feedback loop is well tuned in the cost estimating process — the actual cost incurred on the current project is incorporated into the database. Two main reasons for the lack of a dynamic feedback with existing data sources are:

- a) they have their roots in the averages of averages and so the actual production from any one project has less significance, and
- b) the lack of a methodology to continuously collect data and feed into an archive.

The experience database addresses these two issues by using an autonomous and continuous source for data and the mechanism of archiving does not work based on averages, rather the actual cycle times. The experience database is a cumulative source of data, which means an estimator could use all the data or a subset of the data upon discretion. The subset could be defined by a particular calendar period, by shift, or by any other distinguishing parameter.

### **5.2.4 From a Non-Electronic To a Digital Format**

Stutz [1997] compares the different technologies to archive data based on cost, life, security and functionality. Digital format of data offers several advantages in the form of archival, search, retrieval and manipulation. The two forms of data in the experience database — performance and operating conditions — are in digital format. The performance data from the vehicle instrumentation is in a well-structured digital format. The operating conditions data collected in paper format can be converted into digital format through direct data entry. The power of the digital format can be used to search for records that match specified conditions. Computer-based

manipulation can be used to derive performance measures as well as graphical outputs, which are very difficult otherwise.

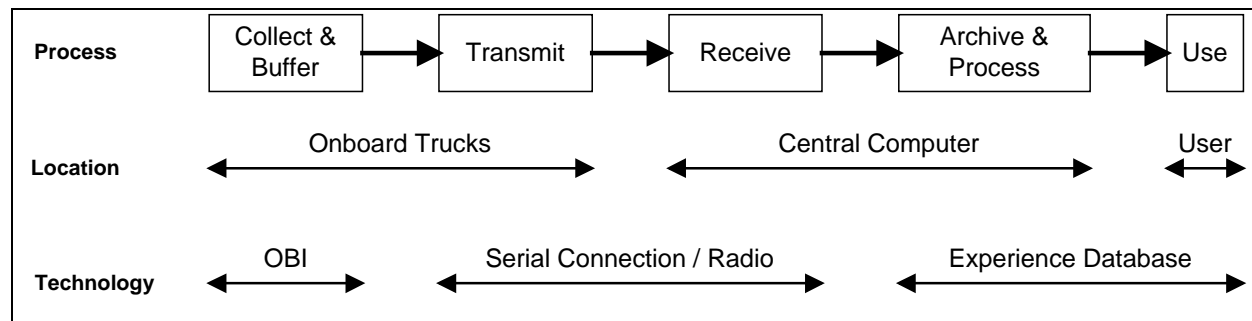
Digital form of data is necessary because collecting and archiving data is not an end by itself. Digital data serves at least two purposes:

- 1) visually present the performance of an operation and hence, aid in improvement, and
- 2) provide input to analysis tools to test various scenarios and hence, aid in improvement.

The preceding sections have highlighted some of the reasons why the experience database is projected as a new paradigm in production data collection. The salient feature is that a warehouse of data such as the experience database will improve the precision and reliability of the estimates.

### 5.3 ROLE OF ONBOARD INSTRUMENTATION IN EXPERIENCE DATABASE

Figure 5-2 shows the different aspects of the data collection system for the experience database. The onboard instrumentation (OBI) used for this project involves two systems developed by Caterpillar, Inc., namely, TPMS<sup>®</sup> and VIMS<sup>®</sup>. These systems are incorporated as an integral part of the truck's mechanism. The role of these systems is to collect and buffer the production data onboard. The data are downloaded before the buffer is overrun using serial cables. Recent modifications allow the download in a wireless form.



**Figure 5-2: Process, location and technology aspects of the data collection system**

The data is in machine-readable format when it is downloaded. A conversion program transforms the data into a well-structured form. The end product of most onboard instrumentation system is the data by itself. The role of the experience database is to take this well-structured data as input and convert it to information that can be used for managing ongoing operations as well estimate future operations. The creation and maintenance of the experience database requires other forms of data, which is explained in Section 5.4.

It is possible to replace OBI with a technology such as GPS. GPS may be able to record more information such as the time for each loader pass or swing angle etc. The location and process aspects will change according to the technology. There will always be tradeoffs between using one technology versus another; for example, a data collection system using GPS will not able to record the payload on the truck.

## **5.4 DATA FORMATS**

Three forms of data are required in order to achieve the goal of a company- or project-specific, dynamic and electronic source of production data. They are performance data, information on operating conditions and descriptors. Each one of these forms and the requirements for the experience database is explained below.

### **5.4.1 Performance Data**

The performance data is available from directly from the onboard instruments. The performance data for this study is provided by TPMS<sup>®</sup> and VIMS<sup>®</sup>, onboard instrumentation systems developed by Caterpillar, Inc. Therefore, the scope of the cycle time data is defined by the outputs of these two systems. The performance data for the experience database includes load, haul, dump, return times and payload. The components of the cycle time are available in a well-structured form for every cycle.

The performance data also contains a date and time stamp. The date stamp is important in two ways: a) it is a link to the operating conditions recorded on a daily basis, and b) it is a characterizing factor in and of itself. The time stamp assists in characterizing production based

on shift. Characterizing based on location and to a lesser extent shift explains the role of management, a factor that is used in deterministic calculations [Peurifoy *et al.* 1996, pp211].

While using simulation to analyze operations, the modeler is interested in activity and idle times. The activity times are the input and idle times are the output of a simulation system. A simulation model can determine if the resources will be in an idle state based on the activity times and the interaction between resources. It is therefore important to separate activity and idle times while recording data. Onboard instrumentation can generate data for both activity and idle times based on the logic explained in [Chapter 3](#).

#### **5.4.2 Information on Operating Conditions**

It is accepted that no two construction projects are alike. It is also agreed that there are several factors that govern the performance of a project. Therefore, data collected by onboard instrumentation by itself does not give a complete meaning to the data. Useful information can only be determined by recording the operating conditions under which the performance data were recorded. Since these factors are subjective — requires judgement by a human — it is very difficult to record them using the same onboard instruments. Operating conditions have to be recorded via an interactive mode. Operating conditions are considered as factorable information rather than data in traditional data collection methods. For example, performance manuals [Caterpillar 1994, pp4-117-118] treat the operating conditions such as material as qualitative factors.

Most operating conditions data are qualitative in nature. The qualitative data list includes, but not restricted to, type of material, floor conditions, space constraints, loading or dumping patterns and surface conditions. Each cycle time record is linked to a set of operating conditions. It is not possible to record operating conditions for every cycle in an interactive manner. Therefore, a representative set of operating conditions is recorded for a period, typically a day, and linked to all cycles within the period.

A very important consideration regarding the operating conditions data is to resolve the issue of “who” will record them. Construction personnel such as the truck operator, an area foreman, a

section superintendent, or a project engineer could be the data collector. Availability of time, granularity of information, cooperation, and incremental burden are some of the issues that needs to be addressed in the implementation of the experience database.

### 5.4.3 Descriptors

Descriptors are specification-based data that provide a frame of reference to the performance data in order to extract the relative variance. Equipment-specific descriptors include model of the loading and hauling equipment, type of loading arrangement — shovel, back hoe, front-end loader, target payload for the hauling equipment, target load time for the loader-hauler combination, and the rimpull curve of the hauler. These are termed as reference values and are stored in a library. The reference values are used for characterizing and normalizing the performance data recorded by the onboard instruments. For example, the loading method — shovel, backhoe and front-end loader — can be used as a characterizing factor. Target payload and load time can be used for normalizing the payload and load time as obtained from the OBI.

Project-specific descriptors are used for haul and return activities. Haul road profile in terms of length, grade, and rolling resistance is an example of project-specific descriptor. These descriptors are not part of the specification-based data but provide a frame of reference to the haul & return activities. The profile data is used in calculation of the theoretical travel times which are then used for normalizing the haul and return times. These descriptors are described in detail in [Chapter 7](#).

## 5.5 CHARACTERIZATION

Characterization in the process of linking performance records in terms of cycle time to the corresponding operating conditions. The operating conditions, which affect the global operating environment, are termed as global factors while operating conditions, which affect the performance on a particular portion of the cycle, is called project-specific factors. Global factors are higher order factors and are a function of the project location and the loading method of the equipment. Project-specific factors such as material type, surface conditions are applicable within the boundaries of the global factors, say a project or a loading method.

Characterization is an implicit process during manual data collection because a definite set of discriminate sample data is collected. While automated data collection techniques overcomes some of the limitations associated with manual data collection, it gives rise to significant difficulties regarding the characterization of the data to reflect the actual conditions under which the data were collected. The automated data collection process has no built-in mechanism to characterize cycle time data because characterizing data requires the capability to record the conditions under which the cycle time data are collected. Since conditions on a construction site constantly change, manipulating the data and deriving useful information requires characterization. For example, a stream of load time can be used to derive the mean and variance in the operation. However, if the conditions under which the load times are observed varies between well-blasted rock and common earth, a unique value of mean and variance does not produce useful information. This is the same difficulty expressed in case of the manuals and handbooks, which encompass a wide range of projects. If instead the data stream is categorized based on a characterizing factor — in this example, type of material being loaded — then the value of information is enhanced.

Table 5-1 shows a list of candidate factors that can be used for characterizing the stream of data. Each of these factors can have several discrete values. For example, material could have values that include well-blasted rock, poorly blasted rock, common earth, organic muck, or clay. Each record obtained from the instrumented vehicles is tagged with a particular value of each characterizing factor. Therefore, the values of the characterizing factors have to be recorded when the conditions change, typically at least once a day.

**Table 5-1: Candidate factors for data characterization**

<b>Load Area</b>	<b>Haul</b>	<b>Dump Area</b>	<b>Return</b>
Material	Length	Floor conditions	Length
Shift	Gear shifts	Space constraints	Gear shifts
Space constraints	Surface condition		Surface condition

## 5.6 NORMALIZATION

Useful information from the data generated by onboard instruments can be created in two ways. First, visual representation of the data provides an immediate response about an ongoing operation and helps in productivity improvement. Second, characterized data can be used to plan and estimate future projects. Extending data from ongoing operations to project future operations requires a form of normalization, which guarantees the reusability of the data. Reusability of the data depends upon the extraction of relative variation in each component of the cycle.

The extraction of relative variation for the load activity is accomplished through normalizing the field data using measures such as the rated payload and the standard load time for a given loader-truck combination. The variation in the normalized payload and load time can then be applied to the loader-truck combination under similar conditions in a future project. It is important to note that the knowledge of variation may be related to the operating conditions such as method of loading, type of material etc.

Haul and return activities pose a challenge which is complex. The normalization of load activity can be considered a simple scaling mechanism where only limited combinations of loaders and trucks are possible within a fleet. The combinations of different properties of haul segments — length, grade, rolling resistance — could result in an infinite set of possible roads. Therefore, normalization based on the influencing factors such as length, grade, rolling resistance requires a reference value for every possible combination of haul segments. It is not feasible to calculate and store a reference value for every possible haul road. Therefore, rigorous treatment of normalizing the travel times such that it can be applied to future projects is very important and is the subject of discussion in [Chapter 7](#).

## 5.7 COMPONENTS OF THE EXPERIENCE DATABASE

The information that can be extracted from the experience database can be divided into two divisions: descriptive statistics and visual representation. The purpose of the descriptive statistics is to provide information in a stochastic format so that it can be used as input to process

simulation. The purpose of the visual representation is to present the voluminous data in an effective and intuitive manner so that a manager can have an immediate response about the operation.

### **5.7.1 Production Statistics**

Production statistics characterize and summarize the production data. These statistical measures are generally referred to as moments of the data. The first moment of the data is the mean, the second standard deviation, the third skewness and the fourth kurtosis. Each moment characterizes the distribution that summarizes the data.

Mean and mode are two of the commonly used numerical measures of the central tendency of the data. Mean is the average of all values in a data set while the mode reflects the value that has the highest likelihood of occurrence. Mean cycle time gives the first impression about an operation. The mean value satisfies the sufficient and necessary data input for deterministic job studies, which use a single point estimate. The mean however does not provide an insight into the variance or the standard deviation of the operation.

Variance or the standard deviation is a measure of the spread of the data set. The variance or the standard deviation of an operation is explained by a frequency plot of the data. Standard deviation along with the mean is the most elemental way to describe the data set. The duration of the load, haul, dump and return activities can be treated as random variables owing to the inherent uncertainties involved with each activity. Since there is a possibility to obtain an infinite number of values between a lower and a upper bound, most random variables such as load time, payload, haul time, dump time and return time are considered as continuous random variables. The chances of obtaining a single discrete value is zero. The chance of obtaining a range between a lower and higher limit is given by the area enclosed by the cumulative frequency plot.

Skewness is a measure of the symmetry of a distribution that models the data. Symmetrical data sets have a skewness equal to zero while a positive skewness reflects a skew to the right. Law and Kelton [1991] note that most distributions encountered in practice is skewed to the right.

Kurtosis is a measure of the peakness of a distribution that models the data. Kurtosis also measures the ‘tail weight’ of a distribution [Law and Kelton 1991]. A normal distribution has a kurtosis of three.

Figure 5-3 shows the moments for both payload and load time of a sample data set. The moments present a variety of information. The mean and standard deviation present a first impression about the consistency of the operation. On a closer inspection of skewness and kurtosis, it is possible to extend the understanding of the operation in terms of the form of distribution that can be used to model the operation. For example, a positive skewness of load time for all the projects suggests that the distribution is skewed to the right. The relatively high value of kurtosis for load time suggests that the distribution may have a narrow peak. Although it is possible to construct a distribution from the moments, a graphical representation of this data will be more intuitive in determining the distribution that best fits the data.

SI TECODE	Obs	Variabl e	Mean	Std Dev	Skewness	Kurtosis
A	21680	LOADTI ME	2. 4998732	1. 6884888	6. 7244308	84. 1377374
		PAYLOAD	137. 6196656	20. 0655605	-0. 3772942	0. 4501778
B	2655	LOADTI ME	2. 7810358	1. 8410527	5. 9593752	81. 9927235
		PAYLOAD	90. 9452655	10. 2501938	-0. 1697715	0. 7552127
C	10409	LOADTI ME	4. 5051600	2. 3386561	2. 9724799	26. 3952729
		PAYLOAD	106. 7792199	31. 7400294	0. 1242899	-0. 7986332

**Figure 5-3: Moments of a sample data set**

The first step in construction a probabilistic density function (PDF) of a variable is to inspect the histogram of the data. Several techniques including visual fit, moment matching and maximum likelihood are available to determine the form of PDF that best defines the data [AbouRizk *et al.* 1994]. Converting field data into a PDF facilitates the replication of the variable within a simulation model with a good level of confidence. An example of a comparison of field payload data as represented by the histogram of the observed values and the resultant distribution used as input to simulation as represented by the curve is shown in Figure 5-4. Most simulation engines support *Uniform, Normal, Exponential, Beta, Weibull* and *Triangular* distributions. It is beyond the scope of this document to provide details of all distributions, instead information will be

provided on an as-needed basis. Interested readers are directed to Johnson *et al.* [1994], Law and Kelton [1991], and Carson and Banks [1984].

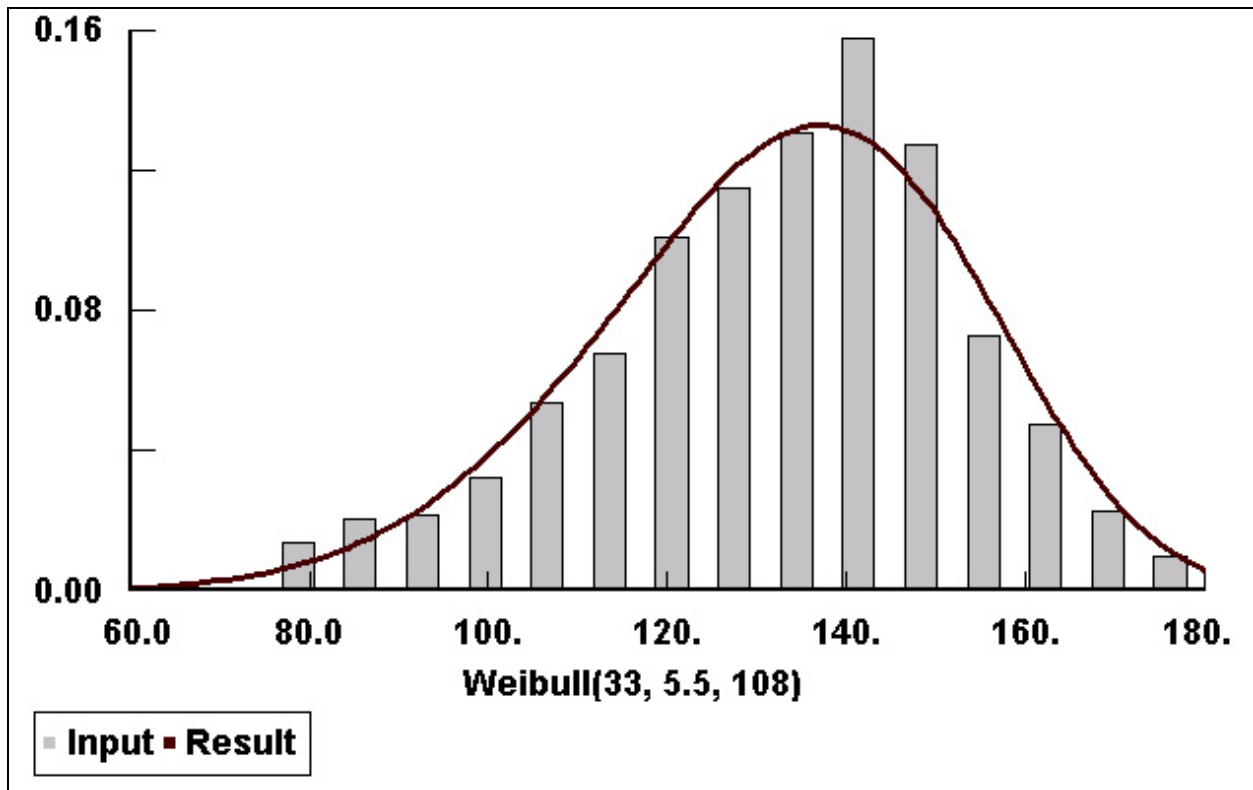


Figure 5-4: An example of modeling payload for input to simulation

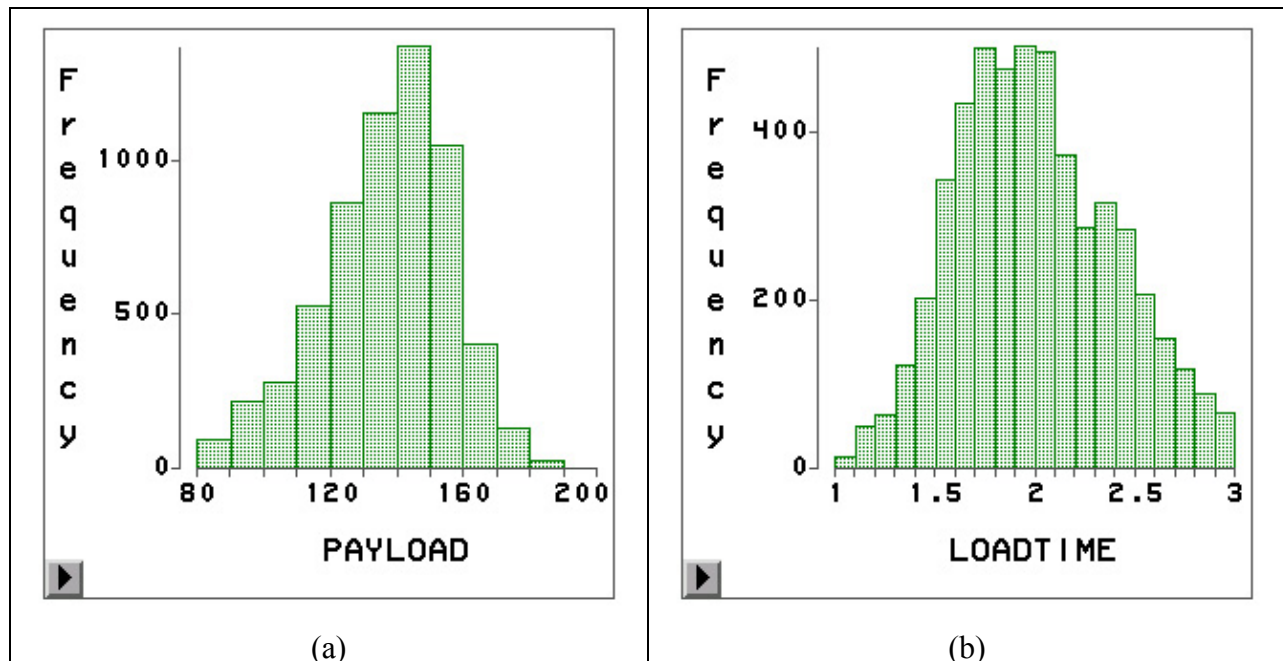
## 5.7.2 Visual Representation

Converting data to information using graphical representation and visualization techniques is a powerful form of data analysis. Tufte [1983] notes that the way to describe, explore, and summarize a set of numbers is to look at the graphic representation of the numbers. Graphics are a medium to foster reasoning about quantitative information and observed any pattern that might be embedded in the data.

### 5.7.2.1 Histograms of Payload and Load Time

Histograms are very powerful in depicting the variation in a variable. An example of histograms for payload and load time is shown in Figure 5-5. An inspection of the histograms gives an

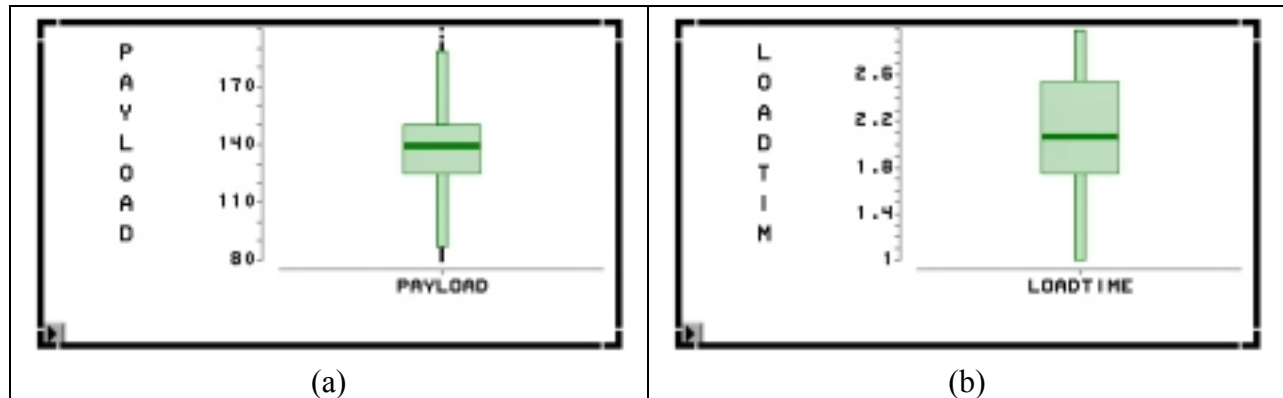
immediate response about the operation. A single point estimate such as average would have camouflaged the spread in the data. By illustrating the production operation through a histogram, it may be possible to characterize a good operation by the degree of variance in the operation. Therefore, an experienced shovel operator may be expected to have a lower variance or a higher consistency than a novice. Operations where factors such as load area, load floor and rock fragmentation are consistently well managed will also yield consistent results.



**Figure 5-5: Histograms of payload and load time of a shovel-truck operation**

### 5.7.2.2 Box Plots of Payload and Load Time

Box plots are pictorial representations of the distribution of values of a continuous variable. The central line in each box marks the median value or the 50th percentile. The edges of the box mark the first and third quartiles, or the 25th and 75th percentiles. By combining these three values in a schematic diagram and plotting individual markers for extreme data values, the box plot provides a concise display of a distribution (Tukey 1977). The box plots for the same set of field data as given in Figure 5-5 are shown in Figure 5-6. These clearly show the median, percentile values and ranges of the data.



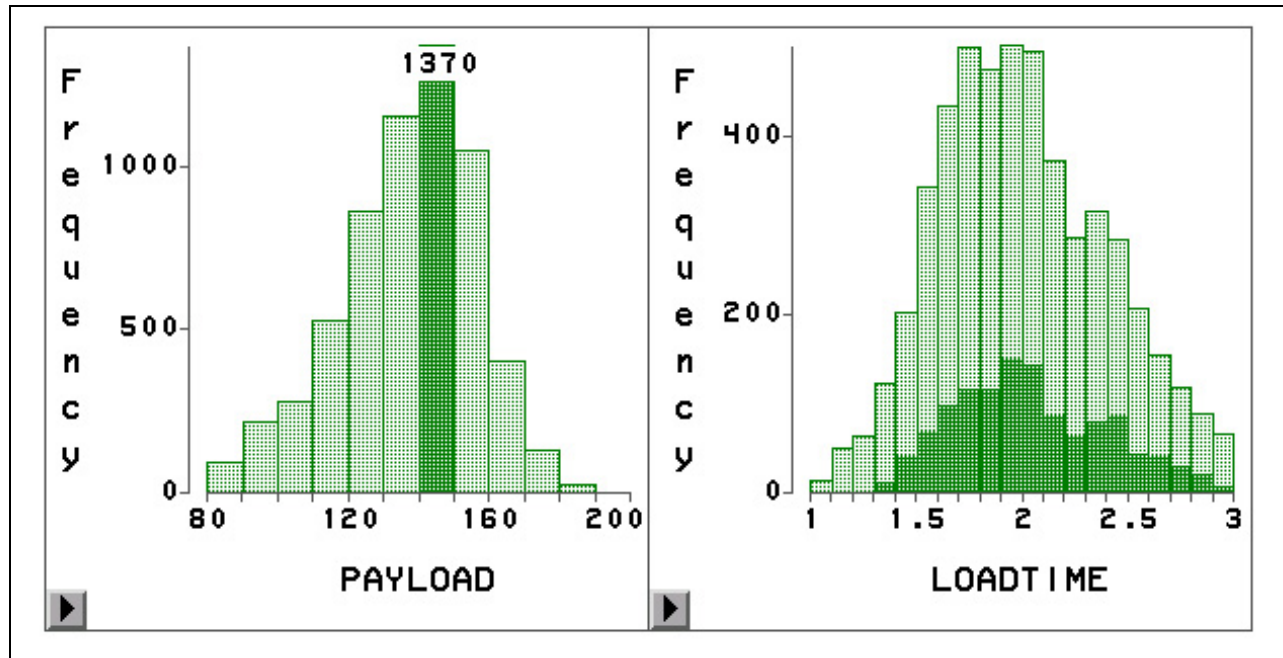
**Figure 5-6: Box plot representation of payload and load time**

### *5.7.2.3 Relation Between Payload and the Distribution of Load Time*

The two variables in consideration, payload and load time, are inherent with uncertainty, i.e., any values of payload and load time are possible. Consequently, both these variables can be treated as continuous random variable. Therefore, the chance of obtaining a unique value of payload and load time is very zero. The notion of a range serves well in determining the chances of obtaining an interval of values.

Figure 5-7 shows two interrelated histograms. The payload histograms, on the left, shows that a load between 140t and 150t occurred 1370 times in a total number of 6156 cycles. The probability of obtaining a load in this range is thus  $1370/6156$  or 22%. It is also important to determine the load time related to this range of payload. The histogram for load time corresponding to this range is shown by a darker shade. It is possible to generate a series of load time histograms for different ranges of payload. The result would be a number of different histograms, which integrated together, would provide more information. It is clear that a more powerful graphical representation is required to depict the simultaneous variance in payload and load time and to determine the effect of payload on load time, if any.

The value of visual representation is in the ability to recognize patterns and convey useful information from field data in an intuitive manner, thereby promoting the “data rich – information rich” paradigm.



**Figure 5-7: Histogram depicting a range of payload and the corresponding distribution of load time**

The two components of the experience database — production statistics and visual representation — were discussed in this section. The role of the two components in the experience database as well as their role in this research framework was briefly introduced. [Chapters 6 to 8](#) take up these measures in detail for each component of the earthmoving cycle.

## **5.8 ROLE OF THE EXPERIENCE DATABASE**

A paradigm shift – creating a specific and dynamic electronic database of production data – was proposed to address some of the limitations of the current methods. An experience database was proposed as a new paradigm in production data collection. This section links the experience database to the motivation behind this research as outlined in [Chapter 1](#).

### **5.8.1 Planning and Estimating Earthmoving Operations**

The experience database contains both performance data collected by the onboard instruments and information on operating conditions collected interactively. The process of characterization makes the field data more useful by associating operating conditions to performance data. Normalization allows the reusability of the data by distilling the relative variance. The

experience database is able to provide probabilistic input information to process simulation models because onboard instrumentation yields a sufficiently large volume of normalized data for each of the situations described by the characterizing factors. It is obvious that the experience database is the first opportunity to provide reliable and realistic data for planning, estimating and managing earthmoving operations.

### **5.8.2 Methods Improvement of Ongoing Operations**

Methods improvement refers to bettering of existing methods by an immediate evaluation of the method being used [Parker and Oglesby 1972]. One of the steps involved in methods improvement is to record data on the operation. Manual methods such as stopwatches provide only a sample of data pertaining to a period of operation, typically an hour. One of the limitations of a stopwatch study is that the scope of information is strictly restricted to the data that is recorded. Vehicle instrumentation provides an opportunity to capture productivity data in a continuous manner. Graphical formats of these data provide an immediate response to the performance of the operation and an opportunity to improve existing methods. In describing the role of time-lapse video on methods improvement, Parker and Oglesby [1972] note that

*“...users of time lapse photography achieve their goal of methods improvement and better on-the-job communications with informal discussion sessions. The film itself becomes the agenda for the meeting... In some organizations this informal technique has been so successful that users see no further advantage from more formal techniques...”*

Visual representation of the onboard instrumentation data can provide the same function as the time lapse photography.

## **5.9 SUMMARY**

The purpose of this chapter is to prepare the foundation of the framework of this research. This chapter expanded on the thesis statement in [Chapter 1](#) by describing the concept of the experience database. An experience database is a repository of as-built productivity information. It is a data warehouse that is company- or project-specific, dynamic and in an electronic format. It contains performance data such as components of cycle times as well as job conditional data such as material type, haul road surface characteristics that influence performance.

The development of the experience database is fostered by vehicle instrumentation. The process, location, and technology aspects of a data collection system involving vehicle instrumentation was also discussed. Onboard instrumentation is one form of vehicle instrumentation system that essentially monitors the health parameters of the equipment. The same system can be extended to collect and buffer productivity data based on certain logistics.

The concepts outlined in this chapter will be transformed into procedures which will be used in developing performance measures and determining the operating conditions that affect the performance for each component of the earthmoving cycle.

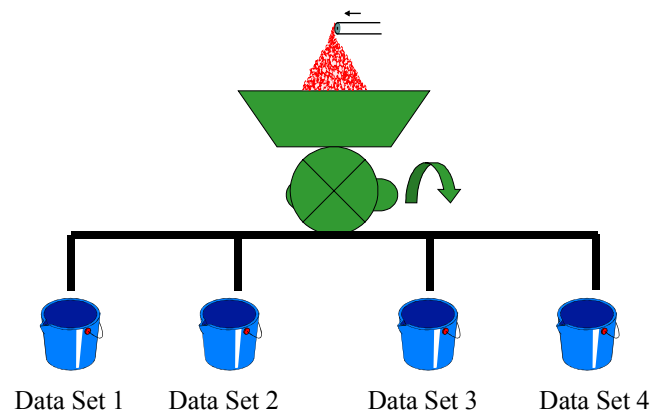
The reader is requested to bear with the compartmentalization of this section of the dissertation. This is done to facilitate the discussion of the methodology from the viewpoint of procedures as well as the components of the earthmoving cycle. [Chapter 6](#) through [Chapter 8](#) will develop procedures for the performance measures for the load, haul & return, and dump activities. [Chapter 9](#) through [Chapter 11](#) will define a range of possible operating conditions and using statistical test, identify those which affect performance for the load, haul & return, and dump activities. [Chapter 12](#) and [Chapter 13](#) will integrate the components and describe the steps involved in implementing the concepts of the experience database.

# CHAPTER 6: PERFORMANCE MEASURES FOR THE LOAD ACTIVITY

The overall framework for the experience database was presented in [Chapter 5](#). The purpose of this chapter is to develop performance measures to model the performance of the load activity. These performance measures will be used in the planning of future operations as well as improving existing methods. Predicting the performance of the load activity for a future operation involves the estimation of parameters of a probabilistic distribution using the historical data. Improving methods of ongoing operations involves the development of graphical tools. This chapter will address:

- the format of data available for the load activity,
- measures required to predict the load activity, and
- measures required to manage the load activity.

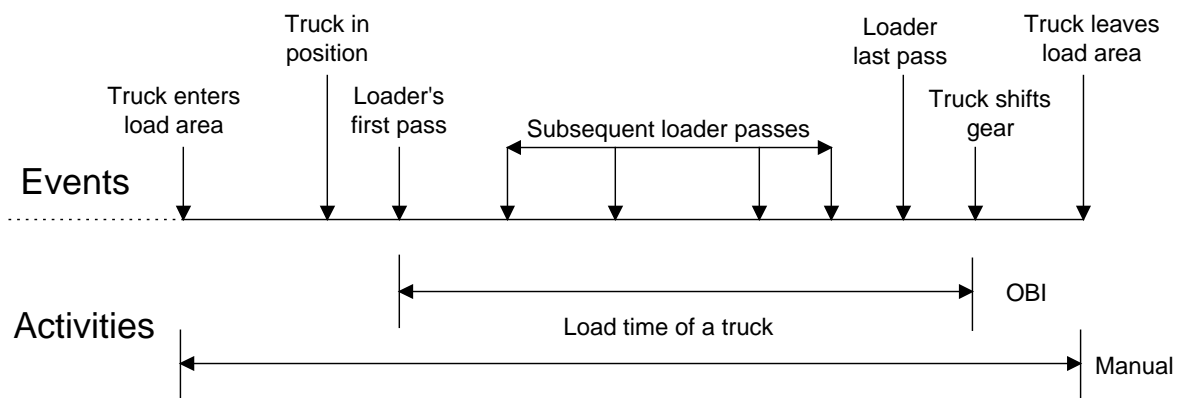
Characterization was briefly introduced in [Chapter 5](#) as the process of associating operating conditions to the performance data. All data within the experience database can be grouped based on certain characterizing factors as shown in Figure 6-1. For example, data set 1 could contain all data for night shift and data set 2 could contain all data for day shift. A data set will be used as the basis in the development of the performance measures. The description of the characterization process of the load activity is described in detail in [Chapter 9](#).



**Figure 6-1: Schematic representation of a data set**

## 6.1 DEFINITION

There are several possible definitions for the duration of the load activity. Figure 6-2 shows the definition as applicable to the onboard instrumentation and manual techniques. Some observers believe that the load activity starts as soon as the trucks get into position or when the loader starts to dig into the material for the first pass. When using on-board instrumentation on the trucks to calculate the load time, it is not possible to measure a parameter unless there is a change in the state of the truck. The sensors on the truck must be able to sense or detect a change. The change in suspension pressure is the parameter detected in the case of load activity. Therefore, the load activity begins as soon as the first loader pass of the material lands on the bed of the truck. The change that is detected to determine the end of the load activity is the shift in transmission and / or the speed. Therefore, the end of the load activity is at the point when the operator shifts from neutral gear and starts to move the truck.



**Figure 6-2: Definition of load time**

It is clear based on the above definition that not all forms of data regarding the load activity are collectible. The two forms of data that are collected are the load time of a truck and the payload in the truck. It is essential to understand that value of load time and payload are recorded at the time the truck departs the load area. The payload in the truck is measured through a surrogate parameter — strut pressure. It is not possible to record the number of loader passes for each truck, the swing angle, the depth of cut, etc with TPMS<sup>®</sup> or VIMS<sup>®</sup>. Although such information

would be provide additional insights into the load operation, load time and payload are necessary and sufficient to perform a variety of analyses, especially for providing input to simulation models.

## 6.2 PREDICTING LOAD TIME AND PAYLOAD OF A TRUCK

The simplest way to estimate the load time and payload of a loader-truck combination based on the historical data is to generate the average of all cycles that have been archived. The average is an unbiased estimator taking into consideration all possible operating conditions. The estimate however falls into the same trap as standards and manuals by ignoring specific conditions. A data set as described in the beginning of this chapter selects cycles that match specific operating conditions. The central tendency and variance of this data set is determined by describing a probabilistic density function (PDF). For illustrative purpose, consider that the load time of a particular loader-truck combination (descriptors) corresponds to a *Normal* distribution with mean 3.0 and standard deviation 0.5 when the material type is rock.

The next step is to extend the information contained in this PDF to a future operation. It is fair to state that the best estimate for load time for the same loader-truck pair when loading rock is *Normal*[3.0, 0.5]. However, the estimate loses its importance if a different size truck is used with the same loader because the absolute value of the mean and standard deviation has very little meaning. Extending absolute values from one operation to another does not provide the correct basis. It is necessary to extract the relative variance from the ongoing operation and apply this variance to a future operation. Relative variance is the variance associated with a dimensionless measure and can be extracted by normalizing each instance of the load time in the data set by a reference or target value ( $R_i$ ) as shown in Eq(5). A PDF of the normalized values provides a clear knowledge of the relative variance involved in the operation. The best estimate for load time as shown in Eq(6) for this new loader-truck combination can be given by the product of its reference value ( $R_j$ ) — explained further in Section 6.2.1 — and the PDF corresponding to relative variance. The extension of relative variance from one loader-truck combination to another is dependent on a range of operating conditions such as loading methods, match factor etc. and is discussed in [Chapter 9](#). If a company is interested in the performance of

a particular loader-truck combination in its fleet under different operating conditions,  $R_i$  and  $R_j$  are the same while the relative variance is defined by specified operating conditions.

$$v_a = \frac{t_a}{R_i} \quad (5)$$

$$E = R_j * f(v_a) \quad (6)$$

where

$v_a$  is the normalized load time for each cycle based on the reference value,

$t_a$  is the load time for each cycle as recorded by the onboard instruments,

$R_i, R_j$  are the reference values for the  $i^{\text{th}}$  and  $j^{\text{th}}$  combination of the descriptors,

$E$  is the estimate for a future operation, and

$f(v_a)$  is the PDF that describes the variation in the normalized load time.

The procedure for predicting the payload follows the same line of explanation as the load time. Load time and payload together represent the performance measures of the load activity. There is a range of possible operating conditions such as loading method, material etc which affect the performance of the load activity. Each set of operating conditions is associated with a unique PDF for normalized load time and normalized payload. The use of an appropriate PDF in estimating a future project depends on the expected conditions. The advantage of normalizing is that the reference value is isolated which makes the PDF applicable to other truck-loader pairs. Describing and understanding the variance in a quantitative form is the subject of this chapter while determining the operating conditions that affect the performance is described in [Chapter 9](#).

### 6.2.1 Reference Value

The role of the reference value is in the isolation of the variance in the operation through the scaling mechanism as explained in Eq(5). The reference value is a function of the descriptors — loader-truck combination. The reference value corresponds to a standard value specified by the

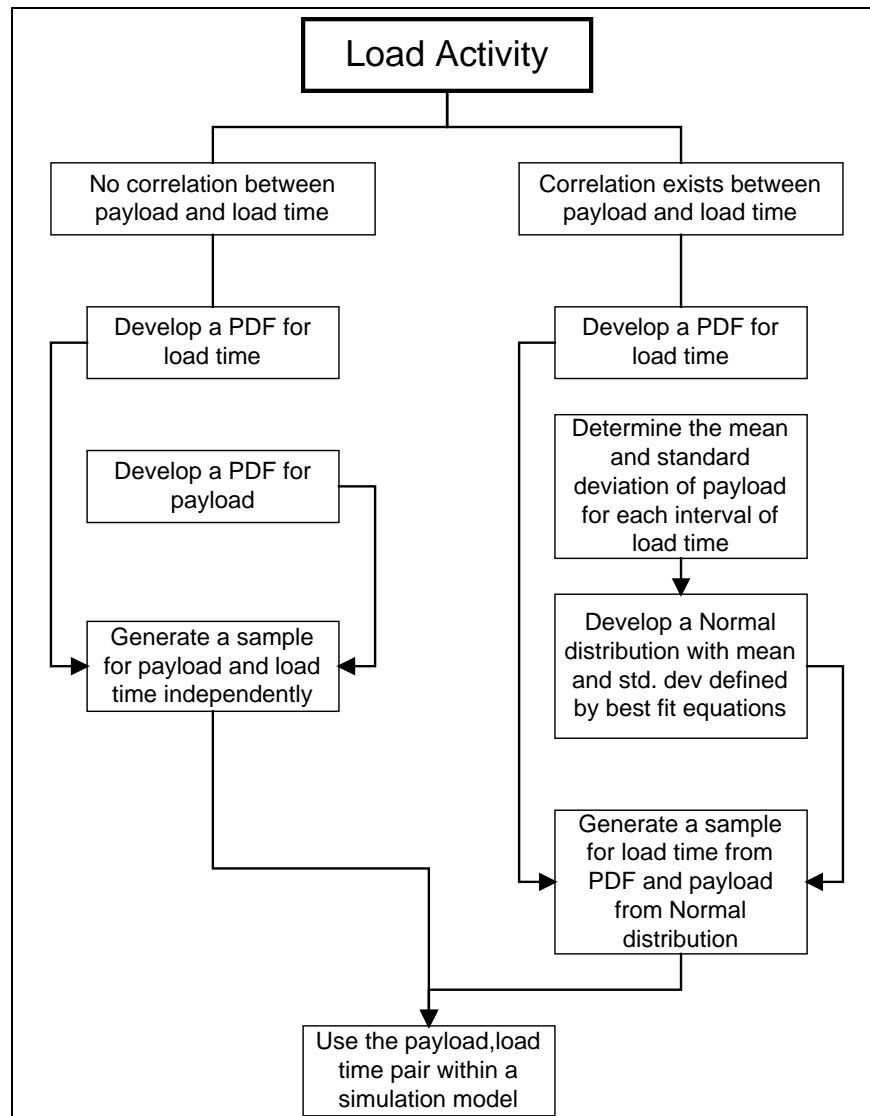
equipment manufacturer and usually, does not include the job conditions. It is possible that the loader and the truck may be from different manufacturers and hence, the standard value will be provided by the company that owns the equipment. The reference values are considered fixed and stored in a library.

### **6.2.2 Variance in Normalized Load Time and Normalized Payload**

The payload and load time recorded for every cycle by the onboard instruments is normalized based on the rated payload and the standard load time for the loader-truck combination. The normalized data is used to fit a PDF which in turn, becomes the estimator of variance. In deriving the PDF of the normalized data, a data set corresponding to a particular set of operating conditions is used. It is important to realize that a PDF of the normalized data is a function of the operating conditions although it is independent of the reference value. The rest of this chapter is devoted to describing the variance in detail. A schematic representation of the procedures involved in describing the variance is shown in Figure 6-3.

## **6.3 VARIATION UNDER INDEPENDENCE ASSUMPTION**

The reader is reminded that the value of load time and payload recorded by the onboard instrumentation is recorded at the instant the truck leaves the load area. It is possible that there may or may not exist any relationship between the payload and the load time of a truck. Although it seems intuitive that a relationship is inevitable, this assumption is important in defining the variation in payload and load time. The discussion on this section assumes that there is no relationship between payload and load time of a truck. A relationship between payload and load time is taken into account and an appropriate methodology defined in Section 6.5.



**Figure 6-3: Process diagram for developing performance measures for the load activity**

### 6.3.1 Payload

A standard distribution that best describes the payload is determined using standard procedures [Law and Kelton 1991]. Then the probability of obtaining a particular range of payload is modeled by Eq (7).

$$P(U_p > p > L_p) = \int_{L_p}^{U_p} f(p) dp \quad (7)$$



where

$P(x)$  is the probability of a random variable  $x$ ,

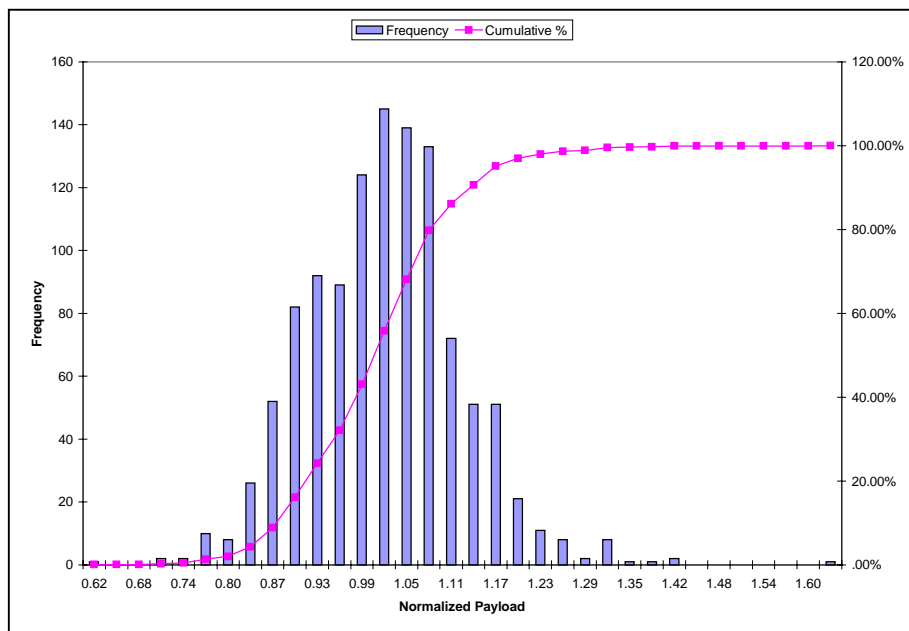
$L_p$  and  $U_p$  are lower and upper limits of the range of payload,

$p$  is the payload, and

$f(p)$  is the PDF that describes the variation in payload for the entire range.

Figure 6-4 shows a graphical representation of Eq(7) wherein the integral of the PDF is represented by the area enclosed by cumulative frequency line within the specified limits.

Since all discrete values of payload are theoretically possible, the variable payload is treated as a continuous random variable. Therefore, the probability of obtaining a specific value of payload is zero and hence, the need to use a range to determine the probability.



**Figure 6-4: Frequency distribution of payload**

AbouRizk and Halpin [1992b] used a transformed method to determine the statistical properties of construction data. They used the values of skewness and kurtosis to determine the type of distribution associated with various construction activities. The mathematical form of the transformation is given by Eq(8) and Eq(9).

$$\theta_1 = \frac{\beta_1}{1 + \beta_1} \quad (8)$$

$$\theta_2 = \frac{1}{\beta_2} \quad (9)$$

where

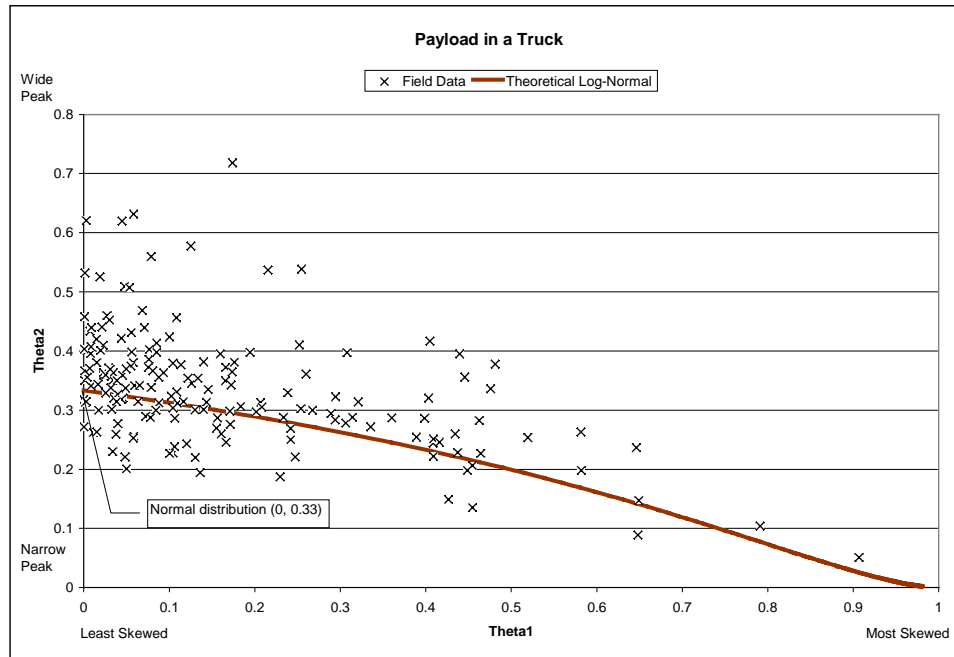
$\theta_1$  and  $\theta_2$  are the transformed parameters,

$\beta_1$  is square of the coefficient of skewness and

$\beta_2$  is the coefficient of kurtosis.

The plane  $\theta_1$ -  $\theta_2$  can be used to determine the type of distribution of an activity. For example, a Normal distribution has a coefficient of skewness of 0 and kurtosis equal to 3. Therefore, data corresponding to a Normal distribution will lie on (0,1/3) on the  $\theta_1$ -  $\theta_2$  plane. Higher order distributions will lie on a line or occupy a region in the plot. Figure 6-5 shows the field data from all the projects used in this study plotted on a  $\theta_1$ -  $\theta_2$  plane.

From all the data available for this study, the payload on the truck for a given loader on a given date and a given shift is considered as one activity and is represented by one data point on the plot. Most of the data points appear to lie around (0, 0.3) on the  $\theta_1$ -  $\theta_2$  plane. These points correspond to a value of skewness of zero and a kurtosis of around 3. This suggests the distribution corresponding to payload could be modeled as a Normal distribution. For reference, a line corresponding to Log-Normal distribution is shown in the figure. It can be noted that the Log-Normal offers the next best alternate distribution to model the data.



