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I am submitting herewith a thesis written by Brent Alan Thornton entitled "Validation of Predictive Production Rates Using Historical Data" I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering

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Karen C Chou, Major Professor

We have read this thesis and
Recommend its acceptance

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Accepted for the Council

Associate Vice Chancellor and
Dean of The Graduate School

Validation of Predictive Production Rates Using Historical Data

A Thesis Presented for the Master of Science Degree

The University of Tennessee at Knoxville

Brent Alan Thornton
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ABSTRACT

The Tennessee Department of Transportation (TDOT) is currently using production rates that were developed from past experience and some historical data to estimate contract duration These production rates tend to underestimate the time duration of a project Research by the University of Tennessee, Knoxville has developed predictive production rates based on on-site construction operations observed in 1997-1998. The P_{95} values were developed on the basis that the contractor would complete an operation 95% of the time Without making any comparisons to past performance, the development of the P_{95} values was based limited observations Historical data were collected, analyzed, and used to make comparisons to the predictive production rates.

This thesis concentrates on the comparisons of historical data Historical production rates were determined based on information retrieved from inspector's diaries, asphalt plant books, field books, and final record books. Comparisons between the historical production rates and the predictive production rates could then be made to determine if the P_{95} values were applicable The P_{95} values were then used to estimate the time duration of the twenty-two operations studied and compared to the number of days reported for completion of the operations

There appears to be a large discrepancy in production rate between the historical records and the P_{95} model One major reason is the interpretation of days reported. Without sufficient information from the historical records, the days reported

were conservatively defined as full days of operation This interpretation can easily lead to lower than actual production rates

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Low productivity has often been a problem in the construction industry. While the overall U.S economy has been increasing its annual productivity at an annual rate of close to 3%, the construction industry has averaged an annual increase of less than 1% (Adrian, 1987). Estimating project duration is a problem the construction industry has had to deal with in the past and remains a concern today. Wide variations in project size and conditions lead to difficulties in estimating project duration The overestimating of project duration leads to increased costs for the users and periods of time when seemingly no work is being completed Also, knowing that the project's duration has been overestimated, the contractor may choose to move the labor force off that project and work on other more profitable projects Underestimating the project duration, however, results in contractors having to accelerate the construction process The quality of work suffers and costs increase when contractors bidding on a project feel that the construction time is unreasonably short. Contractors either do not bid on that contract or they raise their bid price to account for any liquidated damages that may occur due to the time constraints

The Tennessee Department of Transportation sponsored a research contract with The University of Tennessee to develop unit production rates that will help to better estimate the duration of construction projects Twenty-two construction operations were identified for the study These operations comprise approximately 75% of the work on a typical construction project The research team collected observed data from the field and developed the predictive production rates These predictive production rates were used to estimate the duration of an operation with a 95% confidence level. All of the production rates were based on a limited number of observed data and a small portion of an operation Hence, it is desirable to verify the developed model with historical records where the projects are completed

1.2 OBJECTIVE OF RESEARCH

The objective of this thesis is, first, to compare the historical production rates to the predictive production rates. Then the duration of the twenty-two operations is estimated based on the predictive production rates and compared to the duration recorded in the historical data to complete the operation Chapter 2 describes the methods to retrieve, extract, and analyze the historical data Chapter 3 shows the results of the historical analysis, estimates of the operations, and discussions of results Chapter 4 draws conclusions on what was discussed in the thesis and makes recommendations on the recording of data during the construction process.

CHAPTER 2

METHODOLOGY

2.1 INTRODUCTION

The purpose of this research is to compare the production rate prediction model developed at the University of Tennessee, Knoxville (UTK) with data collected by the Tennessee Department of Transportation (TDOT). Historical data obtained from the Tennessee State Archives in Nashville were used for the comparison The Tennessee Department of Transportation stores all files associated with a completed contract in the state archives for a period of 10 years Production rates for typical highway construction operations were extracted from the archived data Once the historical production rates were determined, a comparison to the production rates using the prediction model was made

2.2 HISTORICAL PRODUCTION RATE

TDOT has supplied the research team with a list containing all contracts and the associated tasks let from 1989-1995 This information was used in the determination of which contracts would be suitable for comparisons. A representative sample of contracts was chosen from the four regions of Tennessee based on contract size and the number of construction operations pertaining to the research project Next, the chosen contracts had to be retrieved from the Tennessee State Archives Final record books, asphalt plant books, field books, and diaries were utilized in the data analysis process. The final record book contained the contract history and a complete list of tasks involved on the project Figure 2-1 shows a sample page from the final record book of Contract 3014 Important information to the research project such as contractor, contract cost, contract start and completion dates, and the number of days needed to complete the contract can be found on this page. A sample list of construction operations from the same final record book was extracted and is shown in Figure 2-2 Each operation has an item number, unit of measure, unit price, quantity, and cost associated with the item number The production rate was determined using the final quantity given in this portion of the final record book Information on asphalt items were taken from the summary sheet of the asphalt plant books. Figure 2-3 shows a sample of an asphalt summary sheet taken from Contract 2739 for asphalt grade A-S. Listed on the summary are the date when material was laid and a summation of asphalt quantities The number of days reported for all of the operations, except for asphalt, listed in Table 2-1 was either found in field books or the inspector's field diaries Figure 2-4 is an example of the mineral aggregate operation taken from the field book of Contract 2957. The date was recorded when material was laid Also, a description was recorded telling where the material was laid In the absence of information defining the "days reported" in the field book, a day reported was assumed to be a full day of work An example of the inspector's diary extracted from Contract 7509 is shown in Figure 2-5. The inspector's diary consisted of a daily report including weather conditions, type of work, location of work, crews and equipment, and any remarks the inspector

HISTORY

CONTRACT NO. 3014

PROJECT NO.	REFERENCE NO	COUNTY	ROUTE NO.
27004-3263-14	NH-43 (13)	GIBSON	43

PROJECT DESCRIPTION: GRADE, DRAINAGE, CONSTRUCTION OF 3 PRESTRESSED CONCRETE I-BEAM BRIDGES, OF A BOX BRIDGE, AND PAVING WITH BITUMINOUS MATERIALS ON A SECTION OF STATE ROUTE NO. 43 FROM EXISTING 4-LANE SECTION NORTH OF MILAN TO SOUTH OF REYNOLDS ROAD.