**Figure 6-5: Distribution to model payload data**

The Normal distribution can also be explained based on vehicle instrumentation. One of the additional components of the vehicle instrumentation is the use of red-green light on the sides of the truck. These lights help the loader operator to gauge the payload with respect to the target payload [Chironis 1987, pp53]. The microprocessor onboard calculates the average load per loader pass (stored in the buffer temporarily) and projects the payload at the end of the subsequent pass. If the projected value is less than 90% of the target value, then the green light stays on while closer to 90% makes the red light flash. Once the loader pass is completed and if the payload actually exceeds the target value then the red light stays on. This visual indicator is specially designed to reduce the variance in the payload. Since both lighter and heavier loads in comparison to the target load is possible, it is likely that the form of distribution resembles a Normal.

### 6.3.2 Load Time

The probability of obtaining a particular range of load time can be developed in a manner similar to payload and is given by Eq(10).

$$P(U_t > t > L_t) = \int_{L_t}^{U_t} f(t) dt \quad (10)$$

where



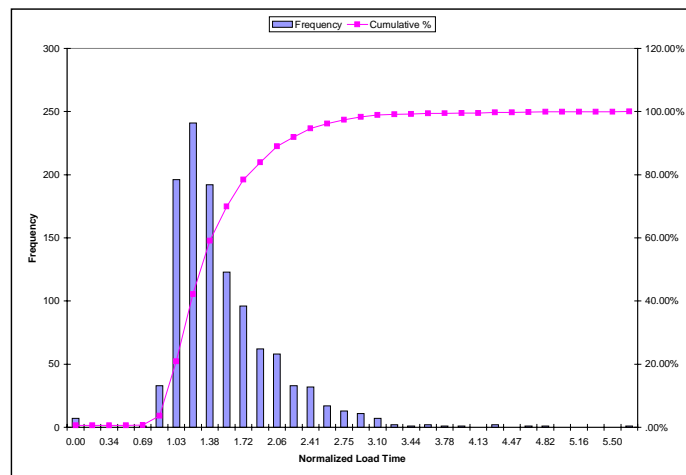
$L_t$  and  $U_t$  are lower and upper limits of the range of load time required,

$t$  is the load time, and

$f(t)$  is the PDF that describes the variance in load time for the entire range.

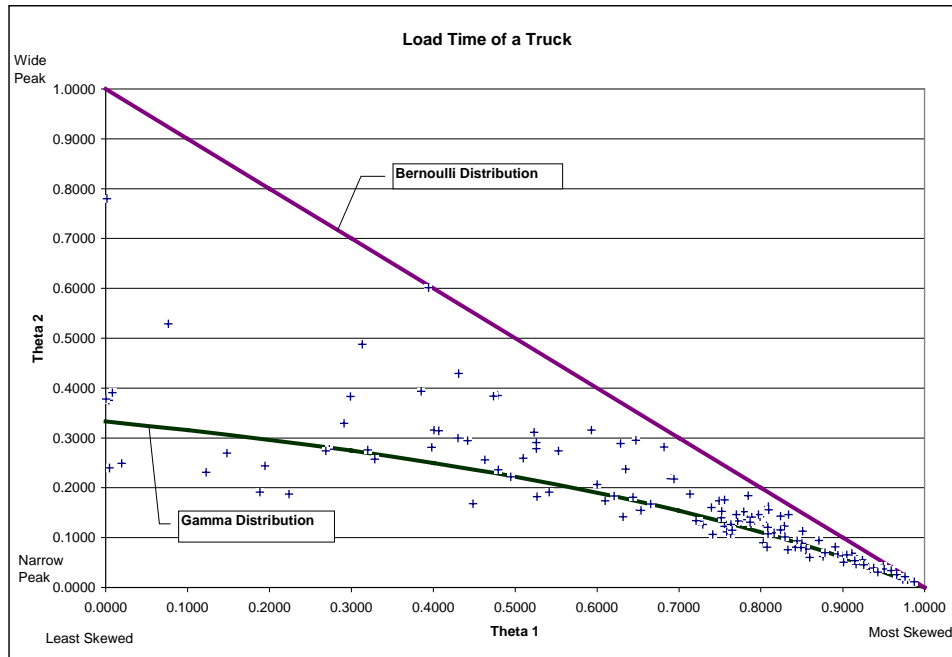
Figure 6-6 presents the graphical form of Eq (10) where in the integral of the PDF is represented by the area enclosed by the cumulative frequency line within the specified limits.

It is again highlighted that since all discrete values of load time are theoretically possible, the variable load time is also treated as a continuous random variable.



**Figure 6-6: Frequency distribution of load time**

AbouRizk and Halpin [1992b] reported that the duration of most construction activities could be modeled as a Beta distribution. The same  $\theta_1$ - $\theta_2$  plane, as used in discussion on payload is adopted for illustrating the type of distribution that can be used for load time.



**Figure 6-7: Distribution to model load time data**

The region enclosed by the Gamma distribution and the Bernoulli distribution describes the Beta distribution. From the field data, it is clear that most instances of the load time of a truck can be modeled by a Beta distribution, confirming to the findings of AbouRizk and Halpin [1992b]. The cluster of data points for values of  $\theta_1 > 0.70$  and for values of  $\theta_2 < 0.20$  suggests the distributions are skewed and have a narrow peak. Unlike payload, the chances of obtaining a shorter load time in comparison to a target load time is much lesser than the chances of obtaining a longer load time. There is a possibility that the tail of the distribution extends towards higher values of load time.

### 6.3.3 Payload and Time

The distributions presented Eq (7) and Eq (10) do not consider the combination effect. The distribution does not give an idea about the chances of obtaining a payload-time pair. A distribution that presents the joint frequency of a payload-time combination may be much more informative about the operation. The combined probability of obtaining a particular range of payload and load time is given by Eq (11).

$$P(U_t > t > L_t, U_p > p > L_p) = \int_{L_t}^{U_t} \int_{L_p}^{U_p} f(t, p) dp dt \quad (11)$$

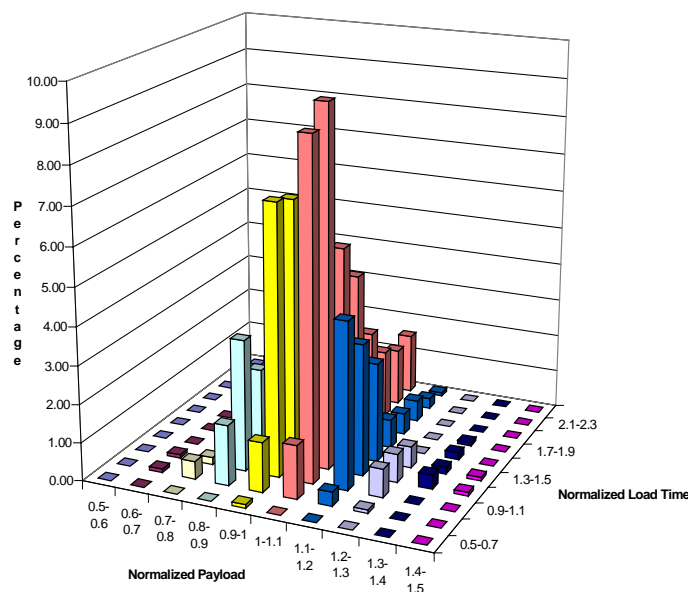


where

$f(t, p)$  is the surface represented by the joint frequency distribution of load time and payload.

It is complex to develop a mathematical form of  $f(t, p)$ . Based on the independence assumption made earlier in this section,  $f(t, p)$  can be obtained by independently sampling  $f(t)$  and  $f(p)$ .

Figure 6-8 shows the graphical form of the joint probability histogram. The normalized payload and load time form the x- and y-axis respectively while the percentage of occurrence with respect to the total number of data points is represented by the height of the bar. The integral of the joint frequency distribution in Eq (11) is represented by the envelope created by the bars.



**Figure 6-8: Joint frequency of payload and load time**

Although Figure 6-8 represents frequency of various payload-time pairs, the mathematical form and the process of fitting a bivariate distribution becomes complex. It is difficult to visualize the variance in payload, load time and the location of the modal region simultaneously. A more powerful form of graphical representation of the data is required. A PLT Map is designed to

depict the joint probability distribution as well as the variance in each variable. A PLT Map is created by extending Figure 6-8 using the concept of contours. A PLT Map clearly illustrates the location of the modal region. The established knowledge that payload can be modeled as a Normal distribution is used to develop the mathematical form of the bivariate distribution in Section 6.5.

## 6.4 PLT MAP

The mathematical form of the data as given in Eq (11) is necessary and sufficient to drive simulation models. However, they do not present an intuitive format to understand and communicate the data. This requires the transformation of data to information by appropriate data visualization techniques.

Converting data to information using graphical representation and visualization techniques is a powerful form of data analysis. Tufte [1983] notes that the way to describe, explore, and summarize a set of numbers is to look at the graphic representation of the numbers. Graphics are a medium to foster reasoning about quantitative information.

The objective in this case is to represent the joint frequency distribution of payload and load time. It is also important to highlight the location of the modal region and any relation between payload and load time, if any. Tufte [1983] suggests the use bivariate frequency plots, which are similar to contour plots.

A PLT Map (Payload- Load Time Map) describes the joint frequency of payload and load time. An example of a PLT Map is shown in Figure 6-9. The abscissa is represented by normalized payload and the ordinate by normalized load time. The contour plot uses color (pattern) to indicate areas with equal probability, the legend for which is shown above the plot. For example, the payload-time pair (1-1.1, 1.1-1.3) occurs with a probability of 9-10%. The payload-time pairs represented by a particular color (pattern) have equal probability of occurrence. The shape or the footprint of the plot, the location of the modal region and the area occupied by each color (pattern) provide interesting insight into the operation.

### 6.4.1 Creating a PLT Map

The data set from onboard instrumentation contains actual payload and actual load time. The payload and load time are normalized based on the rated payload and standard load time for the loader-truck pair.

A grid, in the form of a spreadsheet, is created with payload and time as the respective axes. The width of the grid of the grid is chosen appropriately, in this above example, a width of 0.1 units is used for payload and 0.2 for load time. Each cycle time record is examined and placed in the appropriate cell. There could be a possibility that some payload-time pair falls beyond the boundary of the grid. Such a pair of payload-time is termed as outlier. The boundaries of the grid can be adjusted based on the proportion of the outliers. The count of data points within each cell is normalized based on the total number of points in the data set. The isometric perspective of this grid is the histogram shown in Figure 6-8 and the corresponding plan view is a PLT Map as shown Figure 6-9.

It is not difficult to imagine that a continuous distribution can be constructed for each row or column. For example, Figure 6-10 shows a series of continuous distributions of payload for discrete intervals of load times. Thus, the distribution discussed in Eq (10) can be imagined to be projected view of the ones shown in Figure 6-10.

### 6.4.2 Using the PLT

In order to determine the probability of occurrence of a payload-time pair, the appropriate cross hair is located on the map. The color code corresponding to the cross hair represents the frequency of occurrence of that particular combination. Since the count of data points is normalized, the volume of space enclosed by the map is equal to one. Therefore, the frequency of occurrence directly corresponds to the probability of the payload-time pair.

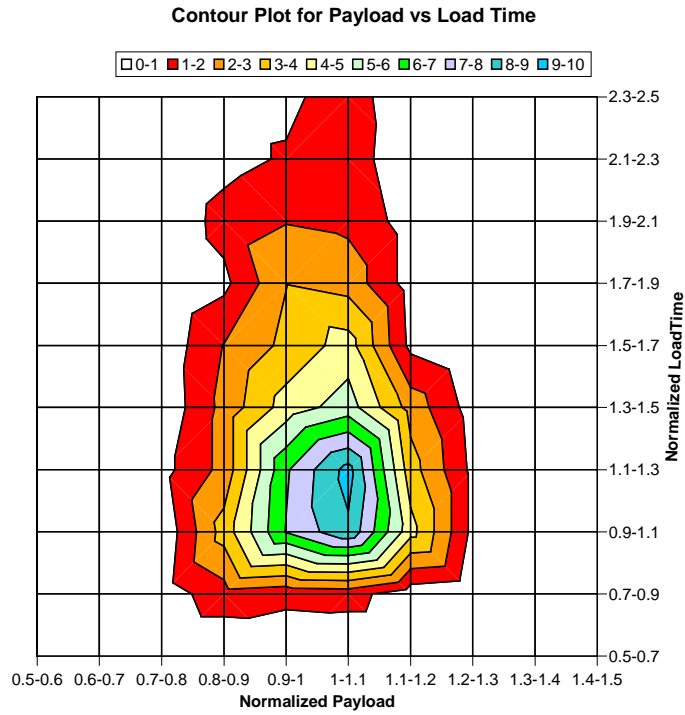


Figure 6-9: An example of a PLT Map

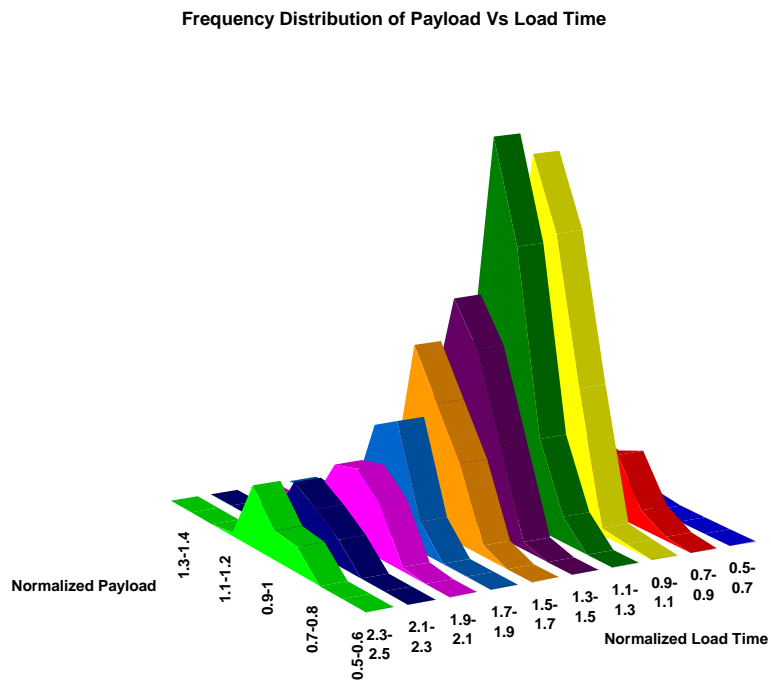


Figure 6-10: Continuous distributions of payload for discrete intervals of load times

The location of the modal region and the shape of the footprint of the plot offers interesting insights. If the modal region has a high frequency, it reflects the consistency with which the loading operation achieves a particular value of payload in a particular time. Since the volume of the surface is equal to one, the product of the area and height of the modal area is an important factor to be recognized.

A general observation is that most PLT Maps have concentric rings with one modal region. This represents an operation wherein a significant number of cycles produce a similar pattern of payload-time pairs. Such a PLT Map is a result of almost uniform operating conditions. However, there is a possibility of multi-modal regions with concentric regions. This reflects at least two different sets of operating conditions during which the data is collected. For example, if the material type for a period consists of both rock and loose earth, there is a possibility that it generates a bimodal region.

## **6.5 VARIATION UNDER DEPENDENCE ASSUMPTION**

The discussion in Section 6.3 assumed that the payload and load time are independent. The significance of the independence assumption is that both payload and load time can be independently sampled from their respective distributions. It is possible to generate a high value for load time and a low value for payload for an instance of the load activity and vice versa. It is possible that a longer load time could generate a higher payload. The most elemental way to determine if a correlation exists is to observe the PLT Map. If the PLT Map has elliptical regions and the ellipses makes an angle with the payload axis, then there exists a relation between payload and load time. This relation is strong if the ellipses make a  $45^\circ$  angle. The discussion in this section makes use of the knowledge of this relation to derive the joint-probability function of payload and time.

The procedure under this assumption follows a two-step process. First, the load time — treated as the independent variable — is modeled as a continuous distribution as described earlier. Based on the observation made using Figure 6-7, it is acceptable to model load time by a Beta distribution as given by Eq (12).

$$P(t) = \text{Beta} [a, b, s_1, s_2] \quad (12)$$

where

$P(t)$  is the PDF describing the load time,

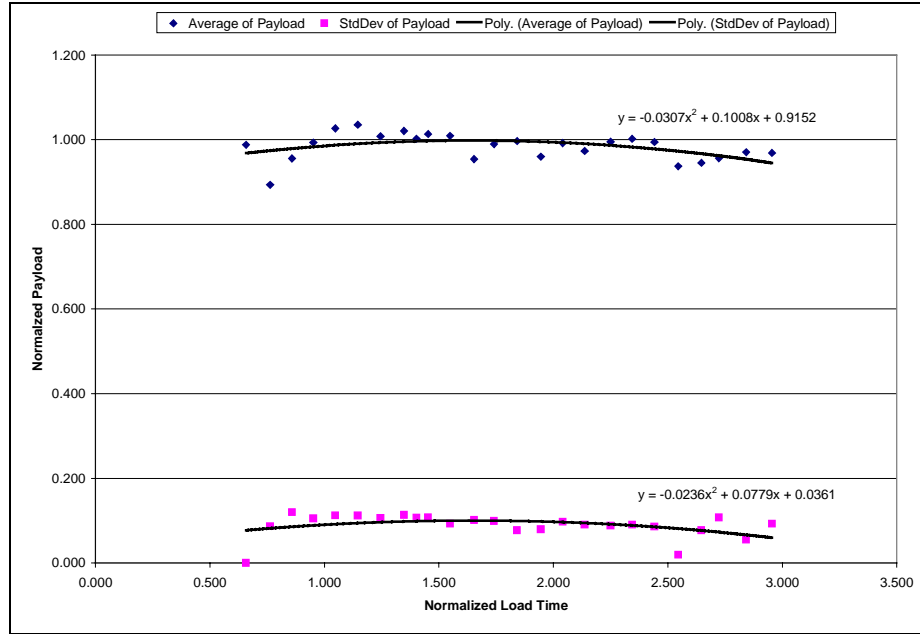
$a$  is the lower bound of the distribution,

$b$  is the higher bound of the distribution,

$s_1$  and  $s_2$  are scale and shape factors respectively of a Beta distribution.

The second step is to parametrically define payload in terms of the load time. Figure 6-5 established that payload could be modeled as a Normal distribution. The intent is to develop equations that describes the mean and standard deviation of payload in terms of load time so that the Normal distribution can be used to generate a payload sample. By creating a simple scatter plot, it is only possible to obtain an expected value (avg. value) of payload. In order to obtain the standard deviation, further manipulation is required.

The equations for mean and standard deviation are developed by constructing a grid of payload and load time in a manner similar to the one explained for the PLT Map. The difference in this construction is that instead of the count of data points in the cell, the mean and standard deviation of payload is computed. The data from the grid is used to generate a graph as shown in Figure 6-11. The average value of load time for an interval, the corresponding average and standard deviation of the payload are plotted.



**Figure 6-11: Parametric form of payload and load time**

This plot reflects the loci of means and standard deviations for the different distribution as shown in Figure 6-10. This graph and the form of equations offer interesting insights that will be discussed in Section 6.7.2. The best-fit equations for mean and standard deviation of payload are shown in Figure 6-11. The next step is to define a Normal distribution with a mean and standard deviation using these best-fit equations. Eq (13) shows the form of the Normal distribution.

$$P(p) = \text{Normal} [-0.0307t^2 + 0.1008t + 0.9152, -0.0236t^2 + 0.0779t + 0.0361] \quad (13)$$

where

$P(p)$  is the PDF that describes the payload,

$t$  is an instant of load time that is generated by the Beta distribution defined in Eq (12).

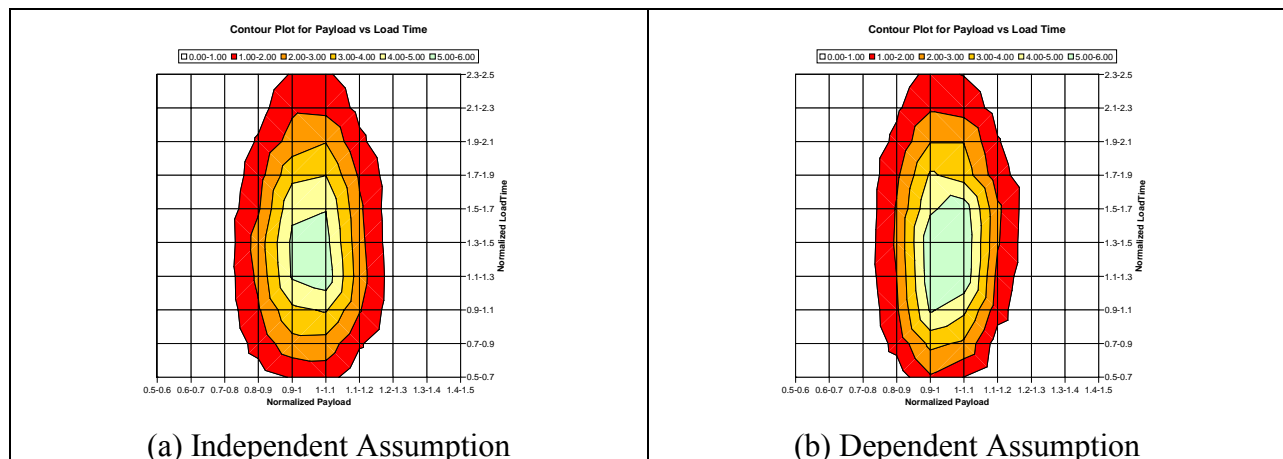
Sampling from Eq (12) and Eq (13) generates a payload-time pair coordinate. The purpose of developing such a parametric form of payload-time relationship is two-folds:

1. Among the various mathematical forms of the joint probability function  $f(t,p)$  in Eq (11), the distribution shown in Eq (13) is the simplest and the easiest to use within a simulation engine.
2. The use of prior knowledge that there exists a correlation between payload and load time and that payload follows a Normal distribution simplifies the approach.

During a simulation run, a pair of time-payload coordinates is generated for modeling each instance of the load activity. PLT Maps created from data simulated using the independent and dependent assumptions are shown in Figure 6-12. In this particular example, there is very little difference between the two PLT Maps.

The more interesting observations relate to the similarities between the PLT Map created using field data as shown in Figure 6-9 and the PLT Maps simulated using the PDFs as shown in Figure 6-12 are:

- a) The range of payload represented by the field data and the simulated data correspond to the same range (0.7 to 1.3).
- b) The modal region for the field data and the modal region for the simulated data fall in the same region.



**Figure 6-12: PLT Maps simulated from the PDFs**

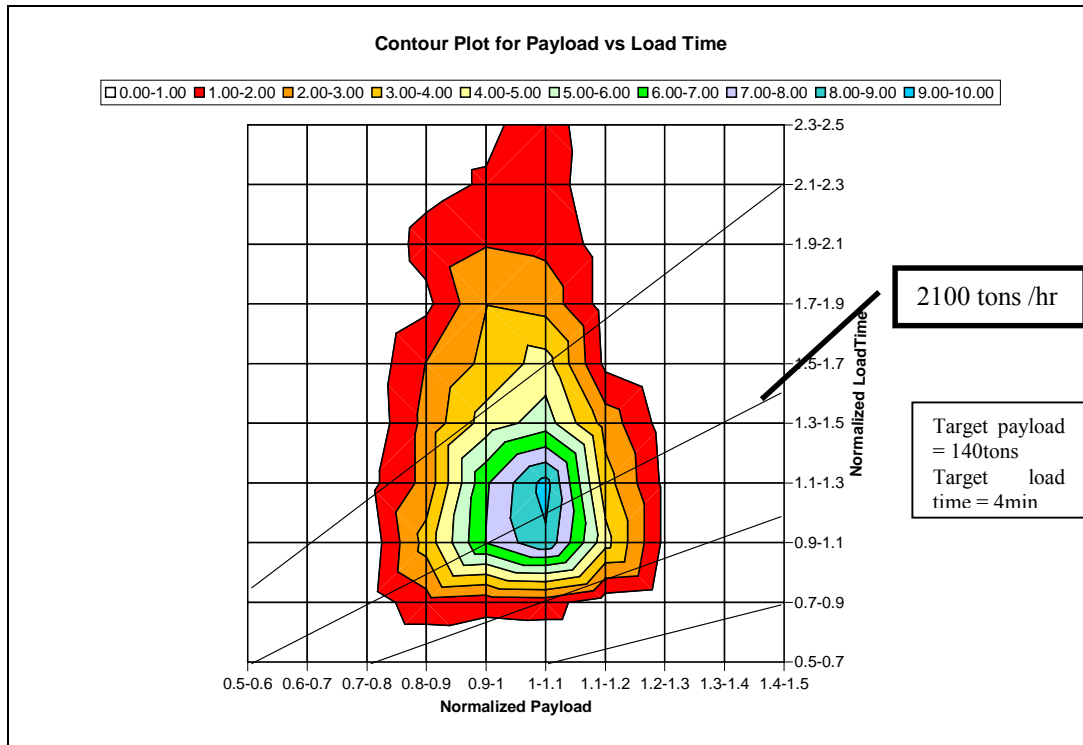
The principal reasons for the differences between the PLT Maps generated from the field data and the ones simulated using a parametric form of payload and time are:

- a) the goodness of fit in describing the load time as a unique Beta distribution,
- b) the regression coefficient for the best fit line for both mean and standard deviation of payload in terms of load time,
- c) the goodness of fit in describing the payload as a Normal distribution, and
- d) the validity of the assumption that a relationship exists between payload and load time.

An important point to note regarding the field data is that the trucks are loaded in integer passes. Schexnayder *et al.* [1999] reported that there appears a good match between volumetric load and full shovel buckets cycles. Such granularity in the data is smoothed out while describing the data using the parametric form. Moreover, a Normal distribution is used for the entire range of payload. It is clear from Figure 6-10 that different distributions can be modeled for each range of load time. Similarly, it is noted that the distribution that describes the load time and the equations that describe the mean and standard deviation will differ between ranges of data. The data can be dissected into as many granular slices as needed by the application. However, the simplicity and the convenience of modeling the field data in a manner described in this section is appealing.

## 6.6 PRODUCTION OF THE LOADING OPERATION

The information presented in [Sections 6.3-6.5](#) focuses on the payload and load time as individual components. This approach is necessary and sufficient for operations analysis using a tool such as simulation. Simulation considers the uncertainties in each activity's duration, resource interaction and external constraints to determine the production of the system as a whole. It is possible to identify if the operation is loader- or truck-critical using simulation. However, in the absence of a tool such as simulation, it is possible to make assumptions such as the loader is critical and hence, compute the production based solely on the loading tool. In such cases, it should be possible to generate the frequency of production achieved by the loading tool.



**Figure 6-13: PLT Map showing iso-production lines**

Figure 6-13 shows a PLT Map with “iso-production” lines, for example, a line indicating a production of 2100 ton / hr is shown. These lines connect payload-load time pairs that generate equal values of production. The probability of achieving a particular value of production is the summation of the probability of payload-load time pairs along the corresponding line. Sweeping the PLT Map for each value of production yields the probability density function of production. However, the PLT Map does not present the variation in production in a direct manner. A histogram of production values is created from the data in a direct manner and is explained below.

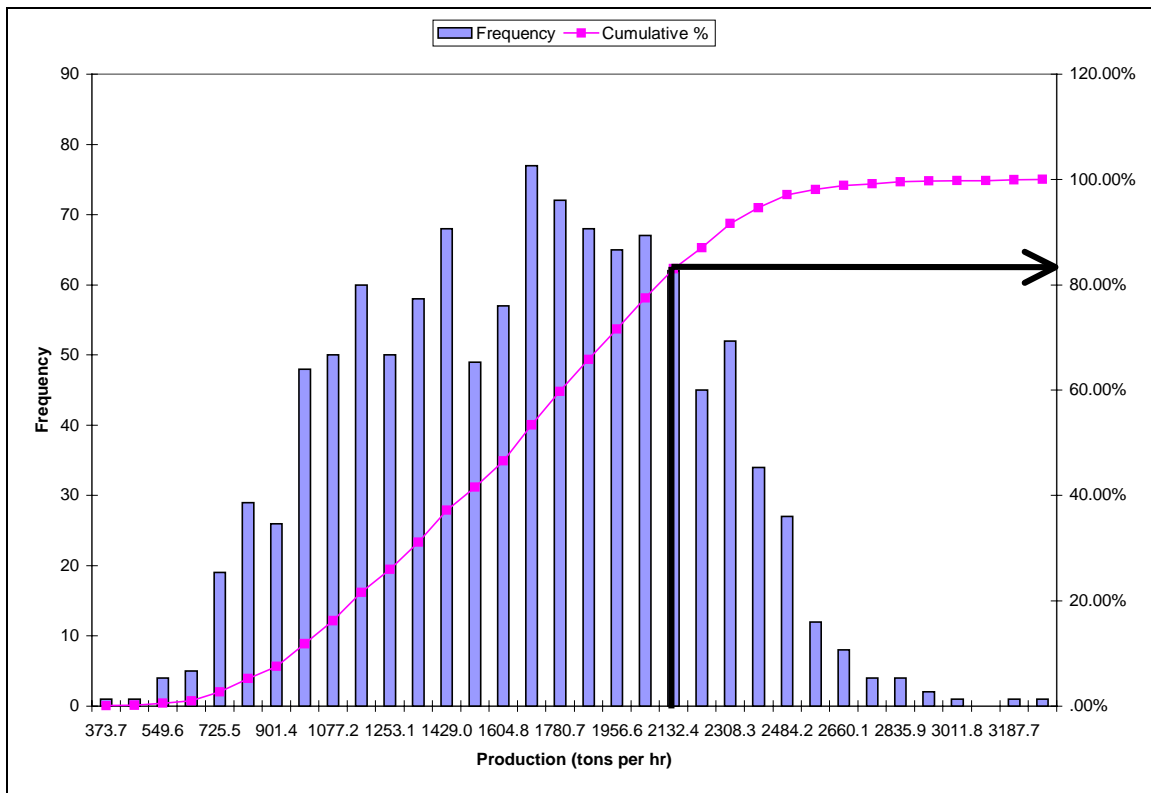
The simplest way to generate the histogram of production values of the loading operation is to generate values of instantaneous production by dividing the payload by load time. It is again emphasized that these instantaneous values of production can be considered as the system production only under the assumption that the loader is critical or the operation is over-trucked. Table 6-1 shows a spreadsheet containing the payload, load time and the corresponding

production values for a loading operation. A histogram of the production values is shown in Figure 6-14.

**Table 6-1: Spreadsheet showing a portion of the onboard instrumentation data and the corresponding values of instantaneous production**

Payload (tons)	Load Time (min)	Production (tons/ hr)
128.3	4.35	1769.7
135.7	3.52	2313.1
135.4	4.32	1880.6
126	4.65	1625.8
133.4	3.43	2333.5
115.2	3.6	1920.0
130.1	4.15	1881.0
127.4	7.75	986.3
136.5	5.32	1539.5
112.6	2.98	2267.1
111.1	3.38	1972.2
118.2	3.43	2067.6
127.6	3.98	1923.6
119.9	3.5	2055.4
128.8	3.78	2044.4
124	4.18	1779.9
124.6	5.28	1415.9

It is clear that the histogram and the cumulative frequency curve can be used to address the probability of obtaining a certain value of production. It can also be used to identify a range of production that corresponds to a particular probability. The production identified in such a manner can be used for estimating future projects when no further information is available which then implicitly drives the assumption that the operation is loader critical.



**Figure 6-14: Frequency distribution of instantaneous production of the loading tool**

An “iso-production” line corresponding to 2100 tons / hr was shown in Figure 6-13. The probability of achieving this production can be computed by integrating the surface of the PLT Map corresponding to the iso-production line of 2100 tons / hr. Since the total volume of the PLT Map is equal to one, the integral by itself denotes the probability of achieving this production. Since the production values are considered as continuous random variable, denoting the probability of a specific value of production may be less meaningful compared to a range or a cumulative value, such production less than or equal to 2100 tons /hr. The region on either side of the iso-production line indicates the probability of obtaining lesser or greater production compared to the one represented by the iso-production line.

Another value of computing this probability of production values is to calculate the instantaneous value by dividing the payload by load time. The histogram shown in Figure 6-14 is generated using the instantaneous values of production. The frequency of occurrence of production equal to 2100 tons / hr is shown by a strong line on the histogram. Projecting this value on the cumulative frequency curve, it is possible to derive the probability of obtaining a particular value

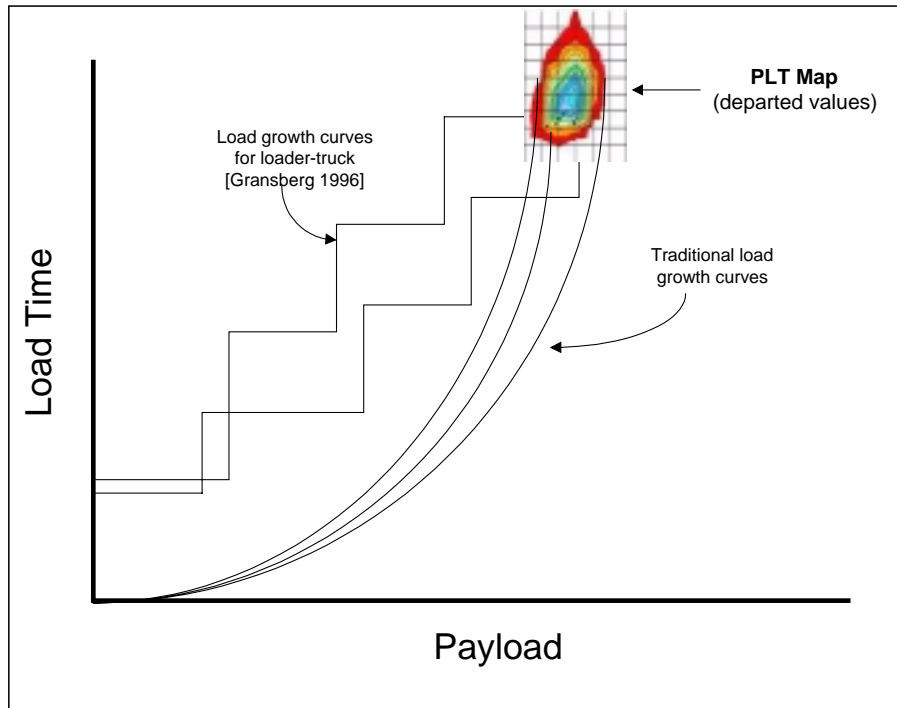
of production. In this example, the probability of obtaining a production of 2100 tons / hr or less is about 82%. In other words, the probability of exceeding a production of 2100 tons / hr is just 18%. This information will assist the estimator in calculating production, duration and cost under the assumption that the loader is critical.

## **6.7 THE ASSUMPTIONS ANALYZED**

This section revisits the premise of correlation between payload and load time with the knowledge of the procedures for modeling input data based on the two assumptions. This inquiry might appear rather trivial based on intuition, which suggests that there should exist a direct correlation between payload and load time. In order to provide insights, the discussion is divided into two sections: a) established knowledge in terms of load-growth curves, and b) analysis of field data and operations.

### **6.7.1 Load-Growth Curves**

Load-growth curves are a graphical representation of relationship between payload and load time [Day and Benjamin 1991]. These curves have been specially used for scraper operations although their scope can be extended to loader-truck system [Gransberg 1996]. The load-growth curve for a loader-truck operation would have step-increments instead of a continuous curve as in the case of the scrapers. Since a PLT Map visually presents the field data, it will be used as the basis for discussion. The principal difference between the load growth curve and the PLT Map is that the load growth curve presents the continuous increment in payload for every additional increment in load time whereas the PLT Map represents just the departed value of payload and load time. Figure 6-15 shows the relation between a load growth curve and a PLT Map. The PLT Map does not consider the payload and time when the truck is partially, say 50 or 75% full or in other words, the “growth” process.



**Figure 6-15: Relation between the load growth curve and a PLT Map**

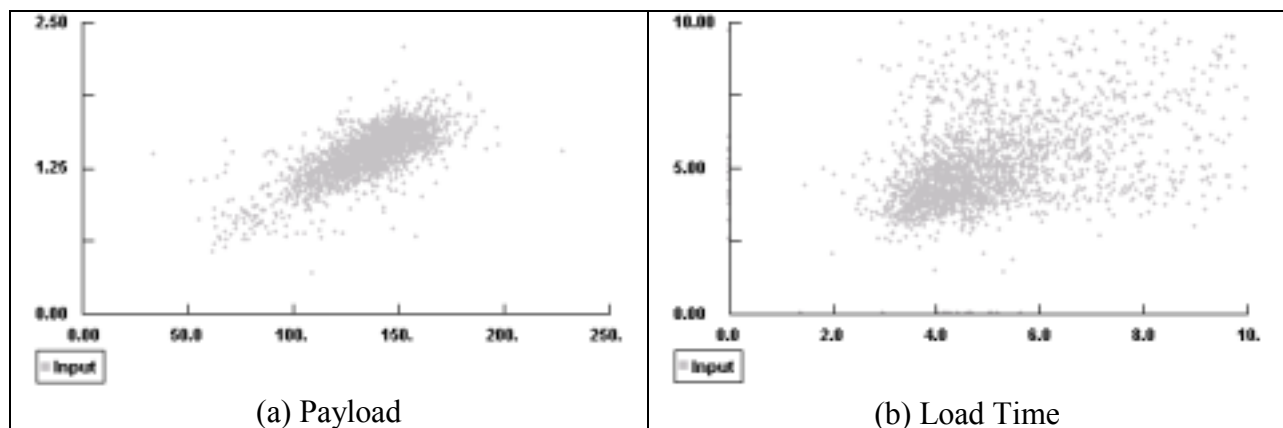
The load growth process clearly shows the correlation between payload and load time, increase in payload with increase in time until the asymptote is reached. However, the correlation of departed values in a PLT Map is not very obvious because each cycle's payload and load time are independent of one another. The payload-load time correlation assumption has to be evaluated on a case by case basis.

### 6.7.2 Field Data and PLT Map

The PLT Maps extends the role of load-growth curves by presenting the variances involved in both payload and load times. If there existed a relationship between payload and load times, a common axis to the concentric contours would make an angle with respect to the abscissa. A very strong relationship would indicate an angle of  $45^\circ$ . Instead, the common axis is nearly perpendicular to the abscissa on most occasions. On further investigation it is found that the principal reason for such a behavior is due to the metric that is recorded — load time of a truck.

Figure 6-16 shows a special form of scatter plot for payload and load time. In this plot, adjacent points in the same sequence of input data are plotted. The scatter plots shown in the figure is a typical representation of data obtained from OBI. It is interesting to observe the plot for payload resembles a line with a slope of  $45^\circ$  while the plot for load time is scattered. The explanation for this observation is as follows.

The load time of a truck is function of the time to load one pass and the number of passes required to fill a truck. Each loader pass is a function of digging time, swing load time, dumping time and swing empty time. Among the four components, only the digging time has a strong correlation with the payload. Since digging time is only a part of each loader cycle, its overall effect is dampened. Payload on each loader pass and the number of passes to load a truck may be dependent events but they are independent for each truck. In other words, the load time of one truck has no bearing on the other and that is why the plot is scattered. On the other hand, payload for each truck is maintained within a narrow range based on the red-green lights and that is why the points resemble a straight line.



**Figure 6-16: A scatter plot of payload and load time**

A very interesting point is the parabolic nature of the payload-time curve as shown in Figure 6-11. It may be counter-intuitive to image how the payload may be lighter on longer load cycles, an observation also made by Schexnayder *et al.* [1999]. The reason for this is that on certain cycles, the loader spends a sufficiently long time in digging and is unable to produce enough payload commensurating with the load time. Therefore, there is a chance that the truck after having spent a long time in the load area is instructed to leave with a lighter load.

The correlation between payload and load time is not directly evident and even if it exists, it may not be a very strong relation such as the one shown by a load-growth curve. A different form of relationship — different set of equations — may be required for smaller ranges of load time. The choice of using the assumption must be evaluated on a case by case basis.

Sections 6.2 discussed the methodology required for predicting load time and payload of future operations based on historical data. Sections 6.3- 6.7 developed performance measures and procedures for predicting the load activity. The following section will use the same performance measures to address the methods improvement of ongoing operations.

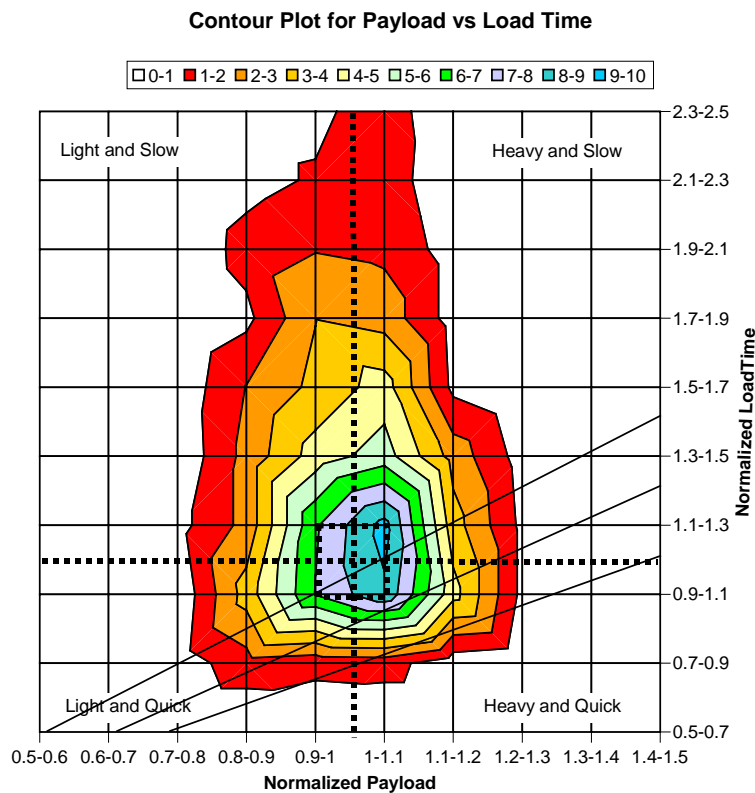
## 6.8 MANAGING THE LOAD ACTIVITY

The PLT Map by itself conveys a lot of information such as variation in the payload and load time, and location of the modal value. Further extraction of information is possible by constructing a box and superimposing it on the PLT Map. A value of payload lesser than the target value is considered as a light payload while a value higher than the target is considered as a heavy payload. Similarly, any load time can be categorized as quick or slow based on the target value. In this example, since two different states are possible for each payload and load time, a four-quadrant box is used for illustration purpose and is shown in Figure 6-17.

The four quadrants are appropriately named, *light and quick*, *light and slow*, *heavy and slow*, and *heavy and quick* based on target payload and load time. Operating in the region marked light and quick, as well as heavy and slow could result in the same productivity. For example, loading 100t in 1min is the same as loading 200t in 2min. The intersection of the two target values is the ideal situation. Trying to achieve the modal region to exactly coincide with the target payload and load time reflects unrealistic expectations. A notion of range would better serve the purpose considering the uncertainties associated with construction. A target window of operation is defined for a range of payload and load time. For example, the window could correspond to  $\pm 10\%$  of the target payload and load time. The target window then defines the goal of the operation. If the job is in its nascent stage and everyone is in the early part of the learning curve, a bigger target window can be defined. The size of the target window can be reduced as the job progresses in time. The target window for an easy operation could be smaller than one that is

difficult. The target window or defining a goal becomes a tool for project management that reflects both reality and reasonability. Goal setting has proven to be a beneficial process in the logging industry [Latham and Baldes 1975].

There are three other lines shown in the Figure 6-17, which represent payload-time pair that corresponds to the same production. For example, if the normalized payload of 0.5 units can be achieved in 0.5 units of time, then 1.4 units of payload can be achieved in 1.4 units of time. The slopes of the lines are dependent on the scale used for payload and load time as well as the target values used. The concept is that one can achieve the same production being light and quick or heavy and slow. It will become evident when field data from different projects are used that some site superintendents constantly vary their operation between the two states in order to keep up with other aspects such as a gradient haul road etc.



**Figure 6-17: Target window on a PLT Map**

Among the four quadrants, the heavy and quick is the one with the highest production. Let it be assumed that current production of the loader is such that the modal region lies in the light and quick quadrant. A directive to the operator to increase the payload and at the same time decrease the load time may be unreasonable. On the other hand, the instructions to the operator could be in two phases — to increase the payload by spending longer time if needed, and then reducing the load time maintaining the consistency in payload. This results in the modal region moving from the light and quick quadrant to heavy and quick quadrant in a practical manner.

## 6.9 SUMMARY

Chapter 5 laid out the overall framework of the experience database. This chapter focussed on the performance measures for the load activity. The methodology for predicting load time and payload was explained with an emphasis on isolating the variance from the reference values. The summarization of field data in the form of PDF described the central tendency as well as the variance. The important objective is to be able to understand the simultaneous variation in payload and load time. The discussion of variation in payload and load time was discussed under the independent and dependent assumptions. Describing the simultaneous variation in payload and load time in the form of joint probability function is complex.

A PLT Map was developed to visually represent the simultaneous variation in payload and load time and any correlation between the two variables. By describing the difference between the load growth curve and the PLT Map, the correlation of payload and load time was analyzed. It is important to note that the onboard instruments record the payload and load time at the time the truck departs the load area. The use of a target window as a project management tool was also illustrated.

The data stream generated by the onboard instruments in the truck contains uncharacterized data. For example, it does not contain information regarding the size of the loading tool, type of loading method, type of material or name of project. It is not possible to derive any useful information from the data unless the conditions under which the data are collected are known. This situation reflects the paradigm “data rich information poor.” Figure 6-18 shows a PLT Map generated from uncharacterized data from the onboard instruments.

Characterization of data is required to derive useful information and hence knowledge from the data. Characterization is the process of associating operating conditions with the performance data collected by the onboard instruments. At the beginning of this chapter, the reader was asked to assume that a homogenous data set was being used in the development of the performance measures. The subset of homogenous data is derived by characterization. The performance measures developed in this chapter will be carried forth to the process of determining a range of operating condition that affect the performance of the load activity. That discussion is presented in [Chapter 9](#).

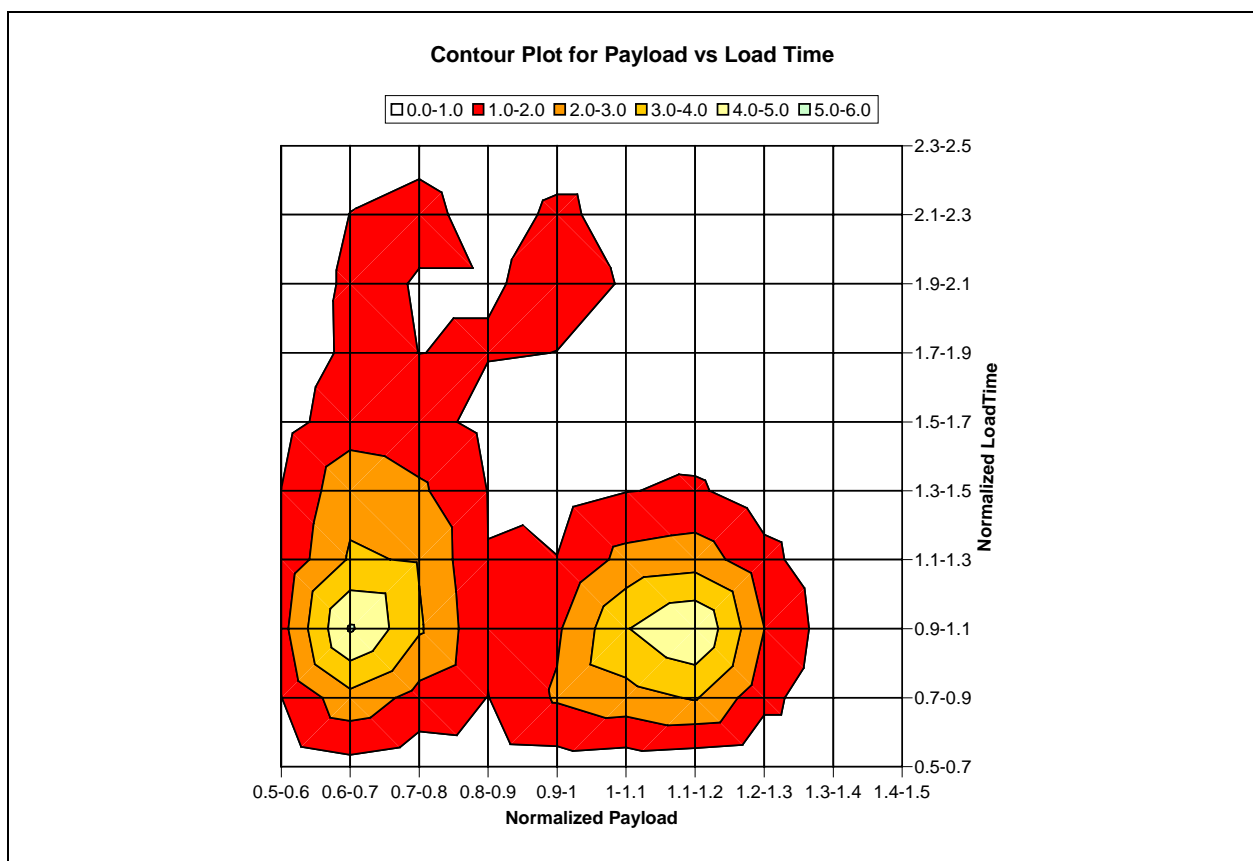


Figure 6-18: PLT Map generated by uncharacterized data

# CHAPTER 7: PERFORMANCE MEASURES FOR THE HAUL & RETURN ACTIVITIES

Chapter 6 developed procedures for the performance measures for the load activity which were presented as concepts in Chapter 5. This chapter will develop procedures for performance measures for the haul and return activities. These performance measures will also be used in defining a range of operating conditions and using statistical tests, determine those which effect the haul and return activities. The discussion on the effect of operating conditions is presented in Chapter 10. This Chapter will address the following:

- haul and return time as defined by onboard instrumentation,
- measures required to predict haul and return activities, and
- measures required to manage haul and return activities.

The descriptor in the case of the load activity was the loader-truck combination. Since there is a finite number of loader-truck combinations, at least within a company, a unique reference value is defined for each combination. However, the descriptors for the haul and return activities include the number of segments, haul and grade for each segment, and the order of segments. Infinite combinations of descriptors are possible. It is not practical to define a reference value to all possible haul roads. The normalization process is therefore more complicated than a simple scaling process used in the load activity. The normalization process has to be efficient enough to be simple and at the same time distill the variance in the operation. Extracting, quantifying and understanding the variance in the operation is the cardinal purpose of this research. The first step in understanding the haul and return activity is to understand the way onboard instruments record the haul and return time.

### 7.1 DEFINITION OF HAUL AND RETURN TIMES

The onboard instrumentation systems used in this research, TPMS<sup>®</sup> and VIMS<sup>®</sup>, record duration of haul and return activity based on certain logic. Figure 7-1 and Figure 7-2 graphically shows the logic involved in recording the haul and return times. The notable feature is that these systems automatically separate the travel time from the idle time, making it convenient to study haul and return time exclusively.

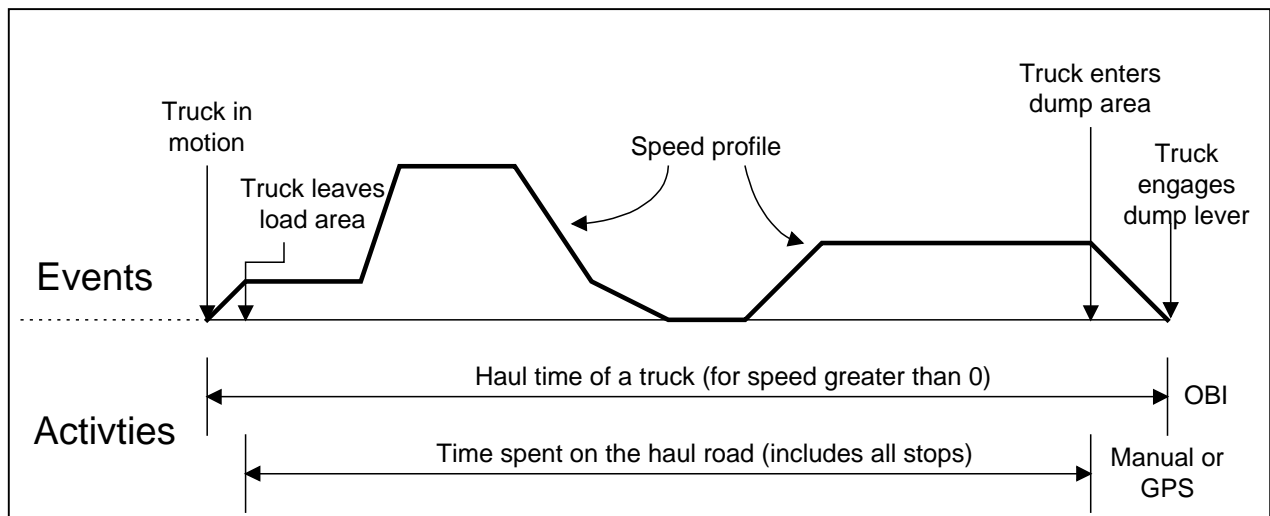


Figure 7-1: Definition of haul time

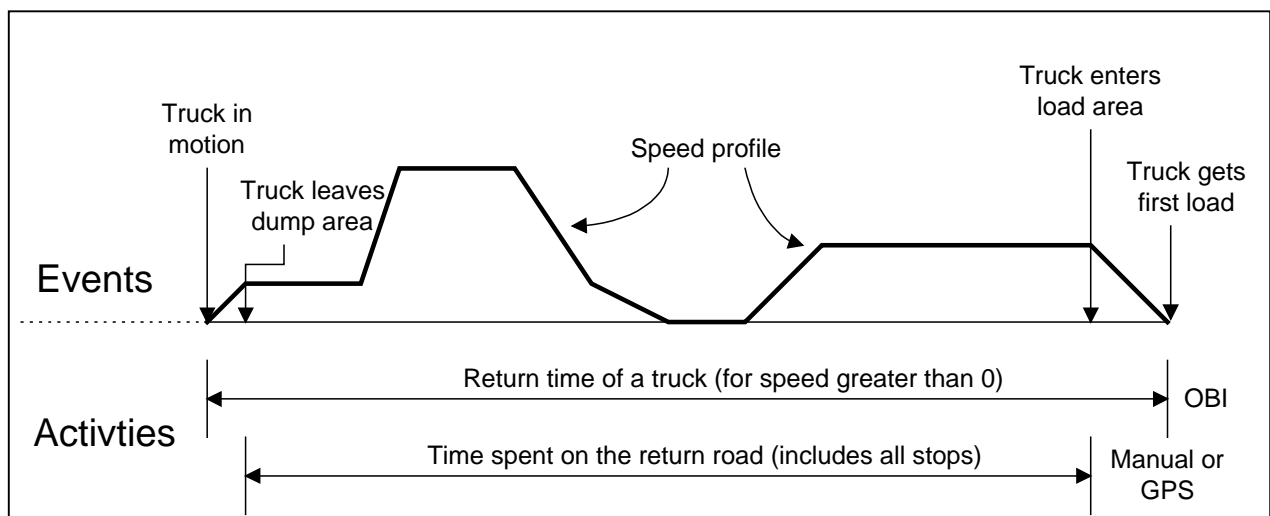


Figure 7-2: Definition of return time

The truck is said to be loading as long as there are discrete increments in the strut pressure. Once the truck is loaded, the transmission is shifted to gear and the parking brakes released. This event triggers the end of the load activity and the beginning of the haul activity. The duration of the haul activity will extend until the dump lever is engaged. The return activity starts as soon as the truck's body is returned to its normal state and ends when the first load is placed on the truck in the load area. The travel time and the wait time, if any, are separated by using speed as the distinguishing factor. The data recorded for the haul and return activities are haul time, haul distance, return time and return distance.

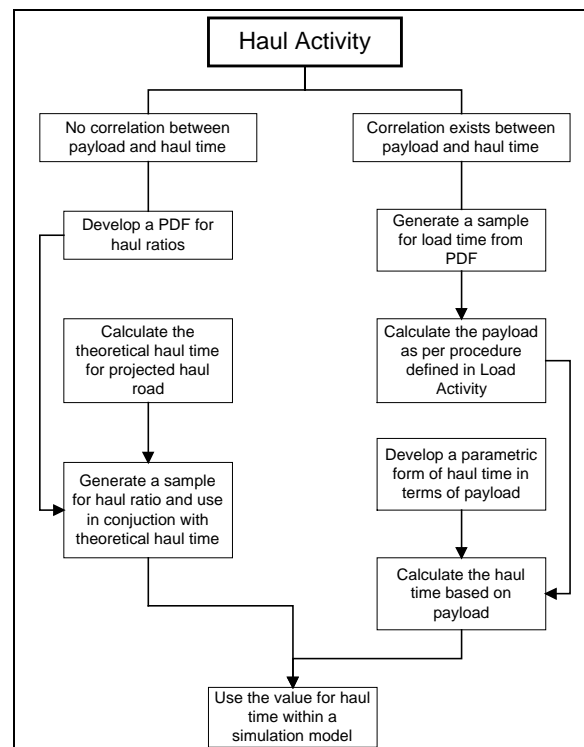
It is worth pointing out the need for and the use of wait time as different from the travel time. Wait time indicates the amount of time the truck actually remains at speed equal to zero. Most of the times this is necessitated by site constraints such as cross-traffic, space constraints etc. The wait times are a function of the operation and external conditions. It is very difficult to anticipate and provide for these conditions from individual equipment's point of view; in fact, it is the system dynamics that determine the role of such conditions and system simulation is a powerful tool to model and evaluate the dynamics of the system. Moreover, in estimating the performance of a unit (travel time of a haul truck), it is not possible to include the effect of the system. Therefore, the need to separate the travel time from the wait time facilitates the comparison of actual travel time (under idealistic conditions) and the corresponding theoretical travel time.

It is clear that not all forms of data are available. For example, the instantaneous values for grade and speed, which could have provided a lot of additional information is not directly available. The aggregate form of haul distance and haul time does not help to pinpoint the location of deficiencies on the haul road. The acceleration and deceleration pattern and gearshifts if available could help determine the location of deficiencies. It is important to point out that some of the newer versions of onboard instrumentation systems do have the capability to record instantaneous speeds and gearshifts. Most of this information is however stored in the buffer and cleared from memory at regular intervals. The development of the procedures required to quantify the variance in haul and return activities is based on the availability of data in the form of haul time, haul distance, return time and return distance.

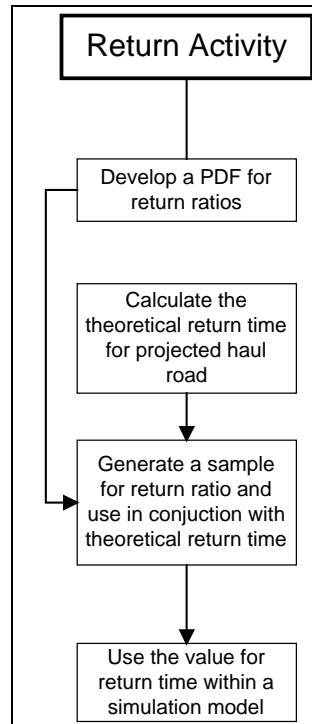
The procedures for developing the performance measures for haul and return activities are shown in Figure 7-3 and Figure 7-4 and explained subsequently.

## 7.2 PREDICTING HAUL AND RETURN TIME

The experience database is assumed to have some data that represents several haul operations. The data in the experience database is grouped into data sets, the meaning of which was explained in the opening section of Chapter 6. The reader is reminded that a data set consists of homogenous data, which can be associated with a particular set of conditions. Associating the cycle time data with site conditions is called characterization and is taken up in detail for the haul and return activities in Chapter 10. In this case, each data set is assumed to have cycle time data regarding one particular haul road.



**Figure 7-3: Procedures for performance measures for haul activity**

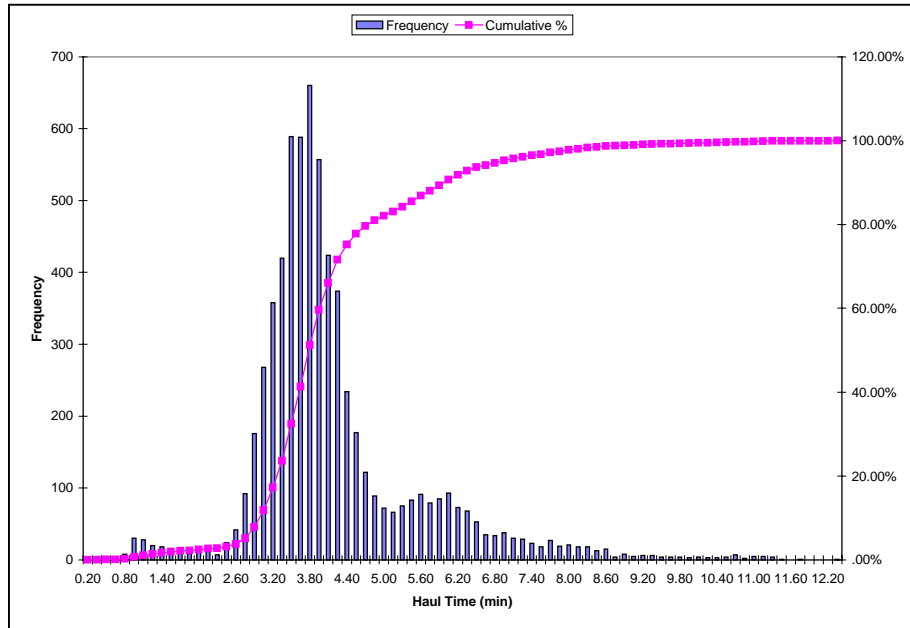


**Figure 7-4: Procedures of performance measures for the return activity**

The simplest way to use the information in a data set to predict the haul and return time of a future operation is to look at the histogram. Figure 7-5 shows a histogram of haul time for a sample data set. The histogram depicts the central tendency and variance of the haul operation. The information rendered by the histogram cannot be directly used to predict the haul or return of another operation because this histogram is unique to one haul road. Some of the difficulties in extending the haul time from one haul road to another are:

- The haul geometry of any two haul roads are not the same. The haul geometry refers to the total length and the difference elevation between the starting and ending point of the haul road.
- If the total length of any two haul roads are the same, the length and grade of each segment may be different. It is possible that in one case the haul is downhill while in the other case it is uphill.

- Even if the length and grade of each segment of two haul roads are the same, the order of segments could be different. The order of segments has an impact on the acceleration, deceleration and coasting capability.



**Figure 7-5: A histogram of haul times from a sample data set**

The only method to extract and quantify variance from haul and return times is to normalize them in a manner similar to the load activity and is given by Eqs (14) to (17)

$$v_h = \frac{H_{ah}}{R_i} \quad (14)$$

$$v_r = \frac{H_{ar}}{R_i} \quad (15)$$

$$E_h = R_j * f(v_h) \quad (16)$$

$$E_r = R_j * f(v_r) \quad (17)$$

where

$v_h$  is the variation of actual haul time for each cycle from the reference value,

$v_r$  is the variation of actual return time for each cycle from the reference value,

$H_{ah}$  is the haul time for each cycle as recorded by the onboard instruments,

$H_{ar}$  is the return time for each cycle as recorded by the onboard instruments,

$R_i, R_j$  are the corresponding reference values for haul and return for the  $i^{\text{th}}$  and  $j^{\text{th}}$  combination of the descriptors,

$E_h$  is the estimate for haul time in a future operation,

$E_r$  is the estimate for return time in a future operation,

$f(v_h)$  is the PDF that describes the variation of the haul time, and

$f(v_r)$  is the PDF that describes the variation of the return time.

The important difference between the normalization process for the load activity and the haul and return activities is that the possible combinations of the descriptors for the load activity is a small set whereas the possible combinations of the descriptors for the haul and return activities are numerous. It is not practical to maintain a reference value for each combination.

### 7.2.1 Reference Value

The reference value is unique to a combination of descriptors that define a haul road. The descriptors for a haul road are the number of segments, the length and grade of each segment and the order of segments. The calculation of the reference value for a set of descriptors is a complex process, which is explained later in Section 7.3. A closer inspection of the definition of the reference value for the haul and return activities suggests that they are the theoretical estimates of the haul and return times for a given haul road. Therefore, Eq (14) and (15) can be re-written as

$$R_h = \frac{H_{ah}}{H_{th}} \Big|_{(n,l,g,r,p)} \quad (18)$$

$$R_r = \frac{H_{ar}}{H_{tr}} \Big|_{(n,l,g,r)} \quad (19)$$

where

$R_h$  is the haul ratio,

$R_r$  is the return ratio,

$H_{ah}$  is the actual haul time for each cycle as recorded by the onboard instruments,

$H_{th}$  is the theoretical estimate for haul time,

$H_{ar}$  is the actual return time for each cycle as recorded by the onboard instruments,

$H_{tr}$  is the theoretical estimate for return time,

$n$  is the number and order of segments in the haul road,

$l, g, r$  are the length, grade and rolling resistance of each segment, and

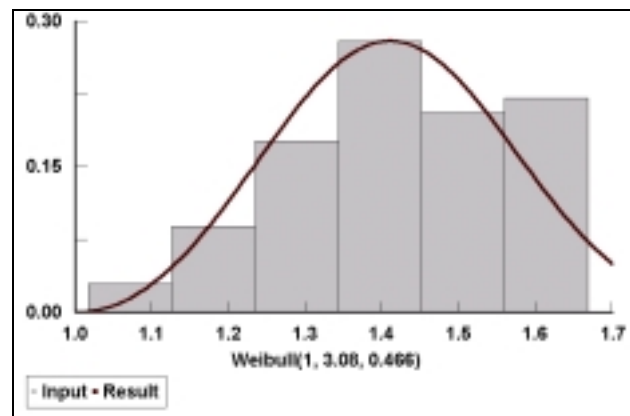
$p$  is the payload on the truck.

The haul and return ratios are calculated by dividing the actual haul and return times by the corresponding theoretical estimate for the same combination of descriptors. The inclusion of the same combination of descriptors facilitates the exclusive extraction and quantification of relative variance in the operation. The important point to be observed is that the reference value or the theoretical estimate is not stored in a library rather calculated dynamically. Note that payload ( $p$ ) is one of the descriptors in Eq (18). Payload is an important factor in the determination of haul time and will be discussed in detail in [Chapter 10](#).

### 7.2.2 Variance

The haul and return ratio is calculated for each cycle in the data set. A histogram of the ratio reflects the relative variance in the operation. A probability distribution function (PDF) can be

described to the ratios, an example of which is shown in Figure 7-6. The estimate for a future operation is defined by product of theoretical estimate of that operation and the PDF of the ratio.



**Figure 7-6: A histogram and a PDF of ratios**

### 7.3 DETERMINING THE THEORETICAL TRAVEL TIME

There are several methods to determine the theoretical haul and return times of a vehicle. They range from simple hand calculations to comprehensive computer program. The intent of this section is to bring out some of the important features of each method and hence their application in the calculation of the ratios as described in Eqs (18) and (19).

Manual computation involves determining the duration required for each segment and then calculating the summation of duration for all segments [Peurifoy *et al* 1996, Day and Benjamin 1991]. The duration for each segment is based on the maximum speed possible on the segment. The maximum speed is a function of the power or throttle position, equivalent grade of the segment and the gross (empty in the case of return) weight of the truck. The maximum speed can be replaced with an average speed through use of factors [Karshenas 1989, Day and Benjamin 1991]. The travel time calculated by this method is not very accurate. Some of the reasons for the inaccuracy are:

- use of factors to convert maximum speed to average speed,
- use of constant speed over the length of the segment,

- use of instantaneous acceleration and deceleration, and
- non-inclusion of coasting and retarding features.

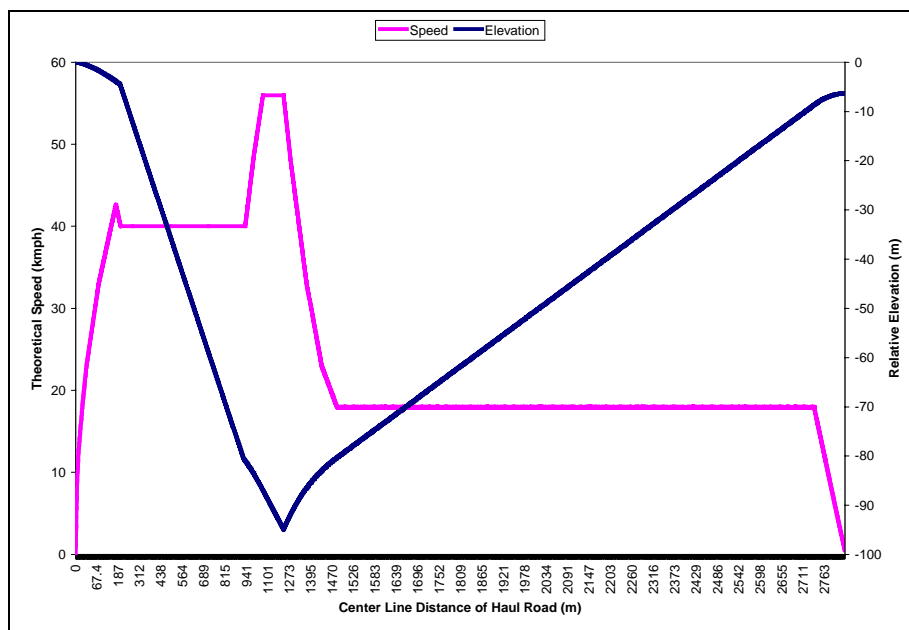
Several commercially available programs can calculate the travel time of a vehicle with a good level of accuracy. Examples of such programs include VehSim<sup>®</sup> [Morgan 1984], Consult<sup>®</sup> [<http://www.vce.volvo.com>] and TALPAC [<http://www.runge.com>]. Some of the programs include intuitive graphical user interface. The input to these programs consists of the length, grade, rolling resistance and the maximum allowable speed on each segment. These programs calculate the duration for each segment and hence, determine the travel time for the entire haul road. The biggest drawback with these programs is that they operate in black box environment. The considerations and assumptions taken into the calculation of the travel time is not made available to the user.

The need to calculate the travel time taking into consideration all the effects explained in this section necessitated the development of a custom-built *Travel Time Calculator*, which can realistically simulate the travel time of a vehicle. The *Travel Time Calculator* is based on numerical integration technique wherein the instantaneous speed is calculated for each time interval. The acceleration is calculated based on the tractive effort available as determined by the rimpull curve. Further details of the travel time calculator are presented in [Appendix A](#). The salient features of the calculator are summarized below.

- The instantaneous speed for each time interval is calculated by the tractive effort available, resistance offered by the weight of the vehicle and the properties of the haul road. Neither uniform speed nor any factors are used in determining the speed of the vehicle.
- The speed at any time interval is calculated based on the speed in the previous segment and the corresponding acceleration calculated using tractive effort. Therefore, there is no question of instantaneous acceleration or deceleration.
- Deceleration is used for coasting on an intermediate segment as well as for bringing the vehicle to a stop on the last segment.

- The velocity profile for the entire length of the haul is available, an example of which is shown in Figure 7-7.
- The gear position at any point in time is also available.

The availability of the routines to calculate various aspects of the calculator also serves another purpose. Payload is mentioned as one of the descriptors in Eq (18). It was shown that the payload in a truck is not constant and varies for each cycle during the development of the PLT Map in Chapter 6. This necessitates the computation of travel time for each cycle using the actual payload and hence the ratio for each cycle. Using a rated payload can save the number of computations but then the variance in ratio developed using Eq (18) will contain some noise due to the difference in payload between the numerator and the denominator.



**Figure 7-7: An example of speed profile as generated by travel time calculator**

This section explained the role of the travel time calculator in developing the haul and return ratios. Once the ratio corresponding to each cycle is determined, a PDF can be used to describe

the variance in ratios as shown in Figure 7-6. The next section will discuss the meaning of the ratios.

#### 7.4 THE RATIOS EXPLAINED

The role of the descriptors in Eq (18) is to provide a common basis in comparing the actual travel time and the theoretical travel time. For example, the same number and order of segments, the same length, grade and rolling resistance of each segment are used in both numerator and denominator. There are several other factors such as surface conditions, obstacles, width of the haul road, which cannot be incorporated in to the calculation of the theoretical travel time. These factors are the cause for variance in the ratios. Therefore, the ratio can be interpreted as the actual haul time relative to the estimated haul time. A ratio higher than one suggests that the actual haul time is greater than the theoretical haul time. The drawback about comparing the travel time for the entire length of the haul is that it conceals the location of inefficiencies in the haul road. Further insights on the ratio can be provided by observing the actual speed to the theoretical speed for every point on the haul road.

Assume that the instantaneous speed for each point on the haul road is available from the onboard instrumentation. Figure 7-8 shows the actual and theoretical speed profile of a hypothetical haul road. The theoretical haul time is calculated based on full-throttle speed. The two profiles would have been the same under idealistic conditions. It is obvious that there are some differences between the actual and theoretical speed of the road. The quantification of the actual speed to theoretical speed can be derived as follows.

$$\theta_i = \frac{S_{ai}}{S_{ti}} \quad (20)$$

$$R_h = \bar{\theta} = \frac{1}{L} \int_0^L \theta_i \quad (21)$$

where

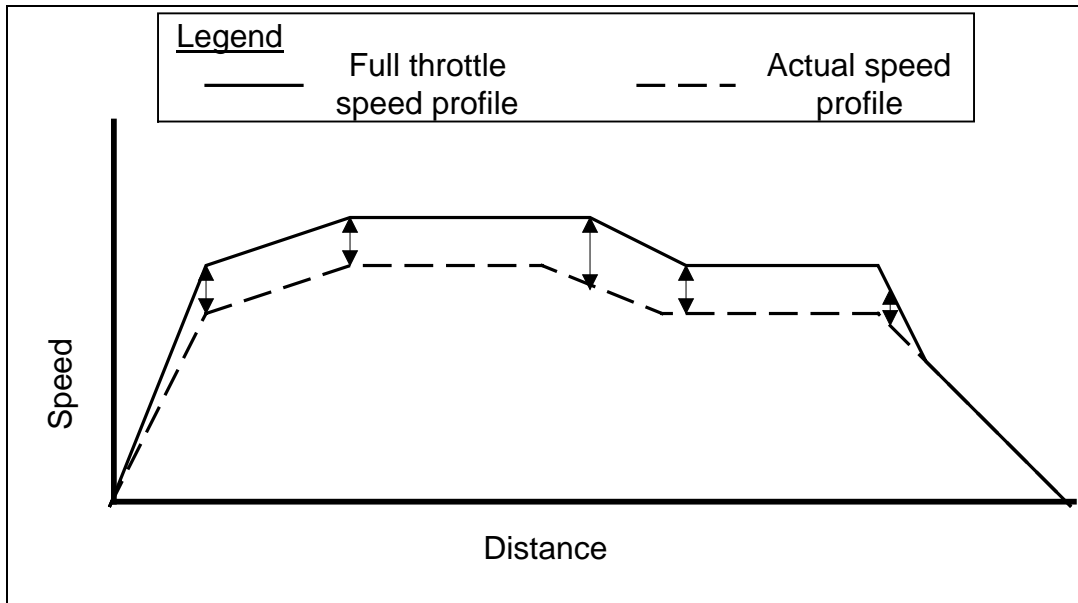
$\theta_i$  is the ratio of actual to theoretical instantaneous speed at the  $i^{\text{th}}$  location on the haul road,

$s_{ai}$  is the actual speed at the  $i^{\text{th}}$  location on the haul road,

$s_{ti}$  is the theoretical speed at the  $i^{\text{th}}$  location on the haul road,

$\bar{\theta}$  is the average value of  $\theta$ , and

$L$  is the total number of discrete locations on the haul road.



**Figure 7-8: Actual and theoretical speed profiles of a haul road**

Calculating  $R_h$  in the form of Eq (21) will provide a realistic estimate of the effect of factors on the variance of travel time. Each value of  $\theta$  will provide an idea of how fast the operator is willing to drive in relation to the maximum speed at that location. Each value of  $\theta$  and the corresponding location on the haul road can be inspected to determine any deficiency in the haul road. The mean and the variance of the ratios will directly point to the effect of factors on travel time. However, the difficulty in using this procedure is the availability of instantaneous speed along each point on the haul road. Until the time such data is available, a modification can be made to Eq (21) so as to use the data which is available from the onboard instrumentation system.

$$\hat{\theta}_h = \frac{H_{ah}}{H_{th}} \quad (22)$$

$$\hat{\theta}_r = \frac{H_{ar}}{H_{tr}} \quad (23)$$

where

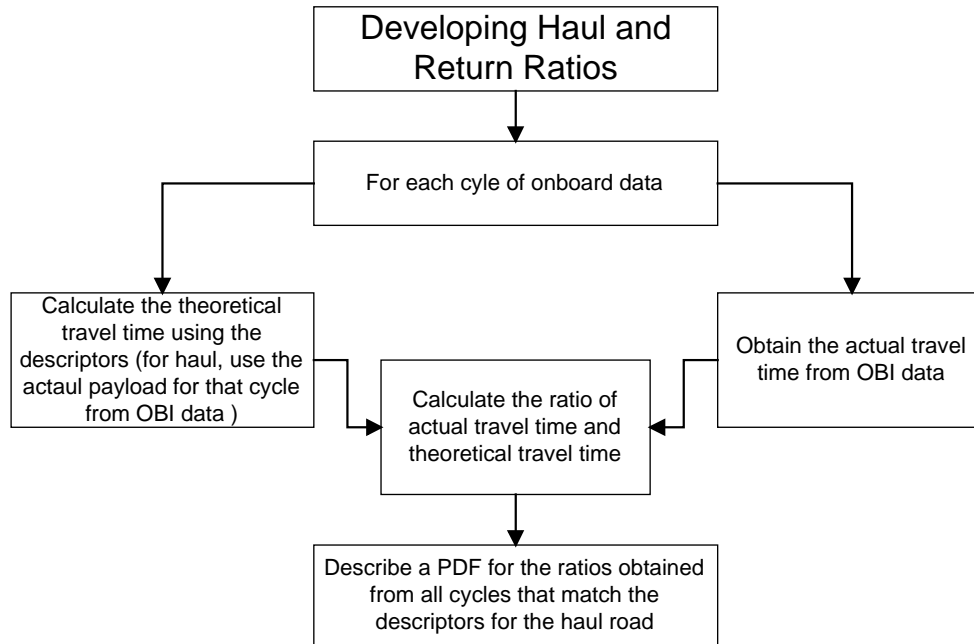
$\hat{\theta}_h$  is the estimator of  $\bar{\theta}$  for haul, and

$\hat{\theta}_r$  is the estimator of  $\bar{\theta}$  for return.

Eq (22) and Eq (23) are exactly the same as Eq (18) and Eq (19). The only form of data available from the onboard instruments that can be used is total travel time for haul and return. The value of  $\hat{\theta}_h$  and  $\hat{\theta}_r$  may point to deficiencies in the haul road but will not be able to locate them. The use of travel time from the onboard instruments nevertheless gives an insight into the variance of the operation. The procedure of developing the PDF of the ratios is summarized in Figure 7-9.

#### 7.4.1 Absolute Value of the Ratios

The absolute value of the ratios is the reflection of the incremental time used by a truck to travel between a source and a destination in comparison to the theoretical travel time between the two points. In the example shown in Figure 7-6 the ratios vary from 1.0 to 1.6 suggesting that the increase in travel time varies from 0 to 60%. The ratios are typically greater than one. The reason for the variance is the effect of operating conditions and possibly, operator training. A small portion of this variation may be attributed to the variance in the estimate for length, grade and rolling resistance of the haul road in calculating the theoretical travel time. The length of the first segment is usually calculated from a center of mass of the load area. Similarly, the length of the last segment is calculated to the center of mass of the dump area. The actual length traversed by the truck could be different from the estimated length. The inflective points in grade are difficult to determine along each point on the haul road. The estimate for rolling resistance, which relies on human judgement, is also very crucial factor in determining the theoretical travel time.



**Figure 7-9: Procedure for developing the PDF of travel time ratios**

#### 7.4.2 Variance of the Ratios

Variance in the ratio is a reflection of the balance in the system. If the likelihood of observing ratios from 1.0 to 1.6 is almost the same, then travel time is being effected more by interaction of other resources rather than the site conditions themselves. A closer observation of the example presented in Figure 7-6 shows that 90% of all ratios lie between 1.3 and 1.6. An over-trucked operation which causes the operators to drive at varying speeds, a slower operator among the fleet, extensive cross-traffic are some of the causes for a high variance in the ratios. A high variance can also be the result of improving or degenerating haul road conditions over time. Envisioning these factors in a future project or anticipating them in the form of expected conditions in a future project may not be very easy. Therefore, care must be taken to understand the reason behind the variance in the current project and hence, its role in estimating a future project.

### 7.5 PARAMETRIC DEFINITION OF HAUL TIME

A parametric definition of haul time is the ability to express haul time in simple algebraic terms of payload. In [Section 6.5](#), the parametric definition of payload in terms of load time illustrated

how a payload-time pair was generated dynamically at run time within a simulation model. In Section 7.2.1, it was briefly pointed out that haul time is a function of payload. Therefore, a parametric definition of haul time in terms of payload will be able to generate a load time-payload- haul time combination at run time. The parametric definition of haul time is useful for two reasons:

1. Every sample of load time can generate a unique value for payload at run time within a simulation model. If there exists a strong correlation between haul time and payload, then it is necessary to calculate the haul time for each instant of payload.
2. Calculating the haul time as described in Section 7.3 within a simulation engine is not straightforward. It also places a burden on the performance of simulation models by significantly increasing the number of computations.

Two other observations are due before the development of the procedure. First, a parametric form of haul time is only valid for a particular haul road. Second, the effect of payload on haul time is different for different haul roads. The role of payload on haul time is discussed in detail in [Chapter 10](#).

The main step in developing the parametric form of haul time is to plot the theoretical haul time of the haul road under consideration as a function of payload as shown in Figure 7-10. This plot is accomplished by repeatedly using the travel time calculator with increasing values of payload. Equations are developed to describe the haul time as a function of payload. In this particular example, the haul times fall into two distinct regions for the range of payload included. A linear relationship can be constructed for each of the regions as shown in Eq (24). The reason behind the data appearing in two distinct regions is the range of gears used. For the lower payload region, there were three downshifts while for the higher region there were only two.

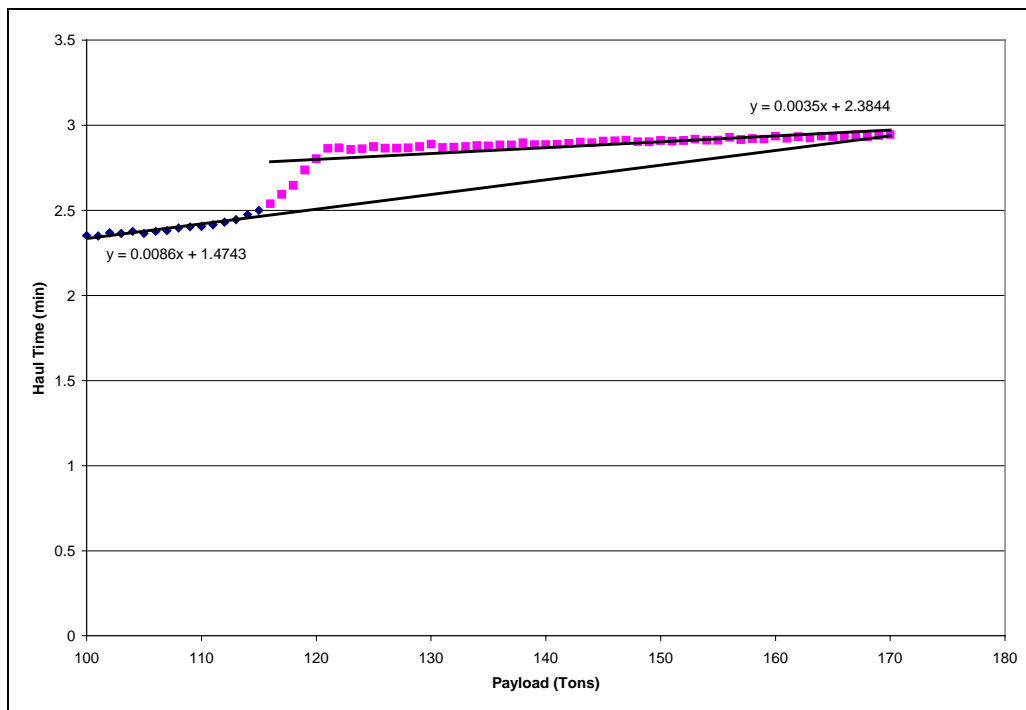
$$H_{th} = \begin{cases} 0.0086p + 1.47 & p < 115 \\ 0.0035p + 2.38 & p > 115 \end{cases} \quad (24)$$

Implementing the parametric form of haul time within a simulation model is a three-step process.

**Step 1:** Generate a sample for load time from the PDF which describes the load time.

**Step 2:** Compute the value of payload based on the sampled load time as described in [Section 6.5](#).

**Step 3:** Compute the value of haul time based on the payload as described in Eq (24).



**Figure 7-10: Parametric definition of haul time in terms of payload**

Use the value of load time and payload for the load activity and haul time for the haul activity within a simulation model. Note that return time is not a function of payload and is sampled independently from a PDF that describes the return time. It is possible to observe that actual haul time observed on the field is seldom a simple function of payload; in fact, it is possible that the haul time is independent of the payload. This observation can be explained by the lack of a controlled experiment. A truck is never going to be less than 75% or 80% full and therefore, the observed haul times correspond to a small range of payload. The noise in the data inherent due to the nature of operation and other factors that effect the haul time causes the haul time to appear independent of payload.

## **7.6 USING PERFORMANCE MEASURES TO MANAGE HAUL AND RETURN TIMES**

Managing an on-going haul operation is primarily the ability to study the effect of operating conditions and improving the performance of the activity. For example, haul times from a particular period of operation is obtained from the onboard instrumentation. The ratio of actual to theoretical haul time is calculated as per the procedures described earlier. A frequency plot of the ratio gives an immediate response to the efficiency of the operation.

The mean and standard deviation are good indicators of the performance. If the mean of the ratios is high, say in the order of 1.5 and above, the data suggests that one or more operating condition is having a detrimental effect on hauling. Conditions such as irregular haul surface, poor visibility, narrow width of the road, and presence of potholes are examples of job conditions that effect the performance. On the other hand, it might be indication that the estimates for length and grade for the haul segments need to be reevaluated.

A larger spread in the ratio suggests some imbalance in the system, such as one slow operator. Since on most construction site passing of trucks is not allowed, there is a possibility that some cycles are slower than the other. The frequency plot provides a simple performance measure to determine the efficiency of the operation.

## **7.7 SUMMARY**

This chapter developed procedures for performance measures for the haul and return activities which were presented as concepts in [Chapter 5](#). Discussions of the descriptors revealed that the normalization process for haul and return activities was an order complex in comparison to the load activity. It is not possible to develop reference values for every possible haul road. Therefore, a dynamic method of calculating the reference value was proposed and explained. The reference value in case of the haul and return activities is the theoretical estimate for the travel time.

The ratio of actual travel time as recorded by the onboard instruments to the theoretical travel time is generated for each cycle. The theoretical travel time is computed by a custom-built travel time calculator. The necessity to develop a custom built calculator was due to the inaccuracies of manual methods and the non-availability of functional details of commercial programs. A PDF is described to the ratios, which then explained the variance in the operation. This relative variance is independent of the effect due to descriptors and is solely a function of the operating conditions. Therefore, this variance can be applied to a future project with similar expected conditions.

A parametric definition of haul time, which describes the haul time in simple algebraic terms of payload, was illustrated. The parametric definition facilitated the computation of haul time within simulation engine, which do not have the built-in services of a travel time calculator. The three-step procedure involves generating a sample for load time, calculating the payload based on the sampled load time and then calculating haul time based on the payload.

Managing on-going operations using the performance measures was also explained. A histogram of ratios from an operation gives an immediate feedback about the efficiency of the operation. A high value for the mean of ratios suggests that one or more job factors have a detrimental effect on the operation. Conditions such as irregular haul surface, poor visibility, narrow width of haul road, and the presence of potholes are some examples of such detrimental factors. A large spread in the ratios suggests that there is some imbalance in the system, typically the result of over-trucked operations or one slow operator.

At the conclusion of this chapter, it is clear that the performance measures are in place for the haul and return activities. A histogram of ratios as shown in Figure 7-6 gives an immediate response about the operation while the mean, variance and higher moments in the ratios can be used to define a PDF. The biggest challenge is to address the operating conditions which govern the variance in the haul and return ratios and hence, the respective PDFs. The process of defining a range of operating conditions and using statistical tests to determine those which affect the performance is the focus of [Chapter 10](#).

# CHAPTER 8: PERFORMANCE MEASURES FOR THE DUMP ACTIVITY

Dump is the fourth elemental process in an earthmoving operation. The load, haul and return activities were discussed in [Chapters 6 & 7](#). This chapter presents a discussion on the dump activity by defining the activity, the format of data required, the methodology to derive information regarding the variance and hence, the use of variance in estimating future projects. Since the onboard systems used in this research, VIMS<sup>®</sup> and TPMS<sup>®</sup>, do not specify the dump time, the discussion on this activity is presented in a qualitative form.

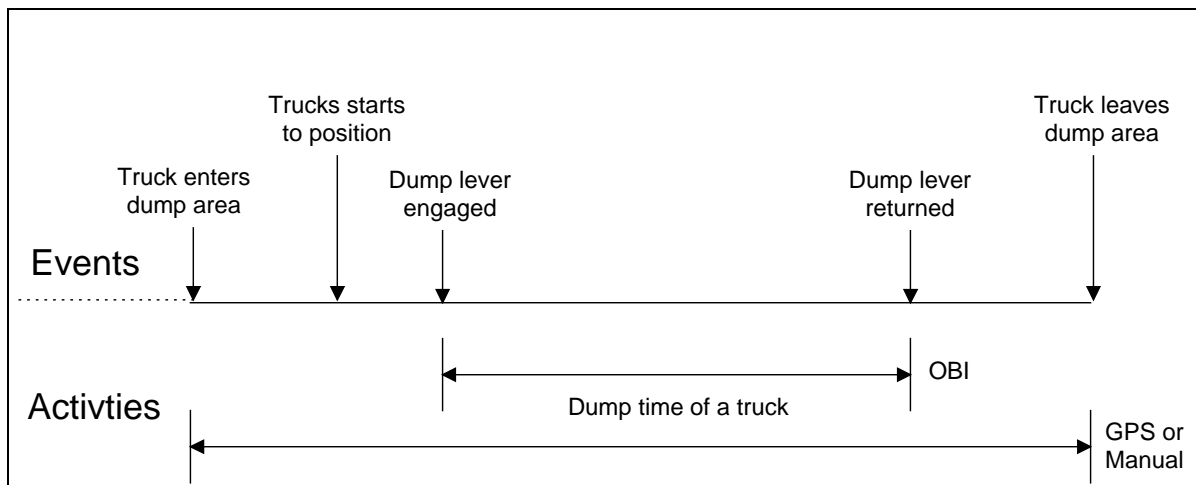
## 8.1 DEFINITION

Haulers can be classified as bottom-dump, forced-dump or rear-dump based on their mechanism to unload their payload as shown in Figure 8-1. The trucks used in this research are rear-dumps and will be the basis of discussion in this chapter. The process of dumping is activated by a dump lever in the cab of the truck, which energizes the cylinders that push the body of the truck into a pivotal motion. The pressure in these cylinders is released as soon as the body of the truck returns to its normal position. While the cylinders are pressurized and the body is in an inclined position, the truck is restricted to move very slowly due to the possibility of damaging stresses on the frame. Some onboard instruments can record these changes in state and hence derive a duration for dumping. VIMS<sup>®</sup> and TPMS<sup>®</sup> however do not specify a duration for dump.



**Figure 8-1: Different types of dump mechanisms in a truck**

Figure 8-2 shows the different events and corresponding activity duration which can be captured using various technologies. The simplest measurement is the duration for which the dump lever is activated. This gives the time for which the bed is raised and hence, the duration of the dump activity. It is clear that a physical sensing mechanism is required to measure the duration for the dump activity. A non-contact mechanism such as GPS will not be able to record the dump activity but only the time spent in the dump area. It is possible that the duration of the dump is included into the state called “waiting loaded.” The logic for ‘waiting loaded’ is that the pressure in the strut is greater than that due to an empty truck and the speed is zero. Since there is a possibility that the truck could also wait on the haul road due to other resource interaction, it is difficult to extract the actual dump time from the waiting loaded time. It is not possible to isolate the dump activity in a direct manner and so, is not included in the actual implementation of this study. This chapter outlines the mechanism that can be used in event that the dump time is available.



**Figure 8-2: Definition of dump time**

## 8.2 PREDICTING DUMP TIME

The duration of dump is a univariate process — is characterized or dependent on one random variable, which is the time to dump. The procedure to derive information on variation in the dump activity is similar to the load activity. The philosophy of using a reference value for normalizing is extended to the dump activity and is shown in Eq (25) and (26).

$$v_d = \frac{t_d}{R_i} \quad (25)$$

$$E_d = R_j * f(v_d) \quad (26)$$

where

$v_d$  is the normalized dump time,

$t_d$ , the actual duration of the dump time as recorded on the field,

$R_i, R_j$ , the reference value for the  $i^{th}$  and  $j^{th}$  combination of descriptors, and

$E_d$ , the estimate for a future project.

### 8.2.1 Estimating the Reference Value

The reference value for the duration of the dump activity for a particular truck can be obtained from the values specified by the equipment manufacturer similar to the discussion presented under the load activity. This duration specified by the manufacturer can be used as the reference value under a standard condition. It is possible that the operators start to move the truck with the bed up in the air so as to create a jerking motion. This jerking motion discharges any material adhering to the body of the truck. Since the bed is up and the pressure in the cylinder is still greater than the normal position, it may be necessary to consider the maximum speed allowed with bed-up to determine the reference value.

### 8.2.2 Estimating the Variance

If the dump time for each cycle is extracted from the data set generated by the onboard instruments and normalized by the reference value as explained by Eq (25), the relative variance can be isolated. The main purpose is to extract, understand and quantify this variance by defining a PDF to the normalized dump time. The PDF is used to replicate the dump time within a simulation model.

### **8.3 MANAGING THE DUMP ACTIVITY**

Often times the dump activity is overlooked when it comes to the analysis of an operation. Loading and hauling activities are always the center of focus in optimizing and improving performance. The dump activity however plays a critical factor in maintaining the balance of the rest of the operation. A histogram of the normalized dump time provides a simple graphical method to determine the performance of the dump activity. The mean and the standard deviation are good measures of the efficiency of the activity. A high value for the mean of the normalized dump time indicates that some factors such as the material or the underfoot condition have an adverse effect on the dump time. A high deviation suggests that the conditions on the site may be constantly changing.

### **8.4 SUMMARY**

This chapter completes the study of performance measures of the different components of an earthmoving operation – load, haul, dump and return. In the discussion on the research framework in Chapter 5, it was pointed out that operating conditions are a very important part of the experience database. Defining the range of operating conditions using statistical tests to determine those which affect the performance is discussed for load, haul & return, and dump activities in [Chapter 9](#), [10](#), and [11](#) respectively.

# CHAPTER 9: DEFINING OPERATING CONDITIONS WHICH AFFECT THE LOAD ACTIVITY

[Chapter 6](#) concluded by presenting a PLT Map of uncharacterized performance data. The purpose of this chapter is to select factors that define the operating conditions and using statistical tests, determine those which affect the performance of the load activity, and hence characterize the PLT Map based on operating conditions.

The conditions on a construction site constantly change making it difficult to extend the cycle time data from ongoing operations to future operations without linking the performance records to the corresponding operating conditions. Therefore, the onboard instrumentation data, by themselves, offer very little information for estimating future projects. In order to convert the data to information and then to knowledge requires the characterization of the data.

Characterization is the process of linking the performance records to the corresponding set of operating conditions. [Chapter 5](#) outlined the reasons for characterization within the framework of this research. This chapter will use the performance measures developed in [Chapter 6](#) as well as statistical procedures discussed in [Chapter 2](#) to evaluate the role of each operating condition. The information on operating conditions was collected using technologies presented in [Chapter 4](#). [Chapter 12](#) will explain in detail the procedures involved in implementing these technologies for this research.

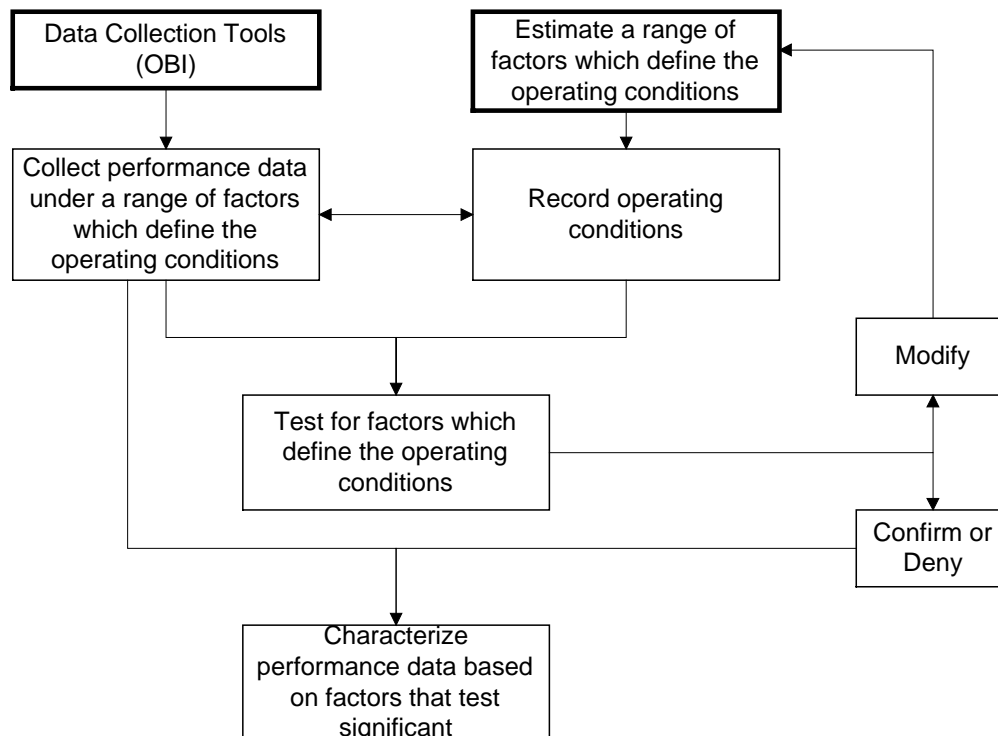
This chapter will address the following:

- selection of factors that define the operating conditions which effect the load activity,
- collection of performance data under these operating conditions, and
- performing statistical tests.

The statistical tests were performed on the performance data collected directly from the onboard instruments. Normalizing the data will conceal the cardinality of the data and make it difficult to draw any conclusion.