PROJECT ENGINEER JAMES E MOORE, JR.

CONTRACT AWARDED DATE: 03-02-94
WORK ORDER EFFECTIVE: 04-13-94
TIME LIMIT: 350 DAYS
ORIGINAL CONTRACT AMOUNT: $12,634,108.49
CONTRACTOR: DEMENT CONTRUCTION CO.
CONTRACTOR'S SURETY· UNITED STATES FIDELITY AND GUARANTY COMPANY
DBE GOAL AS AWARDED (%):
13.0 %
SUB CONTRACTORS (DBE Subs in parenthesis)
WMC Contracting Co , Inc
Traf Mark
All-Brite Inc
(Garden Hire Construction Co., Inc.)
(Payne Steel) (Cultra)

CONTRACTOR STARTED WORK 05-02-94
CONTRACTOR COMPLETION DATE: 12-04-97
DAYS CHARGED: 363

ENGINEERING PARTY·

TITLE	NAME	SS#
OPERATIONS SPECIALIST II	MIKE LANE	345-60-5111
TRANSPORTATION ASSISTANT II	GERALD DUNCAN	412-68-2249
TRANSPORTATION ASSISTANT I	JERRY MELTON	412-62-9589

FINAL INSPECTION BY.	PETE DEER	FHWA ENGINEER, DATE – August 21, 1997
FINAL INSPECTION BY.	TOMMY STUTTS	TDOT ENGINEER, DATE – August 1, 1997

FINAL CONTRACT AMOUNT $ 14,689,008.97

Figure 2-1. Contract History Sheet from the Final Record Book of Contract 3014

CONTRACT # 03014
PROJECT NO. 27004326314
REFERENCE NO. NH-43(13)
COUNTY GIBSON

			ORIGINAL ESTIMATE QUANTITIES				FINAL ESTIMATE QUANTITIES			
ITEM NO.	ITEM DESCRIPTION	UNIT	QUANTITIES	UNIT PRICE	AMOUNT	REFERENCE	QUANTITIES	OVERRUN	(UNDERRUN)	AMOUN
209.07.01	DUMPED ROCK	TON	504.000	22.0000	11088.00	FB4 P41	2134.600	1630.600		46961.2
209 08	TEMPORARY SILT FENCE	L F	74940 000	0.4000	29976.00	FB4 P45	39364.700		-35575.300	15745.8
209 10 01	SEDIMENT TRAP	EACH	4 000	600.0000	2400 00	FB4 P48	5 000	1 000		3000.0
209.12 02	EROSION CONTROL BLANKET (TYPE 2)	S Y	21127.000	1.1000	23239.70	FB4 P49			-21127.000	
209 20.03	POLYETHYLENE SHEETING	S Y	147.000	2.0000	294.00	FB4 P52			-147.000	
303 01	MINERAL AGGR, TYPE A BASE, GR D	TON	185320 000	7.2500	1343570 00	FB8 P50	192451.900	7131 900		1395276.2
303 01 01	GRAN. BACKFILL MATERIAL FOR STRUC	TON	5616.000	10.0000	56160.00	FB5 P53	8168.600	2552 600		81686.0
303.02	MIN AGGR, TYPE B BASE, GRADE (	TON	1681.000	10.0000	16810.00	FB8 P66	6497.400	4816.400		64974.0
307.01 03	AGGREGATE (BPMB-HM) GR A-S MIX	TON	32178.000	20 1100	647099.58	PMB 5	39344.200	7166 200		791211.8
307 04.31	POLYMER MOD ASPHALT CEMENT GR A-S	TON	1081 000	241.0000	260521 00	PMB 5	1336 220	255.220		322029.0
307 04 33	POLYMER MODIFIED (BPMB-HM) GR B-M	TON	30098.000	30.1400	907153 72	PMB 4	25422.020		-4675.980	766219.6
307 04 38	PLYMR MOD BIT PLT MX BS(HM)GR A	TON	42118.000	29.3100	1234478.58	PMB 5	43836.350	1718 350		1284843.4
402 01	BITUMINOUS MATERIAL (PC)	TON	472 000	100.0000	47200 00	FB16 P16	153 510		318 490	15351.0
402.02	AGGREGATE FOR COVER MATERIAL (PC)	TON	1867.000	10.0000	18670.00	FB15 P69			-1867 000	
403 01	BITUMINOUS MATERIAL (T C)	TON	62 000	160.0000	9920 00	FB16 P70	85 240	23.240		13638.4
407 01	RMVL & DSPSL OF EXIST SURF (CONC)	S Y	115 000	13.2000	1518 00	FB4 P28	174 000	59 000		2296.8
411 01 01	MINERAL AGGREGATE (ACS) GRADING D	TON	13909 000	18.1100	251891.99	PMB 2	17139 500	3230 500		310396.3
411 01 27	POLYMER MODIFIED ASPHALT CEMENT G	TON	888 000	241.0000	214008 00	PMB 2	1146 630	258 630		276337.8
411 03 10	ASPH CONC SURF (HM) GR E (SHLD)	TON	2283 000	28.5100	65088 33	PMB 1	2925 870	642 870		83416.5
604 01 01	CLASS A CONCRETE (ROADWAY)	C Y	1005 000	181 0000	181905 00	FB5 P46	988.000		17 000	178828.0
604.01 02	STEEL BAR REINFORCEMENT (ROADWAY)	L B	169424 000	0 4000	67769 60	FB5 P46	168103 000		-1121 000	67321 2
607 03.02 18	CONC PIPE CULVERT (CLASS III)	L F	21066 000	18.5000	389721 00	FB7K P40	21077 600	11.600		389935.6
607 05 02 24	CONC PIPE CULVERT (CLASS III)	L F	2278 000	26 0000	59228 00	FB7K P40	3616 600	1338 600		94031 6
607 06 02 30	CONC PIPE CULVERT (CLASS III)	L F	176 000	35 0000	6160.00	FB7K P40	263 200	87 200		9212 0
607 07 02 36	CONC PIPE CULVERT (CLASS III)	L F	1192 000	46.0000	54832.00	FB7K P40	801 200		-390 800	36855.2
607 08.02 42	CONC PIPE CULVERT (CLASS III)	L F	830.000	60.0000	49800.00	FB7K P40	465 100		-364.900	27906.0
607 09 02 48	CONC PIPE CULVERT (CLASS III)	L F	40.000	75 0000	3000 00	FB7K P40			40 000	
607 37 01 15	C M PIPE CULVERT	L F	78 000	12.0000	936 00	FB12 P3	180 000	102 000		2160.0
607 37 02 18	C M PIPE CULVERT	L F	406.000	14 0000	5684 00	FB12 P4	72.000		-334 000	1008.0

Figure 2-2. List of Operations Associated with Contract 3014 from the Final Record Book

RECAP OF TICKET BOOK

DATE	TICKET BOOK NO.	TONS MIX	TONS A.C.	TONS MIN. FILLER	TONS MIN. AGGR.	ACCUM. TONS MIX	ACCUM. TONS A.C	ACCUM. TONS MIN. F	ACCUM TONS MIN. AGGR	BATCHES DAILY	ACCUM. TOTAL BATCHES
11-28-94	1.	168.43	5.558		162.872	168.43	5.558		162.872		
7-27-95	2	614.69	20.285		594.405	783.12	25.843		757.277		
7-28-95	3	96.10	3.171		92.929	879.22	29.014		850.206		
8-25-95	4	1188.45	39.219		1149.231	2067.67	68.233		1999.437		
8-26-95	5	742.90	24.516		718.384	2810.57	92.749		2717.821		
9-23-95	6	617.71	20.384		597.326	3428.28	113.133		3315.147		
9-25-95	7	765.70	25.268		740.432	4193.98	138.401		4055.579		
9-26-95	8.	700.11	23.104		677.006	4894.09	161.505		4732.585		
9-29-95	9.	539.50	17.804		521.696	5433.59	179.309		5254.281		
9-30-95	10	161.55	5.331		156.219	5595.14	184.640		5410.500		
11-24-95	11	450.11	14.854		435.256	6045.25	199.494		5845.756		
			199.494		5845.756						
Bk 1	Total										
Item	307-01.03			Item	307-01.04						
	Mineral Agg				Asphalt	Cement					
	5,845.756 Tons				199.494	Tons					

Figure 2-3. Example of Asphalt Summary Sheet for Contract 2739

Table 2-1. List of All Contracts and the Operations Associated with the Individual Contracts

		Contract Number																																																					
		Region I																											Region II												Region III								Region IV							
Description	Unit of Measure	2209	2324	2337	2361	2385	2417	2452	2456	2476	2481	2483	2547	2563	2573	2614	2623	2628	2662	2702	2704	2763	2783	2786	2790	2962	7361	7509	8787	2588	2700	2867	2877	2951	7511	8124	8240	8392	8402	8436	8490	2638	2730	2749	2957	3556	3935	4017	4251	2674	2739	2780	2825	2864	2947	2967	3014
Road & Drainage Excavation	CY		x					x	x		x																x	x				x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
Borrow Excavation	CY		x						x	x	x																x	x				x	x			x	x	x	x	x	x	x		x	x	x	x	x		x			x	x		x	x
Mineral Aggregate Mix	TONS	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x
Asphalt Grade A-S	TONS						x	x		x		x														x	x		x			x			x	x	x	x	x	x	x		x	x	x	x		x	x	x	x	x	x			x	x
Asphalt Grade A	TONS		x					x	x		x	x																x	x			x	x	x		x	x		x	x	x	x	x	x	x	x			x	x		x	x	x		x	
Asphalt Grade B-M	TONS		x				x	x	x	x	x	x		x	x	x	x	x	x		x	x	x	x				x	x	x	x	x	x	x		x	x		x	x		x	x	x	x	x				x	x	x	x		x	x	
Asphalt Grade D	TONS	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x
Concrete Ramp Pavement	SY						x					x														x			x																			x	x	x	x				x	x	
Steel Erection	LF																																																								
Class A Concrete Roadway (Box Culvert)	CY							x																		x	x	x				x	x		x	x	x		x	x			x	x	x	x	x		x	x	x		x		x		x
Steel Bar Reinforcement Roadway (Box Culvert)	LB							x																		x	x	x				x	x		x	x	x		x	x			x	x	x	x	x		x	x	x		x		x		x
Class A Concrete (Box Bridge)	CY		x						x																			x											x					x		x											
Steel Reinforcement (Box Bridge)	LB		x						x																			x											x					x		x											
Epoxy Coated Reinforcement	LB		x														x																	x			x	x	x		x	x							x	x		x	x				
Class D Concrete Bridge Deck	CY		x														x																	x								x							x	x		x	x				
Steel Piles 10"	LF		x			x											x																	x				x	x		x	x							x								
12" Concrete Pipe Culvert	LF																										x																														
15" Concrete Pipe Culvert	LF																																																x								
18" Concrete Pipe Culvert	LF					x		x		x	x																x	x					x		x		x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x		x	x	x
24" Concrete Pipe Culvert	LF					x		x		x																	x	x					x		x	x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x		x
30 " Concrete Pipe Culvert	LF							x		x																	x	x					x		x	x	x		x	x	x		x	x	x	x		x	x	x	x	x	x		x		x
36" Concrete Pipe Culvert	LF							x		x																	x	x					x		x	x	x	x	x	x	x		x	x	x		x	x	x		x	x	x		x	x	x

Table 2-1. List of All Contracts and the Operations Associated with the Individual Contracts (continued)