## 9.1 METHODOLOGY

The methodology followed for investigating the characterizing factors for the load area is shown in Figure 9-1. The data collection tools for performance data and information on operating conditions were described in Chapters 3 & 4 respectively. A range of factors which define the operating conditions, is estimated for each project — the hypothesis being that the load activity is influenced by these factors. By performing statistical tests on the performance data associated with these factors, the influence of each of the factor is confirmed or denied. The factors that test successfully are used for characterizing the performance data which is later normalized in the experience database.



**Figure 9-1: Methodology for characterizing performance data**

## 9.2 SELECTION OF FACTORS WHICH DEFINE THE OPERATING CONDITIONS

In Figure 9-1, one of the first steps in the methodology is to estimate a range of factors which define the operating conditions. Several sources including standard references in literature, Peurifoy *et al.* [1996], Nichols and Day [1999], O'Brien *et al.* [1996], and Church [1981] state that a shovel production is affected by numerous factors including class of material, height of cut, angle of swing, size of hauling units, operator skill and physical condition of the shovel. The references also note that production of a backhoe is influenced by digging depth, working radius for digging and dumping, dumping height, clearance factors for superstructure and boom, and hoisting capability. In addition, engineers, foremen and operators involved on the projects used in this study were interviewed for their experience. The two notable inclusions to the list of factors are slope of the toe and floor conditions especially when using a wheel loader.

Parker and Oglesby [1972] note that men as well as animals are affected by changes in the solar-day cycle. Since two of the projects on which data was collected had both day and night shift operations and the site management were different on the two shifts, it is possible that shift has an impact on the load activity.

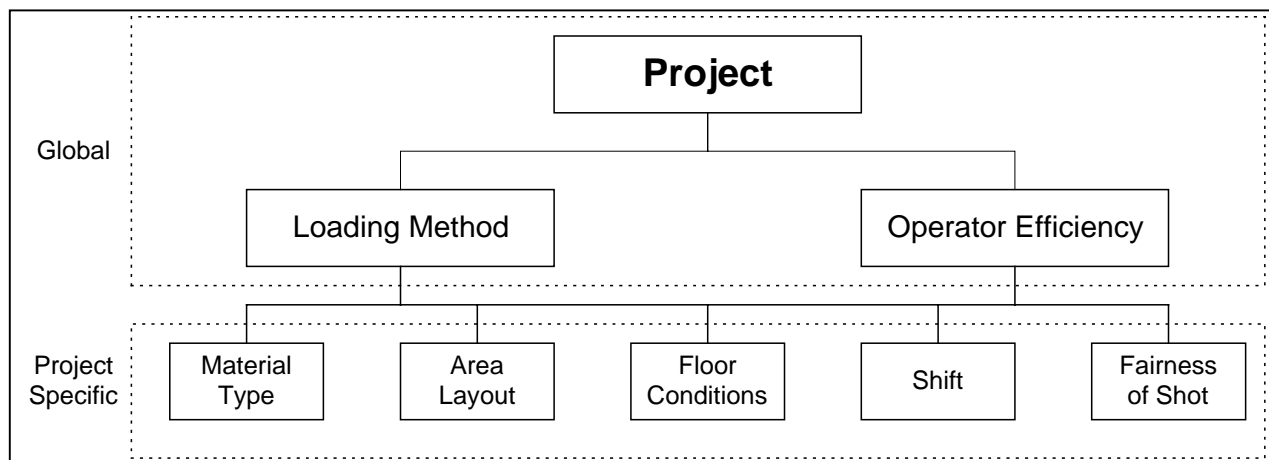
Each factor described above has impact on the payload or load time or both. The data available or collectible plays a big role in determining the factors than can be included in the study. The box in

Figure 9-1 corresponding to 'Collect performance data under range of factors which define the operating conditions' must be accomplished by the technologies explained in [Chapters 3 & 4](#). For example, the swing angle of a shovel or a backhoe impacts the load time of a truck. None of the technologies (onboard instruments or interactive) being used for this research has the capability to record the swing angle for each cycle. Therefore, a list of factors which affect the load activity is developed based on the capabilities of the different technologies — used for collecting performance data and information on operating conditions — as applicable to this research.

It is important to specify the methods by which these factors are recorded — represented by the box ‘record operating conditions’ in

Figure 9-1 before describing the factors that effect the load activity. VIMS<sup>®</sup> records the clock time of the cycle, which can be used to extract information on shift. However, VIMS<sup>®</sup> cannot record most of the subjective information such as material type, swing angle etc. The information regarding the loading tool is also not recorded because the instrumentation is located on the truck. An interactive system such as a paper form and images as explained in Chapter 4 is required to record subjective information.

The factors which define the operating conditions can be grouped into two levels of hierarchy as shown in Figure 9-2. The hierarchical levels are global and project specific factors.



**Figure 9-2: Hierarchical order of factors that influence the load activity**

Project, loading method and operator efficiency occupy a higher order in classifying the factors that can be used to characterize the load activity. These three factors are therefore discussed first in Sections 9.3. Project specific factors such as material, space constraints, are analyzed within the boundaries of the global factors, i.e., within a project and a loading method in Section 9.4.

An influence diagram is presented for each project specific factor, which consists of intermediate response (represented by ellipses) and the outcome of the various responses (represented by

boxes with rounded edges). An analysis of each factor uses both statistical procedures and visual representation.

## 9.3 EVALUATING GLOBAL FACTORS

### 9.3.1 Projects

A project is a function of fleet, material type, management role, and several other factors. The effect of all these factors considered together is the focus of attention in this section.

All data available — in its raw format from the field — from the different projects were pooled together. The null hypothesis tested was if the data from the different projects were homogenous.

Table 9-1 presents the results of the statistical tests on payload and load time. The test statistics for both payload and load time from the four tests indicate that the null hypothesis can be rejected. It is possible that due to a large sample size it is highly likely that the statistical tests will deduct some form of difference in the data and hence reject the null hypothesis. The moments of the data — mean, standard deviation, skewness, and kurtosis — are presented in Table 9-1 to give additional insight. It is clear that the moments of the data as well as the statistical tests support one another's conclusion that the data sets are not homogenous.

It may appear very trivial to compare different projects, with different fleets, different conditions and different management styles. Normalizing the payload and load time with corresponding reference values can be used to bring the data to a common basis. The choice of reference values is not sanctified as they can bias the data in any way. A qualitative analysis can be presented based on the *confounding* effect.

Confounding occurs when it is impossible to run all different factor level combinations under the same operating conditions [Rosenkrantz 1997]. For example, consider the operating conditions in the form of material, the nature of the equipment, experience of the operator and management style. It is not proper to compare the performance of different projects on a level ground since it is not possible to test each project with each level of these conditions. It may be possible to study

the effect of some of these factors within each project. The levels of different factors cannot be held a constant level while studying one parameter.

Based on the results from the statistical tests, it is fair to state that each project is unique. The underlying significance of this statement is that each project is unique. Therefore, defining a single parameter such as an average to the entire data set is meaningless. This is precisely the difficulty raised with respect to the standards, handbooks and performance manuals. It also strengthens the case for the experience database. Operating conditions within a particular project will be compared for the remainder of characterization process. Operating conditions which test significant to all the projects will be used as a basic set of characterizing factors.

**Table 9-1: Results from statistical tests on payload and load time for the different projects**

SI TECODE	Obs	Vari able	Mean	Std Dev	Skewness	Kurtosis
A	21680	LOADTIME	2.4998732	1.6884888	6.7244308	84.1377374
		PAYLOAD	137.6196656	20.0655605	-0.3772942	0.4501778
B	2655	LOADTIME	2.7810358	1.8410527	5.9593752	81.9927235
		PAYLOAD	90.9452655	10.2501938	-0.1697715	0.7552127
C	10409	LOADTIME	4.5051600	2.3386561	2.9724799	26.3952729
		PAYLOAD	106.7792199	31.7400294	0.1242899	-0.7986332

<u>Test</u>	<u>Statistic</u>	<u>Conclusion</u>
ANOVA	Payload Pr > F = 0.0001 Load time Pr > F = 0.0001	The mean payload, load time for the three projects are different
GLM – Levene	Payload Pr > F = 0.0001 Load time Pr > F = 0.0001	The variances in payload and load time for the three projects are different
Kruskal-Wallis	Payload Prob > CHISQ = 0.0001 Load time Prob > CHISQ = 0.0001	The data sets corresponding to payload and load time are not homogenous
Kolmogrov-Smirnov	Payload KSa = 52.8230 Load time KSa = 48.2395	The distributions of the payload and load time data for the three projects are different

### 9.3.2 Loading Methods

Loading method is primarily a function of the loading equipment and to an extent, the physical match of the loader and the truck. This section focuses on studying the effect of the loading equipment on the different sizes of trucks.

The different types of loading methods applicable within the context of this research are front shovel, backhoe and wheel loader. An example of each method is shown in Figure 9-3. The applicability and efficiency of each type is explained in Peurifoy *et al.* [1996]. A loading tool can be classified as stationary – shovel and backhoe, and moveable – wheel loader. The delivery of force for digging and movement may be different in each case.



**Figure 9-3: Different types of loading methods**

Physical geometry refers to the physical match-criteria between the loader and truck. Physical geometry has a significant impact on the loading method. A very important consideration between a loader-truck pair is the reach of the loader. This is not a very big factor in the case of a backhoe because it usually operates from a bench. Geometry plays a vital role in the case of a wheel loader especially during the last few passes when the truck already contains some payload. The impact on the shovel is based on the ability to raise the bucket and bring it centrally over the truck body.

Table 9-2 shows the results of Duncan's multiple range test, an option within GLM, for the different loading methods used in this study. The instructions to read the results are as follows. If the mean payload or the mean load time are not statistically different, they are given the same letter under the column 'Group.' The letters by themselves have no meaning except that they

represent two fleets with the similar means. For example, mean payload for fleet 1 and 2 are not statistically different and so, they are represented by the same letter A. But the mean payload for fleet 3 is statistically different from fleet 2 and fleet 4 and so, is given a different letter, in this case B.

Each fleet is a combination of a loader and a truck. Therefore, fleet 1 is a combination of loader FS1, and truck B. Front shovels are referred to as FS, backhoes as BH, and wheel loaders as WL. Big trucks are referred to as B and small trucks as S. The number used as suffix for the loader indicates the relative size. Therefore, the front shovel FS1 is bigger (in specifications) than the FS2. The front shovel FS1 is the biggest machine among all the equipment used in the study while the backhoe BH2 is the smallest. The backhoe BH1, front shovel FS2 and the wheel loader WL are similar in specification. The fleets 1, 2, 3, and 4 use the same big trucks (B) while 5, 6, 7 and 8 use the same small trucks (S).

**Table 9-2: A multiple range comparison of fleet payload and load time**

Group	Mean	Fleet=(	Truck+	Loader)	Group	Mean	Fleet=(	Truck+	Loader)
A	137.62	1	B	FS1	A	7.455	4	B	BH2
A									
A	136.947	2	B	BH1	B	6.0219	8	S	BH2
B	118.798	3	B	WL	C	5.2762	2	B	BH1
C	103.2	4	B	BH2	C	5.2437	3	B	WL
D	90.945	5	S	FS2	D	3.2384	6	S	WL
E	81.303	6	S	WL	D	3.2048	7	S	BH1
E					D				
E	80.376	7	S	BH1	E	2.781	5	S	FS2
E					E				
E	79.349	8	S	BH2	E	2.4999	1	B	FS1

(a) Payload

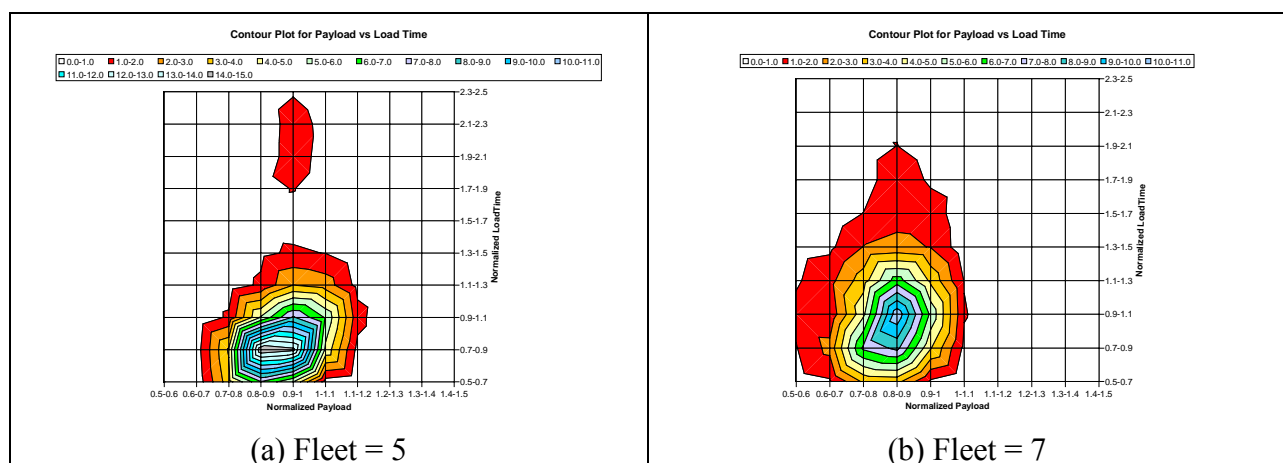
(b) Load Time

It is interesting to note that the payload for the big trucks when loaded by either the shovel (FS1) or the backhoe (BH1) is not significantly different while when loaded by a wheel loader it is

significantly different. The similarity in the payload can be explained by the red-green lights on the trucks while the difference can be explained by the physical geometry. There is significant difference in the load time of the big trucks (B) when loaded by the shovel (FS1) and the backhoe (BH1). There is no difference between the loading methods of backhoe (BH1) and the wheel loader (WL). The reasons can be attributed to the match factor, number of passes and material type.

In the case of the small trucks, only the front shovel (FS2) shows a significant difference in payload. The equivalency in the specification of the loading tool and the match factor play a critical role in the similarity of payload. It is interesting to note that the mean loading time appears to be within limits of one another for the different loading methods. Although the multiple range comparison considers the standard deviation, the values of standard deviation or the variance is not shown as part of the result. PLT Maps are used to highlight the variances in the operations, which may be very important in estimating production of a future operation.

Figure 9-4 presents a comparison of PLT Maps for two different fleets where the loading tools FS2 and BH1 are similar in specification. After having discussed the multiple range comparison based on mean payload and load time, the PLT Maps provide additional insight into the variance of the operation. It is evident that although the variances in payload for the two fleets are similar, there is a conspicuous difference in the variance in the mean time.



**Figure 9-4: A comparison of PLT Maps for two different fleets**

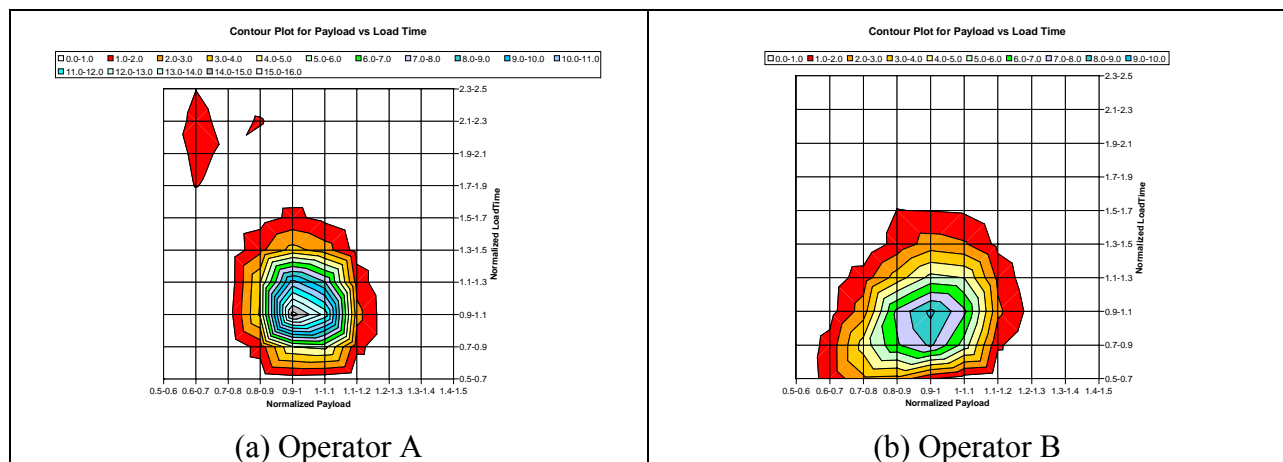
It is emphasized that the onboard instrumentation records load time from within the trucks, which is independent of the loading method. Using the data from the trucks by themselves

without the knowledge of the loading method does not provide sufficient information. In line with the discussion present in Section 9.3.1, the loading method is a significant factor in characterizing the performance.

### 9.3.3 Operator Efficiency

Operator efficiency is a function of the person operating the loading equipment. Since the OBI are located on the truck, extracting the data for a particular loading equipment from the available data is not easy. Hence a qualitative discussion is presented in this section.

The operators of excavation equipment are skillful and well trained since the equipment they operate is heavy, powerful and expensive. Variations are considered an integral part of such repetitive operations. The skill of the operator lies in keeping the variation to the minimum. The operator's efficiency is an integral part of the operation and cannot be measured easily even in discrete levels. Operator efficiency may be used as a characterizing factor only if a particular operator works the same machine every time. It is not considered for characterizing the load activity within the scope of this research. On the other hand, PLT Maps such as the ones shown in Figure 9-5 for two different operators may reveal differences in approach, if any.



**Figure 9-5: A comparison of PLT Maps for two different operators**

## 9.4 EVALUATING PROJECT SPECIFIC FACTORS

This section analyzes the factors such as material type, area layout, floor conditions and shift within the boundaries of a project and a loading method. A closer inspection of the experimental design requires data from all factors under each category. For example, data on all types of materials must be available for each project under all loading methods. Therefore, the analysis is performed on the data which is available.

### 9.4.1 Material

This section focuses on the material that is excavated and loaded on the truck. Every performance record is linked to the type of material loaded on the truck. The procedure for linking these two forms of information is described in [Chapter 12](#).

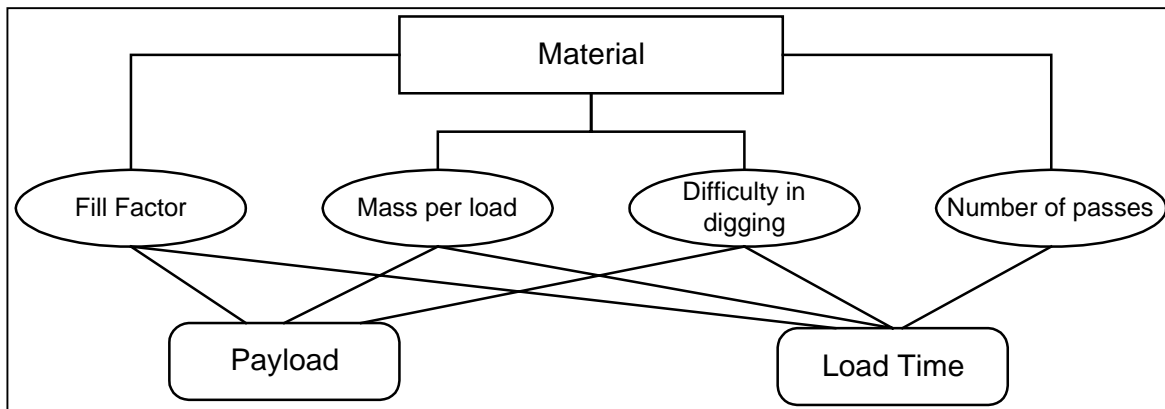
The bulk movement of material is the principal objective of the earthmoving operations. Removing the material from its bank state is measured by the payload on the truck and the time taken to load the truck.

Caterpillar [Caterpillar 1997] and Volvo [Volvo 1995] present a list of material and their corresponding densities. In recording this parameter, it is difficult to keep track of all kinds of material. There is room for honest difference of opinion about whether a formation is hard or soft, and conditions are average, poor or ideal [Nicholas and Day 1999]. Therefore, a hierarchical classification and measurement approach is constituted as shown in Table 9-3. The hypothesis is that material is one of the operating conditions which affects the performance of the load activity.

The influence diagram for material is presented in Figure 9-6. The material type has an impact on the fill factor, mass per load, the difficulty involved in digging and the number of passes needed to load the truck. These in turn effect the payload or the load time or both as shown in the figure.

**Table 9-3: Classification of material**

Classification	Type of Material
Easy digging	Unpacked earth – common earth
Medium digging	Packed earth – earth mixed with some rock
Hard digging	Shot rock and tough soil with soft rock
Tough digging	Sandstone, shale, limestone

**Figure 9-6: Influence diagram for material***Fill Factor*

The rated heaped capacity of a loader bucket is the net volume of earth that be contained in the bucket [Peurifoy *et al.* 1996]. This capacity has to be corrected for an average bucket payload based on the characteristics of the material. Fill factors are used to make such corrections. Well-blasted rock and granular material can fill a bucket more than big pieces of boulders. The voids in the bucket can lead to a lower payload. Experience suggests that the fill factor has an equal impact on the payload and the load time.

*Mass per load*

Mass per loader pass refers to the mass of the material that can be carried in a loader bucket. The mass of the material is directly related to the density of the material for a given volume of a bucket. Therefore, a light material such as light sand or loam may fill the bucket but then weigh lesser than equal amount of rock. A lighter mass of material carried in a loader bucket may necessitate additional passes, which in turn effects the load time. The density of the material also plays a big role in the value of payload on the truck as well.

*Difficulty in digging*

The difficulty in digging is related to both the material and the type of the loading tool. For a stationary unit such as a shovel or a backhoe, there are four components that make up the time for a loader pass: digging time, swing loaded time, dump time and swing empty time. The swing times are replaced by movement times for a moving unit. The digging time is dependent on the material in the bank state (or stockpile) in both the cases. The swing and dump times can be considered as fixed part of the loader cycle. The relation between payload and load time, if it exists, is due to the digging time component. The difference between a full bucket and a partial bucket is only the time saved in digging the material, which is just a fraction of the load time of a truck. This is precisely the phenomenon reported by Schexnayder *et al.* [1999] where the optimal load time corresponds to payload due to integral number of loader passes. However, it is not possible to measure the time per loader pass for every cycle with the current technologies. The calculation of time per loader pass from the load time of a truck is not straightforward since the number of passes is a random variable.

*Number of Passes*

The number of passes is a function of material, fill factor and the match between the truck capacity and loader bucket capacity. According to Nicholas and Day [1999],

*“It is a good practice, although not always essential, to match the size of the loading and hauling units. If large shovels are used with small trucks, time is wasted centering the bucket and material will be spilled off the sides.”*

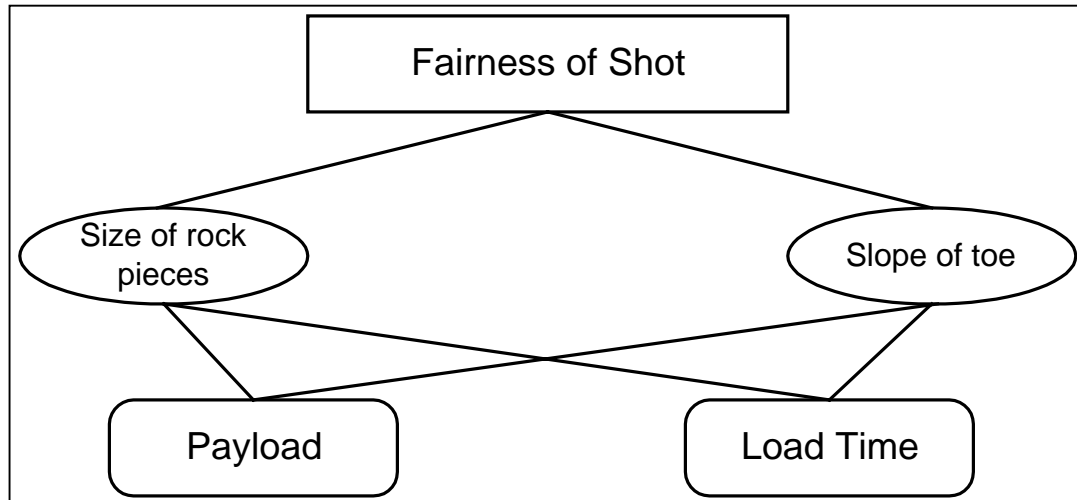
The cohesiveness and the granularity of the material effect the amount of material that can be loaded into a bucket. This in turn impacts the number of passes the loader has to make to fill the truck. Well-shot rock may fill a bucket more completely than poorly-shot rock which may necessitate additional loader passes to make up for voids.

#### *Fairness of shot*

Fairness of shot influences the difficulty of digging when the material type is rock and is discussed here because of its impact on the load activity. The influence diagram for fairness of shot is shown in Figure 9-7. The fairness of a shot depends on the spacing of the holes, diameter of the holes and amount of powder used in the shot. The effect of a shot can be measured by the size of the rock pieces and slope of the toe. Big boulders produce big loads; however, the time to pick up the boulder and the amount of voids in the loader bucket may necessitate additional passes. The slope of the toe is a very important factor for the wheel loader. Since the wheel loader achieves its digging force by the crowding action, a sloping toe could prove detrimental. It is difficult to imagine the fairness of a shot to be used as characterizing factor in planning future projects. Instead, it serves the role of a metric to evaluate a shot in an indirect manner.

Among the three projects used in this study, Project B had only one type of material. The statistical tests for the characterizing factor material is restricted to the other two projects. A complete multiple range analysis is performed on the data from Project C since it was the only project with more than one loading method.

Prior to presenting the results on material, it must be pointed out that category of material was associated with each cycle. The procedure for implementing this process is explained in [Section 12.2.1](#).



**Figure 9-7: Influence diagram for fairness of shot**

Results from statistical tests are presented in Table 9-4 and corresponding PLT Maps are presented in Figure 9-8 for Project A. A summary of the observation is as follows:

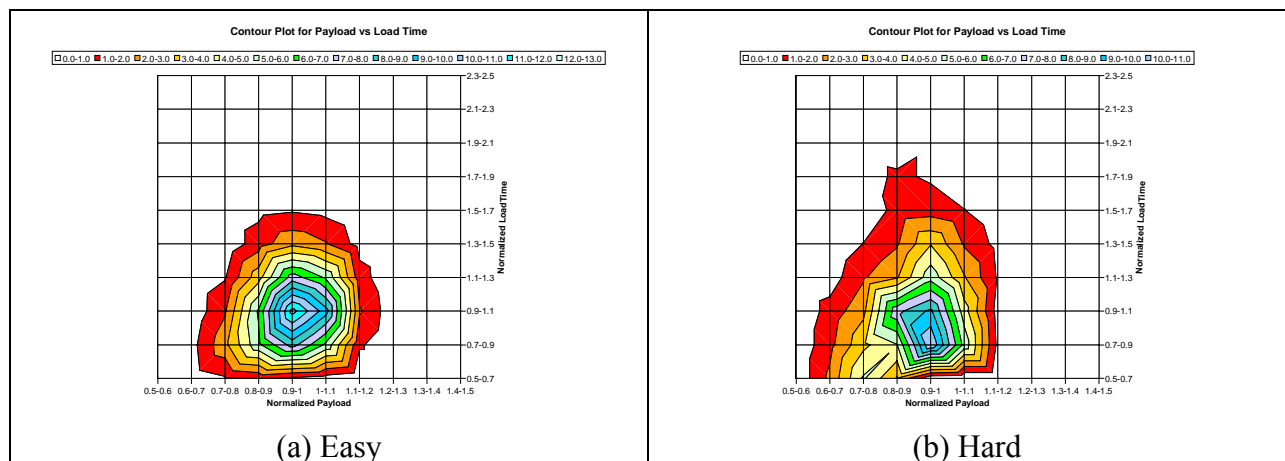
- Project A shows some form of homogeneity in payload and load time. Although some of the statistical tests reject the null hypothesis, an inspection of the moments of the data provides a domain-specific outlook. The statistics reveal that the payload and load times are within practical limits; for example, a range of 6t in payload is almost practically indiscernible. The consistency in payload is supported by the use of red-green lights as visual indicators. The consistency in load time may be the resultant of different factors such as operator efficiency and management style. However, the KS test suggests that the same PDF model cannot be used for the different types of material for payload and load time.

**Table 9-4: Results of statistical tests on Project A for characterizing factor- Material**

MATERIAL	N Obs	Vari able	Label	Mean	Std Dev	Skewness	Kurtosi s
Easy	4518	LOADTIME	LOADTIME	2.3197676	0.8307493	1.8076860	2.9496630
		PAYLOAD	PAYLOAD	136.7252036	17.6696193	-0.9016324	0.5521404
Medi um	218	LOADTIME	LOADTIME	2.1839908	0.4864582	1.4739869	3.2344611
		PAYLOAD	PAYLOAD	130.5604128	15.9948186	-0.0805430	-0.3696189
Hard	498	LOADTIME	LOADTIME	2.2390361	0.6818249	1.5685579	2.7758712
		PAYLOAD	PAYLOAD	135.0649799	16.1421200	-0.6947603	0.2339209

<u>Test</u>	<u>Statistic</u>	<u>Conclusion</u>
ANOVA	Payload Prob > F = 0.0001 Load time Prob > F = 0.0077	Mean payload for materials are different Mean load time for materials are different
GLM-Levene	Payload Prob > F = 0.0216 Load time Prob > F = 0.0001	Variation in payload are not different Variation in load time are different
Kruskal-Wallis	Payload Prob > CHISQ = 0.0001 Load time Prob > CHISQ = 0.5014	Payload data sets are not homogenous Load time data sets are homogenous
Kolmogrov-Smirnov	Payload KSa = 3.59715 Load time KSa = 1.59203	There are differences in the payload and load time distribution for different materials



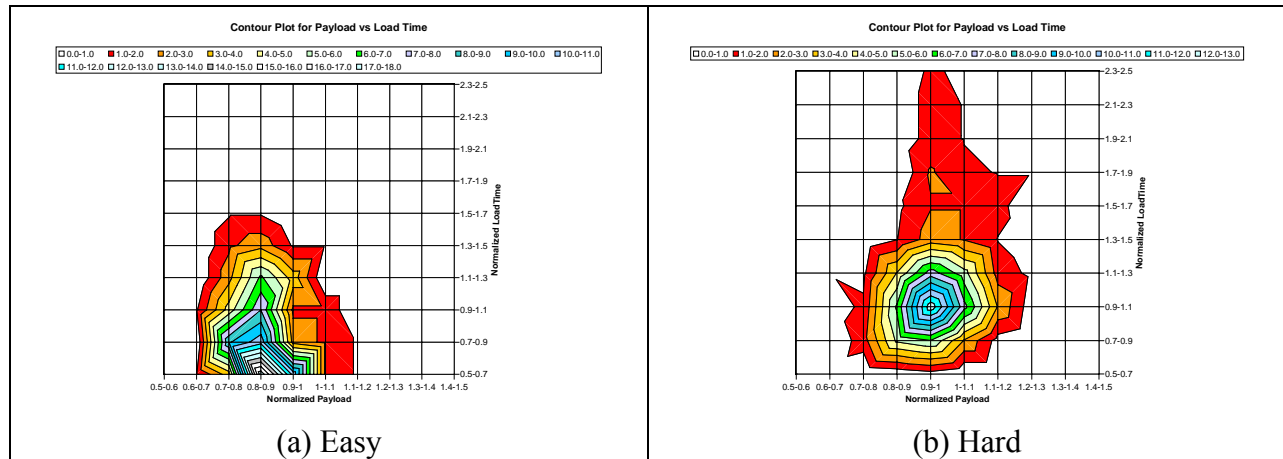
**Figure 9-8: A comparison of PLT Maps for different types of material on Project A**

**Table 9-5: Results of statistical tests on Project C for characterizing factor- Material**

MATERIAL	N Obs	Vari able	Label	Mean	Std Dev	Skewness	Kurtosis
Easy	129	LOADTIME	LOADTIME	2.5783721	0.5647148	1.6740549	3.9447121
		PAYLOAD	PAYLOAD	72.2054264	9.2277123	0.5399205	0.3991695
Medium	1245	LOADTIME	LOADTIME	3.8000321	1.6173657	0.8992798	-0.0818900
		PAYLOAD	PAYLOAD	88.5388755	24.7810616	0.7103744	0.8669285
Hard	4932	LOADTIME	LOADTIME	4.4561496	1.5623643	0.3933261	-0.6339573
		PAYLOAD	PAYLOAD	109.1717559	27.0299835	-0.2412920	-0.7296466
Tough	40	LOADTIME	LOADTIME	5.0062500	1.0655147	0.9726493	0.4499587
		PAYLOAD	PAYLOAD	143.4575000	5.4138894	0.1267999	-0.7132791
<u>Test</u>		<u>Statistic</u>			<u>Conclusion</u>		
ANOVA		Payload Prob > F = 0.0001 Load time Prob > F = 0.0001			Mean payload for materials are different Mean load time for materials are different		
GLM-Levene		Payload Prob > F = 0.0001 Load time Prob > F = 0.0001			Variation in payload are different Variation in load time are different		
Kruskal-Wallis		Payload Prob > CHISQ = 0.0001 Load time Prob > CHISQ = 0.0001			Payload data sets are not homogenous Load time data sets are not homogenous		
Kolmogrov-Smirnov		Payload KSa = 14.0967 Load time KSa = 10.0494			There are differences in the payload and load time distribution for different materials		

For project C, the results from statistical tests and the respective PLT Maps are shown in Table 9-5 and Figure 9-9 respectively.

- Project C shows the results in the classical form — the increase in load time from easy to tough digging. The average payload also increases with the difficulty in digging. This suggests that the density of material has an impact on the payload. A completely filled truck with mud or loam may correspond to a lower payload than a truck loaded partially with a high-density material such as rock. The variation and the homogeneity for payload and load time are statistically different suggesting that material is a characterizing factor.



**Figure 9-9: A comparison of PLT Maps for different types of material for a loading method under Project C**

Table 9-6 presents a multiple range comparison of material type for different loading methods in Project C using the Duncan's test within GLM. There are several important observations relating to this set of results, a brief outline of which is presented below.

- The grouping for different types of material would have been the same for a given loading method had the effect of material on payload been negligible.
- The order of mean payload and load time suggests that each loading method may be effective in a particular material type.
- Match factor and number of passes appear to have an effect on the load time. Fleets 2 & 3 represent a combination where the ratio of truck capacity to loader bucket capacity is the same between them. The mean load times for different types of material for these fleets are the same (shown by the same letter). The number of passes required for fleets 2 & 3 are greater than the other fleets. This observation may lead to the suggestion that the number of passes may have an effect on the mean load time.

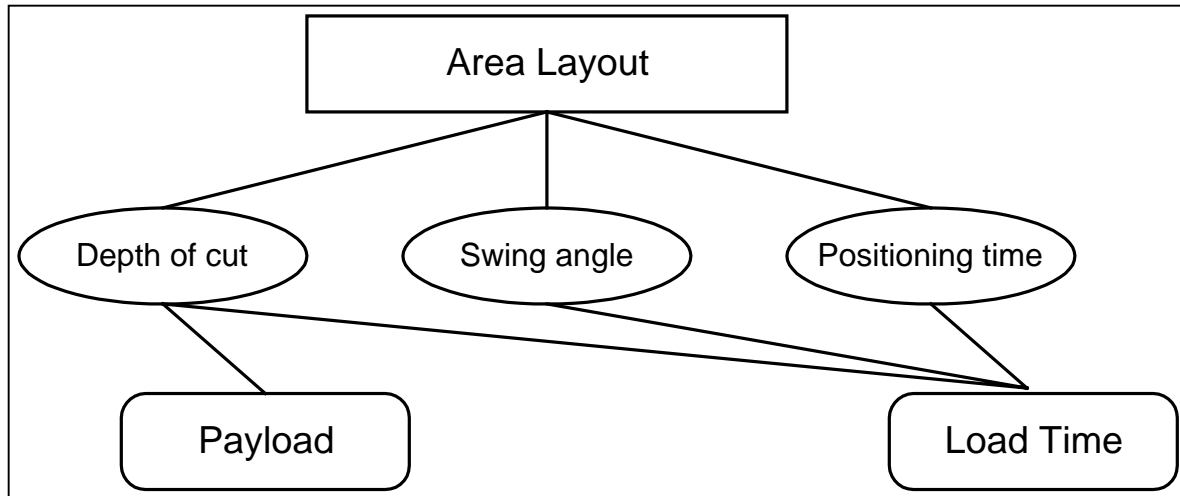
The tests confirm the hypothesis that material is a characterizing factor and has to be recorded on the field.

**Table 9-6: A multiple range comparison of material type for different loading methods**

Fleet	Grouping	Mean		Mean		
		Payload	MATERIAL	Grouping	Load Time	MATERIAL
<b>6</b> <b>(S+WL)</b>	A	84.05	Hard	A	3.33	Medium
	A					
	A	81.67	Medium	B	2.76	Hard
	B	67.77	Easy	C	2.46	Easy
<b>3</b> <b>(B+WL)</b>	A	119.88	Hard	A	4.97	Medium
				A		
	B	97.92	Medium	A	4.95	Hard
<b>7</b> <b>(S+BH1)</b>	A	86.88	Hard	A	3.54	Hard
	B	77.16	Medium	B	3.08	Medium
	B	76.31	Easy	C	2.68	Easy
<b>2</b> <b>(B+BH1)</b>	A	143.46	Tough	A	5.01	Tough
				A		
	B	134.85	Medium	A	4.98	Hard
	B	131.24	Hard	A	4.79	Medium
<b>8</b> <b>(S+BH2)</b>	A	82.91	Medium	A	6.52	Medium
	B	77.87	Hard	B	5.26	Hard

### 9.4.2 Area Layout

The area layout describes the space constraints in a load area. Space constraints effect the boom and stick movement for stationary units such as shovels and backhoes while for a mobile unit such as a wheel loader it effects the travel time between the stockpile (pit) and the truck. The influence diagram for area layout is shown in Figure 9-10.



**Figure 9-10: Influence diagram for area layout**

### *Depth of cut*

It will be difficult to fill the bucket in one pass up the face if the depth (height) of the face from which the loading tool is excavating is too shallow. The operator will have a choice of making more than one pass to fill the bucket. This in turn increases the time per cycle, or with each cycle carry a partly filled bucket to the truck. Although the visual indicator (red-green lights) helps in obtaining the target load, a partially filled bucket has an impact more on the load time than payload. Schexnayder *et al.* [1999] note that the operator starts to rely on the light indicators to appraise whether the truck is full. They also add that the human factors effect is that when that red light starts to flash load cycle time suffers because the operator recognizes that the truck payload will be exceeded if the next pass is too large.

### *Swing angle*

Swing angle refers to the movement required from the point of digging to the position of the truck. A shovel or a backhoe may sometimes have to swing more than 180° to make an on-side loading. As for a wheel loader, the optimal swing angle is about 45° [Church 1981]; however, space constraints can cause the swing angle to be greater than 45° or may necessitate more than a three-point turn. The additional time spent by the loader in moving or swinging is considered part of the load time since instrumented trucks measure the time between first pass and the gear-shift after the last pass.

*Positioning time*

Positioning time is a function of the relative position of the loading tool and the truck. A smooth movement of the boom and the stick ensures the best production for both the shovel and the backhoe. Space constraints may cause the truck to be positioned away from the loading tool or at an inconvenient angle. The movement of the loading tool is restricted in either case. The distance between the wheel loader and the truck produces a much more pronounced effect. The rule of thumb is to have a maximum of one tire rotation between the stockpile (pit) and the truck. If PLT Maps for two different trucks with the same loader for the same material are different, one of the main causes could be the different positioning of the trucks with respect to the loader.

The layout of a load area can be divided into two levels: adequate and constrained. Adequate space in case of a wheel loader refers to a free movement and maneuver space while in case of a backhoe or shovel it refers to unhampered swing of the bucket. Recording the space constraints in a continuous manner is difficult and time consuming because the space in the load area is constantly changing during the course of the operation.

Unlike material, it is not possible to associate the space constraints to each cycle. Therefore, performance data from two operations where the space constraints were almost constant throughout a particular period are used for the statistical analysis. The data sets correspond to two night shift operations for the same fleet (7) from Project C. The size of the data set may affect the window of critical values in the statistical tests. But working a small and definite data set makes sure that the operating conditions in terms of the space constraints were the constant for a given period and any effect in payload and load time can be attributed to space constraints.

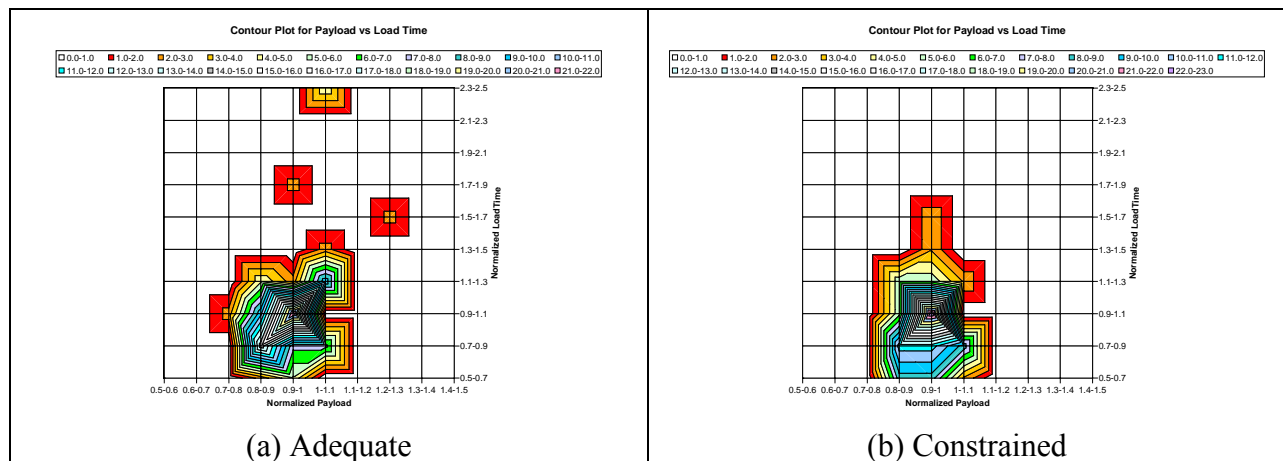
The results from statistical tests shown in Table 9-7 indicate that the null hypothesis cannot be rejected, i.e., the data sets are homogenous. The same data is presented visually through PLT Maps in Figure 9-11. The conclusion is that space constraint is not a significant factor in characterizing the load activity. It is expected that the space constraint will play a critical role in operations involving wheel loaders. It will also be interesting to evaluate the role of space constraints as the definition and recording this variable evolves in course of time.

**Table 9-7: Results of statistical tests for characterizing factor- Area Layout**

LOADSPAC	N Obs	Variabl e	Label	Mean	Std Dev	Skewness	Kurtosis
Adequate	41	LOADTIME	LOADTIME	3.1385366	1.1264625	2.2419049	5.8204873
		PAYLOAD	PAYLOAD	84.9048780	7.4563379	0.5411190	1.1214710
Constrained	36	LOADTIME	LOADTIME	2.6769444	0.8517472	-0.2726291	2.4056045
		PAYLOAD	PAYLOAD	82.5194444	10.8378917	-3.7294740	18.6487857

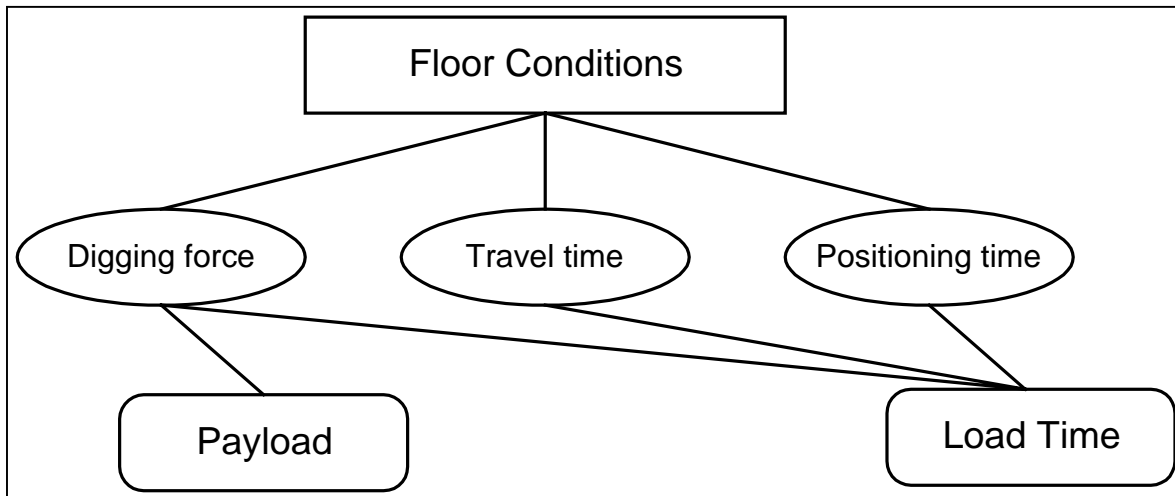
<u>Test</u>	<u>Statistic</u>	<u>Conclusion</u>
ANOVA	Payload Prob > F = 0.2594 Load time Prob > F = 0.0485	Mean payload and load time are not statistically different for different spaces
GLM-Levene	Payload Prob > F = 0.4457 Load time Prob > F = 0.3738	Variation in payload and load time are not statistically different for different spaces
Kruskal-Wallis	Payload Prob > CHISQ = 0.5069 Load time Prob > CHISQ = 0.1112	Data sets for payload and load time are homogenous
Kolmogrov-Smirnov	Payload KSa = 0.7062 Load time KSa = 0.1966	The differences in the distributions of payload and load time for different spaces is not significant



**Figure 9-11: A comparison of PLT Maps for area layout for a loading method under Project C**

### 9.4.3 Floor Conditions

Floor conditions refers to the underfoot condition of the load area. The effect of the floor conditions is more pronounced on the moveable unit such as the front-end loader compared to a shovel or a backhoe due to the continuous movement between the stockpile and the truck. The influence diagram for floor conditions is given in Figure 9-12.



**Figure 9-12: Influence diagram for floor conditions**

#### *Digging force*

Both the backhoe and the shovel generate its digging force by leveraging on the floor beneath their tracks. A hard, level and stable underfoot conditions, especially made of rock helps to transfer force to the bucket. The effect of floor conditions on the wheel loader is less pronounced as much of the force is transferred by the crowding action of the bucket. The digging force has an impact on both the payload as well as load time.

#### *Travel time*

Travel time is associated only with the wheel loader. A pitching floor is more adverse compared to a flat surface. An uneven floor or a very soft floor can also be detrimental to the movement of the loader from the stockpile (pit) to the truck. The impact on travel time is directly transferred to the load time since it forms a significant part of the load time of a truck.

*Positioning time*

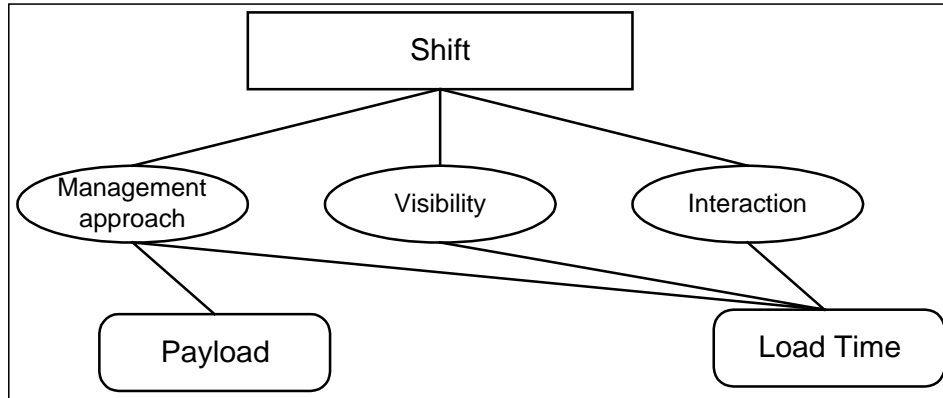
The effect of positioning time is the same as presented under area layout. The only difference here is that the cause of positioning time is due to floor conditions instead of the space constraints. Truck operators try to avoid very soft or uneven surface to make they can leave the load area immediately after the truck is loaded. The uneven surface also has a role in the recording of payload by the instrumentation because the pressures in the cylinders are not the same, which can have an impact on the accuracy of the measurements made by the sensors.

Among the data available for this project, wheel loader operations constitute only a small proportion. Additionally, there was no appreciable change in the floor condition when the wheel loader was in operation. Therefore, performing statistical tests may not be very meaningful. Theoretical knowledge, experience and observation of field operations suggest that floor conditions could be a characterizing factor and should be recorded on the field.

**9.4.4 Shift**

The influence diagram for shift is shown in Figure 9-13. The factor shift is categorized into two discrete states – day and night. On most occasions, although the senior site-level management is the same for both the shifts, the foreman and the superintendent — the decision-making authority on the field, are different. Therefore, instructions given to the crew are different. Day operations may involve additional workload such as contending with cross traffic by other resources, slide slope maintenance and inspection. On the other hand, visibility may aid the bucket fill factor during the day shift.

Table 9-8 and Table 9-9 present the results from statistical tests for the characterizing factor shift for Project A & C respectively. The PLT Maps illustrating the same set of data are presented in Figure 9-14 and Figure 9-15 (fleet=2).



**Figure 9-13: Influence diagram for shift**

Important observations and their analyses are summarized below.

- The mean and variation in payload is significantly different for both the shifts for the two projects. The principal reason for this consistency is the red and green lights on the trucks that indicate if the target payload has been reached. The lights provide a visual indicator for the payload and hence, the consistency. The variation in payload for both the shifts on both the projects are similar suggesting that the loader operator’s window of operation is well defined.