Description	Unit of Measure	Contract Number																											
		Region I																											
		2209	2324	2337	2361	2385	2417	2452	2456	2476	2481	2483	2547	2563	2573	2614	2623	2628	2662	2702	2704	2763	2783	2786	2790	2962	7361	7509	8787
42" Concrete Pipe Culvert	LF							x									x												
48" Concrete Pipe Culvert	LF							x		x																			
54" Concrete Pipe Culvert	LF							x																					
60" Concrete Pipe Culvert	LF							x																					
Type 12 Catch Basins 0' - 6' Depth	EACH					x				x	x																x	x	
Type 12 Catch Basins 6' - 8' Depth	EACH									x	x																x		
Type 12 Catch Basins 8' - 10' Depth	EACH									x																	x		
Type 12 Catch Basins 10' - 12' Depth	EACH									x																	x		
Type 12 Catch Basins 12' - 14' Depth	EACH																												
Concrete Parapet	LF		x			x				x							x												
Concrete Median Barrier	LF						x				x	x														x			

Description	Unit of Measure	Contract Number																											
		Region II												Region III								Region IV							
		2588	2700	2867	2877	2951	7511	8124	8240	8392	8402	8436	8490	2638	2730	2749	2957	3556	3935	4017	4251	2674	2739	2780	2825	2864	2947	2967	3014
42" Concrete Pipe Culvert	LF				x			x	x		x	x			x	x	x	x					x	x	x		x		x
48" Concrete Pipe Culvert	LF				x			x	x	x	x	x			x		x		x	x		x	x				x		
54" Concrete Pipe Culvert	LF					x		x				x			x			x											
60" Concrete Pipe Culvert	LF				x					x			x		x									x					
Type 12 Catch Basins 0' - 6' Depth	EACH						x				x	x			x	x	x	x		x	x				x		x		x
Type 12 Catch Basins 6' - 8' Depth	EACH						x					x			x	x	x	x		x	x				x		x		x
Type 12 Catch Basins 8' - 10' Depth	EACH						x					x				x	x	x		x							x		
Type 12 Catch Basins 10' - 12' Depth	EACH											x					x	x											x
Type 12 Catch Basins 12' - 14' Depth	EACH																x	x											
Concrete Parapet	LF					x			x	x	x		x							x	x				x				
Concrete Median Barrier	LF			x									x								x		x						

Date	Pounds	Tons	Accu. Tons		Remarks
10-19-94	88,080	44.04	44.04		DETOUR Rd S.R. 263 MAINT STONE
11-03-94	809,030	404.52	448.56		DETOUR Rd. S.R. 263
11-08-94	46,160	23.08	471.64		SHoulder Stone S.R. 263 DETOUR
11-18-94	32,320	16.16	487.80		SHoulder Stone S.R. 263 DETOUR
12-08-94	44,280	22.14	509.94		MAINT STONE Field RAMP TURNER Rd
01-18-95	185,180	92.59	602.53		STA. 54 too ± DETOUR Rd. LandFill Haul Rd MAINT STONE
01-25-95	182,140	91.07	693.60		STA. 54 too ± DETOUR Rd. LandFill Haul Rd. MAINT STONE
02-14-95	862,160	431.08	1,124.68		STA 53 too ± DETOUR Rd MAINT STONE 4" DEEP ± (BALALOCK)
02-15-95	245,880	122.94	1,247.62		STA. 53 too ± DETOUR Rd. MAINT STONE 4" DEEP ± (BALALOCK)
02-23-95	92,800	46.40	1,294.02		STA 53 too ± DETOUR Rd MAINT STONE (BALALOCK)
03-02-95	46,700	23.35	1,317.37		STA 53 too ± DETOUR Rd MAINT STONE (BALALOCK)
03-09-95	292,820	146.41	1,463.78		STA 53 too ± DETOUR Rd MAINT STONE
03-21-95	71,640	35.82	1,499.60		STA. 125 tos MAINT STONE
03-22-95	89,200	44.60	1,544.20		STA. 125 tos MAINT STONE OVER PIPE
03-27-95	95,960	47.98	1,592.18		STA. TURNER Rd DETOUR MAINT 53 too (BALALOCK) Pd 1st Rd
04-12-95	715,340	357.67	1,949.85		STA MAINT STONE widened all WATER TANK Rd CHANGE DETOUR (BALA
06-02-95	48,020	24.01	1,973.86		STA
06-12-95	48,580	24.29	1,998.15	Paid on Est #15	STA S.R. 263 DRIVE WAY EARTH(EN) AREA
06-20-95	47,420	21.51	2,019.66		STA USED IN DRIVEWAY SR-263
06-26-95	96,200	48.10	2,067.76		STA. MAINT STONE LANDFill Rd. (BALALOCK)
06-27-95	92,580	46.29	2,114.05		STA. MAINT STONE LANDFill Rd (BALALOCK)
06-28-95	46,740	23.37	2,137.42		STA. MAINT STONE LANDFill Rd (BALALOCK)
06-29-95	143,580	71.79	2,209.21		STA. MAINT STONE WATER TANK Rd (BALALOCK)
06-30-95	47,540	23.77	2,232.98		STA. PUMP STA Rd MAINT STONE (BALALOCK)
07-05-95	46,140	23.07	2,256.05		STA. MAINT STONE LANDFill Rd (BALALOCK)
07-11-95	95,780	47.89	2,303.94		STA. MAINT STONE OVER SPRING BOX @ DETOUR 1271+07 ± (BALALOCK)
07-12-95	95,160	47.58	2,351.52		STA. MAINT STONE HAUL Rd ZINC
07-19-95	45,440	22.72	2,374.24		STA. FRONTAGE Rd. "E"
07-20-95	805,700	402.85	2,777.09		STA BASE STONE FRONTAGE Rd "D" "4"
07-25-95	144,700	72.35	2,849.44	Paid on Est # 16	STA. BASE STONE FRONTAGE Rd "E" "4"
08-09-95	96,080	48.04	2,897.48		STA. ZINC HAUL Rd MAINT STONE

Figure 2-4. Example of Mineral Aggregate Operation taken from Contract 2957

DT-1491

PROJECT DIARY

CONTRACT NO. 7509 PROJECT NO. 32012-3205-24 DATE 4-19-9
REF. NO. RS-113(2) DAY Thursday

TIME CHARGE		WEATHER	TEMP.	RIVER
PREVIOUS	84	Clear	8 A.M. 40°	GAUGE
THIS DAY	1	Partly Cloudy	NOON 58°	RISING ☐
TOTAL	85	Cloudy	4 P.M. 65°	FALLING ☐

RECORDED BY [signature]
SIGNATURE

Gagy. Tech.
TITLE

TIME CHARGE EXPLANATION

PROJECT ENGINEER: [signature]

WORK PERFORMED THIS DATE

LOCATION	TYPE WORK	FORCES & EQUIP.
	Blalock Const.	
51+50	Laid 6-8' Joints of 18" Pipe - Conc.	2 Foremen 10 Skilled Labors 1 Unskilled Labor
32+50 - 36+00	Placed Mtl. in Rdwy for Fill.	2 Trucks 1 Roller 1 Backhoe 1 Dozer 1 Highlift
74+53.29 Clyde Thomas Rd.	Laid 14' of 24 CMP	1 Grader 2 Pickups

VISITORS

CHANGES IN CONSTRUCTION FORCES

ENGINEERING PERSONNEL
WORK PERFORMED THIS DATE

LOCATION	TYPE OF WORK

NAME	TITLE	TIME
Howard Colby	E.I.T.	6 hrs.

ABSENT ETC.

DC Hall	75 "S"

REMARKS AND INSTRUCTIONS

Note: Told foreman Herb Blalock to put a barricade of barrels at 65+00 where pipe was laid in side of Rdwy, or put plywood over hole and cover with stone. He

Figure 2-5. Example of Inspector's Diary taken from Contract 7509 wrote for future reference After all data had been collected, historical production rates were computed for each of the highway construction operations studied Using the following equation,

$$Historical\ Production\ Rate = \frac{Final\ Quantity}{Number\ of\ Days\ Reported} \qquad [\,2\text{-}1\,]$$

a daily production rate could be determined

2.3 OPERATION DURATION USING PREDICTIVE MODEL

After the historical production rates for the highway construction operations were determined, a comparison with the production rate model developed at UTK (Gatlin (1998), Brown (1999)) could be made The production rate model was developed using observed data from selected contracts across Tennessee between 1997 and 1998. The data collected were the times taken for the completion of one cycle of operation These times were modeled as a lognormal distribution A t_{95} time was defined from the model as

$$t_{95} = \frac{\%_{ND}}{100}\left(t_{95,ND}\right) + \frac{\%_{ND}}{100}\left(t_{95,D}\right) \qquad [\,2\text{-}2\,]$$

where, $\%_{ND}$ = percentage of non-delay cycles

$\%_{D}$ = percentage of delay cycles

The following equations were used to calculate the delay and non-delay t_{95} cycle times

$$t_{95,ND} = e^{\lambda_{ND} + 1.645\zeta_{ND}} \qquad [\,2\text{-}3\,]$$

and,

$$t_{95,D} = e^{\lambda_{D} + 1.645\zeta_{D}} \qquad [\,2\text{-}4\,]$$

Substituting the appropriate cycle times in for the delay and non-delay cases, the parameters were calculated as follows:

$$\zeta = \sqrt{\ln\left[\left(\frac{\sigma}{\bar{x}}\right) + 1\right]} \qquad [\,2\text{-}5\,]$$

$$\lambda = \ln\bar{x} - \frac{1}{2}\zeta^2 \qquad [\,2\text{-}6\,]$$

where, $\bar{x}$ = sample average

σ = sample standard deviation

The t_{95} time represents the maximum duration one would take to complete one cycle of the operation 95% of the time. That is, 5% of the cycles would take longer than t_{95} This t_{95} value was used to compute the 95-percentile production rate, P_{95} as

$$P_{95}\ \text{productivity} = \frac{C \times 60\,\frac{\text{mm}}{\text{hr}}}{t_{95}(\text{min})} \qquad [\,2\text{-}7\,]$$

where, C = capacity to be processed per cycle

t_{95} = cycle time at 95% confidence level

The P_{95} represents the minimum production rate that TDOT can expect of the construction operation 95% of the time. This production rate does assume that the contractor would have an adequate size crew and adequate number and appropriate type of equipment available for the construction task The P_{95} production rate, however, does include the effect of normal randomness such as traffic condition, equipment breakdown, labor delays, material delays, the bunching effect, and management as reflected in t_{95} given in Equation 2-1

For a given quantity of a construction operation, the number of days needed to complete the operation is

$$t_{max} = \frac{Final\ Quantity}{P_{95}} \qquad [\ 2\text{-}8\ ]$$

For example, referring to Figure 2-3 the total number of days required to lay 6045 25 tons of asphalt grade A-S was 11 days Based on the P_{95} production rate of 1560 tons/day as determined by the UTK model (Gatlin (1998), Brown (1999)), the number of days needed to lay 6045.25 tons of asphalt is 4 days (6045.25 tons/(1560 tons/day)). The predictive model underestimated the reported duration by 7 days.

CHAPTER 3

COMPARISON OF PREDICTIVE PRODUCTION RATES AND HISTORICAL PRODUCTION RATES

3.1 INTRODUCTION

Data collected for the determination of historical production rates were limited for some of the construction operations as can be seen in Table 3-1. Table 3-1 is a summary of the operations and their associated TDOT production rates, average P_{95} production rates, and average historical production rates. Also listed is the number of contracts used in the determination of the historical production rates. The contracts were divided into three classifications based on the final project cost. Contracts were classified as follows:

Small	Final Cost < $500,000
Medium	$500,001 < Final Cost < $2,500,000
Large	Final Cost > $2,500,000

By grouping the contracts in this manner, production rates could be developed for a range of projects Figure 3-1 represents the production curve for a typical operation referred to as the "S-curve" The flat portion of the curve at the beginning depicts the mobilization of equipment, materials, and labor. As the crew works on the operation, they begin to learn the operation until full productivity is reached The middle portion of the S-curve represents the highest productivity as the crews mastered the operation. Completing the operation involves cleanup and