**Table 9-8: Results of statistical tests on Project A for characterizing factor- Shift**

SHI FT	N Obs	Vari able	Label	Mean	Std Dev	Skewness	Kurtosi s
DAY	3632	PAYLOAD	PAYLOAD	136. 4368282	17. 7892227	-0. 9634550	0. 6767874
		LOADTIME	LOADTIME	2. 3483260	0. 8306093	1. 7570563	2. 7115204
NI GHT	1602	PAYLOAD	PAYLOAD	136. 0239950	16. 8546363	-0. 5310792	-0. 1857579
		LOADTIME	LOADTIME	2. 2114482	0. 7414798	2. 0000401	4. 4741371

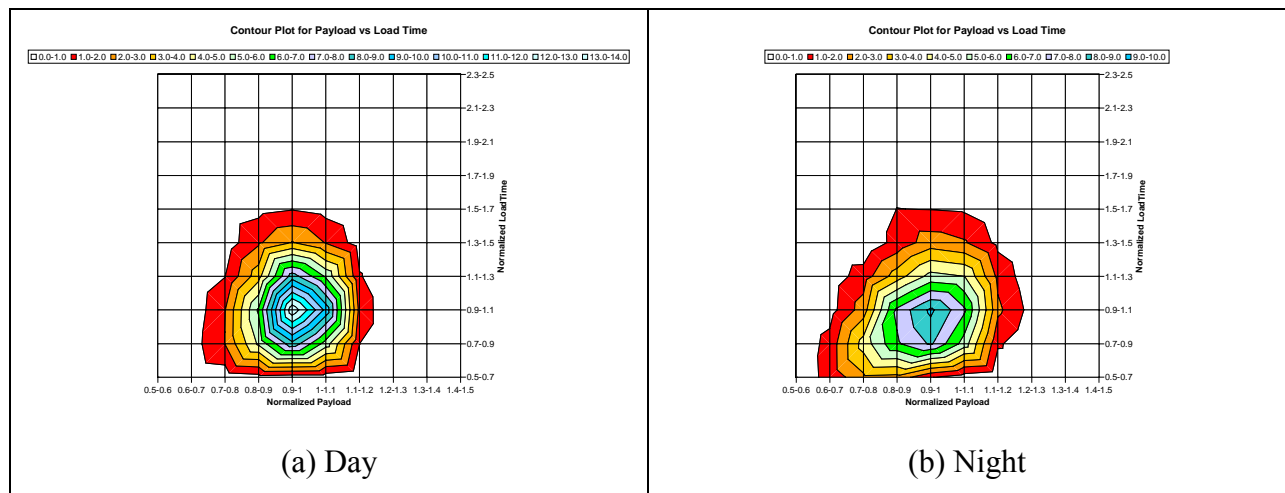
  

<u>Test</u>	<u>Statistic</u>	<u>Conclusion</u>
ANOVA	Payload Prob > F = 0. 4318 Load time Prob > F = 0. 0001	Mean payload for two shifts are not different Mean load time for two shifts are different
GLM-Levene	Payload Prob > F = 0. 0242 Load time Prob > F = 0. 0014	Variation in payload are not different Variation in load time are different

Continued.

Kruskal-Wallis	Payload Prob > CHI SQ = 0.0397 Load time Prob > CHI SQ = 0.0001	Payload data sets are homogenous Load time data sets are not homogenous
Kolmogrov-Smirnov	Payload Prob > KSa = 0.0007 Load time Prob > KSa = 0.0001	There are differences in the payload and load time distribution for the two shifts

- The differences in the load time for the two shifts on both the projects are statistically significant. An inspection of moments suggests that the domain knowledge be used prior to drawing a conclusion. In the case of Project A, the difference in the mean of the load time is 0.13 minutes or 8 seconds. It can be suggested that the mean load times are within practical limits considering that such time intervals are not easy to detect on the field. The KS Test suggests that the PDF model corresponding to the day and night shift may be different.



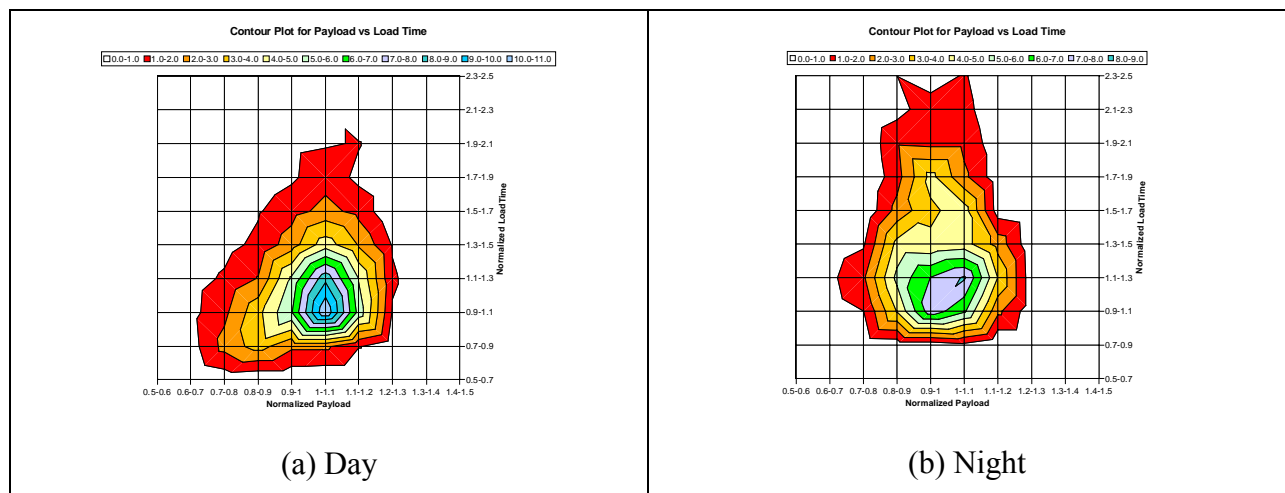
**Figure 9-14: A comparison of PLT Maps for two shifts for a loading method for Project A**

**Table 9-9: Results of statistical tests on Project C for characterizing factor- Shift (Fleet 2)**

SHI FT	N Obs	Vari able	Label	Mean	Std Dev	Skewness	Kurtosi s
DAY	1059	LOADTI ME	LOADTI ME	4.6416619	1.1673970	0.8862598	0.4742288
		PAYLOAD	PAYLOAD	130.4228517	20.1328801	-1.2677346	1.2546110
NI GHT	676	LOADTI ME	LOADTI ME	5.3557396	1.2483883	0.5301057	-0.6738257
		PAYLOAD	PAYLOAD	132.3949704	14.1366266	-0.8319259	1.0104925

Continued.

<u>Test</u>	<u>Statistic</u>	<u>Conclusion</u>
ANOVA	Payload Prob > F = 0.0265 Load time Prob > F = 0.0001	Mean payload for two shifts are not different Mean load time for two shifts are different
GLM-Levene	Payload Prob > F = 0.0001 Load time Prob > F = 0.0001	Variation in payload are different Variation in load time are different
Kruskal-Wallis	Payload Prob > CHISQ = 0.4609 Load time Prob > CHISQ = 0.0001	Payload data sets are homogenous Load time data sets are not homogenous
Kolmogorov-Smirnov	Payload Prob > KSa = 0.0010 Load time Prob > KSa = 0.0001	There are differences in the payload and load time distribution for the two shifts



**Figure 9-15: A comparison of PLT Maps for two shifts for a loading method for Project C (Fleet 2)**

The reasons for the observations could be attributed to the following reasons:

- the site management for the two shifts may be different resulting in different instructions to the crew, and

- Day operations may involve additional work such as side slope maintenance as well as interactions with other resources including inspection.

The conclusion is that shift has an impact on the load activity and should be associated with the performance data for planning and estimating future projects. The PLT Maps from the two shifts for the same period can be used for managing ongoing operations and study any form of improvement.

## 9.5 SUMMARY

This chapter investigated a range of operating conditions which affect the performance of the load activity. This chapter addressed the following issues:

- the selection of factors that define the operating conditions which affect the load activity,
- the collection of performance data under the operating conditions, and
- performing statistical tests.

Statistical procedures discussed in [Chapter 2](#) and performance measures discussed in [Chapter 6](#) were used in the evaluation of the characterizing factors. Individual projects, loading methods and operator efficiency were treated as higher order characterizing factors. All the other factors were evaluated within the boundaries of individual projects and wherever possible, a loading method. Table 9-10 presents a summary of the analysis. The next chapter addresses the operating conditions which affect the haul and return activities.

**Table 9-10: Summary of analysis of factors which can be used for characterizing the load activity**

<b>Hierarchy</b>	<b>Factor</b>	<b>Effect on Load Activity</b>	<b>Comments</b>
<b>Global</b>	Individual Projects	Significant	Project-specific database; promotes the concept of experience database
	Loading Methods	Significant	Application dependent
	Operator Efficiency	Not evaluated	Same operator must work the same machine
<b>Project-specific</b>	Material	Significant	Manually collected data; recorded in discrete levels
	Area Layout	Not significant	Manually collected data; difficult to define and record continuously
	Floor Conditions	Expected to be significant	Not enough data available; could have an impact on operations involving wheel loaders
	Shift	Significant	Extracted from OBI data

# **CHAPTER 10: DEFINING OPERATING CONDITIONS WHICH AFFECT THE HAUL & RETURN ACTIVITIES**

This chapter defines a range of operating conditions and using statistical tests, determines those which affect the performance of haul and return activities.

It was noted in [Chapter 9](#) that the operating conditions on a construction site constantly change making it difficult to extend the cycle time data from ongoing operations to future projects. The need for characterization was consequently established and explained for the load activity. The characterization process in the case of haul and return activities is an order complicated than the load activity. The haul and return activities are influenced by continuous random variables such as length and grade in contrast to the load activity which is influenced by factors such as material that taken on finite discrete values. This results in an infinite number of combinations of factors. The challenge therefore is to determine composite factors that encompass the effects of others and hence develop a method to characterize the haul and return activity.

[Chapter 5](#) outlined the reasons for characterization within the framework of this research. This chapter will use the performance measures developed in [Chapter 7](#) as well as statistical procedures discussed in [Chapter 2](#) to evaluate the effect of a range of operating conditions. The collection of information on the operation conditions is facilitated by the technologies discussed in [Chapter 4](#) and explained in [Chapter 12](#), which discusses how an image database may be used in the implementation of the concepts. This chapter will address the following:

- selection of factors that define the operating conditions which affect the haul and return activities,
- collection of performance data under these operating conditions, and
- performing statistical tests.

## 10.1 METHODOLOGY

The methodology for the analysis of characterizing factors closely follows the one described in [Figure 9-1](#). A range of factors, which define the operating conditions, is estimated for each project – the hypothesis being that haul and return activities are influenced by these factors. Statistical procedures and graphical tools are used to test these characterizing factors. The factors that test successfully are used for characterizing the haul and return activities.

The analysis of operating conditions for haul and return activities is an order complicated in comparison to the load activity. The operating conditions in the form of payload and load time were used in their direct form while analyzing the characteristic factors for the load activity. The normalization process was a simple scaling method where the payload and load time were divided by the rated payload and target load time. Normalization for haul and return activities is much more complicated.

Factors that effect the haul and return activities is a combination of both continuous random variables such as length and grade, and discrete variables such as surface conditions. Handling the continuous random variables becomes further complex since TPMS<sup>®</sup> and VIMS<sup>®</sup> record the duration of haul for the entire distance. For example, adverse grade affects the haul time of a vehicle. The haul road however consists of a number of segments and each segment could have a different grade. The question arises as to whether the steepest grade in the haul road or the difference in elevation between the start and the end of the haul that is critical. The normalization of haul and return activities must consider these effects.

The haul and return times of one haul road is independent of another. In other words, knowing the haul or the return time on a particular haul road does not guaranty a method to predict the haul time or the return time for another haul road. This difficulty was raised in [Section 7.2](#) and the development of haul ratios explained. The haul ratio is defined as the actual time taken on the field to cover a haul road divided by the theoretically estimated time for the same haul road. Normalization of the haul times using the haul ratios takes into the effect the role of the continuous random variables. Normalization is essential prior to characterizing haul and return

activities. The characterization process of the haul and return activities then follows the same methodology as the load activity.

## 10.2 SELECTION OF FACTORS WHICH DEFINE THE OPERATING CONDITIONS

Day and Benjamin [1991 pp170] state that haul time depends on

- the performance characteristics of the hauler for the haul road geometry and other adversities,
- the distance each load is to be hauled,
- the conditions of the haul road – the rolling resistance and coefficient of traction factors for various segments, and
- miscellaneous factors – direction and grade changes that causes acceleration, deceleration and braking; if the rolling resistance is variable; drainage on the haul road.

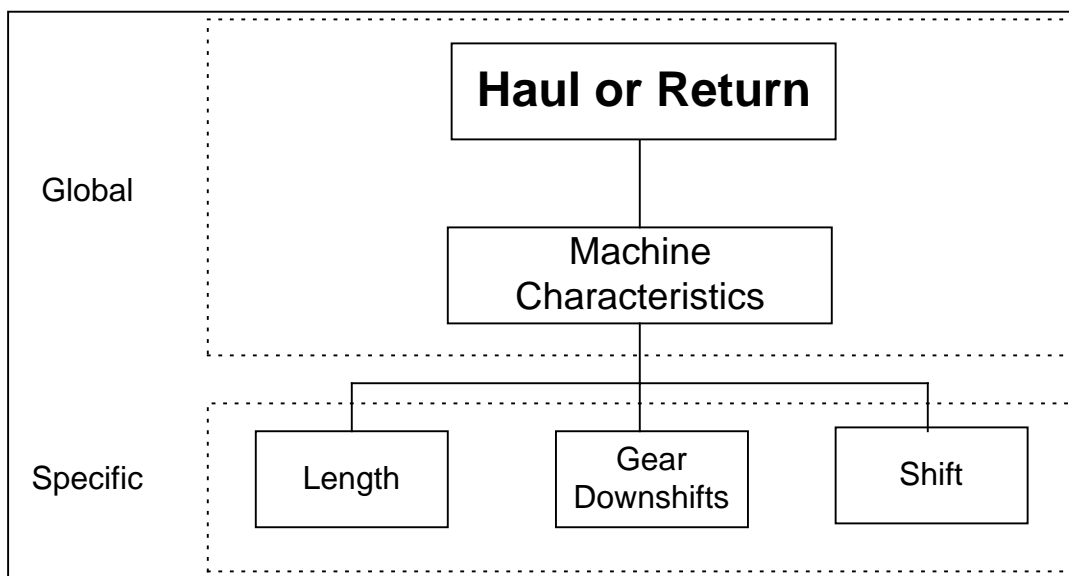
They also add that the return travel is influenced by the same factors as haul however does not play an important role in the selection of the hauler. Peurifoy *et al.* [1996] illustrate through numerical examples the effect of length, grade, rolling resistance and altitude on the haul time. The resistance due to wind may be considered negligible since the haul trucks travel at a comparatively slow speed.

It is important to understand that the data available or collectible plays a big role in the analysis of the characterizing factors. For example, it is not difficult to measure the length and the grade of various segments on the haul road. The route followed by trucks on various cycles throughout the day may not be the same. The length therefore is measured from the center of the load area to the center of the dump area.

The data on haul and return activities available through TPMS<sup>®</sup> and VIMS<sup>®</sup> consists of haul time, haul distance, return time and return distance. Both these systems do not have the capability to record the time taken for a segment because defining a segment for the onboard instrumentation is not possible. VIMS<sup>®</sup> has the capability to record some additional information

on instantaneous speed as well as number of upshifts and downshifts. However, this additional information is stored temporarily and cleared from the memory at regular intervals. The length and grade are surveyed on the site while factors such as the rolling resistance, curvature are obtained through paper forms and images as will be explained in [Chapter 12](#).

Figure 10-1 shows the hierarchical structure of the factors which affect the haul and return activities. The primary inquiry in characterizing these activities is to determine whether the ratios for haul and return for a particular haul road are the same. The next question is to determine if the haul and return ratios are dependent on the machine characteristics. The reader is reminded that two different types of trucks were studied as part of the project and fortunately, the two trucks operated on the same project. Specific factors such as length, gear downshifts and shift are analyzed subsequently.



**Figure 10-1: Hierarchical order of factors which affect the haul and return activities**

An influence diagram is created for each project specific factor, which consists of intermediate response (represented by ellipses) and the outcome of the various responses (represented by boxes with rounded edges). Following this section, an analysis of each specific factor based on statistical procedures and visual representation is presented.

### 10.3 EVALUATING GLOBAL FACTORS

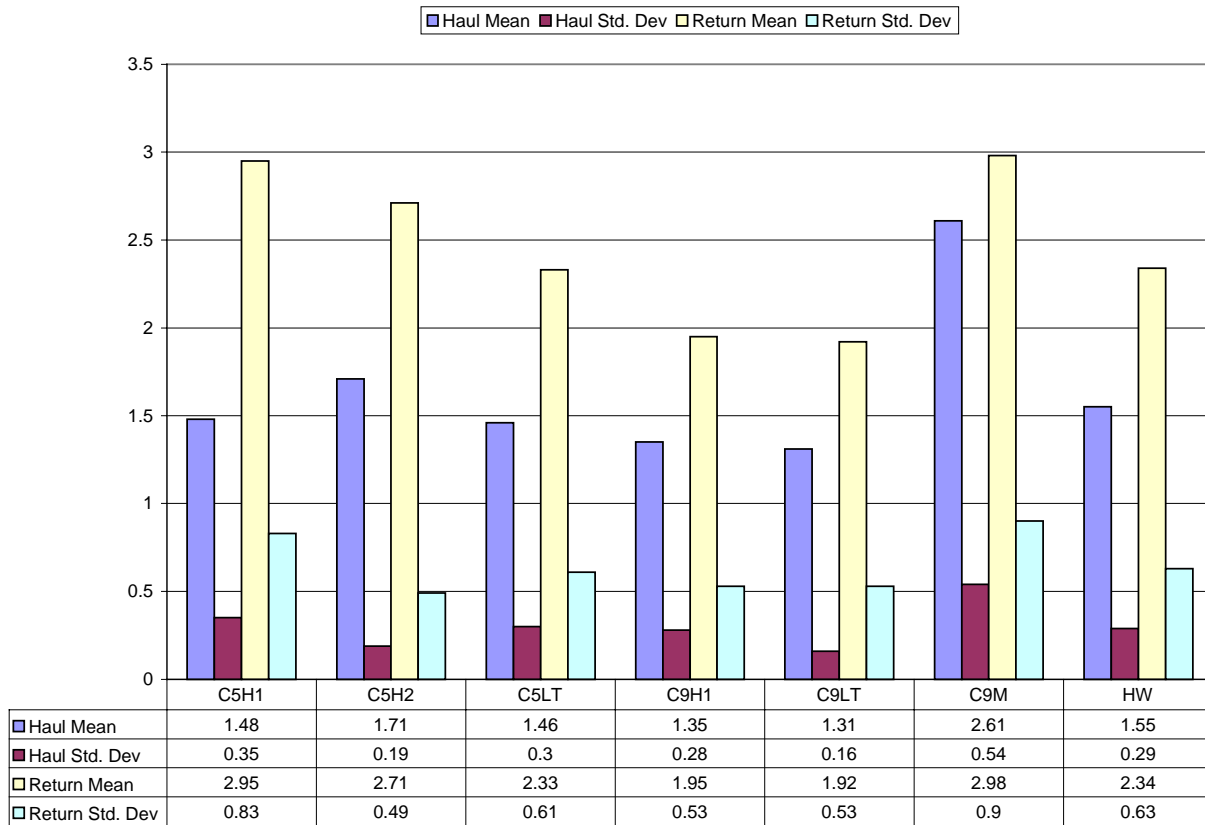
The global factors of haul and return, and machine characteristics are evaluated in this section. Operator efficiency is not included in this analysis because it was found that the same operators did not drive the same trucks every day.

#### 10.3.1 Haul or Return

The principal question in describing the ratios is to determine if the haul ratio and the return ratio for a particular haul route are the same. Figure 10-2 shows the comparison of ratios for both haul and return for various haul roads. The haul roads included in the study varied in length, grade and presence of horizontal curves. Several interesting points arise from this investigation. They are:

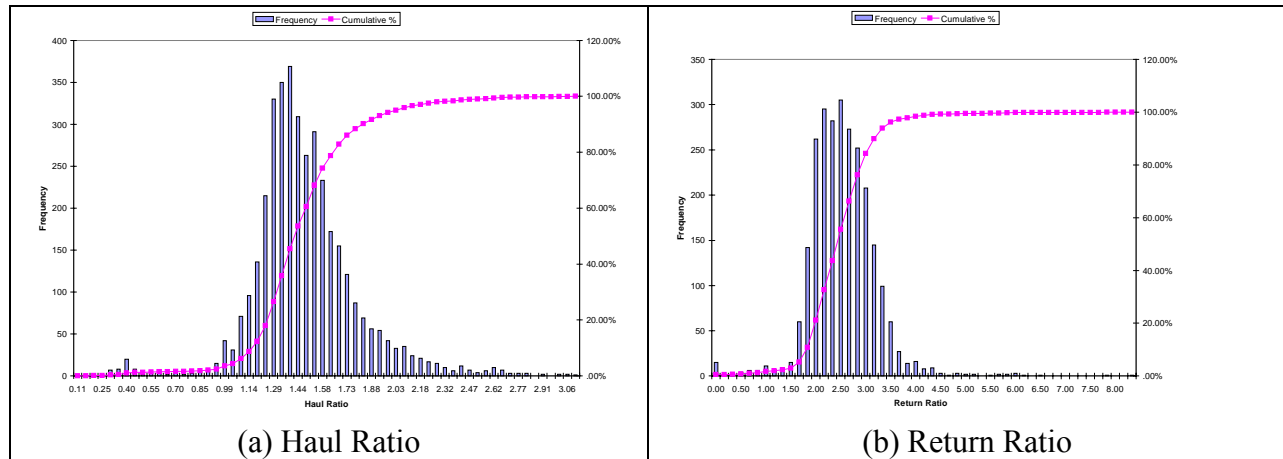
- The means of the haul ratio for different haul roads are not the same. This suggests that the some characteristic differences in these haul roads are having an impact on the performance. The same argument can be extended to the return ratio.
- The standard deviations of the haul ratio for different haul roads are not the same. If the means had been different and the standard deviations the same, it could have been suggested that the ratios for the different haul roads were scaled differently. The length, grade or any other parameter could have been under- or over-estimated while determining the theoretical haul time. Different variances suggest that the consistency of the operations is also different. It may not be appropriate to model the haul and return ratios using the same distributions. The same argument can be extended to the return activity as well.
- It is interesting to note that the mean and the standard deviation the return ratio is greater than that for the haul activity for all haul roads. This result is very important in terms of management. This result suggests that while site management tries to concentrate on hauling operations, the return may actually be the cause for a bottleneck in production. Standard references including Day and Benjamin [1991] note that the return activity is not critical within the entire process. The higher value for return ratios can also be due to an over-trucked operation wherein operators do not see a point in “hurrying up and waiting.” This

result nevertheless throws light on the importance of an otherwise neglected part of the production operation – the return activity.



**Figure 10-2: A comparison of haul and return ratios for various haul roads**

The variances in the two ratios are depicted by the histogram as shown in Figure 10-3. It is interesting to note that there is clear evidence of a shift in the modal area of the haul and the return ratios. Although both the histograms resemble a normal distribution, it is clear that the parameters of the distribution – mean and standard deviation are not the same.

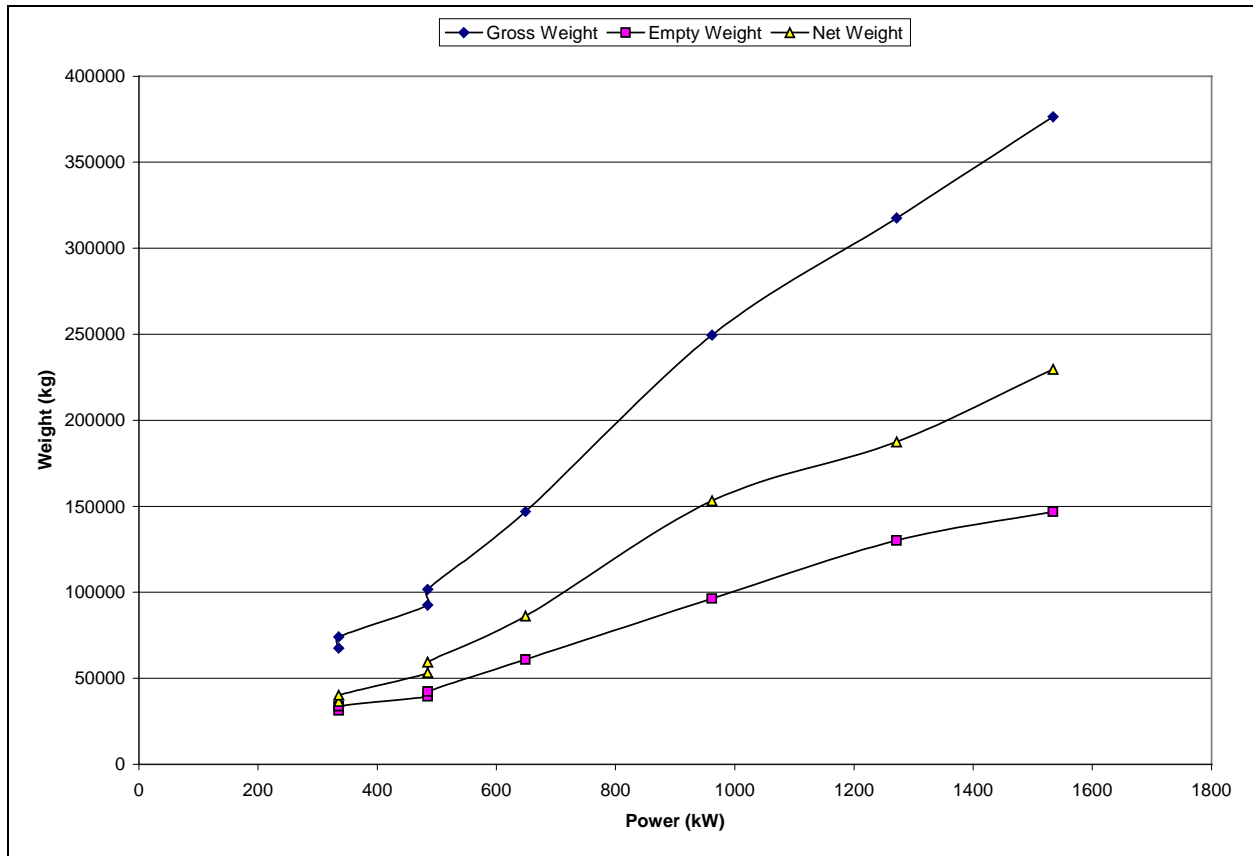


**Figure 10-3: A comparison of histograms for haul and return ratios for haul name HW**

### 10.3.2 Machine Characteristics

The components of a truck that have an influence on the haul time are power to weight ratio and the transmission. Fundamental knowledge of motion states that the speed of a truck is function of engine power and (gross/ empty) weight of the truck. The engine power is transmitted to the drive wheels through a transmission and so, it is appropriate to include transmission ratios and differential reduction ratio in the calculation of vehicle speed and haul time. Although the role of machine characteristics in haul time is straightforward, their role in haul ratios requires additional consideration.

Karshenas [1989] reported that the power to weight ratio for different models of truck for a manufacturer is constant. An example of power to weight ratio for a manufacturer is shown in Figure 10-4. This observation suggests that the haul time performance data from one truck can be extended to another. This statement can only be true if the transmission ratios and the differential reduction ratio are the same, which would have resulted in one common rimpull chart for all trucks. The rimpull chart for each truck is different suggesting that the machine characteristics or the truck type should be considered in characterizing the haul and return ratios.



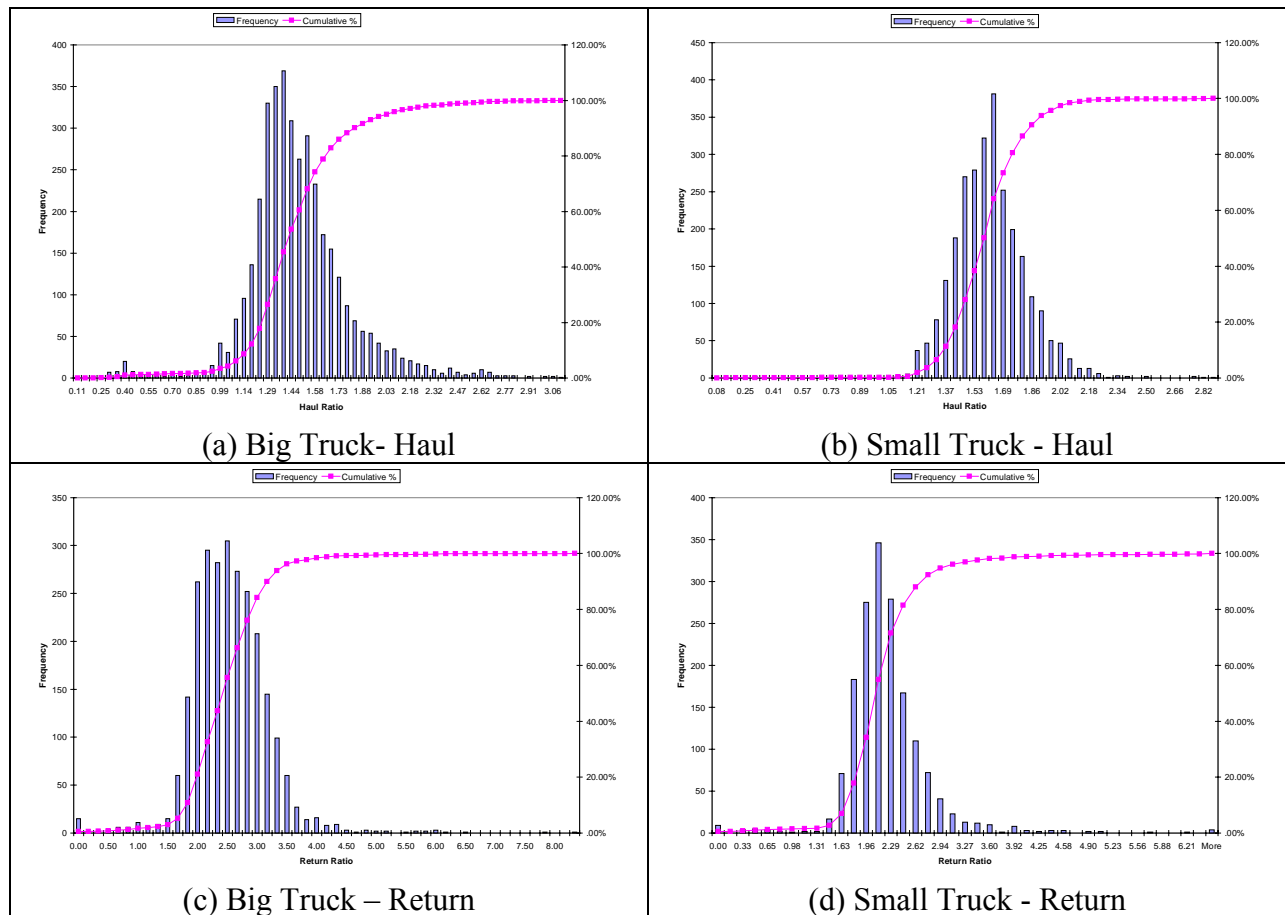
**Figure 10-4: Power to weight ratio of various models of truck from one manufacturer**

Table 10-1 shows the results of statistical test performed on four different haul roads. It is interesting to note the mixed nature of the result – significant difference in haul and return, significant difference in haul alone and no significant difference in both haul and return. As mentioned before in [Chapter 9](#), it is advisable to review the statistical test results with the domain knowledge. Consider the haul road *HW*, the difference in mean for big truck and small truck is 0.08 min, which is 4.8s. It is practically impossible to discern haul times with a difference of 5 seconds. The sample size creates very high degrees of freedom, which in turn reduces the window of critical values.

**Table 10-1: A comparison of statistical tests for characterizing factor – Truck Type**

Haul Name	Mean Haul Time		Mean Return Time		Conclusion
	Big Truck	Small Truck	Big Truck	Small Truck	
C5H1	1.52	1.41	3.22	2.81	Haul & Return no sig. Di fference
C5LT	1.59	1.33	2.59	1.95	Haul & Return sig. Di fference
C9LT	1.33	1.22	1.93	1.84	Haul sig. di fference, Return no sig. di fference
HW	1.60	1.52	2.45	2.15	Haul & Return sig. di fference

Figure 10-5 graphically depicts the variances in the haul and return ratios for two different types of machine. It is clear that the histograms corroborate the results obtained from the statistical tests.



**Figure 10-5: A comparison of histograms for machine characteristics for haul name HW**

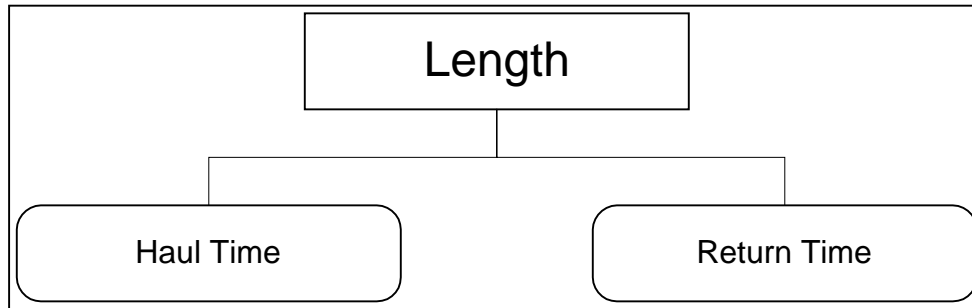
Consider that a company has only big trucks and is using them on a current project. It is expected that the company plans to purchase smaller trucks (from the same manufacturer) for an upcoming project in the near future. It is not irrational to apply the variances of the big truck to the estimation of the haul time of the small truck considering that the means as well as the distributions are not completely different. It provides a better starting point than using a deterministic estimate for the haul time. The concluding remark on this factor is that although machine characteristics are statistically significant, this factor may provide the only opportunity to extend information on variance from one truck to another.

## **10.4 EVALUATING SPECIFIC FACTORS**

The three specific factors that will be evaluated are length, downshifts and shift. The evaluation of the specific factors will be done within the boundaries of haul or return and the same type of truck.

### **10.4.1 Length**

The influence diagram for length is shown in Figure 10-6. It is clear from fundamental laws of motion that length plays a vital role in the determination of haul and return time. It may be however argued that the actual length of the haul road has been taken into account in both the numerator and the denominator of the haul ratio. The answer to this predicament lies in the calculation rather than the definition of the ratio. The ratio is calculated by dividing the total time taken on the field by the time estimated using theoretical methods. The theoretical time is the result of an envelope that defines the force-speed curve at full throttle. The ratio therefore describes how often the actual speed matches the full-throttle speed. The difference between the two speeds is substantial at the time of acceleration and deceleration and much less during steady state. The effect of acceleration and deceleration is substantial on a short haul road while it is minimal or nominal on longer haul roads. It is therefore expected that length will have an effect on the haul time as well as the haul ratio.



**Figure 10-6: Influence diagram for length**

The result from a multiple comparison test for all trucks is shown in Table 10-2. There were eight different haul roads ranging from 500m to 1700m. The observations based on the results are summarized below.

**Table 10-2: Multiple range comparison of haul ratios for length for all truck type**

Grouping	Mean	Length
A	3.47	600
B	2.61	569
C	1.71	1789
D	1.55	994
D	1.49	1572
D	1.46	1722
E	1.35	1695
E	1.31	1720

- It appears that the ratios fall into two groups, less than 1000m and greater than 1000m in length. The haul road with a length of 1789m is the only form of aberration in this observation.
- The haul ratios decrease as the length increases. The reason for this observation is that acceleration and deceleration play a significant role on haul roads that are short in length. Since the haul ratios reflect the average of differences between the actual speed and the full-

throttle speed, longer haul roads with substantial proportion of steady state speed produces lower ratios.

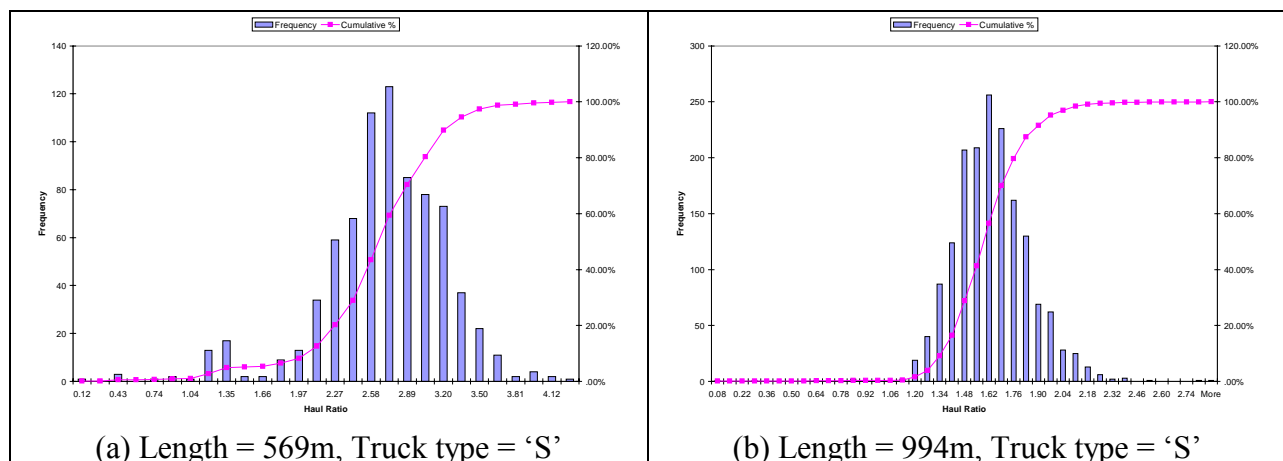
Table 10-3 shows the results for the multiple comparison for one truck type – Big. The grouping of length is further confirmed by these results. It can be observed that the means of haul ratios for haul length equal to or greater than 1000m falls within a practical limit.

**Table 10-3: Multiple range comparison for haul ratios for length for truck type 'B'**

Grouping	Mean	Length
A	3.14678	600
B	1.59311	1722
B		
C	1.52152	994
C		
C	1.41253	1572
D	1.21785	1720

Figure 10-7 presents a graphical representation of the distribution of ratios for two different lengths of haul for the other truck type. The shift in the mean and the modal region complies with the statistical results that length is a factor in the haul ratio.

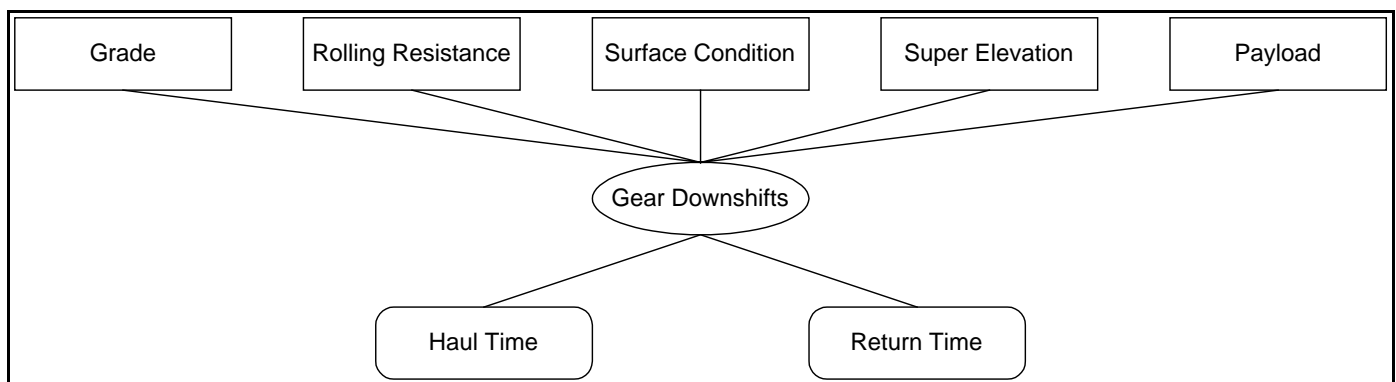
The concluding remark is that length is statistically significant in characterizing haul ratios.



**Figure 10-7: A comparison of histograms for two different haul lengths for truck type = 'S'**

### 10.4.2 Sequence of Downshifts

It was stated in the opening paragraph of this chapter that the challenge is to develop or determine composite factors, which can encompass the effects of other factors to simplify the characterization process. Sequence of gear downshifts or just downshifts is a one such special factor that encompasses the effects other factors and is defined by number of directional changes in the gear shifts. Figure 10-8 shows the influence diagram for the factor downshifts. Its not a primary factor and is the result of other factors such as grade, rolling resistance etc. The number of downshifts is estimated for a particular haul road using the *Travel Time Calculator*.



**Figure 10-8: Influence diagram for sequential downshift**

#### *Grade*

Grade refers to the slope of individual segments that make up the haul road. The free body diagram of a moving vehicle is a common feature on any reference construction equipment. A simple explanation states that an uphill grade requires more tractive effort than a downhill grade. The role of grade in the haul ratio is two-folds:

1. the effect of steep downhill grade that requires retarder control, and
2. the effect of rolling (constant change of directional grades) haul road versus a constant grade haul road.

### *Rolling Resistance*

Day and Benjamin [1991] state that the rolling resistance is caused by the effects of friction in the wheel bearings, the flexing of the side walls of the tires and the condition of the supporting surface. Rolling resistance is typically measured by the amount of tire penetration into the ground. The failure to maintain the haul road can result in a rutted, soft, uneven haul road, which may have a detrimental effect on the haul time.

### *Surface Condition*

The factor surface condition is different from rolling resistance. Surface condition refers to the evenness of the surface. A surface could be hard, smooth, without penetration under load, watered and well maintained such as the one shown in Figure 10-9. A pothole or obstacle on such a road could however impact the ability to accelerate and decelerate. The presence of such impediments can have an impact on the actual haul time and hence, the ratio. Although Volvo [1995] presents a way to categorize these obstacles, it is clear that recording surface conditions along the entire length of the haul road is not an easy task.



**Figure 10-9: An example of surface condition**

### *Super Elevation of Curves*

It is clear from fundamental laws of motion that the speed on a curve segment is related to the radius of curvature of the segment and the super elevation available. Operators negotiate a curve depending upon their comfort level in terms super elevation, vehicle stability, visibility etc. The

variance in approach among operators manifests itself in the ratio. Super elevation therefore has an impact on both the haul time as well as haul ratio.

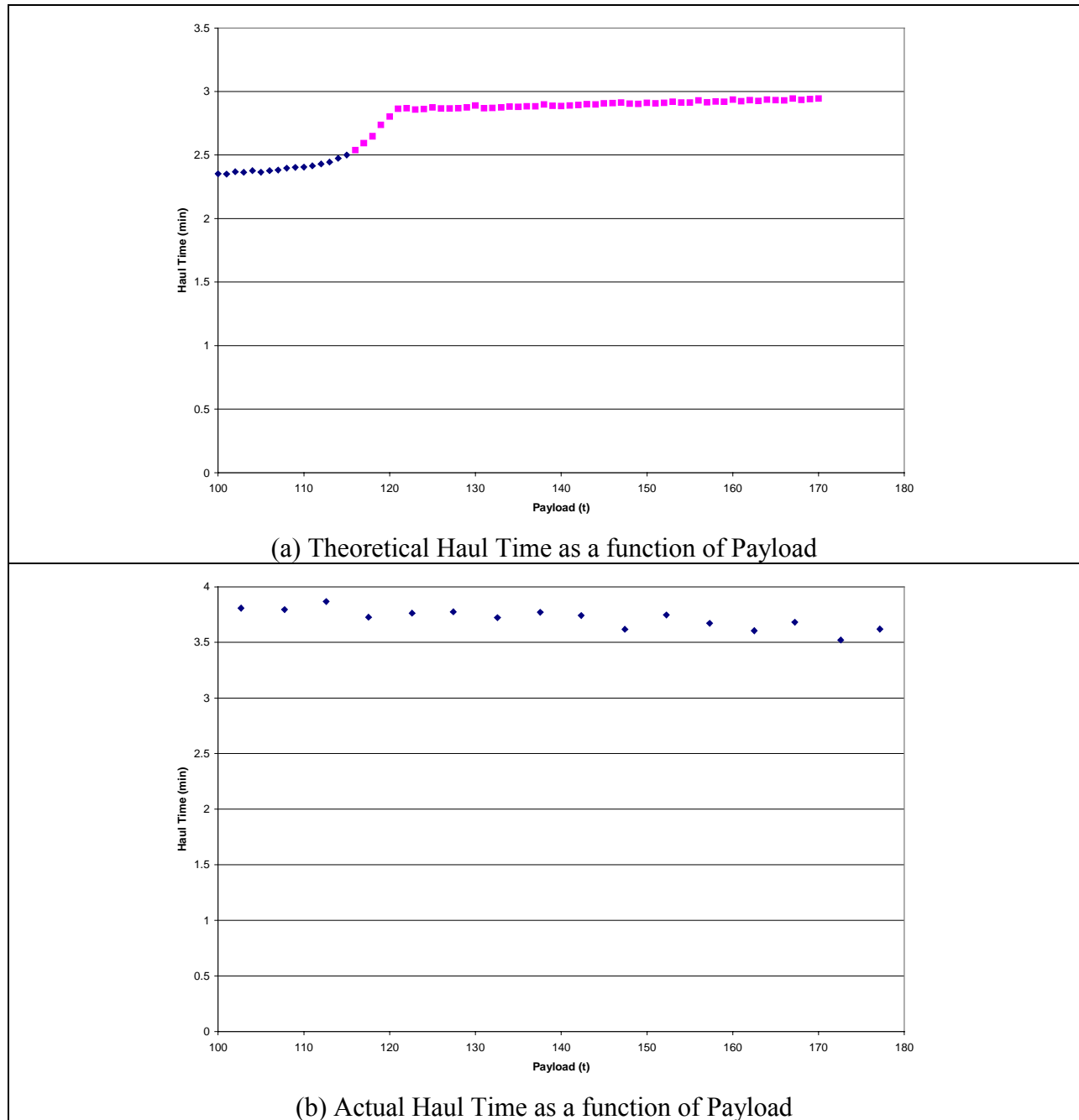
### *Payload*

Payload on a truck has an impact on the haul time because it determines the tractive effort required for the motion. The role of payload may be an important consideration when the grade or the rolling resistance of the haul road changes regularly. It was stated in [Section 7.2](#) that the actual payload will be used in calculation of the haul ratio. Using actual payload in the calculation of the haul ratio involves intensive computing. Significant number of computations can be saved if payload does not impact the haul ratio. It is therefore necessary to evaluate if actual payload on the truck or the rated payload could to be used to determine the theoretical haul time in the calculation of the haul ratio.

### *Determining the effect of payload on haul ratio*

The factor *payload* refers to the amount of material loaded on the truck. It was stated in the discussion on machine characteristics that the power to weight ratio was constant for all trucks pertaining to one manufacturer. In Figure 10-4, gross weight refers to the empty weight of the truck plus the rated payload, which is also indicated by net weight. A loaded truck could however carry a payload that is different from the rated payload. Figure 10-10 shows the effect of payload on haul time.

Figure 10-10a is a reflection of laws of motion wherein the speed and hence, the haul time of a truck is function of the payload. The two distinct regions in the plot reflect the different set of gears used for the corresponding payload. Figure 10-10b shows the actual haul time for the same haul road. It is interesting to note that the haul time is almost invariant with respect to payload; on the other hand, the haul time can be observed to decrease with increase in payload. This observation is typical for different haul roads; the only difference is that the points follow a curve that is parabolic suggesting that the haul time starts to increase after a particular value of payload [Schexnayder *et al.* 1999]. At least two reasons can be postulated for this behavior.



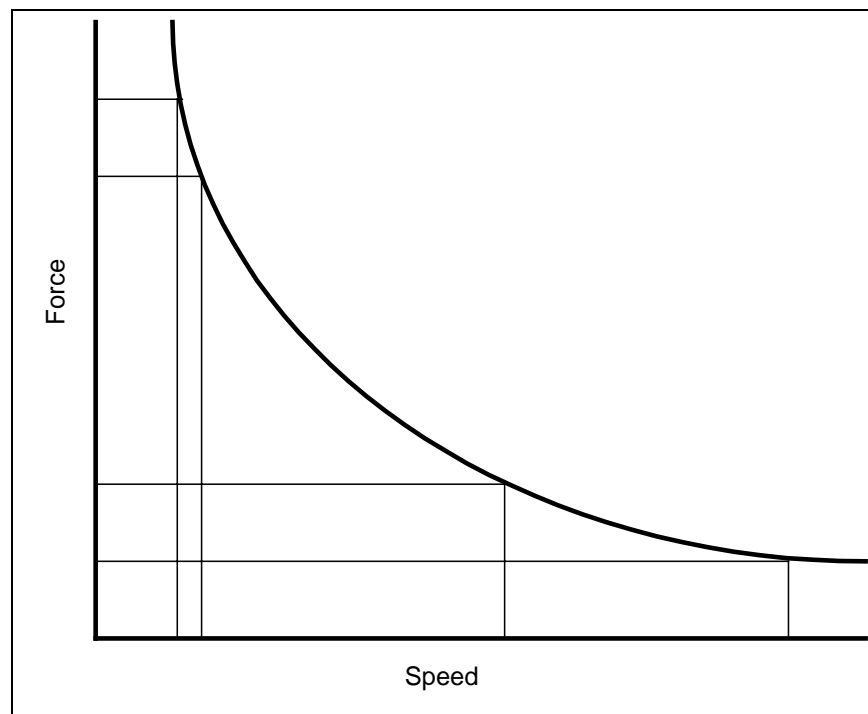
**Figure 10-10: Effect of payload on haul time**

1. Consider the standard force-speed curve as shown in Figure 10-11. Since power is constant, the shape of the curve is asymptotic (this curve can also be considered as a continuous form of a rimpull chart for any particular truck). It is clear that a change in force (required) at higher values of force results in a smaller change in speed compared to the same change in force (required) at lower values of force. The actual payload on the truck represents the

payload the time the truck departs the load area. The truck seldom has a payload that is less than 75% of its capacity. This observation suggests that an increment in payload may not result in a substantial change in speed — substantial enough to be detected in the inherent noise in the data.

2. The second reason can be attributed to the rideability characteristics of the truck. When the truck is empty or partially loaded, the pressure on the suspension is nominal and so, the center of gravity of the truck is higher than that of a fully loaded truck. It is possible that the operators tend to feel more stable while operating a loaded truck. Therefore, instances of heavier payload may sometimes result in shorter haul times.

These two reasons submit a reasonable and valuable insight to the observations made by Schexnayder *et al.* [1999] regarding haul time as a function of payload. Given these observations, it becomes necessary to evaluate the role of payload in calculating the theoretical haul time prior to arriving at the haul ratios.



**Figure 10-11: Force-Speed relationship**

A paired t-test is used to test if there is significant difference in using the actual or the rated payload in the calculation of the haul ratio for one truck type – ‘Big’. The results of the

statistical tests are presented in Table 10-4. For all the haul roads, it appears that there is a significant difference between the ratios using actual and rated payload. It is also interesting to note that the mean difference is positive in every case, which suggest that the ratio determined using the actual payload is always higher than that due to rated payload. This observation can only be true if the theoretical estimate of haul time using the actual payload is consistently lesser than the one estimated using rated payload. A closer observation suggests that such a scenario is possible if the actual payload is consistently less than the rated payload, which is confirmed by the mean of payload for Project C in Table 9.1.

**Table 10-4: Effect of payload on haul ratio for truck type ‘B’**

Haul Name	Mean of Ratio Using			Conclusion
	Actual Payload	Rated Payload	Difference	
C5H1	1.41	1.14	0.27	Sig. Difference
C5LT	1.59	1.24	0.35	Sig. Difference
C9LT	1.22	1.08	0.14	Sig. Difference
HW	1.52	1.38	0.14	Sig. Difference

A multiple range comparison on all trucks is presented in Table 10-5. The pair-wise comparison is statistically more powerful than the multiple range comparison because it considers the dependency in the two ratios (actual and rated payload). The main purpose of generating the multiple range comparison is to show that there is a significant difference in the haul ratio when the haul road is either short or has significant number of downshifts. It is therefore essential to incorporate the actual payload into the calculation of theoretical haul time and hence, the ratios for at least haul roads that are either short or demonstrate a change in grade, rolling resistance or uneven surface.

Payload is addressed in detail to explain the assumptions made during the development of the haul ratio in Section 7.3.1. Terborgh [1949 pp92] notes that

*“...derivation of the adverse minimum is of course much too cumbersome and time-consuming for practical use, its real value being as a foundation for short-cut procedures in harmony with it.”*

**Table 10-5: Multiple range comparison of haul ratios for payload for all trucks**

DS	Length	Grouping	Mean	PAYLOAD
2	1572	A	1.49	A
		A		
		A	1.35	G
2	1789	A	1.71	A
		A		
		A	1.64	G
2	1722	A	1.46	A
		B	1.27	G
3	1695	A	1.35	A
		B	1.23	G
3	1720	A	1.31	A
		B	1.23	G
2	569	A	2.61	A
		B	2.52	G
1	994	A	1.55	A
		B	1.45	G

One can now establish a simple set of short-cut procedures in a similar manner for calculating haul ratios having gone through the details.

- If the haul segments are rolling and the grade changes in direction frequently, it is essential to include the actual payload in the calculation of the haul ratio.
- If the haul segments are constant in grade, it is optional to include the actual payload in the calculation of the haul ratio.
- Since payload is already incorporated both into the numerator and denominator of the haul ratio, its effect has been neutralized and hence, need not be considered as a characterizing factor.

Figure 10-12 presents the result of a general linear model test for the haul ratio. Haul ratio using actual payload is considered as the dependent variable. Downshifts (DS) and length are modeled as the source of variation in the dependent variable. The null hypothesis is that the dependent variable, haul ratio, is not linearly dependent on the sources, namely, downshifts and length. The rejection value  $Pr > F = 0.0001$  suggests that the null hypothesis can be rejected. In other words, the two sources, downshifts and length contribute to variance in the dependent variable, haul ratio. It is also interesting to note that the  $R\text{-Square} = 0.49$ , which indicates the sources together contribute to 49% of the variation in the haul ratio. Such a value for  $R\text{-Square}$  is significant considering the sample size.

General Linear Model's Procedure					
Dependent Variable: ARATIO		ARATIO			
Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	2	1013.90023090	506.95011545	3017.60	0.0001
Error	6280	1055.02599273	0.16799777		
Corrected Total	6282	2068.92622363			
	R-Square	C. V.	Root MSE	ARATIO Mean	
	0.490061	24.10554	0.40987531	1.70033689	
Source	DF	Type I SS	Mean Square	F Value	Pr > F
DS	1	0.18547170	0.18547170	1.10	0.2934
LENGTH	1	1013.71475920	1013.71475920	6034.10	0.0001
Source	DF	Type III SS	Mean Square	F Value	Pr > F
DS	1	360.95333144	360.95333144	2148.56	0.0001
LENGTH	1	1013.71475920	1013.71475920	6034.10	0.0001
Parameter	Estimate	T for H0: Parameter=0	Pr >  T	Std Error of Estimate	
INTERCEPT	2.655406632	155.91	0.0001	0.01703170	
DS	0.417346368	46.35	0.0001	0.00900374	
LENGTH	-0.001465127	-77.68	0.0001	0.00001886	

**Figure 10-12: Results from statistical tests on the effect of payload and downshifts on haul ratios**

The results also indicate that downshift by itself is less significant. Since length along with downshift can explain only 49% of the variance in the haul ratio, it leads one to believe that there

may be other factors that contribute to the variance. It is also possible that high order terms of these factors may increase the R-Square value.

An observation of the parameter estimate provides some additional insight. The parameters can be written in an equation form as shown in Eq (1).

$$R_h = 2.65 + 0.42d_s - 0.0015l_h \quad (1)$$

where,

$R_h$  is the haul ratio,

$d_s$  is the downshifts, and

$l_h$  is the length of the haul road.

The important point is to note the sign of the coefficients for  $d_s$  and  $l$ . The positive sign for the coefficient of  $d_s$  indicates that the haul ratio increases with an increase in downshifts while a negative sign for  $l$  indicates that the haul ratio decreases with an increase in length. This statement confirms the previous results obtained for downshifts and length individually.

Since the actual number of downshifts for a haul road is not directly available from OBI, it is important to realize that the factor downshifts need to be estimated. The *Travel Time Calculator*, developed as part of this dissertation, has the capability to predict the gear position at every time instant as shown in Figure 10-13 and hence calculate the number of downshifts.

### 10.4.3 Shift

Table 10-6 presents the results of statistical test for the characterizing factor, shift. The mixed indicate that the shift has an impact on some of the haul roads while it has no impact on others. It is interesting to note that the mean of night shift operation for both haul and return time is lesser than the day shift operation. This confirms the notion that the night shift operations are more production-oriented jobs. It appears that shift can be used as an optional factor in characterizing haul and return.

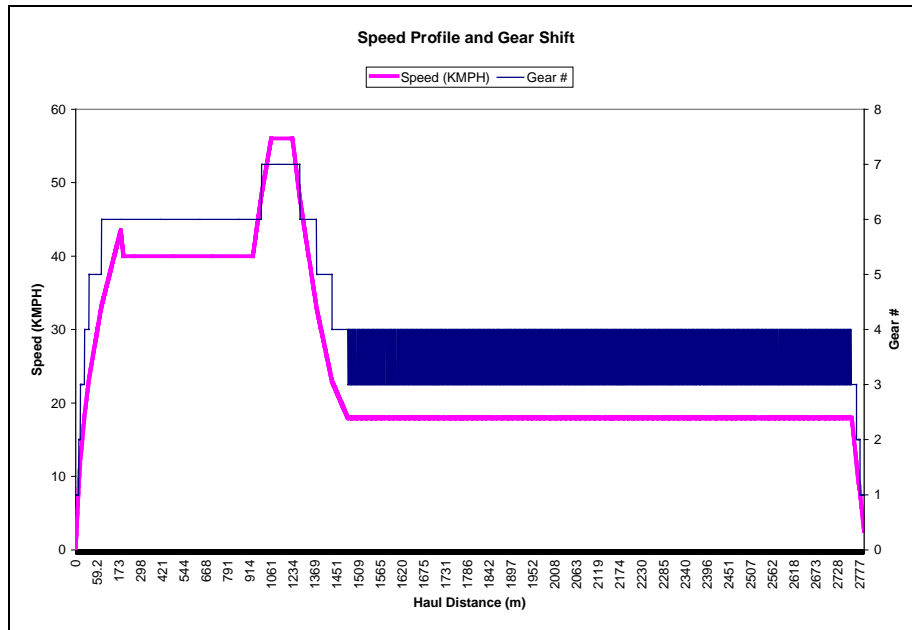


Figure 10-13: Speed profile and gear position for a haul road

Table 10-6: A comparison of statistical tests for characterizing factor - Shift

Haul Name	Mean Haul Time		Mean Return Time		Conclusion
	Day Shift	Night Shift	Day Shift	Night Shift	
C9H1	1.54	1.14	2.31	1.56	Haul and Return sig. di fference
C9LT	1.32	1.30	1.94	1.88	Haul sig. di fference; Return no sig. di fference
C9M	2.64	2.58	3.02	2.95	Haul and Return no sig. di fference
HW	1.60	1.52	2.55	2.16	Haul and Return sig. di fference

### 10.4.4 Miscellaneous Factors

There are two other miscellaneous factors which have an effect on the haul time although quantifying their effect is very difficult. The two factors are width of haul road and visibility.

#### *Width of Haul Road*

The haul road is used for both directions in most sites as shown in Figure 10-14. It is possible that the operators do not travel at full throttle speed when there is another truck in the opposite

direction or if the width of the haul is narrow. It is not easy to quantify the width all along the haul road and so, it need not be included in the list of candidate factors for characterization.



**Figure 10-14: Effect of haul road width on haul time**

### *Visibility*

The factor *visibility* refers to the ability to see from the cab as shown in Figure 10-15. It is difficult to measure this factor even in discrete terms. The forms of difficulty relating to visibility are

1. presence of fog or weather-related elements, and
2. line of sight due to curvature of road (especially inner lanes).

Poor visibility causes the operator to use less than full throttle, which in turn leads to variation in the haul time. A histogram of haul ratios can serve as a metric in evaluating its influence on the haul activity. It may be difficult to characterize the haul ratio based on visibility.



**Figure 10-15: An operator's visibility from the cab**

## 10.5 SUMMARY

Chapter 5 outlined the reasons for characterization within the framework of this research. This chapter used the performance measures developed in Chapter 7 as well as statistical procedures discussed in Chapter 2 to evaluate the effect of operating conditions on haul and return times. The collection of information on the operating conditions is facilitated by the technologies discussed in Chapter 4 and explained in Chapter 12, which discusses how an image database may be used in the implementation of the concepts. This chapter investigated the characterizing factors for the haul and return activities.

This chapter addressed the following issues:

- the selection of factors that define the operating conditions which affect the haul and return activities,
- the collection of performance data under these operating conditions, and
- the statistical tests to determine the significance of these factors.

Haul and return, and machine characteristics were treated as global factors. It was found that the return ratios were consistently higher than the haul ratios for any particular haul road. Other specific factors such as length, downshifts and shift were studied within the boundaries of the global factors. Table 10-7 presents a summary of the analysis of operating conditions which affect the haul and return activities. The next chapter will study the operating factors that have an effect on the performance of the dump activity.

**Table 10-7: Summary of analysis of operating conditions which affect the performance of the haul and return activities**

<b>Hierarchy</b>	<b>Factor</b>	<b>Effect on Haul and Return Activities</b>	<b>Comments</b>
<b>Global</b>	Haul or Return	Significant	Return ratios were consistently higher than haul ratios for any haul road
	Machine Characteristics	Significant	Some features of Machine characteristics such as power to weight ratio and transmission provides the only way to extend data collected from one truck to another
<b>Specific</b>	Length	Significant	Longer haul road produce a lower mean compared to shorter haul roads.
	Gear Downshifts	Significant	Downshifts is a composite factor for change in grade, rolling resistance, surface conditions, super elevation, width etc.
	Shift	Mixed	Optional factor extracted from OBI data

# CHAPTER 11: DEFINING OPERATING CONDITIONS WHICH AFFECT THE DUMP ACTIVITY

This chapter defines a range of operating conditions which affects the performance of the dump activity. Chapters 9 & 10 discussed the characterization process of the load, haul and return activities within the framework of this research as presented in Chapter 5. Since the onboard instrumentation used for this research do not possess the capability to record the dump time, the discussion on the characterization process of the dump activity will be qualitative.

## 11.1 SELECTION OF FACTORS WHICH DEFINE THE OPERATING CONDITIONS

The factors which influence dump activity can be hierarchically categorized as shown in Figure 11-1. Machine characteristics is treated as the global factor because its influence is part of all other factors. Specific factors such as material, underfoot conditions and space constraints are evaluated within the global factor.

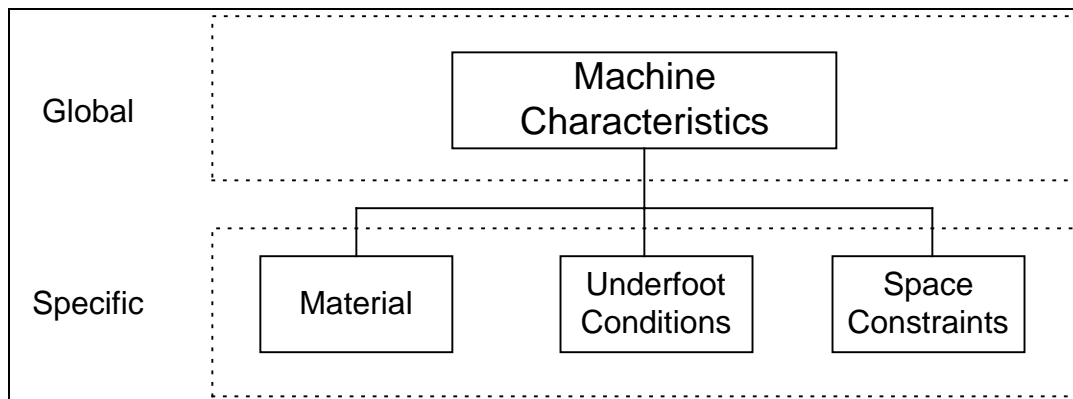


Figure 11-1: Hierarchical order of factors that influence dump time

### 11.1.1 Machine Characteristics

The type of dump mechanism and the size of the truck are two principal machine characteristics that have an impact on the dump time. There are three possible dump mechanisms on a truck — bottom dump, forced dump, and rear dump as shown in Figure 11-2. Peurifoy *et al* [1996] describe the application of bottom and rear dump mechanism. The bottom dump mechanism has chute-like opening on the floor of the body and the material falls through by its own weight. Granular material such as rock will empty out quicker in comparison to a cohesive material. A forced dump mechanism, which is relatively new, has an ejector that pushes the material from the body in a manner similar to a scraper. The time taken to empty out the contents are almost independent of the material type. A rear dump mechanism operates on a pivotal motion of the truck body to empty out its contents. The material starts to fall under its own weight as the body of the truck is lifted.



**Figure 11-2: Different types of dump mechanisms in a truck**

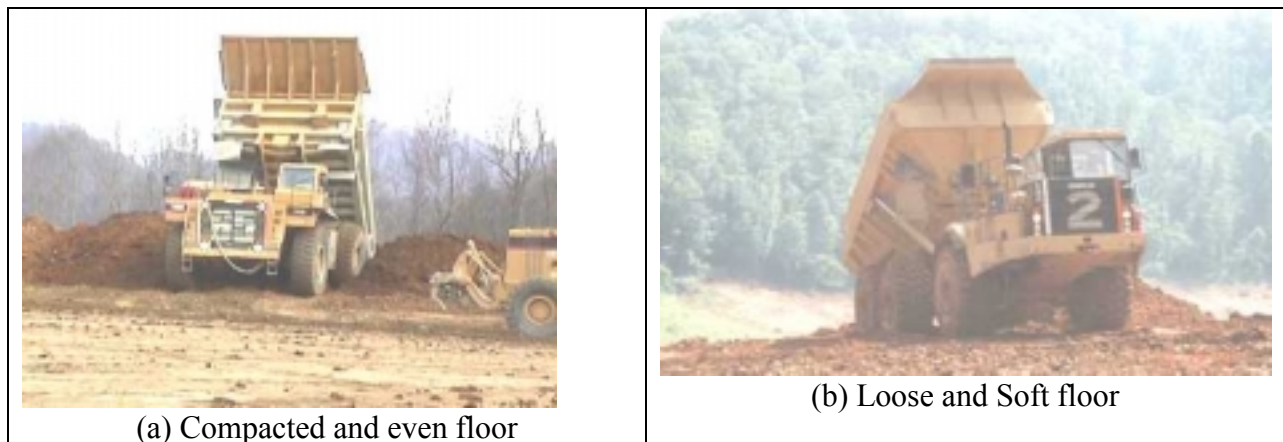
The size of a truck has an impact on the rate at which the material is unloaded from the body. The clearance available or the capacity of the receiving mechanism plays a significant part in a bottom-dump mechanism. A forced-dump mechanism for a big truck will take longer to empty out its content in comparison to a smaller truck. There is a limitation to the rate at which the body can be safely lifted in a rear dump mechanism. The size of the truck and the amount of material play a significant role in determining the dump time in all the three mechanisms.

### 11.1.2 Material

Peurifoy *et al* [1996 pp239] note that both bottom and rear dump mechanisms should be considered when the material to be hauled is free flowing or has bulky components. Cohesive material such as wet clay may require additional thrust in the form of jerky motion. Most truck manufacturers restrict the maximum speed at which a truck can travel with its body in the upright position, which in turn impacts the dump time.

### 11.1.3 Underfoot Conditions

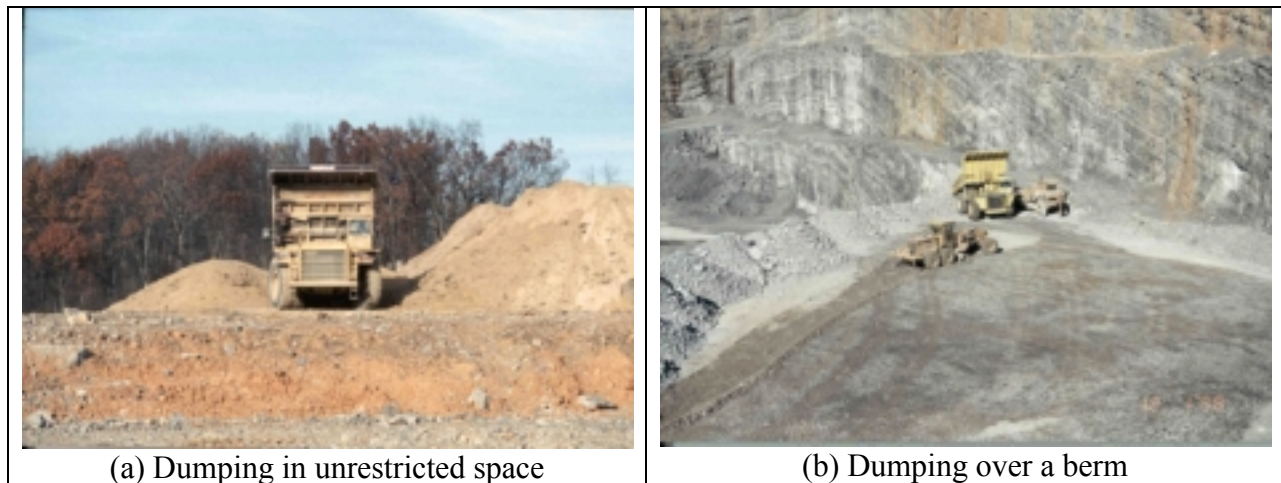
The underfoot conditions has an impact on the time spent in the dump area. Figure 11-3 shows images of two different types of underfoot conditions in a dump area. If the duration between the time at which the transmission is shifted to the reverse gear to the time at which the truck's body comes down to normal position is considered, then underfoot condition has an impact on the travel time and hence, the time in dump area. Underfoot conditions can be classified as compacted as in a structured fill or loose as in a wasted pad. The high rolling resistance of a loose and soft floor causes difficulty to backup. The soft and uneven floor also causes instability while raising the body of the truck, which is one of the principal motivation behind the introduction of the forced-dump mechanism.



**Figure 11-3: Different types of underfoot conditions in the dump area**

### 11.1.4 Space Constraints

The time spent in the dump area is also a function of the space constraints. Figure 11-4 shows examples of two different scenarios of space availability. Peurifoy *et al.* [1996] note that the rear-dump trucks are capable of dumping into restricted locations or over the edge of a bank or fill. Dumping over edge of a bank or a berm requires the ability to maneuver into position and remain stable while the body is in the air. Bigger trucks pose a greater difficulty in vision, especially during the night shift, for maneuvering and positioning.



**Figure 11-4: Different types of space constraints in the dump area**

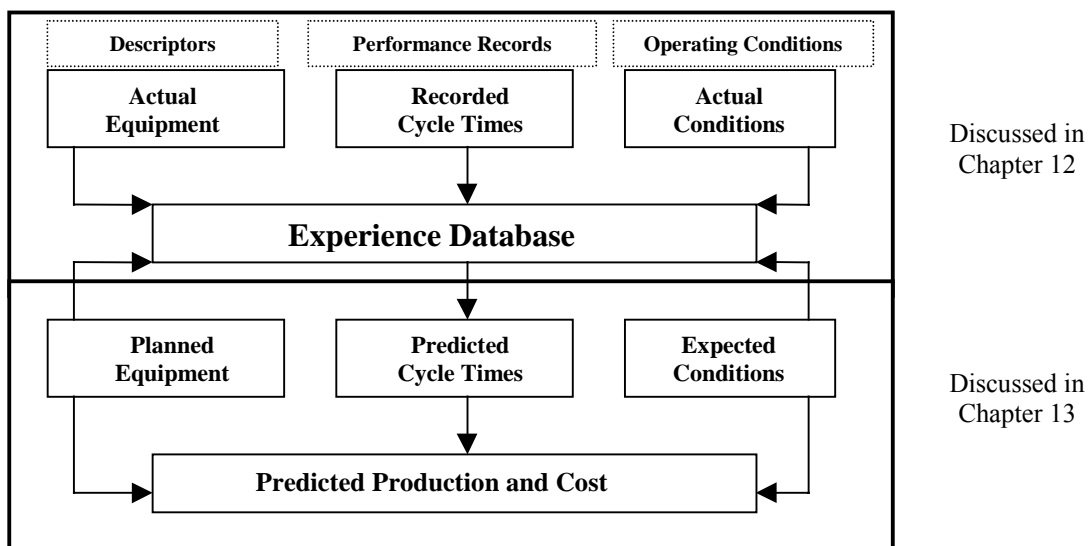
## 11.2 SUMMARY

Only a qualitative discussion on the factors which affect the dump was presented since the onboard instrumentation used in this study do not have the capability to record the dump time exclusively. Machine characteristics, material type, underfoot condition and space conditions were presented as candidate operating conditions that can affect the performance of the dump activity. This chapter concludes the discussion on the characterization process of the different activities involved in earthmoving. At the conclusion of this chapter, the performance measures as well as the statistical analysis of those operating conditions which affect the performance are complete. The next section of this dissertation will present the implementation aspects of this study.

# CHAPTER 12: DEVELOPING THE EXPERIENCE DATABASE

Figure 12-1 is reproduced from Chapter 5 to remind the reader of the framework of the experience database. The development of performance measures and the statistical testing of operating conditions were illustrated by focussing on each component of the cycle time, namely, load, haul & return, and dump. The performance measures for load, haul & return, and dump activities were discussed in [Chapters 6, 7 and 8](#) respectively. The statistical testing of operating conditions on load, haul & return, and dump activities were presented in [Chapters 9, 10 & 11](#) respectively.

This section integrates the performance measures and operating conditions for each component of cycle time to implement the concept of the experience database. The procedures implemented in the development of an experience database will be explained in this chapter. [Chapter 13](#) details the procedures involved in using the experience database.



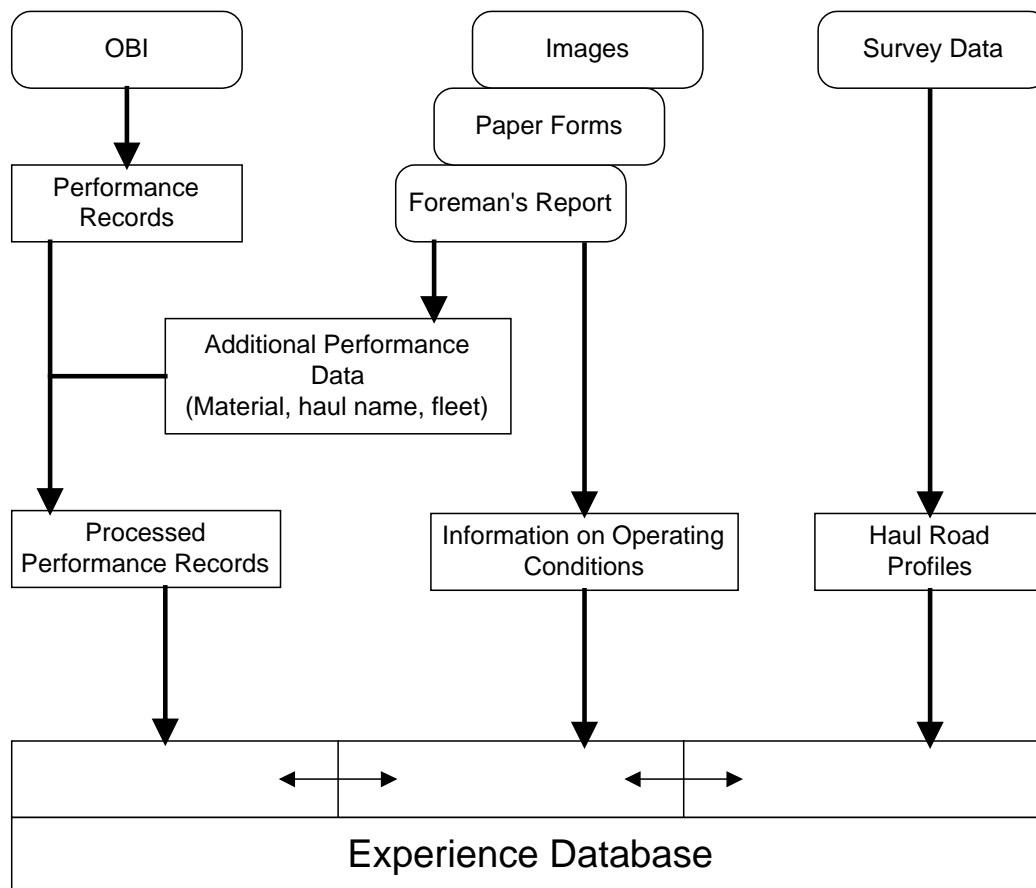
**Figure 12-1: The framework of the experience database**

This chapter includes a discussion on:

- the system developed to collect performance records,

- the system developed to collect information on operating conditions, and
- the creation of a prototype for the experience database.

Figure 12-2 shows the procedures involved in developing the experience database. OBI was used to collect performance records. Images, paper forms and foreman's reports were used to collect information on the operating conditions. Survey data was used to collect the information on haul road profiles. These three forms of information when linked together appropriately defines the experience database. The remainder of this chapter is devoted to explaining various steps involved in putting the information together and creating the experience database.



**Figure 12-2: Procedures for developing the experience database**

## **12.1 SYSTEM TO COLLECT PERFORMANCE RECORDS**

Performance records refer to the duration of the components of cycle time as actually observed on the field. Onboard instrumentation in the form of TPMS<sup>®</sup> and VIMS<sup>®</sup> were used to collect the performance records. These systems are well developed and highly structured and hence, there was no need to modify any aspects of these systems. Certain procedures were used in collecting performance records using these systems. These are described under the following headings: downloading data, calibration and data format.

### **12.1.1 Downloading Data**

One of the components of the onboard instruments is the presence of a buffer that can store a limited number of performance records. The two systems used in this study have the capability to store about 1500 cycles of data as part of their buffer. The performance records were downloaded once a week, which was well within the limit of 1500 cycles and the buffer was cleared after the download. Data from different trucks were downloaded to the laptop computer between shift changes or during breaks. This reduced the chances of losing any data due to malfunctioning of equipment. Data downloaded from each truck were grouped according to the serial number of the truck. All files downloaded from different trucks on a given day were stored in a folder with a name reflecting the date of the download and the truck serial number. The management on one of the projects was interested in monitoring the daily production for a week. The performance records were downloaded on a daily basis for this particular scenario.

### **12.1.2 Calibration**

The only concern on the accuracy of the payload data in the performance records was the effect of calibration. TPMS<sup>®</sup> and VIMS<sup>®</sup> require that a truck be driven a very slow speed on a level ground and brought to halt without engaging the brakes. Truck drivers in all the projects involved in this research were instructed to calibrate the trucks at the beginning of each shift to maintain the accuracy of data. However, there were some instances when abnormal values for payload and load times were recorded.

### 12.1.3 Data Format

Cycle time data as collected by the TPMS<sup>®</sup> and VIMS<sup>®</sup> systems are highly structured. The buffer actually stores electronic pulses from various sensors on the truck. A conversion program, which transforms these pulses to cycle times is run after the data are downloaded. This gives the flexibility to expedite the download process in the short window of time that is available between shifts.

The performance data can be viewed on the computer screen or exported to an ASCII file, which in turn can be imported to other applications such as a spreadsheet program. The components of a cycle including date, clock time, payload, load time, haul time, haul distance, return time, return distance and the total cycle time are presented in a columnar format. There are some differences between the two systems such as the format for date and time, and the order of columns however for all practical purposes, the two systems can be considered structurally the same. There is no need to add, delete or modify any column or any format of data collected by the onboard instrumentation. An example of raw data as directly obtained from onboard instrumentation is shown in Table 12-1. This raw form of the data requires further processing in terms of additional fields before it can be imported into the experience database and this processing is explained in Section 12.2.

**Table 12-1: Sample data as obtained from onboard instrumentation**

Date	Time	Payload	Empty Travel	Empty Dist	Empty Wait	Load Time	Loaded Wait	Loaded Travel
11/11/98	18:58	92.4	3.55	0.4	1.35	2.33	1.15	6.93
11/11/98	19:30	65	4.45	0.9	17.28	3.2	0.83	5.82
11/11/98	19:58	88.5	5.3	0.9	13.83	2.48	0.48	5.82
11/11/98	20:26	98.9	5.37	0.9	12.72	3.12	0.57	6.08
11/11/98	20:53	84.9	5.45	0.9	13.07	2.43	0.42	5.67
11/11/98	21:20	93.9	5.62	0.9	13.77	4.02	0.6	2.67
11/11/98	21:46	84.8	4.02	0.3	16.15	2.92	0.6	2.43
11/11/98	22:16	89.3	3.32	0.3	18.62	3.87	0.87	3.23
11/11/98	22:44	84.9	2.83	0.3	7.25	15.08	0.43	2.65
11/11/98	23:18	89.6	3.65	0.4	19.6	8.2	0.42	2.65
11/12/98	0:23	91.1	3.48	0.3	44.17	14.3	0.72	1.95
11/12/98	0:54	80.9	3.95	0.3	16.57	3.72	0.53	6.02
11/12/98	1:20	87.5	5.35	0.9	6.73	6.32	1.28	6.62
11/12/98	1:47	80.6	4.88	0.9	6.4	9.63	0.47	5.8
11/12/98	2:14	81.6	5.08	0.9	9.35	7.58	1.9	2.62
11/12/98	2:46	91.7	1.95	0.1	22.43	3.68	1.47	2.08
11/12/98	3:08	77.8	1.92	0.1	4.98	8.98	0.55	6.1
11/12/98	3:26	87.1	5.78	1	6.9	2.65	0.5	2.12
11/12/98	3:45	81.1	1.93	0.1	7.38	6.83	0.6	2.42
11/12/98	4:06	91	2.38	0.1	6.05	8.77	0.87	2.45

## 12.2 PROCESSING ADDITIONAL PERFORMANCE DATA

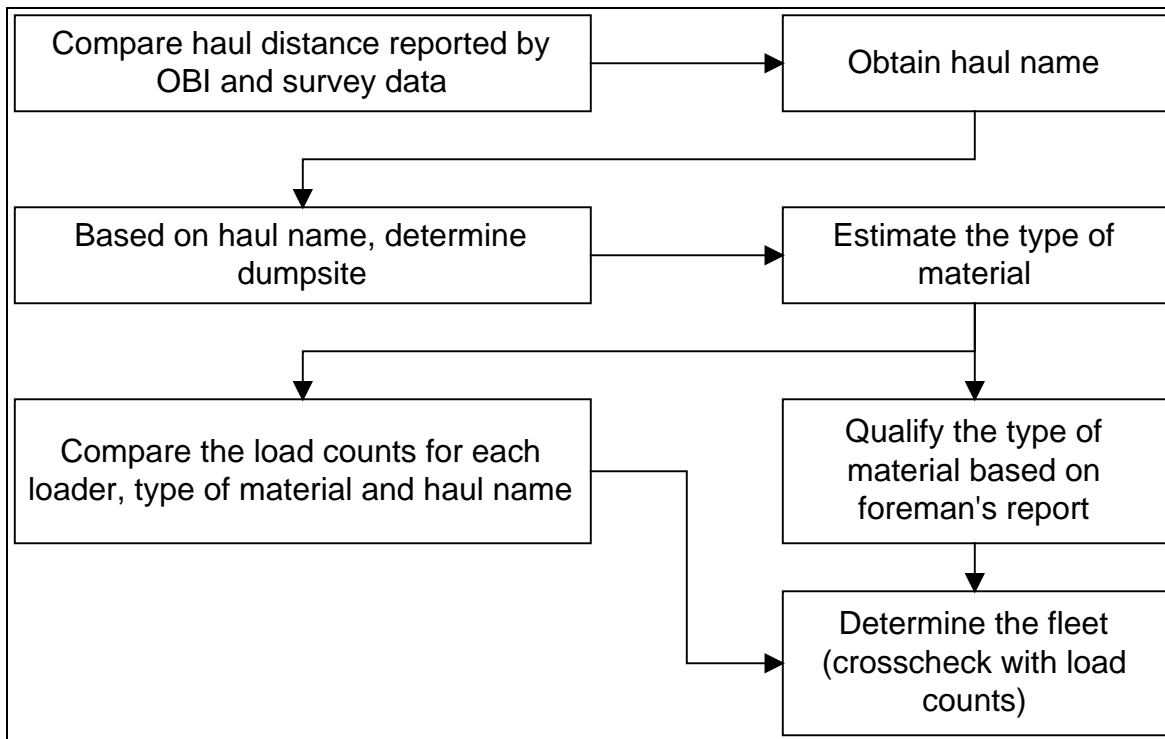
Material, fleet, and haul name are dynamically changing variables. These variables could have been entered along with information on other operating conditions. However, the dynamic nature of construction operation creates an impediment in recording one representative value for these variables for a given period of time. Associating the payload and load time data for one shift with one type of material is possible when there is one loader with many trucks of the same type, moving earth from one cut to one fill. In such cases, recording one fleet, one haul name and one material type does not pose any difficulty. However, if there are  $m$  types of loaders and  $n$  types of trucks on the site and the  $n$  trucks can visit the  $m$  loaders in any manner, the variable fleet has to be recorded for every cycle. It is also possible that the material at the cut is constantly varying which in turn requires that material type for each cycle be recorded. If there is more than one dumpsite, then the haul names have to be recorded for each cycle. The information was extracted from different sources of data and domain knowledge of the operation. Figure 12-3 presents the procedures used in extracting this information.

### 12.2.1 Associating Material, Haul Name and Fleet to Each Performance Record

The foreman's reports as made available for this study included information on the location of the different loading tools (if more than one was used), the load counts of a particular truck-loader combination and truck loads dumped at each site. OBI data and survey data, which was used to develop the haul road profile, provided the distance between cut and fill locations.

The haul distance as reported by the OBI and the survey data were compared to determine the haul name. The haul routes used on a single day were fortunately distinguishable based on the length. Determining the haul name also suggested the location of the dumpsite, which in turn was useful in estimating the type of material. Simple domain knowledge such as 'if the dumpsite is quarry, then material is shot rock' was used to assess the material type. The foreman's report was used to further qualify the material as well-shot or poorly shot rock. Using the load count for each truck from each loader, material type and the dumpsite, the fleet (loader-truck)

combination can be extracted. Every performance record can be associated with material, haul name and fleet in this manner.



**Figure 12-3: Procedures for processing additional information**

### 12.2.2 Night Shift Operations

On the field, the night shift operation starts at, say, 6:30pm on one day and continues to 5:00am on the next day. As for the OBI data, 6:30pm to Midnight is considered as one calendar day while the other half is considered another day. Additional care was taken to use the appropriate foreman's reports in processing night shift data.

The need to create the spreadsheet format of the data from OBI as shown in Table 12-1 can be appreciated based on the manipulation required in processing this additional information. The format facilitates the sorting and additional data entry involved during processing. Table 12-2 shows the data after the processing is complete.

**Table 12-2: Performance records after processing information on material, haul name, fleet**

Date	Time	Payload	Load				Loaded				Material	Haul Name	Fleet
			Empty Travel	Empty Dist	Empty Wait	Time	Loaded Wait	Travel	Loaded Dist				
11/11/98	18:58	92.4	3.55	0.4	1.35	2.33	1.15	6.93	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/11/98	19:30	65	4.45	0.9	17.28	3.2	0.83	5.82	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/11/98	19:58	88.5	5.3	0.9	13.83	2.48	0.48	5.82	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/11/98	20:26	98.9	5.37	0.9	12.72	3.12	0.57	6.08	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/11/98	20:53	84.9	5.45	0.9	13.07	2.43	0.42	5.67	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/11/98	21:20	93.9	5.62	0.9	13.77	4.02	0.6	2.67	0.3	Hard	HighWall	Hitachi 1800 + 777	
11/11/98	21:46	84.8	4.02	0.3	16.15	2.92	0.6	2.43	0.3	Hard	HighWall	Hitachi 1800 + 777	
11/11/98	22:16	89.3	3.32	0.3	18.62	3.87	0.87	3.23	0.4	Hard	HighWall	Hitachi 1800 + 777	
11/11/98	22:44	84.9	2.83	0.3	7.25	15.08	0.43	2.65	0.4	Hard	HighWall	Hitachi 1800 + 777	
11/11/98	23:18	89.6	3.65	0.4	19.6	8.2	0.42	2.65	0.4	Hard	HighWall	Hitachi 1800 + 777	
11/12/98	0:23	91.1	3.48	0.3	44.17	14.3	0.72	1.95	0.1	Hard		Hitachi 1800 + 777	
11/12/98	0:54	80.9	3.95	0.3	16.57	3.72	0.53	6.02	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/12/98	1:20	87.5	5.35	0.9	6.73	6.32	1.28	6.62	1	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/12/98	1:47	80.6	4.88	0.9	6.4	9.63	0.47	5.8	0.9	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/12/98	2:14	81.6	5.08	0.9	9.35	7.58	1.9	2.62	0.1	Hard		Hitachi 1800 + 777	
11/12/98	2:46	91.7	1.95	0.1	22.43	3.68	1.47	2.08	0.1	Hard		Hitachi 1800 + 777	
11/12/98	3:08	77.8	1.92	0.1	4.98	8.98	0.55	6.1	1	Medium	Cut5LoopT	Hitachi 1800 + 777	
11/12/98	3:26	87.1	5.78	1	6.9	2.65	0.5	2.12	0.1	Hard		Hitachi 1800 + 777	
11/12/98	3:45	81.1	1.93	0.1	7.38	6.83	0.6	2.42	0.1	Hard		Hitachi 1800 + 777	
11/12/98	4:06	91	2.38	0.1	6.05	8.77	0.87	2.45	0.1	Hard		Hitachi 1800 + 777	

## **12.3 SYSTEM TO COLLECT INFORMATION ON OPERATING CONDITIONS**

A combination of direct data entry and image catalog was used to collect information on operating conditions. A paper form was developed in a questionnaire-like format using a multiple-choice approach. An image catalog was created for each site using images of operating conditions pertaining to that site. Both the paper forms and the image catalog were given to the foremen with a request that at least one form be filled out per shift. If the foremen preferred to use their daily report, then they were requested to use terminology consistent with the paper form and use the identification number of the images which matched the operating conditions on the site. The forms were collected from the foreman on a weekly basis. A computer program was developed to input the information on performance conditions from a paper format. This is discussed in Section 12.4.

### **12.3.1 Paper Forms**

The paper form was created in a multiple-choice questionnaire format based on the operating conditions and it is shown in Figure 12-4. The questions became progressively more specific beginning with overall site information and narrowing to information on particular areas. Questions regarding particular component of cycle time such as load involved sub-divisions such as material, floor conditions and space constraints. The terms used in the form were explained to the foremen prior to the beginning of the data collection process. Similar terms were used in the textual description in the image catalog. The foremen were asked to check the alternatives that most closely matched the operating conditions and /or include the ID number of the image that most closely matched the operating conditions. The foremen were requested to fill out one form whenever there was a change in the operating conditions, with a minimum of one form per shift. The paper form was customized for each project used in this research by including only those operating conditions that were pertinent to that project.

**Operating Conditions Form**

Date: \_\_\_\_\_ Site: \_\_\_\_\_ Shift: \_\_\_\_\_

<b>Fleet: What fleet are we looking at?</b>	<b>Loading Method:</b>
<input type="checkbox"/> CAT 5130 and CAT 777s	<input type="checkbox"/> Shovel
<input type="checkbox"/> Hitachi Ex 1800 and CAT 777s	<input type="checkbox"/> Back hoe
	<input type="checkbox"/> Front end loader

Cut (Station) \_\_\_\_\_ Fill (Station) \_\_\_\_\_

**Material**

<input type="checkbox"/> Good common earth	<input type="checkbox"/> Poor shot rock
<input type="checkbox"/> Good shot rock	<input type="checkbox"/> Rock and mud
<input type="checkbox"/> Fair shot rock	<input type="checkbox"/> Stockpiled material

**Load Area Details**

Load Floor	Load Space	Load Pattern
<input type="checkbox"/> Hard and even	<input type="checkbox"/> Sufficient space	<input type="checkbox"/> Side loading
<input type="checkbox"/> Hard and uneven	<input type="checkbox"/> Adequate space	<input type="checkbox"/> Back loading
<input type="checkbox"/> Soft and even	<input type="checkbox"/> Limited space	
<input type="checkbox"/> Soft and uneven		

Toe slope: minimal  substantial

**Haul Road Details**

Haul Surface	Super Elev.	Other information
Hard and even	<input type="checkbox"/> Good super elev. curves	<input type="checkbox"/> Width for one truck only
Hard and uneven	<input type="checkbox"/> Reverse super elev. curves	<input type="checkbox"/> Width for two trucks
Soft and even	<input type="checkbox"/> Flat curves	
Soft and uneven	<input type="checkbox"/> NA	
Wet and slushy		

**Dump Area Details**

Dump Floor	Dump Space	Dump Pattern
Hard and even	<input type="checkbox"/> Sufficient space	<input type="checkbox"/> Drive in, dump and go
Hard and uneven	<input type="checkbox"/> Adequate space	<input type="checkbox"/> Drive in, back up and dump
Soft and even	<input type="checkbox"/> Limited space	
Soft and uneven		
Wet and slushy		




**Figure 12-4: Form for collecting information on operating conditions**

It was not easy to get the foremen to fill out these questionnaires on regular basis for several reasons. The main cause for resistance was that it was an additional burden. It was also pointed out that some of the information requested in the questionnaire was already available in the foreman's daily report. The daily report is filled out by foremen as part their routine and includes information on the location of cut and fill, type of material and load count for each loader and truck. The biggest difficulty in using a foreman's daily report for recording operating conditions is that it did not include all the necessary information. A typical foreman's report does not contain information on floor conditions or space constraints. The other difficulty was the inconsistency in describing the operating conditions.




The foremen involved in this study were provided with a copy of the paper form as shown in Figure 12-4 and were asked to use this as a basis to make entries on the daily report. The foremen were requested to use the comments column on the daily report to note the ID number of the image that closely matched the operating conditions. The foremen were given the option of using the image ID and/ or the textual description with the only requirement being that all aspects of the site were included. Since the daily report is produced once a shift, the information provided is taken as the representation of the operation during the entire shift.

### **12.3.2 Image Catalog**




The concepts of image database and image catalog were explained in [Chapter 4](#). Images from different sites were collected and categorized under three areas, namely, load, haul & return, and dump. Representative images that clearly depicted the operating conditions were selected for creating the area catalog. The catalogs for material, load, haul & return, and dump are shown in Figure 12-6, Figure 12-5, Figure 12-7, and Figure 12-8 respectively. A site catalog for each project was created by choosing twelve images that best represented the different areas. Six images, each about 3.8cm x 5cm, were placed on each side of a sheet which was then laminated for durability. Only images which were pertinent to a project were included while preparing the site catalog for that project. For example, if the loading method on a particular project was by backhoe, then images of a front-shovel or a front-end loader were not included.

Picture	ID Number	Material
	M0001	Well-shot rock
	M0002	Poorly-shot rock (big pieces / boulders)
	M0003	Rock mixed with dirt

Continued.

Picture	ID Number	Material
	M0004	Common earth
	M0005	Rock Substantial toe slope
	M0006	Rock Minimal toe slope

**Figure 12-5: The Material Catalog**

Picture	ID Number	Loading Method	Load Space	Load Floor	Load Pattern
	L0001	Front shovel	Sufficient Space	Hard and even	
	L0002	Front Shovel	Constrained space <90° swing	Hard and rough	Side loading
	L0003	Front shovel	Sufficient 90° swing	Soft and even	Side loading
	L0004	Front shovel	Sufficient <90° swing	Soft and even	Side loading

Continued





Picture	ID Number	Loading Method	Load Space	Load Floor	Load Pattern
	L0005	Back hoe	Sufficient space <math><90^\circ</math> swing	Soft and even	Back loading
	L0006	Back hoe	Adequate space >math>90^\circ</math> swing	Soft and rough	Side loading
	L0007	Back hoe	Constrained space <math><90^\circ</math> swing	Hard and even	Side loading
	L0008	Front end loader	Sufficient space	Hard and uneven	

Figure 12-6: The Load Area Catalog

Picture	ID Number	Haul Surface	Super Elevation	Other
	H0001	Hard and even (rock)		
	H0002	Hard and uneven		
	H0003	Soft and even		
	H0004	Soft and uneven		

Continued.

Picture	ID Number	Haul Surface	Super Elevation	Other
	H0005	Deep ruts		
	H0006		Sharp <u>flat</u> curve with no super elevation	
	H0007		Gentle curve with <u>good super</u> elevation	

Continued.

Picture	ID Number	Haul Surface	Super Elevation	Other
	H0008			Width for one truck
	H0009			Width greater than 2 trucks
	H0010			Steep segment
	H0011			Switchback

Figure 12-7: The Haul Catalog





Picture	ID Number	Dump Floor	Dump Space	Dump Pattern
	D0001	Even Structured fill	Adequate	Back in, dump and go
	D0002	Uneven Waste pad	Sufficient space	Back in, dump and go
	D0003	Even Structured fill	Constrained Over berm	Back in, dump and go
	D0004	Soft and even	Adequate space	Drive in, dump and go

Figure 12-8: The Dump Catalog

The concept of image database is applicable to the customized paper form, which was described in Section 12.3.1, and foreman's daily report. The foremen were asked to use the ID number associated with each image to record the images that closely matched the operating conditions on the site. If the foremen felt that none of the photographs matched the operating conditions, they were given the flexibility to record the conditions in a textual format using a consistent terminology.

The last step in the system for collecting information on the operating conditions is to manually enter the information from the paper forms or foreman's daily report into the computer. A simple program with a graphical user interface was developed as a portion of the prototype of the experience database, which will be discussed in detail in Section 12.4. The information from all the sites was entered on a weekly basis. The information on operating conditions is stored as a table in the database created using MS Access<sup>®</sup> and is shown in Table 12-3.