Table 3-1. Summary of TDOT Production Rates, Predictive Production Rates, and Historical Production Rates

	#	Item #	Description	Unit of Measure	Contract Size	TDOT PRODUCTION	AVERAGE P_{95} PRODUCTION	AVERAGE HISTORICAL PRODUCTION	# of Historical Contracts
CATEGORY I	1	203-01	Road and Drainage Excavation	cy/day	Small	2500	2338	469	1
					Medium	5000	2812	2127	4
					Large	8000	3461	3401	7
	2	203-03 01	Borrow Excavation	cy/day	Small	1000	1458	-	-
					Medium	2000	2324	2303	12
					Large	5000			
	3	303-01	Mineral Aggregate Mix	tons/day	Small	2000	2800	1099	50
					Medium	3000			
					Large	3000			
	4	307-01 03	Asphalt Grade A-S	tons/day	Small	1500	1560	1218	24
					Medium	2000			
					Large	2000			
	5	307-03 09	Asphalt Grade A	tons/day	Small	1500	1808	1130	20
					Medium	2000			
					Large	2000			
	6	307-03 15	Asphalt Grade B-M	tons/day	Small	1200	1400	856	31
					Medium	1500			
					Large	1500			
	7	411-01	Asphalt Grade D	tons/day	Small	1000	1176	913	48
					Medium	1000			
					Large	1200			

Note. * denotes average observed production rates

Table 3-1. Summary of TDOT Production Rates, Predictive Production Rates, and Historical Production Rates (continued)

	#	Item #	Description	Unit of Measure	Contract Size	TDOT PRODUCTION	AVERAGE P_{95} PRODUCTION	AVERAGE HISTORICAL PRODUCTION	# of Historical Contracts
CATEGORY II	8	501-01	Portland Cement Concrete Pavement (RAMP)	sy/day	Small	5000	-	-	-
					Medium	8000	-	-	8
					Large	10000	536*	684	
	9	607-01 to 607-05	Concrete Pipe Culvert 12",15",18",24"	lf/day	Small	200	57*	-	-
					Medium	250	225*	159	50
					Large	300			
	10	607-06 to 607-08	Concrete Pipe Culvert 30",36",42"	lf/day	Small	150	90*	-	-
					Medium	200	146*	129	61
					Large	200			
	11	607-09 to 607-011	Concrete Pipe Culvert 48",54",60"	lf/day	Small	100	64*	40	1
					Medium	125	85*	78	26
					Large	150			
	12	620-03 10	Bridge Parapet	lf/day	Small	-	350*	260	7
					Medium	-			
					Large	-			
	13	711-01	Concrete Median Barrier	lf/day	Small	600	850*	970	8
					Medium	1000			
					Large	1000			

Note * denotes average observed production rates

Table 3-1. Summary of TDOT Production Rates, Predictive Production Rates, and Historical Production Rates (continued)

Category	#	Item #	Description	Unit of Measure	Contract Size	TDOT PRODUCTION	AVERAGE P_{95} PRODUCTION	AVERAGE HISTORICAL PRODUCTION	# of Historical Contracts
CATEGORY III	14	606-02 03	10" Steel Pile	lf/day	Small	-	-	75	1
					Medium	-	-	191	3
					Large	-	-	187	3
	15	611-04 01	Type 12 Catch Basins 0' - 6' Depth	each/day	Small	-	-	-	-
					Medium	-	-	0 9	2
					Large	-	-	1 3	10
	16	611-04 02	Type 12 Catch Basins 6' - 8' Depth	each/day	Small	-	-	-	-
					Medium	-	-	0 3	1
					Large	-	-	1 2	7
	17	611-04 03	Type 12 Catch Basins 8' - 10' Depth	each/day	Small	-	-	-	-
					Medium	-	-	0 3	1
					Large	-	-	0 8	5
	18	611-04 04	Type 12 Catch Basins 10' - 12' Depth	each/day	Small	-	-	-	-
					Medium	-	-	0 3	1
					Large	-	-	0 9	3
	19	611-04 05	Type 12 Catch Basins 12' - 14' Depth	each/day	Small	-	-	-	-
					Medium	-	-	-	-
					Large	-	-	1 0	2

Note * denotes average observed production rates

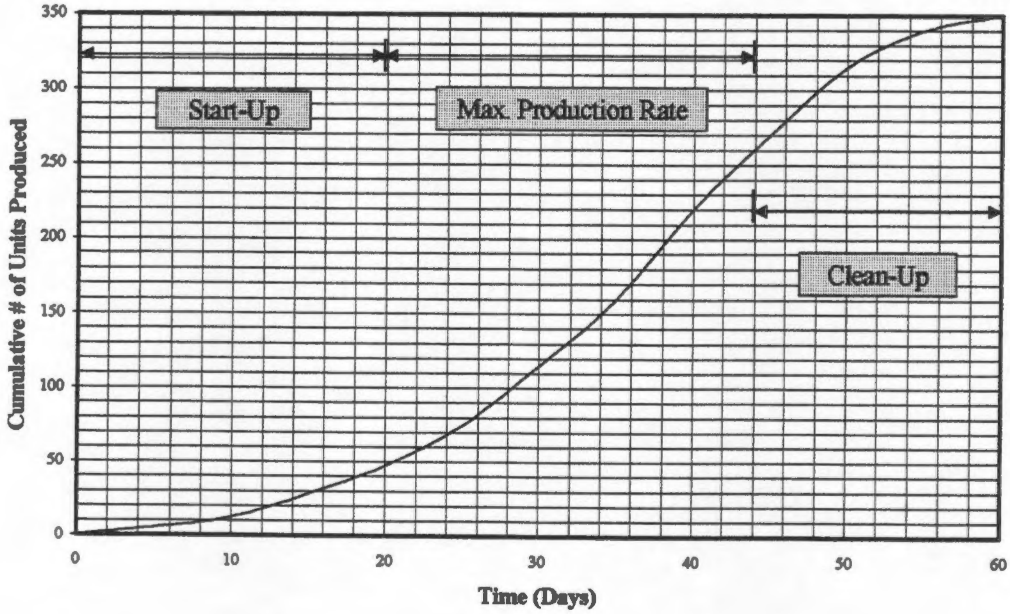

Figure 3-1. Production Curve for Typical Operation

demobilization of equipment. This slows productivity and results in the flat portion at the end of the production curve. For operations consisting of small quantities, crews do not have time to develop the S-curve. In this case, production rates should be lower than the production rates of an operation with larger quantities. Operations with larger quantities take longer and are able to produce the "S" shaped curve; therefore, a higher production rate is better able to estimate the larger quantities.

The following assumption was made to prevent the historical data results from being skewed. Only operations that were recorded to take longer than 5 days to complete, for medium and large projects, were used in the data analysis. A time duration longer than 5 days was chosen because an item with a duration less than this limit would not be on the critical path and would not affect the total time duration for the project This assumption was made to prevent the historical production rates from being underestimated Projects meeting the criteria for small classification were not held to the greater than 5 days assumption. Some operations on small projects take less than 5 days, therefore, all operations and the associated days need to be collected before an appropriate production rate can be determined

Road and drainage excavation, borrow excavation, mineral aggregate mix, and asphalt operations were analyzed by considering all days recorded on small contracts and all days with a time duration greater than 5 days for medium and large contracts For concrete pipe culvert, steel pile, concrete parapet, catch basin, and concrete median barrier operations, all days were considered in the analysis The theory behind this assumption was that these items do not generally make up a large percentage of a project individually For example, a large project may only have one bridge with a dozen piles to be driven In most cases the contractor could set the piles in 5 days or less. This often occurs and the days should be taken into account when analyzing this operation

3.2 COMPARISON OF HISTORICAL PRODUCTION RATES AND PREDICTIVE PRODUCTION RATES

Table 3-2 shows the historical production rate calculations of a typical operation. This summary table represents the mineral aggregate operation. Also listed on this table is the number of days meeting or exceeding TDOT's production

Table 3-2. Summary of Mineral Aggregate Mix Historical Data

Average P95 Production Rate for All Contract Classifications = 2800 tons/day
TDOT Production Rate for Small Contract Classification = 2000 tons/day
TDOT Production Rate for Medium Contract Classification = 3000 tons/day
TDOT Production Rate for Medium Contract Classification = 3000 tons/day

#	Region	Contract Number	County	Contract Size	Final Quantity (tons)	Number of Days	Historical Production (tons/day)	Number of Days Meeting or Exceeding TDOT Production	Number of Days Meeting or Exceeding P95 Production
1	1	2324	Hawkins	Medium	3101	15	0 2	0	0
2	1	2361	Sullivan	Small	3409	4	1	0	0
3	1	2385	Jefferson	Medium	7683	23	1	0	0
4	1	2417	Knox	Large	67428	61	23	5	5
5	1	2452	Anderson	Large	146033	456	14	0	0
6	1	2456	Blount	Small	5288	7	1	0	0
7	1	2476	Knox	Large	44489	166	4	2	3
8	1	2481	Sullivan	Large	39969	68	7	5	5
9	1	2483	Unicoi	Large	42815	30	19	4	6
10	1	2547	Loudon	Small	1095	2	0 2	0	0
11	1	2563	Sullivan	Small	1768	4	0.2	0	0
12	1	2573	Carter	Small	1979	2	1	0	0
13	1	2614	Sevier	Small	1239	2	0 2	0	0
14	1	2623	Unicoi	Medium	2009	20	0.1	0	0
15	1	2628	Washington	Small	2384	2	1	0	0
16	1	2662	Morgan	Small	2348	2	1	0	0
17	1	2704	Hawkins	Medium	7854	11	2	0	0
18	1	2763	Blount	Small	1666	2	0 4	0	0
19	1	2783	Greene	Small	3116	3	1	0	0
20	1	2786	Hawkins	Medium	4143	7	1	0	0
21	1	2790	Jefferson	Small	1400	3	0.2	0	0
22	1	7361	Washington	Medium	30662	113	3	0	0
23	1	7509	Hamblen	Medium	28357	92	3	0	0
24	1	8787	Sullivan	Medium	33141	27	13	3	3
25	2	2588	Fentress	Medium	3623	3	1	0	0
26	2	2700	Franklin	Small	681	1	0.1	0	0
27	2	2867	Hamilton/Sequatchie	Large	195603	115	102	21	29
28	2	2877	Meigs/Rhea	Large	142135	115	54	11	15

Table 3-2. Summary of Mineral Aggregate Mix Historical Data (continued)

#	Region	Contract Number	County	Contract Size	Final Quantity (tons)	Number of Days	Historical Production (tons/day)	Number of Days Meeting or Exceeding TDOT Production	Number of Days Meeting or Exceeding P95 Production
29	2	2951	Overton	Small	3615	30	0.1	0	0
30	2	7511	Hamilton	Large	58338	206	5	0	0
31	2	8240	Fentress	Large	69879	107	14	1	3
32	2	8392	Coffee	Large	28894	35	7	1	2
33	2	8402	Coffee/Franklin/Grundy	Large	457979	232	278	68	72
34	2	8436	Warren	Large	191927	188	60	28	28
35	2	8490	Hamilton	Large	85112	129	17	3	4
36	3	2638	Cheatham	Medium	7885	41	0 5	0	0
37	3	2730	Montgomery	Large	116401	326	13	1	2
38	3	2749	Sumner	Large	98944	152	20	1	1
39	3	2957	Smith	Large	71418	67	23	3	3
40	3	3556	Davidson	Large	198723	281	43	0	0
41	3	3935	Sumner	Medium	19702	17	7	4	4
42	3	4017	Davidson	Large	121865	157	29	7	8
43	3	4251	Williamson	Large	326246	188	174	46	50
44	4	2674	Weakley	Large	97768	88	33	1	1
45	4	2780	Gibson	Medium	13632	55	1	0	0
46	4	2825	Weakley	Large	77818	131	14	2	2
47	4	2864	Decatur	Large	20109	25	5	1	1
48	4	2947	Madison	Large	37075	184	2	0	0
49	4	2967	Weakley	Large	132667	86	63	4	11
50	4	3014	Gibson	Large	192452	320	36	4	10