**Table 12-3: Information on operating conditions collected using paper forms and image database**

Date	Shift	SiteCode	Load Space	Load Floor	Load Pattern	Haul Surface	Super Elevation	Dump Space	Dump Floor	Dump Pattern
11/9/98	Day	SR	Sufficient space	Hard and uneven	Side Loading	Hard and uneven	None	Adequate space	Hard and even	Back in, Dump and Go
11/10/98	Day	SR	Sufficient space	Hard and uneven	Back Loading	Hard and even	None	Adequate space	Hard and even	Back in, Dump and Go
11/12/98	Day	SR	Sufficient space	Hard and uneven	Back Loading	Hard and even	None	Adequate space	Hard and even	Back in, Dump and Go
11/13/98	Day	SR	Sufficient space	Hard and uneven	Back Loading	Hard and even	Reverse	Adequate space	Hard and even	Back in, Dump and Go
11/16/98	Day	SR	Sufficient space	Hard and uneven	Back Loading	Hard and even	Reverse	Adequate space	Hard and even	Back in, Dump and Go
11/17/98	Day	SR	Sufficient space	Hard and uneven	Back Loading	Hard and even	Reverse	Adequate space	Hard and even	Back in, Dump and Go
11/18/98	Day	JB	Adequate space	Hard and uneven	Side Loading	Hard and even	None	Adequate space	Hard and even	Back in, Dump and Go
11/18/98	Day	SR	Sufficient space	Hard and uneven	Back Loading	Hard and even	Reverse	Adequate space	Hard and even	Back in, Dump and Go
11/19/98	Day	JB	Adequate space	Hard and uneven	Side Loading	Hard and even	None	Adequate space	Hard and even	Back in, Dump and Go

### 12.3.3 Haul Road Profiles

The critical component for interpreting the haul and return components of the cycle time is the data on the haul road profiles. Since the onboard instruments cannot record the details of the haul road profile, the service of a human is required to collect this data. The three projects used in this research had three different approaches to providing the haul road profile. Project A had a computer model of the haul road profile, which generated the centerline stations on the plan of the haul road, details of horizontal curves and details of elevation. It was very simple to convert to this information to haul segments with constant grade or section. Project B provided a survey of points along the haul road, which consisted of the elevation and the centerline stations for the mainline. Project C provided an estimate for the length and the grade for each segment. In all the three projects, a baseline profile was established. Any advancement of the load area or the fill was manually recorded and was used to modify the segment details accordingly.

Data on rolling resistance and surface conditions involve subjectivity. Rolling resistance was estimated by the amount of tire penetration [Caterpillar 1996]. The difficulty in estimating the rolling resistance was the uniformity of the value over the length of a segment. The rolling resistance was different at different places along the haul road. A uniform value of rolling resistance was used for each segment. Therefore, rolling resistance is considered a part of the profile data.

Recording haul surface conditions also posed the same form of difficulty. The haul road was sometimes predominantly 'hard and even' but showed the presence of soft spots at different locations. It was found that some foremen were concerned about unfavorable conditions such as soft spots and made it a point to record the haul road as 'soft and uneven'. On the other hand, some foremen neglected a small portion of such unfavorable conditions, which may prove detrimental to the operation. A representative value for haul surface was used for the entire haul road. Therefore, haul surface condition is considered a part of the operating conditions.

Horizontal curves on a haul road are treated as an individual segment. Maximum allowable speed is a function of the curvature and super elevation. Super elevation of curves is neglected

as part of the profile data unless it is inappropriate. Inappropriate super elevation in the form of flat or reverse curves is considered a part of the operating conditions.

The measurement of the haul road profile is required every time there is a substantial change in the length or the grade. Substantial changes to the haul road occur at different frequency depending upon the production. In all the three projects, a baseline profile of the haul road was established. The foreman's daily report contained the station number and the elevation details of the cut and fill locations. A change in the haul road profile if any was calculated based on this information.

## 12.4 CREATING THE EXPERIENCE DATABASE

The system for collecting performance records using onboard instrumentation was described in Section 12.1. A sample set of records was shown in Table 12-1. The system for collecting information on operating factors was explained in Section 12.2. Additional processing of data was necessary because of the dynamically changing conditions. Processed performance records was presented in Table 12-2. Corresponding information on operating conditions was shown in Table 12-3. At this stage, the different forms of data required to build the experience database are in place.

The prototype of the experience database was developed in MS Visual Basic<sup>®</sup> to automate the process of importing performance records and operating conditions and linking them to create the experience database. The database capability of MS Access<sup>®</sup> and the charting capability of MS Excel<sup>®</sup> were used in the development of the prototype.

Figure 12-9 shows the opening screen of the prototype. The user is given the option to choose between importing new data into the experience database or generating information from the experience database. This chapter will discuss the details of the former option while the next chapter will detail the latter option. By choosing the former option, the user is presented with three additional options as shown in Figure 12-10: a) to import performance records, b) to input information on the operating conditions, and c) to input information on the haul roads. Figure 12-11 shows the hierarchical format of the import process.

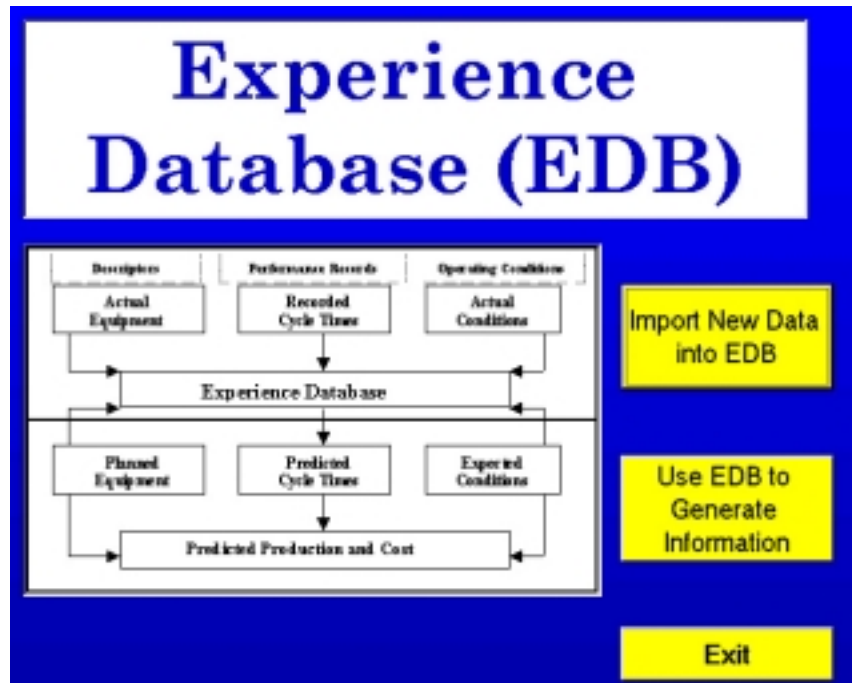


Figure 12-9: The opening screen of the prototype for the experience database

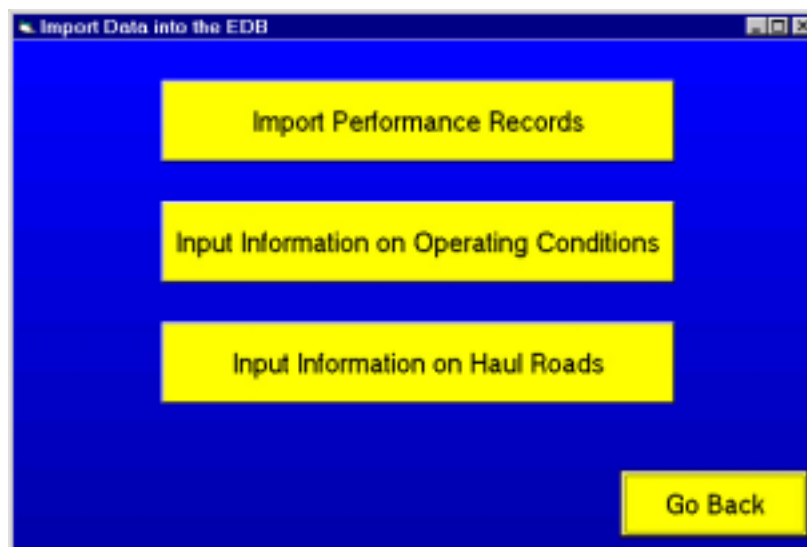
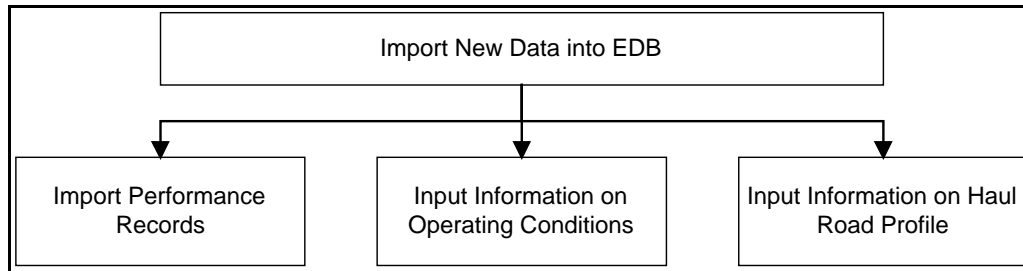


Figure 12-10: Importing different forms of data into the experience database

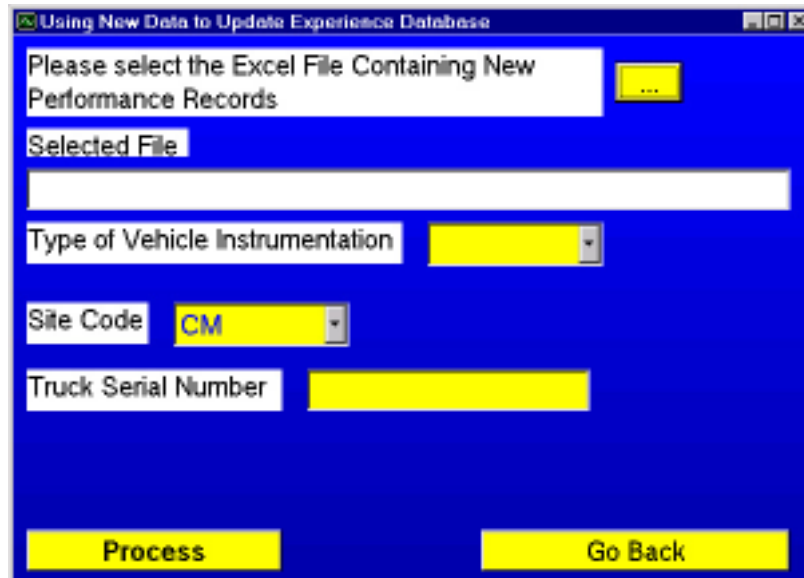


**Figure 12-11: Hierarchical format of the data import / input process**

The three procedures represented by the three options are the essential ones for building the experience database.

#### **12.4.1 Importing Performance Records**

Importing performance records refers to an automated process wherein the performance records with additional information are imported into the experience database. Figure 12-12 shows the details that the user is asked to provide at this point. The user is asked to locate the Excel<sup>®</sup> spreadsheet file containing the processed data, specify the site code, provide the type of onboard instrumentation, and include a serial number, if applicable. It is important to point out that the processed data does not include the site code. The site code, which distinguishes the data from one project from that of a different project, is an important characterizing factor. The effect of project as a global factor was investigated in [Chapter 9](#). The need to specify the type of onboard instrumentation arises because of differences in the order of the columns and the format of data as generated by TPMS<sup>®</sup> and VIMS<sup>®</sup>. The serial number is an optional parameter, which provides the flexibility to study the performance related to a particular truck. This information may be useful in a situation where the particular truck which houses the OBI performs a distinctly different operation than other trucks in the fleet.



The screenshot shows a software window titled "Using New Data to Update Experience Database". The window has a blue background and contains several input fields and buttons. At the top, there is a text box with the prompt "Please select the Excel File Containing New Performance Records" and a yellow button with three dots. Below this is a "Selected File" text box. Further down are two pull-down menus: "Type of Vehicle Instrumentation" and "Site Code", with the latter showing "CM". Below these is a "Truck Serial Number" text box. At the bottom of the window are two yellow buttons: "Process" and "Go Back".

**Figure 12-12: Details required to input performance records**

#### 12.4.2 Inputting Information on Operating Conditions

By going back one level, the user can return to the main import screen shown in Figure 12-10. The next step is to input information on the operating conditions. The information on operating conditions is obtained from the field in the form of paper forms or foreman's report. In Section 12.2, it was pointed out that paper forms and foreman's report were collected from the site on a weekly basis. This information was entered into a digital format using the screen shown in Figure 12-13.

The information required for the operating conditions is very intuitive. The options are provided as pull-down menus wherein the user makes one of the many choices available. After filling out all the fields, the user selects the option marked 'Update,' which then enters the values into the database. This process is repeated for each day for which information on operating conditions is available. After entering the data for the period, the option marked 'Exit' takes the user back to the import screen.

Conditions Data for Earthmoving Operations

Operating Conditions Data Collection Form Site Code JB

Date 12/24/98 Shift Day Weather

Fleet CAT 5130 + 777D

Load Area Details

Space Adequate space

Floor Hard and even

Pattern Back Loading

Dump Area Details

Space Adequate space

Floor Hard and even

Pattern Back in, Dump and C

Haul Road Conditions

Haul Surface Hard and even

Super Elevation Good Super

Other (include info on width, switchback, steep slopes etc.)

Update Exit

Figure 12-13: Inputting information on operating conditions

### 12.4.3 Inputting Information of Haul Road Profiles

The other form of data that is required in creating the experience database is the information on haul roads. Figure 12-14 shows the screen that is used to input the information on haul roads. A library of trucks and their specifications is automatically loaded when this screen is accessed. Based on the truck model number, a maximum speed is suggested. It is up to the discretion of the user to use a maximum speed for each segment. If the segment is a steep downhill segment, the user has to refer to the retarder curves to determine the maximum speed of that segment. By selecting the option marked, 'Create Return Road,' the profile of the return road is created with the grade of each segment automatically reversed. The user can then make any necessary modifications.

**Current Project Details**

Haul Name: I65Ramp Created By: Govi Kannan

Truck Model: CAT777C Max Speed of this Truck: 60.00

**Segment Details**

Length: [ ] Rolling Resistance: [ ] Grade: [ ] Max Speed: [ ]

**Haul Details**

Segment	Length (m)	Rolling Resistance (%)	Grade (%)	Max Speed (kmph)
1	60	3	1	60
2	150	3	-16.1	12
3	60	3	8.1	20
4	360	3	0	60
5				
6				
7				

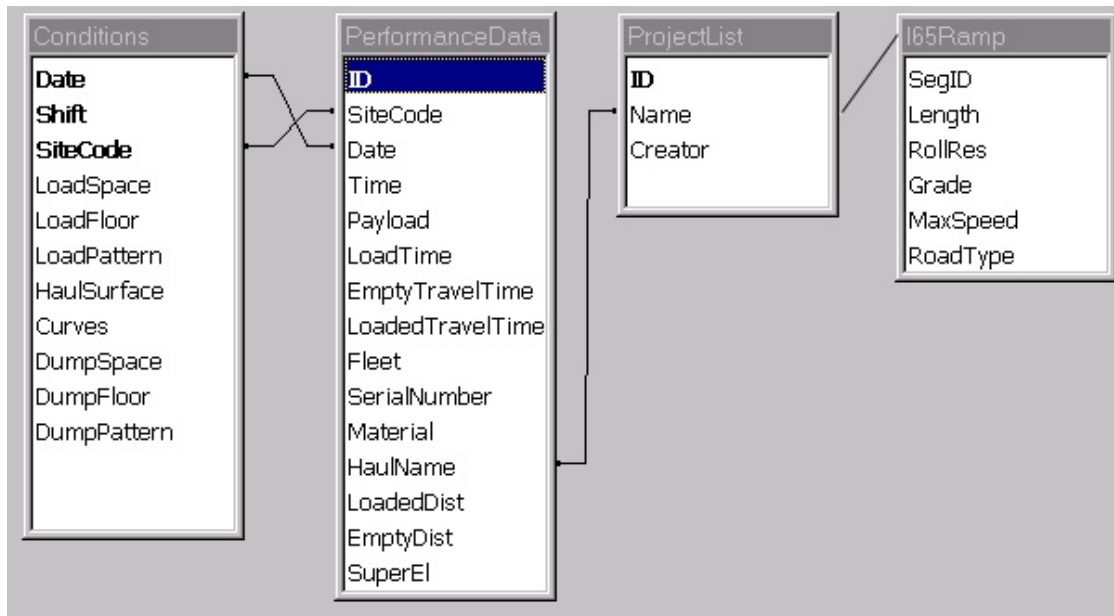
Buttons: Create Return Road, Haul Profile, Return Profile, Save Current Haul Road, Exit

**Figure 12-14: Inputting information on haul roads**

The options ‘Haul Profile’ and ‘Return Profile’ calculate the haul time and return time respectively. The details of this particular haul road can be saved by selecting the option marked ‘Save Current Haul Road.’ The user is reminded that in [Chapter 7](#), it was noted that a *Travel Time Calculator* was developed as a part of this research to calculate the haul ratios. Figure 12-14 is the user-interface of the *Travel Time Calculator*.

#### 12.4.4 Linking Different Forms of Data

This completes the processes required to create the experience database. The physical location of the different forms of data and the corresponding logical relationship is shown in Figure 12-15. The performance records and the information on operating conditions at this stage are stored in two individual tables within the experience database. They are logically linked to one another through the ‘sitecode’ and ‘date’ fields. The performance records are also linked to the table containing haul roads through the ‘haulname’ and ‘name’ fields respectively. Each ‘name’ in the haul road table links to a table with the same name which contains the details of the segment. This implicit linking of performance records to the corresponding operating conditions and the haul roads defines the functional relationship which creates the experience database.



**Figure 12-15: The logical relationship between various components of data within the experience database**

## 12.5 SUMMARY

This chapter described the steps which were taken to implement a prototype of the experience database. The procedures which were implemented in the collection of performance records and information on operating conditions were described. Sample sets of each form of data were also presented. Preprocessing of the data was required because of the dynamic nature of construction activities. Information on haul road profile was the other piece of data that was required to build an experience database.

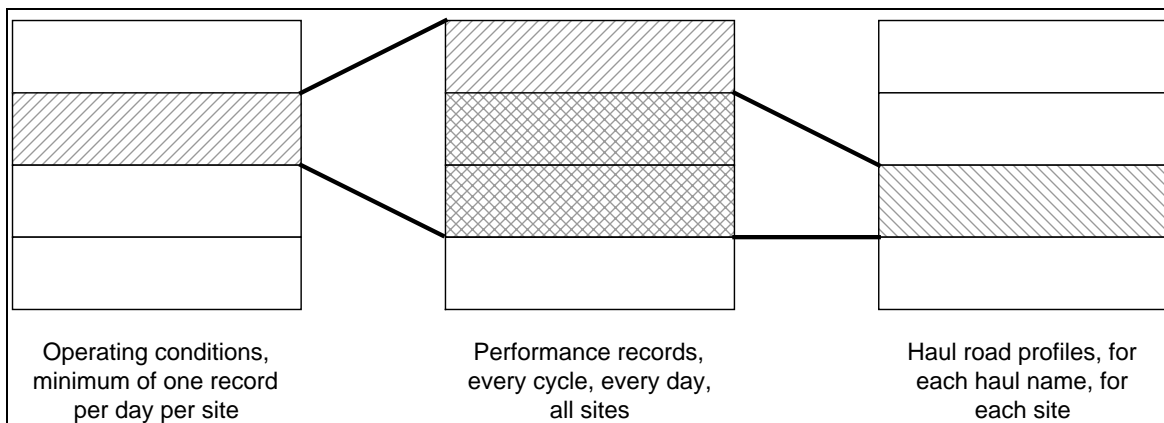
The prototype for building an experience database was implemented using a database program (MS Access®) and a spreadsheet program (MS Excel®) within a MS Visual Basic environment. The essential purpose of using these tools is to be able to rapidly build a prototype by taking advantage of the special capabilities of each tool. Step by step instructions for using the prototype as well as the procedures involved were explained. Finally, a logical format of the experience database was illustrated. At this point, the reader is acquainted with the different

formats of data and procedures required to develop the experience database. The next chapter will describe the implementation steps for using the experience database.

# CHAPTER 13: USING THE EXPERIENCE DATABASE

## DATABASE

Chapter 12 concluded by outlining the creation of an experience database of earthmoving operations. The experience database consists of three different forms of data – the performance records, information on the operating conditions and the haul road profiles. Although these forms of data are stored in individual tables within the database, they are logically linked together to form one source of information. Figure 13-1 shows a schematic representation of the different forms of data within the experience database.



**Figure 13-1: Schematic representation of the experience database**

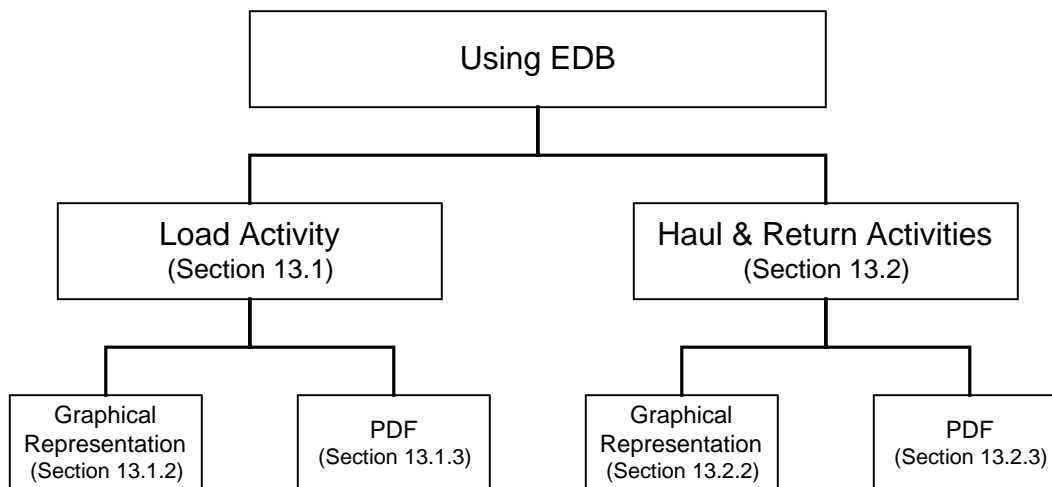
There is at least one record containing the information on operating conditions for a given day and site. Each record on operating conditions will correspond to multiple performance records collected using the OBI. Similarly, there is at least one recording containing the information on haul road profile for each haul name. It is possible that several performance records link with each record in the haul road table.

The term “using the experience database” refers to deriving useful information based on specific operating conditions, which affect the performance of a particular portion of the cycle. This chapter will illustrate the implementation steps for generating:

- a PDF and a graphical representation for the load activity, and

- a PDF and a graphical representation for the haul & return activity.

The layout for using the experience database and hence, the format of this chapter is shown in Figure 13-2. The implementation of each component of cycle time is presented in separate sections because the performance measures for each component is different.



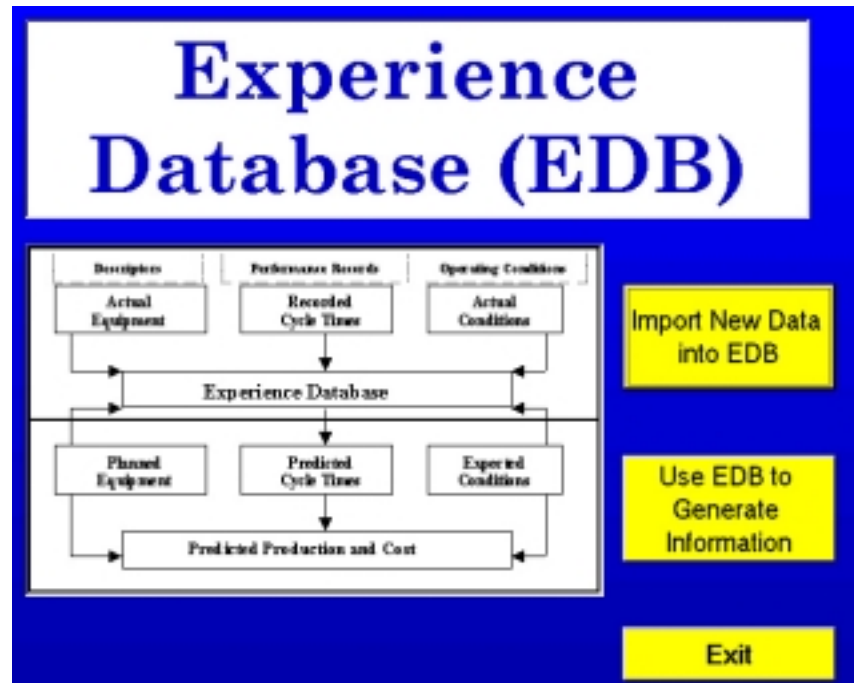
**Figure 13-2: Layout for using the experience database**

### 13.1 USING THE EDB FOR THE LOAD ACTIVITY

Using the experience database for deriving information on the load activity was implemented as a three-step approach. They are:

- a) filtering the records in the experience database so as to obtain only those records which match the specified operating conditions,
- b) defining a PDF for the filtered records, and
- c) generating a graphical representation of the filtered records.

In the discussion on developing an experience database in [Chapter 12](#), the reader was introduced to a prototype of the experience database. The procedures involved in using of the experience database will be explained using the same prototype. The opening screen of the prototype, which is reproduced from [Chapter 12](#), is used as the reference point and is shown in Figure 13-3.



**Figure 13-3: The opening screen of the prototype for the experience database**

In the screen shown in Figure 13-3, the development of the experience database was illustrated by choosing the option marked ‘Import New Data into EDB.’ Using the experience database will be illustrated by choosing the option marked ‘Use EDB to Generate Information.’ By choosing this option, the user is presented with three additional choices as shown in Figure 13-4. This section will discuss how the experience database was used to derive information on the load activity. Section 13.2 will discuss how the experience database was used to derive information on the haul and return activities. The option to derive information on dump activity is not functional at this time due to the lack of data.

### 13.1.1 Filtering Records

In [Chapter 6 & 7](#), the term data set was defined as a subset of all data within the experience database that match the specified operating conditions. Figure 13-5 shows the options for filtering records that match the specified operating conditions for the load activity.

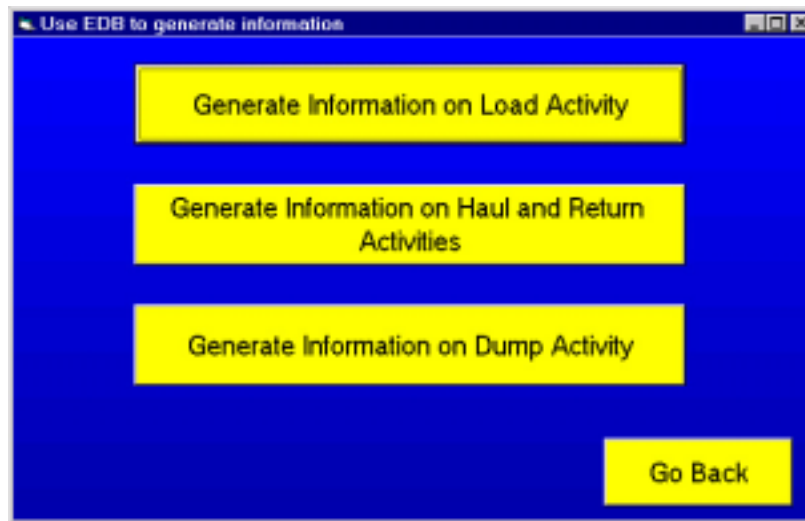


Figure 13-4: Screen showing the different options for using the experience database

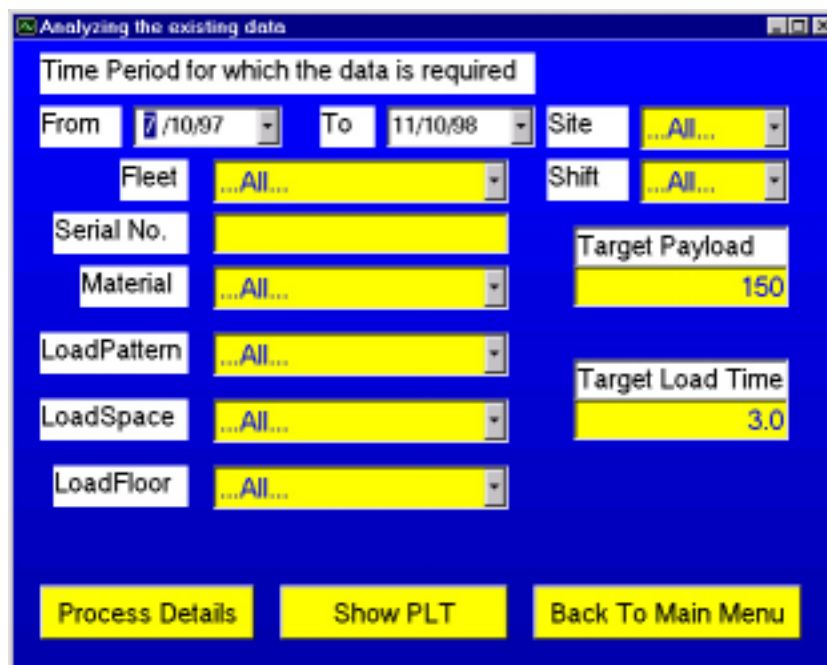


Figure 13-5: Options for filtering performance records for the load activity

The performance records in the experience database were filtered by calendar days by specifying the 'From' and 'To' dates. The pull-down option for the date allows the user to choose the specific dates. Although calendar date was not considered as a characterizing factor in [Chapter 9](#), it may be applicable in situations where a known set of conditions may have occurred during a period. For example, two different blasting crews were at work at two different periods in one of the projects. The effect of the blasting procedures of these two crews on the load activity was

studied by specifying the period corresponding to each crew and then producing the PLT Map for each set of filtered records.

The principal global factor in characterizing performance record is the project or site. It was shown in [Chapter 9](#) that data from each project had to be considered individually and the effect of any other factor such as material should be studied within a project. By specifying the site, performance records relating to a particular site or project are filtered.

The type of loading method or 'Fleet' occupied the next tier in the hierarchy of global factors. The possibility of having two different loading methods (backhoe or front shovel) for the same model of loading tool was not applicable to any of the projects used in this research. Therefore, specifying the fleet implicitly defined the loading tool as well as the loading method. In [Figure 13-5](#), it can be seen that the target values for payload is specified at 150 tons and load time at 3.0 minutes. This is the default value provided to normalize the payload and load time. When the user chooses a particular fleet, the corresponding target values are loaded from a standard library.

The rest of the operating conditions shown in [Figure 13-5](#) correspond to specific factors as described in [Chapter 9](#). It was pointed out that material and shift were influential in all the projects used in this study. It is possible that operating conditions such as 'LoadPattern,' 'LoadSpace,' and 'LoadFloor' are influential in other projects. By choosing appropriate values for each operating condition, the performance records are filtered based on the specified values. By choosing the default value '...All...' the effect of the particular operating condition is not included in the filtering process. The values for each operating factor for a future project is chosen based on the expected conditions.

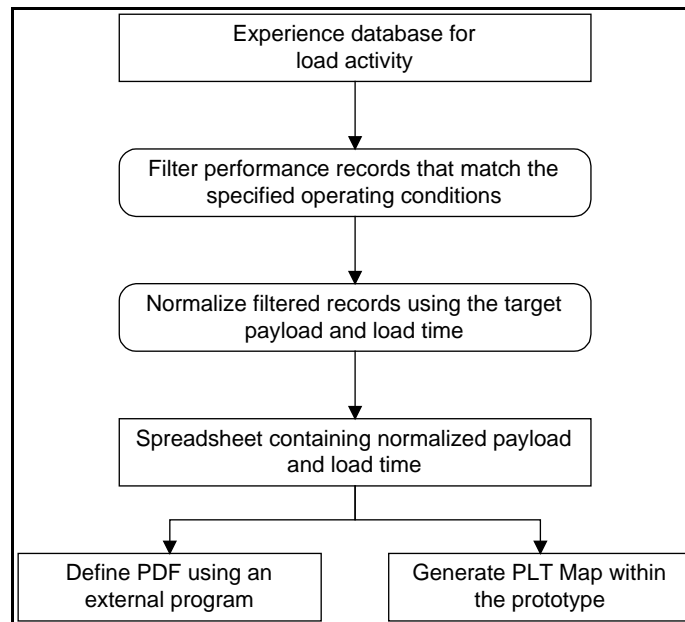
Selecting the options marked 'Process Details' or 'Show PLT' triggers two sequential processes. The first process is a query to the experience database wherein all performance records that match the specified operating conditions are filtered. The second process is the normalization process wherein all the filtered records are normalized by the corresponding values of target payload and load time. The processed details are then stored in a spreadsheet.

A portion of the spreadsheet is shown in [Figure 13-5](#). The spreadsheet consists of two columns, namely, 'Payload' and 'LT in Min.' One of the transformation within the prototype is the

conversion of all time units from “hh:mm:ss” to decimal format. This spreadsheet in turn becomes the input for deriving the PDF and creating the graphical representation (PLT Map). The schematic representation of the processes is shown in Figure 13-7.

Payload	LT in Min
0.82	0.95
1.04	1.56
0.96	1.74
0.83	1.79
0.79	0.95
0.92	1.08
0.85	1.04
0.90	1.07
0.75	0.96
0.83	1.07
1.08	0.99
0.76	0.96
1.08	2.04
0.90	0.93
0.95	2.06
0.99	0.84

**Figure 13-6: A segment of the spreadsheet showing normalized payload and load time after filtering**



**Figure 13-7: Processes involved in deriving the PDF and generating the PLT Map**

### 13.1.2 Determining the PDF

The spreadsheet shown in Figure 13-6 is used to determine a PDF which best defines the data. There are several techniques and tools available to aid in the determination of a PDF which best fits the data. The services of a commercially available program called STAT:FIT [Statfit 1996] was used for this purpose. The limit on STAT:FIT is 8000 data points.

In order to determine the PDF for load time, the column marked 'LT in Min' in Figure 13-6 was copied into STAT:FIT. The histogram of the data was plotted to obtain a first impression of the type of distribution that can be used for describing this data. The distribution also gave an idea about the outliers – abnormal points that skew the data unnecessarily. One of the options in STAT:FIT is 'Auto:Fit,' which determines the type of distribution as well as the parameters of the distribution that best describes the data. The ideal condition is that one distribution closely fits the data. However, there is a possibility that more than one distribution or none of the distributions fit the data. In the former case, the distribution with the highest rank or the one that is most compatible to the simulation engine was chosen. In the latter case, the upper and lower bounds were modified further or the levels of significance were relaxed to increase the chances of finding at least one distribution. For illustrative purpose, the first 100 values of load time in the spreadsheet shown in Figure 13-6 was used to determine the best distribution. Figure 13-8 shows the results of the analysis in STAT:FIT and the forms of distributions and their parameters.

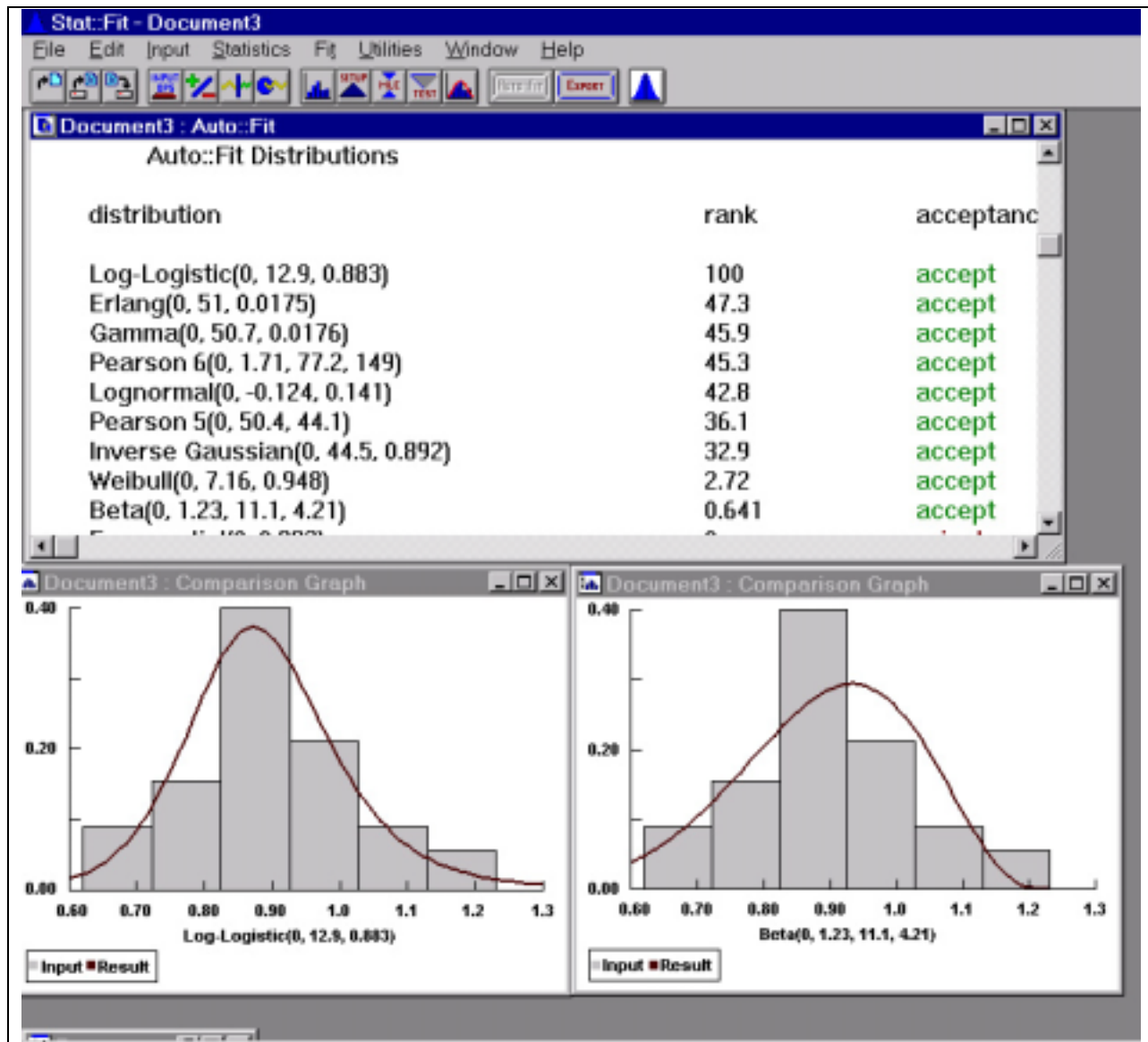


Figure 13-8: Determining the PDF for load time

The same procedure was followed for determining the PDF for payload by copying the column marked 'Payload' in Figure 13-6 into STAT:FIT.

The parametric form of payload in terms of load time has been described in [Section 6.5](#). A pivot table was created for this purpose and is shown in Figure 13-9. The parametric form of payload was obtained by plotting the average and standard deviation of the payload for the corresponding average load time. The graphical plot and the corresponding best fit equation are shown in Figure 13-10.

Data				
Load Time	Average of Load Time	Average of Payload	StdDev of Payload	
0.7-0.8	0.762	0.894	0.086	
0.8-0.9	0.858	0.956	0.120	
0.9-1	0.951	0.993	0.105	
1-1.1	1.047	1.027	0.112	
1.1-1.2	1.146	1.035	0.112	
1.2-1.3	1.245	1.008	0.106	
1.3-1.4	1.347	1.021	0.114	
1.4-1.5	1.452	1.013	0.108	
1.5-1.6	1.549	1.009	0.093	
1.6-1.7	1.653	0.954	0.101	
1.7-1.8	1.741	0.990	0.099	
1.8-1.9	1.842	0.997	0.077	
1.9-2	1.945	0.960	0.079	
2-2.1	2.040	0.992	0.097	
2.1-2.2	2.137	0.973	0.091	
2.2-2.3	2.250	0.995	0.088	
2.3-2.4	2.343	1.002	0.091	
2.4-2.5	2.441	0.994	0.086	
2.5-2.6	2.545	0.937	0.020	
2.6-2.7	2.646	0.945	0.077	
2.7-2.8	2.723	0.956	0.107	
2.8-2.9	2.842	0.971	0.055	
2.9-3	2.955	0.969	0.093	
Grand Total	1.401980198	1.00252861	0.106765479	

Figure 13-9: Pivot table for parametric definition of payload in terms of load time

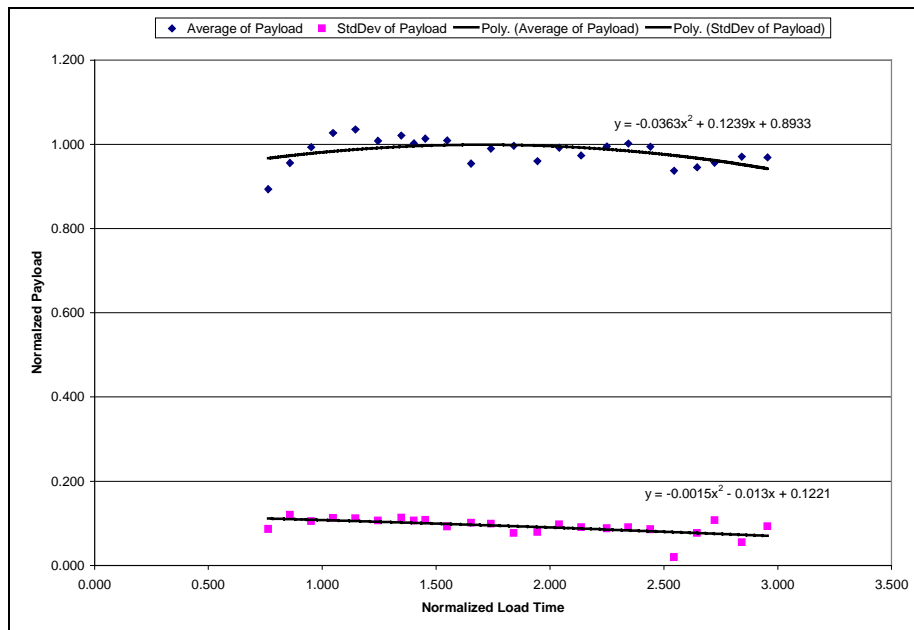


Figure 13-10: Plot of payload in terms of load time

Therefore, on this data

$$P(p) = Normal(M_t, Sd_t) \tag{27}$$

Where

$P(p)$  is the PDF that describes the payload,

$M_t = -0.0363t^2 + 0.1239t + 0.8933$  is the mean of the Normal distribution, and

$Sd_t = -0.0015t^2 - 0.103t + 0.1221$  is the standard deviation of the Normal distribution.

### 13.1.3 Generating the Graphical Representation – PLT Map

Figure 13-5 shows the option marked ‘Show PLT.’ By selecting the option, a PLT Map corresponding to the specified operating conditions is generated and is shown in Figure 13-11. The PLT Map can be printed by right clicking on the window and issuing a print command through MS Excel®.

The generation of a PLT Map is fully automated. However, three different processes were implemented and accomplished within the selection of the option. They are:

- constructing a pivot table,
- normalizing the pivot table, and
- creating the PLT Map.

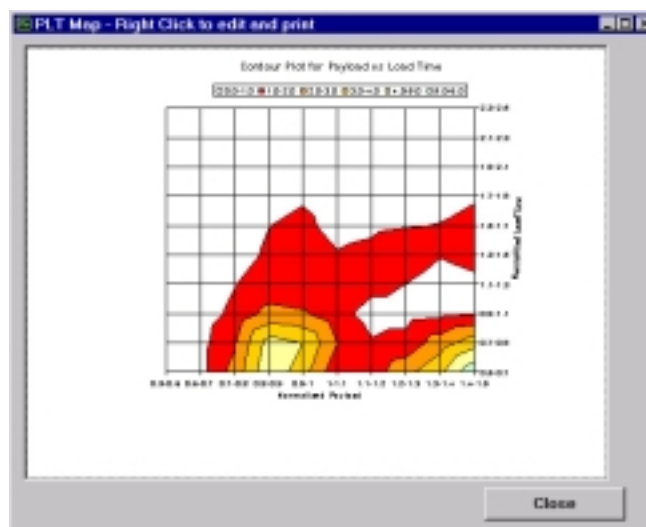


Figure 13-11: A PLT Map generated from the filtered and normalized data

The first process is the construction of the pivot table, which has been explained in Section 6.4.1. The reader is reminded that a pivot table consists of a grid of payload and load time. Each record shown in Figure 13-6 is placed in an appropriate cell based on its value of payload and load time. The pivot created using the normalized payload and load time is shown in Figure 13-12 where each cell represents the count of data points that fall in that range.

Count of LT in Min	LT in Min										Grand Total
Payload	0.5-0.7	0.7-0.9	0.9-1.1	1.1-1.3	1.3-1.5	1.5-1.7	1.7-1.9	1.9-2.1	2.1-2.3	2.3-2.5	
0.5-0.6	42	127	212	158	131	85	65	42	42	17	921
0.6-0.7	84	347	664	403	352	194	149	151	131	92	2567
0.7-0.8	44	212	405	378	281	166	129	125	145	115	2000
0.8-0.9	60	127	150	131	126	99	134	125	108	97	1157
0.9-1	68	274	241	133	78	90	129	142	138	109	1402
1-1.1	48	338	511	301	125	73	63	127	114	109	1809
1.1-1.2	29	400	647	331	147	65	70	113	123	84	2009
1.2-1.3	5	171	260	168	62	28	29	46	53	51	873
1.3-1.4	1	31	59	37	14	7	5	10	10	6	180
1.4-1.5		4	11	7	1	1	1	1	2	3	31
Grand Total	381	2031	3160	2047	1317	808	774	882	866	683	12949

**Figure 13-12: Pivot table showing the actual count of data points in each cell**

The second process is to normalize the pivot table. Using the count of data points does not provide a measure to determine the chance or the probability of obtaining a particular combination of payload and load time. The pivot table was normalized by dividing each cell by the total number of data points. The normalized pivot table makes it easy to observe the relative variance in payload and load time. The normalized form of the pivot table shown in Figure 13-12 is presented in Figure 13-13.

Payload	LT in Min										Grand Total
	0.5-0.7	0.7-0.9	0.9-1.1	1.1-1.3	1.3-1.5	1.5-1.7	1.7-1.9	1.9-2.1	2.1-2.3	2.3-2.5	
0.5-0.6	0.3	1.0	1.6	1.2	1.0	0.7	0.5	0.3	0.3	0.1	7.1
0.6-0.7	0.6	2.7	5.1	3.1	2.7	1.5	1.2	1.2	1.0	0.7	19.8
0.7-0.8	0.3	1.6	3.1	2.9	2.2	1.3	1.0	1.0	1.1	0.9	15.4
0.8-0.9	0.5	1.0	1.2	1.0	1.0	0.8	1.0	1.0	0.8	0.7	8.9
0.9-1	0.5	2.1	1.9	1.0	0.6	0.7	1.0	1.1	1.1	0.8	10.8
1-1.1	0.4	2.6	3.9	2.3	1.0	0.6	0.5	1.0	0.9	0.8	14.0
1.1-1.2	0.2	3.1	5.0	2.6	1.1	0.5	0.5	0.9	0.9	0.6	15.5
1.2-1.3	0.0	1.3	2.0	1.3	0.5	0.2	0.2	0.4	0.4	0.4	6.7
1.3-1.4	0.0	0.2	0.5	0.3	0.1	0.1	0.0	0.1	0.1	0.0	1.4
1.4-1.5	0.0	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Grand Total	2.9	15.7	24.4	15.8	10.2	6.2	6.0	6.8	6.7	5.3	100.0

**Figure 13-13: Pivot table showing the normalized value for each cell**

The third process is the creation of the PLT Map. Points with equal probability are joined together in a manner similar to constructing contours of equal elevation using survey data. The region enclosed by a contour is given a particular color. If the set of operating conditions

specified to filter records are changed or modified in Figure 13-5, then the details have to be processed before creating the PLT Map.

## 13.2 USING EDB FOR HAUL AND RETURN ACTIVITIES

In order to access the experience database for retrieving information on haul and return activities, the option ‘Generate Information on Haul and Return Activities’ is chosen from the screen shown in Figure 13-4. The same processes as used for the load activity were adopted in the case of haul and return activities. The processes are:

- filtering the performance records which match the specified operating conditions,
- determining a PDF to describe the filtered records, and
- generating a graphical representation of the filtered records.

### 13.2.1 Filtering Records

The options for filtering performance records for the haul and return activities are shown in Figure 13-14. The explanation given for such terms as calendar period, site in the discussion on the load activity are also applicable to the haul and return activities. The check box marked ‘Actual Load from OBI’ is not a functional part of the operating conditions. It was added to the system to study the effect of actual payload and rated payload on haul ratios. The details of that discussion have been presented in [Chapter 10](#).

By selecting the option marked ‘Choose Haul Name,’ the user is presented with the interface to the *Travel Time Calculator* as shown in Figure 13-15. The operating conditions for the haul road is specified in terms of the ‘Haul Surface’ and ‘Super Elevation.’

Figure 13-14: Filtering options for the haul and returning activities

Segment	Length (m)	Rolling Resistance (%)	Grade (%)	Max Speed (mph)
1	60.00	3.00	1.00	60.00
2	150.00	3.00	-16.10	12.00
3	60.00	3.00	8.10	20.00
4	360.00	3.00	8.00	60.00
5				
6				
7				

Figure 13-15: Travel Time Calculator interface

The haul name is the link between the performance records and the haul road profiles. It is possible that there is more than one type of truck performing the same haul operation. Therefore, the user is required to choose both the haul name and the truck model from the lists provided. The haul road profile is retrieved from the previously saved version. By selecting the option marked 'Exit,' the user is taken back to the screen shown in Figure 13-14 where the haul name

and the truck model are automatically entered in their respective input boxes as shown in Figure 13-16.

By selecting the option marked ‘Process Haul Ratios’ or ‘Process Return Ratios’ the appropriate set of ratios are calculated and stored in a single column in a spreadsheet. The procedure involved in creating the haul ratio is as follows. From each filtered record, the actual payload and actual haul time are extracted. The actual payload is used to determine a theoretical estimate of the haul time specified by ‘Haul Name’ using the *Travel Time Calculator*. The haul ratio is calculated by dividing the actual haul time and the corresponding theoretical haul time due to the actual payload. The haul ratio for each filtered record is written to a spreadsheet. The calculation of return ratio requires a lower order of computation because the trucks are empty and hence payload is not a part of the calculation. It is sufficient to calculate the theoretical estimate for the return time just once.

**Figure 13-16: Filtering records by choosing the appropriate haul name and truck model**

### 13.2.2 Determining the PDF

STAT:FIT is again used for the purpose of determining the best distribution that fits the filtered records. The spreadsheet facilitates in copying the data to STAT:FIT. Examples of sample distributions which were defined for the haul and return ratios which were filtered based on a particular haul name are given in the screen shown in Figure 13-17 and Figure 13-18 respectively.

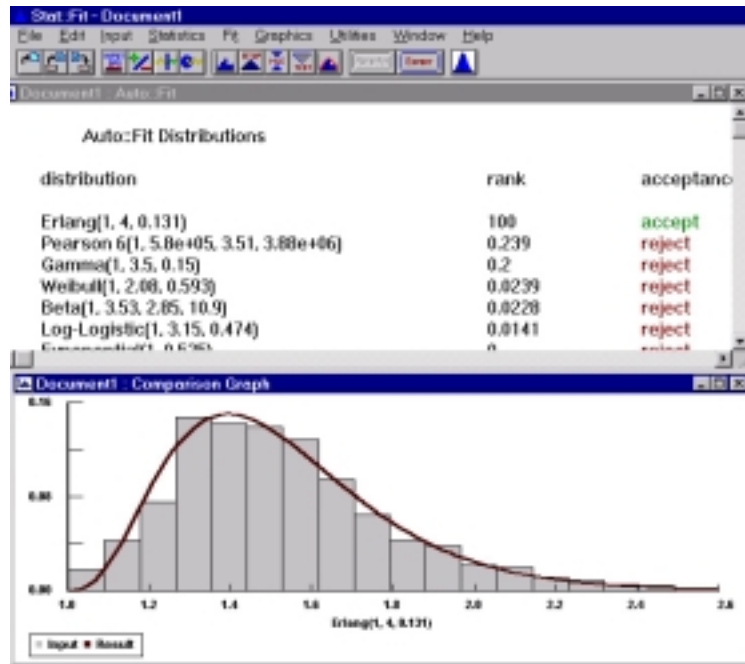


Figure 13-17: PDF for haul ratios

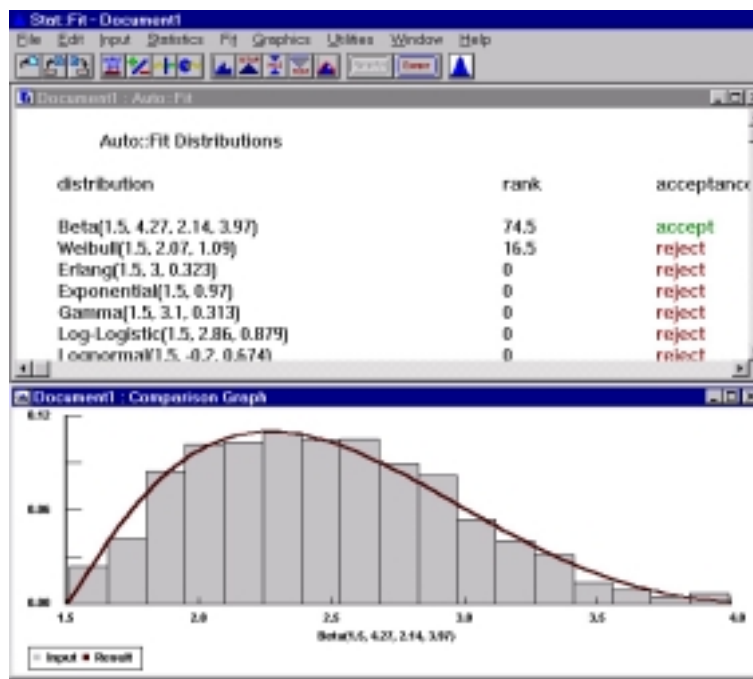
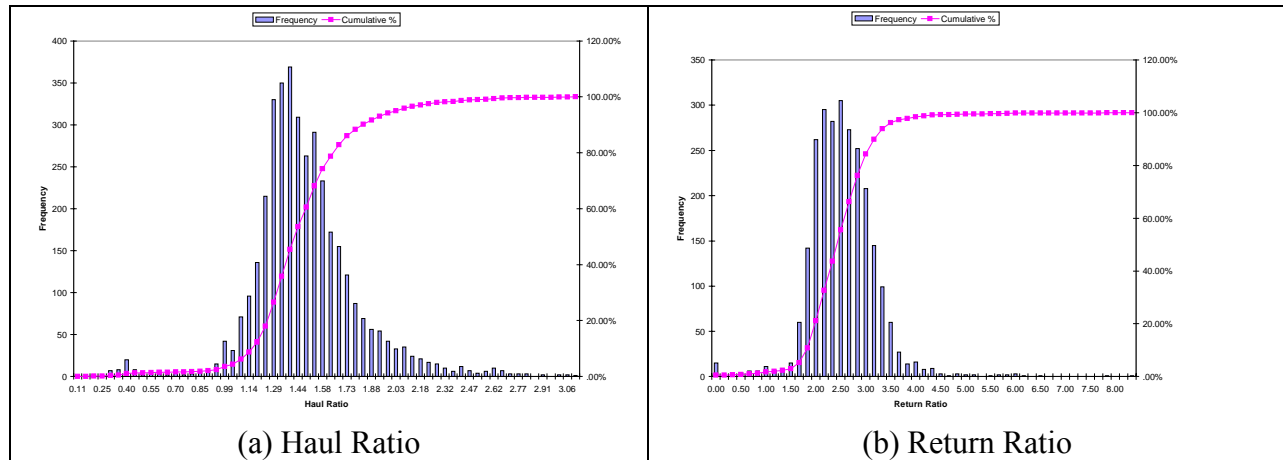


Figure 13-18: PDF for return ratios

### 13.2.3 Generating the Graphical Representation

Chapter 7 described the graphical representation of the haul and return ratios in the form simple histograms. The histograms were created in MS Excel<sup>®</sup>. Samples of haul and return histogram generated are shown in Figure 13-19.



**Figure 13-19: Haul and return ratios for the filtered haul name**

## 13.3 PREDICTING CYCLE TIME COMPONENTS

The PDFs derived for the load, haul and return components of the cycle time describe the relative variance in the operations due to the specified operating conditions. If the same specified operating conditions are expected in a future project, then the probabilistic estimate for the duration of each component can be derived as follows. This derivation is illustrated through an example.

### Example

Let the target load time for the combination of the loader-truck be 2.0 minutes.

Let the target payload of the truck be 100 tons.

Let the theoretical estimate for haul and return times as determined using the travel time calculator be 5.45 minutes and 4.2 minutes respectively.

The estimates for the duration of the activities can then be given by Table 13-1. The durations are product of the reference values and the corresponding PDF. The reference values for load time and payload are the target values and for the haul and return times, it is the theoretical estimate of the respective times.

**Table 13-1: Predicted duration of the activity**

Activity	Estimate for Duration / Payload
Load – Load time	2.0*Log-Logistic(0,12.9,0.883) min
Haul Time	5.45*Erlang(1,4,0.131) min
Return Time	4.2*Beta(1.5,4.27,2.14,3.97)

These distributions of activity duration become the input to simulation models such as those developed in CYCLONE or STROBOSCOPE. It is not within the scope of this dissertation to describe the implementation of these distributions with a simulation model. However, it is worth noting that ‘Payload’ does not refer to an activity duration and hence cannot be used within a simulation engine such as CYCLONE. Programmability and end-user extensibility are essential for incorporating non-duration parameters such as payload distribution. Figure 13-20 shows a snippet of code written in STROBOSCOPE language to implement the parametric form of payload. Details of the STROBOSCOPE language can be found in Martinez [1996].

```

1 VARIABLE nSamples 8000;
2 VARIABLE ltf ScaledBeta[0,1.23,11.1,4.21];
3 SAVEVALUE lt 0;
4 VARIABLE Mean -0.0363*lt^2+0.1239*lt+0.8933;
5 VARIABLE Dev -0.0015*lt^2-0.013*lt+0.1221;
6 VARIABLE PayloadDist Normal[Mean,Dev];
...
...
...
7 COMBI LoadTruck;
8 ONSTART LoadTruck ASSIGN lt ltf;
9 DURATION LoadTruck lt;
10 ONEND LoadTruck Assign Truck.Payload PayloadDist;
...
...
...
11 SIMULATEUNTIL LoadTruck.TotInst>=nSamples;

```

**Figure 13-20: A snippet of code from a model developed in STROBOSCOPE to implement payload distribution**

For the purpose of illustration, line numbers are shown on extreme left of each statement. Line 2 refers to a variable `ltf`, which is set to a `ScaledBeta` function. Every time the variable `ltf` is referred to in the program, it is replaced by the particular value sampled from the `ScaledBeta` function. Similarly, line 4 & 5 show two variables `Mean` and `Dev` which are in turn part of another variable called `PayloadDist` shown in line 6. Line 7 shows the name of the activity, namely, `LoadTruck`. In line 8, every instance of `LoadTruck` triggers the variable `ltf` to be sampled from the `ScaledBeta` function and stored in `lt` (unlike a variable, a `Savevalue` retains its value). The value of `lt` serves as the duration of the `LoadTruck` truck for this instance. The sampled value of `lt` is then used to determine the payload on the truck, which is denoted by `Truck.Payload`. The payload is calculated by sampling from the distribution, `PayloadDist` which is a function of `lt`.

The purpose of explaining this snippet of code is to show how a combination of load time and payload is generated dynamically within a simulation program. The advantage of this method allows the sampling of load time and the calculation of payload at run time. It is not easy to implement the dynamic calculation of payload and load time in a non-programmable environment. The reader may recall that this snippet of code reflects the procedure described in detail in [Section 6.5](#) where the variations in payload and load time were analyzed under the dependency assumption.

## 13.4 SUMMARY

The purpose of this chapter was to explain the steps involved in putting the experience database to work. The steps were illustrated for each component of the cycle time — load, haul and return. For each component, the process of filtering records for the specified operating conditions, generating the graphical representation and defining the data in the form of a PDF were described. Finally, the steps involved in the prediction of duration for cycle time components were explained through an example.

# CHAPTER 14: CONCLUSIONS

This chapter summarizes the accomplishments of this research, the contributions made by this research to body of knowledge, and directions for future research.

## 14.1 SUMMARY

The following issues raised the need for this research:

- The need for a statistically reliable probabilistic data for an activity's performance so as to improve the reliability of results obtained using tools such as simulation.
- The need to create a database of as-built operations which can be used to improve the reliability and confidence of estimates for future operations.
- The need to develop intuitive graphical formats to display production data so that it can be used as an informal technique in improving ongoing operations.

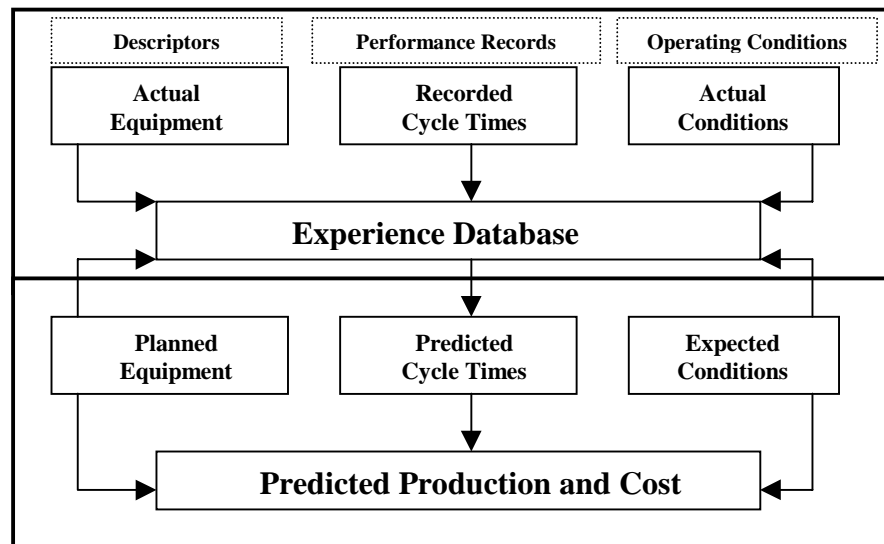
The research needs were addressed through the following:

- The development of performance measures to extract, quantify and understand relative variation in each component of the earthmoving cycle.
- The creation of an experience database in which performance records are linked to the corresponding operating conditions.
- The design and implementation of a PLT Map which can depict the simultaneous variation in payload and load time, i.e., the joint probability distribution surface of payload and load time.

The ability to collect the data required to address these needs as well as to develop the solutions was provided by onboard instrumentation (OBI). Although not specifically designed to collect production data, OBI can be used to collect data in a continuous and autonomous manner. These two features, along with the elimination of error due judgement, provides quality data for the creation and maintenance of the experience database.

The documentation of this research was divided into four divisions, namely, understanding the challenge, developing the methodology, implementing the methodology and review. The core of this research, which is embodied in the divisions developing and implementing the methodology, is recapped here.

Figure 14-1 captures the framework of this research in the form of the experience database. The experience database is a repository of historical data in which performance records are linked to the corresponding operating conditions. The experience database is company- or project-specific, dynamic and in an electronic format. By defining a PDF for the subset of records which match the specified operating conditions, it is possible to provide statistically reliable probabilistic data to improve the reliability of results obtained using simulation.



**Figure 14-1: Framework of research: Experience Database**

The development of an experience database requires performance records in terms of the cycle time data and information on operating conditions. Descriptors, which include the actual equipment, are required to normalize the performance data. In the case of haul and return activities, the descriptors include haul road profiles, which form an important part of the normalization process. The experience database can be put to use by filtering records so as to utilize only those records which match the specified operating conditions.

The performance measures for load, haul and return activities involved extracting and quantifying the relative variance from the performance records for a set of operating conditions. The extraction of variance involves normalizing the activity time using reference values based on the descriptors. The normalizing process in case of load activity is performed by dividing the payload and load time by the corresponding target values. The normalizing process in the case of the haul and return activities was performed by dividing the actual haul and return times by the corresponding theoretical travel time. The theoretical haul times had to be calculated for every cycle using the actual payload. Therefore, a *Travel Time Calculator* was built as part of this research.

The quantification of variance was through the development of the moments of the data and determining a probabilistic distribution which closely matched the data. It is this distribution of variance that will be used along with an appropriate reference value for a set of descriptors on a future operation. The product of the reference value and the distribution provides the input to activity times in a simulation model.

A graphical tool called PLT Map was developed to depict the simultaneous variation in payload and load time. Parametric form of payload in terms of load time, and haul time in terms of payload were described to provide a method for calculating the corresponding parameters within a simulation model.

This division of the dissertation also included a statistical analysis of the effect of operating conditions on various components of cycle time. The operating conditions were structured into two levels of hierarchy – global and project-specific factors. Global factors included projects, loading method and operator efficiency while project-specific factors included material type, floor conditions, haul surface etc. The project-specific factors were analyzed within the boundaries of the global factors.

This analysis served two purposes. First, it determined a list of operating conditions for each component of cycle time which have an effect on the performance. These operating conditions can then be used to characterize the activity's performance. For example, material type was found to be an important operating condition for the performance of the load activity. Secondly,

the analysis facilitated the development of metrics, which can be used as yardsticks to characterize the performance data. For example, length and downshift can explain nearly half the variance in haul times and hence can be used to characterize haul time. Unlike other factors, the number of downshifts is not recorded on the site; it is a byproduct of other factors such as length, grade, rolling resistance, and payload. It was estimated theoretically.

The division on implementing the methodology showed how a prototype experience database was created using real field data and then used to derive production statistics. The purpose of the prototype was to implement the concepts and procedures developed in the previous division. The prototype is based on three principal processes:

1. Importing new performance records and information on operating conditions.
2. Filtering records in the experience database so as to obtain only those records which match the specified operating conditions.
3. Automate the generation of graphical techniques such as PLT Maps and Travel Time Histograms.

The prototype was created in MS Visual Basic<sup>®</sup> using the database capability of MS Access<sup>®</sup> and charting capability of MS Excel<sup>®</sup>. A step by step instruction on using the prototype and the procedures involved were explained. The prototype has the ability to automatically display the graphical representations; however for defining the probabilistic distribution of the data, the services of an external program, STAT:FIT was used. Explanation of data transfer between the two systems and the basic features of STAT:FIT were also illustrated.

## 14.2 CONTRIBUTIONS

This research represents a step change in data collection and analysis for planning and managing earthmoving operations. The experience database contributes to both formal and informal techniques in planning and managing operations. The following list summarizes the contributions made by this research:

1. Described the methodology to create and use an experience database.
  - Designed systems to collect performance records and operating conditions and link the two forms of data. Demonstrated the methodology through the development of a prototype.
  - Showed the strengths and weakness of the onboard instrumentation systems (TPMS<sup>®</sup> and VIMS<sup>®</sup>) for collecting performance records.
  - Reviewed methods for collecting information on operating conditions and showed how the image database (IDB) is one of the best ways of collecting operating conditions.
    - Showed how the IDB helps in providing a common reference for subjective information.
    - Showed how the IDB aids in interpretation and communication.
2. Developed a methodology to derive statistical parameters for defining each component of cycle time.
  - Showed how the data from vehicle instrumentation can be used to develop production statistics and hence improve the validity of results obtained using tools such as simulation.
  - Showed how the relative variance in load and travel times could be extracted using normalization. The normalization in the case of load time is scaling factor based on target payload and load time while in the case of haul time, it is a dynamically computer ratio of actual travel time to theoretical travel time.
  - Confirmed the results obtained by previous research in terms of the distribution which can be used to model construction data [AbouRizk and Halpin 1992b].

3. Showed the importance of operating conditions and the need to link the performance records with the operating conditions
  - Identified and statistically tested operating conditions which can be used for characterizing performance records for each component of the earthmoving cycle.
  - Confirmed and explained various results obtained by previous research in terms of effect of payload on production [Schexnayder *et al* 1999].
  - Developed a metric (sequence of downshifts) as a function of operating conditions which has statistical validity in characterizing performance records pertaining to haul time.
4. Showed how a large volume of data could be transformed into a relatively simple and intuitive graphical format and use the graphical form for managing operations.
  - Showed how graphical representation can be used as an informal technique to improve on-the-job communication.
  - Described how the graphical representation can help managers as well as the site crew to better understand the operation and hence make improvements to current methods.
  - Discussed how the graphical representation can serve as benchmarks for operations under different operating conditions.

### 14.3 PRACTICAL RELEVANCE OF THE RESEARCH

[Section 14.2](#) specifically addressed contributions made towards the body of knowledge. This section emphasizes the practical significance of this research in addition to the academic contribution and hence, highlights the links to the statements made in [Section 1.8](#) on “Industry Relevance.” The practical relevance of this research is illustrated through an example.

#### *Limited Time-Window versus Continuous Data Collection*

The advancement from stopwatches to instrumented vehicles for productivity data collection was explained in [Section 1.3](#). The following example illustrates the significance of continuous data

collection and the need to understand the data analysis process. Stopwatch-based data collection can be imagined to be a limited time-window data collection wherein an observer spends a period of the day to collect relevant data.

Table 14-1 shows a comparison between data collected for limited time-windows and for a continuous format. The column named “time” indicates the time of the day.

**Table 14-1: A comparison of limited time-window and continuous data collection**

Day	Time	Average	Std. Dev	Distribution
1	0730-1000	4.312	0.59	Triangular(3,5.61,4.36)
	1000-1230	5.045	1.31	Log-Logistic(3,3.2,1.67)
	1300-1530	5.262	1.05	Weibull(3,2.45,2.55)
2	0730-1000	4.664	0.53	Weibull(3,3.72,1.85)
	1000-1230	4.351	0.48	Weibull(3,3.09,1.51)
	1300-1530	4.524	0.95	Weibull(3,1.63,1.7)
Continuous		4.422	0.60	LogNormal(0,1.48,0.136)

The data used in the table corresponds to the load time of a truck. It is clear that by choosing to observe the operation for a limited time-window of two-and-a-half hours at different points in a day can result in varying values of average and standard deviation of the load time. The column named “distribution” refers to the probabilistic density function which best models the data for use as input to simulation models.

If the operation is precisely the same for each cycle throughout the day in a manner similar to an assembly line in a manufacturing plant, then it is possible that the distribution for each time-window is the same. The reason for the different forms of distribution for each time-window can be attributed to several factors. Inherent variation in the operation, changes in the type of material, space constraints and floor conditions, and effect of the time of day on the human body are some of the causes for the variation in the operation.

The number of observations during each time window varies from ten to fifteen cycles. The statistical reliability of defining a probabilistic density function for a small data set such as ten or fifteen data points is much lower than defining the distribution for the continuous data set. The

benefits of the continuous form of data collection are that a large volume of data is available and that the data is not limited to a particular time window.

This data analysis highlights the role of continuous data collection in relation to limited time-window observation and hence, its significance in the application to operation analyses tools such as simulation. However, there are some limitations to the continuous form of data collection. Each of these limitations and the corresponding solutions developed as part of this research are discussed next.

#### *Volume of information*

Although the volume of information generated by onboard instrumentation provides a remedy for the statistical requirements of the data analysis process, the burden of understanding a large volume of data, the patterns embedded in them and the causes for reduction in productivity, if any, are not easy tasks. Burch and Strater [1983] note that

*“...Organizational decision makers are subjected to an avalanche of data. Particularly where computers are utilized, great quantities of data are collected, processed and reported. For a given decision maker, these reports might be meaningless, or some relevant information might be found, if the recipient is willing to spend time searching for it.”*

Vorster [1980] cites Quastler and Wolf [1952] on the issue of information overload who state that some of the reactions by individuals to information overload are as follows:

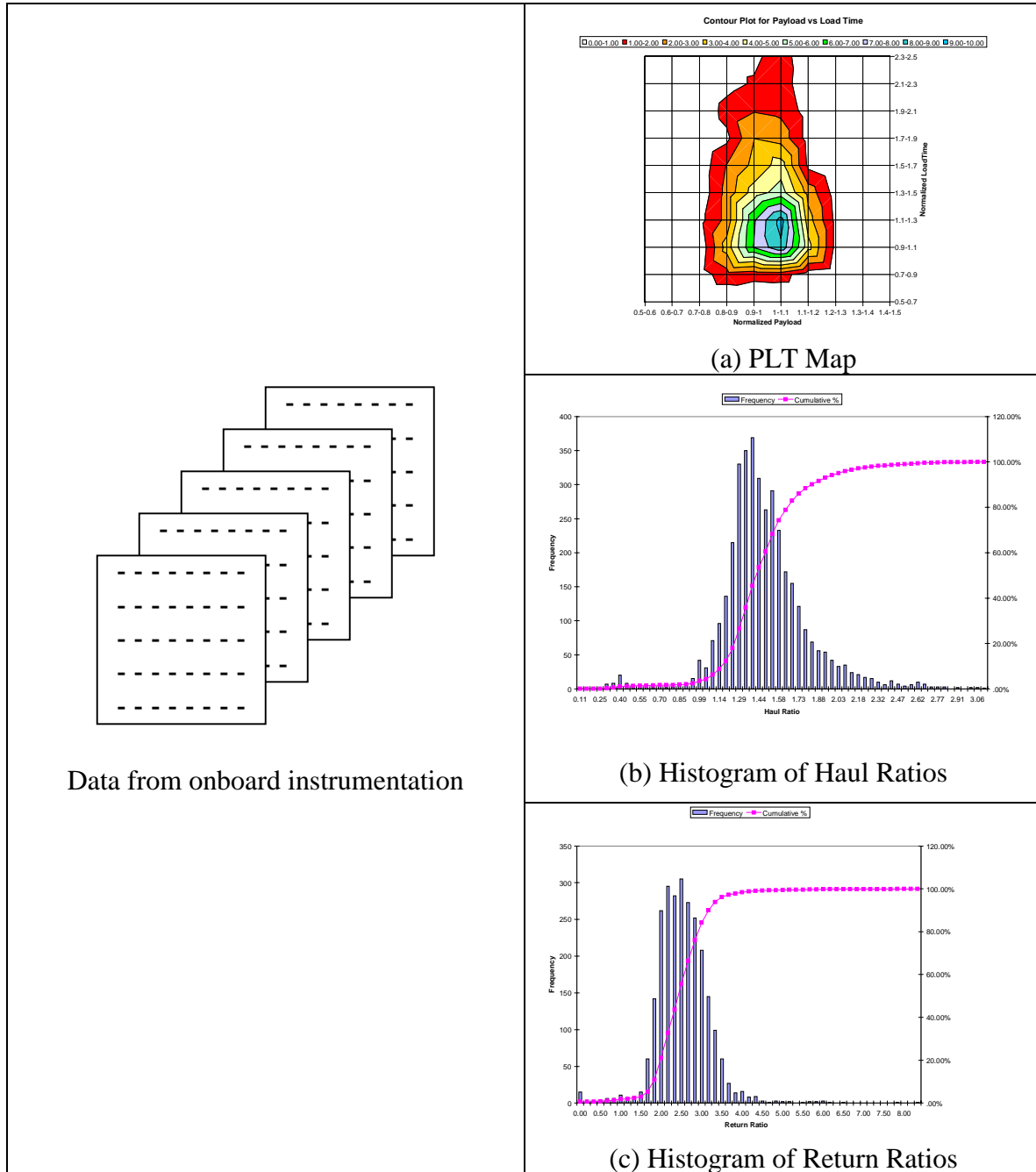
- Omission – not processing.
- Error – incorrect processing and failure to correct.
- Queuing – delay responses to lower load periods.
- Filtering – systematic omission of certain information.
- Approximation – less precise responses.
- Escape – leaving the situation or taking steps to cut off the information input.

This research addressed the issue of information overload by developing powerful yet intuitive graphical techniques. Consider that each truck equipped with the onboard instrumentation system generates productivity data as shown in Figure 14-2. It is not difficult to imagine the overload of information which would occur when data from different trucks for a period of say six months are pooled together. It is not very intuitive to use data in this format for decision making to improve ongoing operations or to project estimates for future operations.

Date	Time	Payload	EmptyTravel	EmptyDist	EmptyWait	LoadTime	LoadedWait	LoadedTravel	LoadedDist
11/06/98	7:45	121.3	5.78	0.9	41.8	7.62	0.58	11.67	1.5
11/06/98	8:24	96.2	11.22	1.5	13.9	3.42	0.52	9.78	1.5
11/06/98	8:57	122.5	8.48	1.5	7	7.07	0.4	10.35	1.5
11/06/98	9:22	101.1	7.95	1.5	2.62	3.87	0.67	9.72	1.5
11/06/98	9:47	128.6	8.1	1.6	5.18	4.18	0.4	7.53	1.1
11/06/98	10:15	116.1	7.1	1.1	5.77	3.33	0.75	10.42	1.5
11/06/98	10:39	99.1	7.75	1.5	5.12	3.62	0.43	7.47	1.1
11/06/98	11:05	128.6	6.63	1.1	6.6	4.75	0.42	7.55	1.1
11/06/98	11:33	113	7.45	1.1	7.7	4.25	0.4	8	1.1
11/06/98	12:39	122.4	0	0	0	0	27.1	8.25	1.3
11/06/98	13:04	127.5	8.9	1.5	3.27	3.77	0.38	8.18	1.1
11/06/98	13:32	132.7	2.8	0.4	2.12	3.9	1.3	7.65	1.1
11/06/98	14:01	128.4	7.25	1.1	5.85	4.85	0.5	10.77	1.5
11/06/98	14:29	134.5	8.07	1.4	7.43	4.33	0.42	7.62	1.1
11/06/98	14:53	134.5	6.2	1.1	5.13	4.35	0.42	7.9	1.1
11/06/98	15:15	140.3	6.62	1.1	2.88	4.32	0.43	8.35	1.1
11/06/98	15:40	135.7	7.15	1.1	3.75	3.97	0.43	9.48	1.4
11/06/98	16:05	128.8	8.42	1.5	5.12	3.62	0.4	7.8	1.1
11/06/98	16:28	137.4	6.7	1.1	3.35	4.45	0.38	7.37	1.1
11/06/98	16:48	154.2	5.92	1.1	4.7	3.5	0.43	5.55	0.8
11/06/98	18:28	116.9	4.53	0.9	13.62	3.38	0.33	6.48	0.8
11/06/98	18:52	130.6	5.25	0.8	9.1	3.68	0.38	6.27	0.8
11/06/98	19:13	119.7	4.92	0.8	1.32	6.82	0.33	7.38	0.8
11/06/98	19:30	116.6	4.57	0.9	1.97	3.78	0.33	5.98	0.8
11/06/98	19:47	121	4.45	0.8	0.53	5.45	0.33	6.68	0.8
11/06/98	20:07	122.3	4.6	0.8	1	6.75	0.4	6.8	0.8
11/06/98	20:33	122.3	5.42	0.8	9.3	4.33	0.32	6.72	0.8
11/06/98	20:52	101.4	4.65	0.8	0.47	5.17	1.38	6.8	0.8
11/06/98	21:10	119.7	4.87	0.8	0.02	5.9	0.38	6.9	0.8
11/06/98	21:30	121.3	4.95	0.9	3.85	4.15	0.37	6.93	0.8
11/06/98	21:50	115.9	5.02	0.9	1.87	5.57	0.38	7.07	0.8
11/06/98	22:10	124.8	4.25	0.8	3.23	4.4	0.62	7.5	0.9
11/06/98	22:40	122	1.58	0.1	8.05	5.22	0.42	6.47	0.9
11/06/98	23:02	132.4	5.53	0.9	3.27	4.93	0.38	8.07	0.9
11/06/98	23:20	115.9	5.55	0.9	1.43	3.45	0.53	7.5	0.9
11/06/98	0:02	135.5	5.48	1.1	0.08	4.25	22.52	10.13	1.9
11/06/98	0:29	151	5.93	1.1	6.8	7.55	0.38	6.65	1.1
11/06/98	0:58	124.1	5.63	1.2	10.75	5.45	0.38	7	1.1
11/06/98	1:18	128.1	6.03	1.1	2.25	2.98	1.18	6.9	1.1
11/06/98	1:35	139.7	5.3	1.1	0.82	3.65	0.45	6.78	1.1
11/06/98	1:56	148.7	6.08	1.1	2.5	5.02	0.43	7.3	1.1
11/06/98	2:18	131.6	6.38	1.1	2.68	4.78	0.38	7.45	1.1
11/06/98	2:36	141.4	5.73	1.1	1.17	3.78	0.38	7.32	1.1

**Figure 14-2: Data from onboard instrumentation system**

Figure 14-3 shows the methodology developed by this research to transform raw data from onboard instrumentation into an useful information which provides the basis for knowledge and application during the process of decision-making.



**Figure 14-3: Transformation of data to information**

Burch and Strater [1983] add that

*“...Instead of producing streams of data to be handled by the decision maker the information system monitors the data and provides information outputs to the decision maker...”*

#### *Effect of Operating Conditions on Performance*

The other significant limitation with onboard instrumentation is the inability to collect information on the operating conditions. It has been pointed at several stages of discussion that the data stream generated by the onboard instrumentation is indiscriminate which means that it is not possible to discern the data based upon the prevailing operating conditions. If data corresponding to different operating conditions are pooled together, the effect of each set of conditions is lost. The average performance under a wide range of conditions is good as an overall indicator but does very little towards generating useful information for any particular set of condition. This research addressed the issue of indiscriminate nature of onboard instrumentation data by developing the experience database wherein the information on the operating conditions is linked to the corresponding performance records.

This section on “Practical Relevance” illustrates the significance of this research to the industry. It also implicitly highlighted the thesis statement developed at the outset of this dissertation. The planning, estimating and managing of earthmoving operations can be improved by:

- a) understanding the data generated by the onboard instrumentation and using the continuous data collection to feed operations analyses tools,
- b) converting the large quantity of data collected into useful information so that a decision maker can be better informed about the operation, and
- c) linking the prevailing operating conditions with the performance records so that the estimates projected for future operations are realistic and reliable.

## **14.4 LIMITATIONS**

The following are some of the limitations of this research:

- The data collected using onboard instruments pertains only to a loader-truck operation. The performance data collected using TPMS<sup>®</sup> and VIMS<sup>®</sup> consists of load, haul and return times. Dump times are not available. The instrumented data cannot be extended to other earthmoving operations such as scrapers, trench work, etc.
- The onboard instrumentation systems used in this research, TPMS<sup>®</sup> and VIMS<sup>®</sup>, are highly structured. However, there are instances when abnormal values are recorded. The performance records are limited by the quality of data generated by these systems. It is also not possible to modify or make changes to the form of data that can be collected.
- Collecting information on operating conditions is subjective and hence is limited by the consistency with which it is recorded on the field. Image database addresses this issue only to an extent where it provides a common reference.
- The frequency with which performance records are collected is not the same as the frequency with which information on operating conditions are collected. A representative set of information on operating conditions is recorded once a day. Therefore, linking a set of operating conditions for a day to the corresponding performance data is limited by the validity of the representative information to the entire day. Although data preparation as discussed in [Chapter 12](#) addresses this issue, it is only a surrogate measure.

## 14.5 DIRECTIONS FOR FUTURE RESEARCH

There are several possible directions for future research. These recommendations are grouped together under appropriate headings.

### *Data Collection*

- Develop a mechanism by which a truck operator can enter certain codes that represent the operating conditions on the onboard instrumentation keypad. This will ensure that the frequency of collecting the performance records and the information on operating conditions is the same.

- Develop a mechanism to record the position of the dump lever, thereby recording the dump time.
- Develop a system to record the number of loader passes required to load a truck. The number of passes may help in understanding further the effect of operating conditions on the load activity.
- Implement a system based on proximity calculation or data loggers to collect the instantaneous speed of the truck. The comparison of actual and theoretical instantaneous speeds will provide insight into the hauling operation.

### *Methodology*

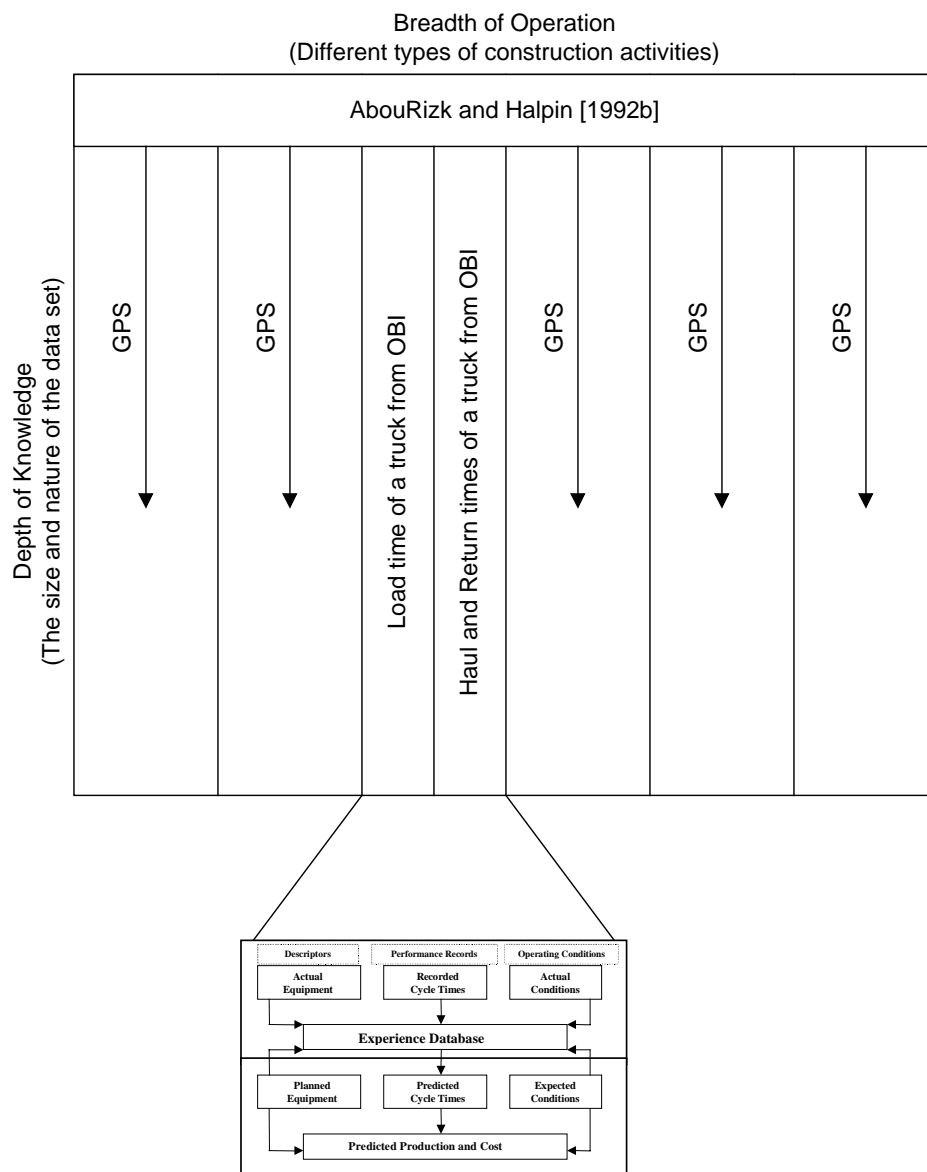
- Develop a method to determine the haul ratio as a function of instantaneous speeds and determine if it is different from calculating the ratio based on travel times.
- Determine actual downshifts and use it to study the effect on haul ratios. The gear downshifts used a characterizing factor in [Chapter 10](#) is a theoretical estimate. A correlation between the actual downshifts and haul ratio may provide a better understanding of the effect.
- Use OBI data to validate a simulation model. Use load, haul and return times as input and validate using wait times as reported by OBI with average wait times in queues.
- Use machine learning techniques such as neural networks to determine and predict the effect of operating conditions on performance.

### *Technology*

Figure 14-4 shows a schematic representation of the breadth and depth of knowledge in construction data. AbouRizk and Halpin [1992b] studied 71 sets of different construction activities. The data used in this study was collected using manual techniques such as stopwatches, time-lapse photography and video taping. They note that the minimum size of sample used was 20 data points. Their study represents a good breadth of construction activities. However, the study does not represent the depth of data. This research, on the other hand,

represents a good depth in one activity, namely, loader-truck operation. Therefore, in order to further the knowledge of construction data, the following alternatives are suggested.

- Use onboard instruments on other equipment such as loaders, scrapers, dozers etc. However, onboard instruments may not be adaptable to a lot of other equipment.
- Use proximity calculations based global positioning technology. A detailed design of a production data collection system using GPS is included in Appendix C. The challenge is to implement the concepts by adapting the technology appropriately.



**Figure 14-4: Breadth and depth of knowledge in construction data**

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# APPENDIX A: TRAVEL TIME CALCULATOR

Fundamental laws of motion states that the forces (F) relating to a moving body is function of its mass and acceleration and is given by Eq (a).

$$F = ma = m \frac{dv}{dt} \quad (a)$$

where

$m$  is the mass,

$a$  is the acceleration,

$t$  is the time interval and

$v$  is the velocity of the body.

The two forms of forces acting on a moving body are tractive (TE) and resistive forces (R) and their relation is given by Eq(b).

$$TE - R = ma = m \frac{dv}{dt} \quad (b)$$

Tractive effort in the case of a truck is a function of the engine power, the gear ratios in the transmission and the speed of the vehicle. Therefore, the tractive effort is different for different gears and is usually given by a rimpull chart by the manufacturer. The resistive force is a combination of grade, friction, air, drag and lifting forces. Since the trucks travel at relatively low speed, resistance due to air, drag and lifting forces are not considered in the computation. The resistive force is primarily due to grade and rolling resistance. In Eq (b), if the acceleration is zero, then the tractive forces and resistive forces balance one another. If this condition does not exist, then there is a positive or negative acceleration; the difference between the forces keeps the vehicles speed changing until an equilibrium is reestablished [Vuchic 1981].

The vehicle's deceleration may be used for two purposes: a) to coast or, b) to bring the vehicle to a stop [Trani 1998]. Coasting is an important consideration in preventing a run-away truck. Consider a truck on a level grade segment followed by a steep downhill grade, which is subsequently followed by several other segments. Since the vehicle is not close to its destination, the logical conclusion is that it can accelerate to a maximum (possible) speed on this segment. If the vehicle enters the downhill grade at that speed, the tractive effort may not be sufficient to hold back the vehicle and that the vehicle can potentially "run-away." In order to prevent this situation, a maximum speed limit from the downhill grade (the speed allowed using the retarder) should be taken into account to determine when the vehicle needs to coast on the level ground. Bringing the vehicle to a stop is determined by the current speed and the ability to decelerate without causing discomfort to the operator. All the above mentioned factors and issues were taken into consideration while developing the *Travel Time Calculator*.

A library of rimpull charts and specifications such as empty mass for different models of trucks is created using the manufacturer's data. For every project, the user is required to enter complete information such as length, grade, rolling resistance and maximum speed (either due to project restriction or retarder control) for each segment and the type of truck. Since it is possible that the maximum speed of a truck is model dependent, it is suggested that the haul time for each truck type be calculated individually. At run time, the user specifies the payload as an argument to the function call and the calculation of the haul time is based on this payload. The pseudo-code for the routine is provided below.

```

Calculate Haul Time (Truck Type, Segment Details, Payload) {
Initialize current position, velocity, time increment
For all segments do {
    Get next segment maximum speed
    Get the starting position of the next segment
    While current position < starting position of next segment, do {
        Increment time
        Determine stopping distance
        Determine acceleration or deceleration
        Velocity = Velocity + time increment * acceleration
        Velocity = Min (Velocity, Maximum speed allowable on segment)
        Current position = Current position + velocity * time increment
    }
}
}

```

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## APPENDIX B: PRODUCTION DATA COLLECTION USING GPS

The proposed design using the global positioning system considers the receiver as a passive position-time collection device. All the processing involved is done off the receiver, on a base computer. This appendix presents a method to convert raw position data to an activity table similar to that of an onboard instrumentation system.

### *Proximity*

Proximity is defined as the distance between each truck with respect to the loader and other reference points on the site such as dump beacon, project office etc. Through simple geometric calculations, the distance between the objects can be determined. A sample proximity matrix is shown in Table 2.

In Table 2, MP1 through MP4 (MP stands for Moving Points) represents four different trucks, RP1 (RP stands for Roaming Points) represents the loader, RP2 represents a dumpsite light-beacon, RP3 represents a secondary dumpsite and FP1 represents a benchmark on the site. Note that the proximity matrix is calculated for every time instant that the data is recorded. It is also worth noting that the matrix can be refreshed for every record because the proximity matrix is used for determining just the status table.

**Table 2: Proximity matrix at a particular instant of time**

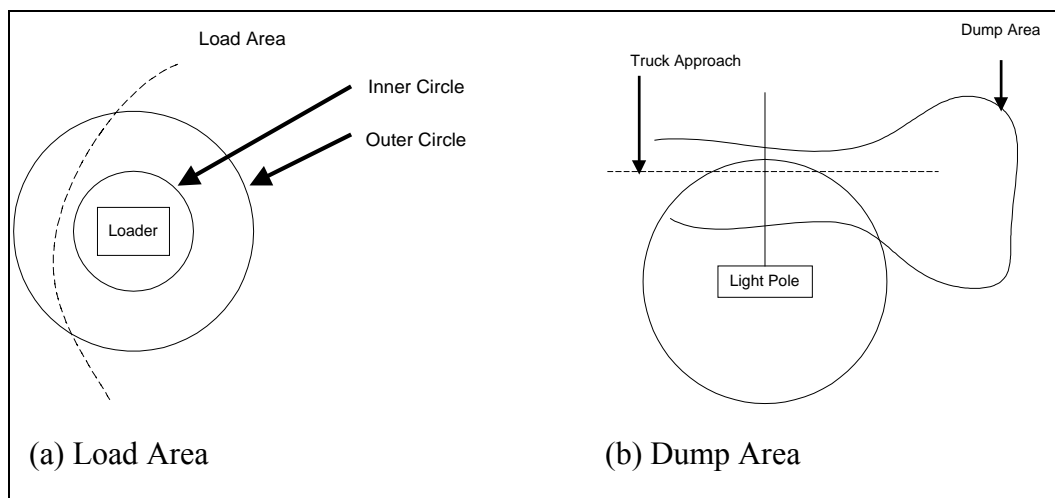
	RP1	RP2	RP3	FP1
MP1	4	200	220	200
MP2	50	150	150	100
MP3	200	5	150	175
MP4	175	200	10	125

### *Rules*

Converting the proximity matrix to a status table involves rules. These rules are domain-dependent. The domain knowledge is a function of the equipment used, site configuration and

elementary construction experience. Figure 5 shows the load and the dump areas and the application of rules.

The diameter of the inner and outer circle can be defined based on the size of the equipment and the space constraints. Consider that the inner circle is 10m in diameter and the outer circle is 25m in diameter. The presence of the truck within the inner circle (proximity of the truck to the roving point = loader) suggests that the truck is loading. It is very unlikely that the truck is hauling, returning or dumping with that proximity value. The only other option is that the truck is probably waiting to get loaded, while the loader is performing some support work. One can conveniently and realistically assume that chance of a loader performing support when a truck is waiting to get loaded is minimal. Now consider that a truck is present within the outer circle but not within the inner circle. This suggests that the truck is far enough from the loader that it cannot be loading. Logically, the other alternatives are that the truck is maneuvering within the load area or it is waiting to get loaded. The distinction between the two states can be made based on the speed of the truck. If the truck's speed is close to zero, then the truck is waiting to get loaded. The same line of reasoning can be extended to the dump area as well.



**Figure 5: Load and dump areas and the corresponding rules**

Determining the presence of a truck in the dump area involves the calculation of the distance between truck and the dump site reference point. Figure 5b is a typical representation of an approach to dumpsite with the global positioning receiver placed on a light beacon. The line of

approach of truck forms a chord to the circle of influence (can be determined based on the vehicle dimension and site configuration). From basic geometry, the shortest distance between the chord of a circle and its center is the perpendicular line drawn from the center to the chord. Therefore, by monitoring the deflection point in the proximity of the truck to the dump reference point, the entry of the truck into the dumpsite can be determined. Similarly, the exit of the truck from the dumpsite can be determined in the same way. The two points can be differentiated using a flag because each entry-exit pair cannot exist independent of one another.

Determining haul and return involves the process of elimination. If a truck is not loading or dumping then the truck is in transit. Transit could include both *hauling* and *returning*; the only mode of identification is whether the load of the truck is greater than its empty weight. Since GPS system does not include physical sensor, a different approach has to be followed. It is obvious that a truck is loaded if it has completed the activity *loading*. By maintaining a variable called *previous\_state*, it is possible to determine whether the truck is hauling or returning. Similarly, by using speed as a parameter, it is possible to determine whether the truck is moving or stationary. The cycle time can be calculated using the difference between two time stamps of identical position.

Revisiting Table 2, it is straightforward to deduce that Truck #1 is loading, Truck #2 is in transit, Truck #3 is at the main dump area and Truck #4 is at the secondary dump area.

### *Status table*

Based on the rules, a status table identifies the action being performed at every instant the data is recorded. Table 3 is an example of a status table for a particular truck. In the example shown in Table 3, the status of a particular truck is *loading* from time instant 4:00:00 through 4:01:45. It is intuitive to determine the duration of the load activity, which is 0:01:45. Since the status table is sorted on time stamp, the duration of an activity is the difference between the last time stamp and the first time stamp for the same status. The status table need not be maintained in the memory because once it is parsed, the activity table can be created.

**Table 3: Status table for a particular truck**

Time Stamp	Status
3:59:55	Waiting To Load
4:00:00	Loading
4:00:05	Loading
...	...
...	...
4:01:45	Loading
4:01:50	Hauling

*Activity table*

An example of an activity table is shown in Table 4. Deriving the activity table is a routine procedure based on the status table. Once the state of the status changes, the duration of the status can be calculated and recorded in the activity table. Note that it is essential to record the date and time for validation as well as the experience database.

**Table 4: Activity table for a particular truck**

Date	Clock	Load Time	Haul Time	Time in Dump	Return Time	Cycle Time
6/19/98	4:00:00	1:45	5:46	0:45	4:24	12:40
6/19/98	4:12:40	1:40	6:00	0:40	5:20	13:40

This activity table is in the same forms as the data from the onboard instrumentation. Therefore, if GPS is used to collect production data, it can provide performance records for the experience database in a manner similar to the onboard instrumentation.

## **Vita**

Govindan Kannan was born on 28<sup>th</sup> June 1969 in Cuddalore, India. He received his primary and high school education at Chinmaya Vidyalaya in Madras. After graduating from high school in 1987, he started to pursue his baccalaureate degree in Civil Engineering at the Regional Engineering College, Tiruchirappalli. After graduating with honors in 1991, he was recruited by the largest construction company in India, Larsen & Toubro to work as a project engineer. During his assignment at the construction site of a steel mill, he became interested in the project management aspects of construction. After serving the company for two years, he went back to graduate school to pursue his interests in construction management. National University of Singapore, Singapore, offered him a full scholarship to pursue graduate studies and became one of the first students to receive a Masters degree in Civil Engineering with emphasis on construction management. While living in Singapore, he visited several Asian countries and Australia. In the fall of 1995, he chose Virginia Tech to continue his academic pursuit by working towards his Ph.D. degree. At Virginia Tech, he served on the Graduate Student Assembly (GSA), the University Athletic Committee (UAC) and as the vice-president of the Indian Student Association (ISA). He was also invited to two honor societies, Chi Epsilon and Phi Kappa Phi. At the time of completing this dissertation, he has job offers from the industry which he hopes to pursue next.

His mother and father are retired and live in India. The other member of his family is Lakshmi, his younger sister who is working her way through her MBA in India. Although he recently became a doctor, Govi is still a bachelor.