Average Weighted Historical Production Rate = 1099 tons/day

rate and the number of days meeting or exceeding the predictive production rate For example, referring to Contract 2867, of the 115 days reported the contractor met or exceeded TDOT's production rate of 3000 tons/day 21 days, and 29 days out of 115 days, the contractor met or exceeded the P_{95} rate of 2800 tons/day This comparison was made to get an indication of whether or not the P_{95} or the TDOT production rate could be met 95% of the time

The operations were divided into three categories for comparisons. operations with predictive production rates, operations with observed production rates, and operations with neither predictive nor observed production rates. The difference between operations with observed production rates and operations with predictive production rates was that operations using the observed production rates had small amounts of data Only operations containing sufficient data to develop a statistical model used predictive production rates For the comparisons, one production rate was equal to one classification size for an operation. Category I utilized historical production rates for road and drainage excavation, borrow excavation, mineral aggregate mix, and asphalt operations for making comparisons to their respective P_{95} values. There were no predictive productions rates developed for concrete ramp pavement, steel pile, concrete pipe culvert, concrete parapet, and concrete median barrier operations, therefore, observed production rates were used to make comparisons in Category II Gatlin (1998) and Brown (1999) were not able to collect data for the catch basin operation, so for Category

III the historical production rates were the only rates available for which to draw conclusions

When developing the average predictive production rates for the operations, the research team used the weighted average approach This approach was used so that any one contract having an unusually low production rate would not have a disproportionate effect on the final averaged production rate The weighted average approach was also used in this research Equation 3-2 shows the calculation of the weighted average historical production rate for each operation

$$Wt.\ Avg. = \sum_{i}\left[\left(\frac{FQ_i}{N_i}\right) * \left(\frac{FQ_i}{\sum_{j} FQ_j}\right)\right] \qquad [\ 3\text{-}2\ ]$$

FQ_i , FQ_j = final quantity from contracts i or j

N_i = number of days reported for contract i

The fraction in the first set of brackets denotes the historical production rate for an operation, discussed earlier. The second set of brackets acts as a multiplier for determining how much the contract's production rate contributes to the final weighted average historical production rate For example, referring to Table 3-3 and Contract 2780, the final quantity was 4658 tons of asphalt grade A-S and there were 12 days reported for completion of the operation. The historical production rate was calculated to be 388 tons/day and the sum of the historical production rates was calculated to be 516419 tons/day. From Equation 3-2, the weighted average was 4 tons/day This contract contributed very little in the final calculation of the average weighted historical production rate

Table 3-3. Summary of Contracts for Asphalt Grade A-S Operation

#	Region	Contract Number	County	Contract Size	Final Quantity	# of Days Reported	Historical Prod. Rate	Weighted Prod. Rate
1	1	Contract 2417	Knox	Large	17971	6	2995	104
2	1	Contract 2452	Anderson	Large	23865	32	746	34
3	1	Contract 2476	Knox	Large	11019	7	1574	34
4	1	Contract 2483	Unicoi	Large	11354	6	1892	42
5	1	Contract 2962	Unicoi	Large	18642	26	717	26
6	1	Contract 7361	Washington	Medium	6730	8	841	11
7	1	Contract 8787	Sullivan	Medium	9031	14	645	11
8	2	Contract 2867	Hamilton/Sequatchie	Large	39872	28	1424	110
9	2	Contract 7511	Hamilton	Large	6905	19	363	5
10	2	Contract 8124	Marion	Large	15080	21	718	21
11	2	Contract 8392	Coffee	Large	883	15	59	0.1
12	2	Contract 8402	Coffee/Franklin/Grundy	Large	47694	27	1766	163
13	2	Contract 8436	Warren	Large	33378	28	1192	77
14	2	Contract 8490	Hamilton	Large	20158	35	576	22
15	3	Contract 2730	Montgomery	Large	19636	30	655	25
16	3	Contract 2749	Sumner	Large	13721	16	858	23
17	3	Contract 3556	Davidson	Large	26490	25	1060	54
18	3	Contract 4017	Davidson	Large	21102	27	782	32
19	3	Contract 4251	Williamson	Large	96682	62	1559	292
20	4	Contract 2674	Weakley	Large	20035	23	871	34
21	4	Contract 2739	Shelby	Large	8820	20	441	8
22	4	Contract 2780	Gibson	Medium	4658	12	388	4
23	4	Contract 2825	Weakley	Large	24371	25	975	46
24	4	Contract 2967	Weakley	Large	18320	16	1145	41

Average Weighted Historical Production Rate = 1218 tons/day

Weighted averages were calculated for each operation and then summed to obtain a final weighted average historical production rate A ratio was calculated to determine how well the historical production rates compare to the predictive production rates Equation 3-3 shows how the ratio was calculated

$$ratio = \frac{Weighted\ Average\ Historical\ \mathrm{Pr}odution\ Rate}{\mathrm{Pr}edictive\ \mathrm{Pr}oduction\ Rate} \qquad [\ 3\text{-}3\ ]$$

Figure 3-2 represents the summary of the operations and their respective ratios For the operations in category I, 78% of the average historical production rates were within a minimum of 60% of the predictive production rates. Nine production rates were used for the comparison; however, one of the production rates had only one datum per operation Discarding that production rate resulted in 89% of the average historical production rates being at least minimum of 60% of the P_{95} values

Category II had six production rates that could be used to make comparisons All of the historical production rates were at least 70% of the predictive production rates Two of the six production rates were at least 15% greater than the observed production rates

Category III did not have predictive production rates to make comparisons, however, historical production rates could be determined. Table 3-1 lists the results of the analysis Nine production rates were developed from the analysis, however, three rates were discarded because there was only one datum per operation The remaining six production rates were averaged and the results showed that one catch basin could be constructed in a day. This is typically the

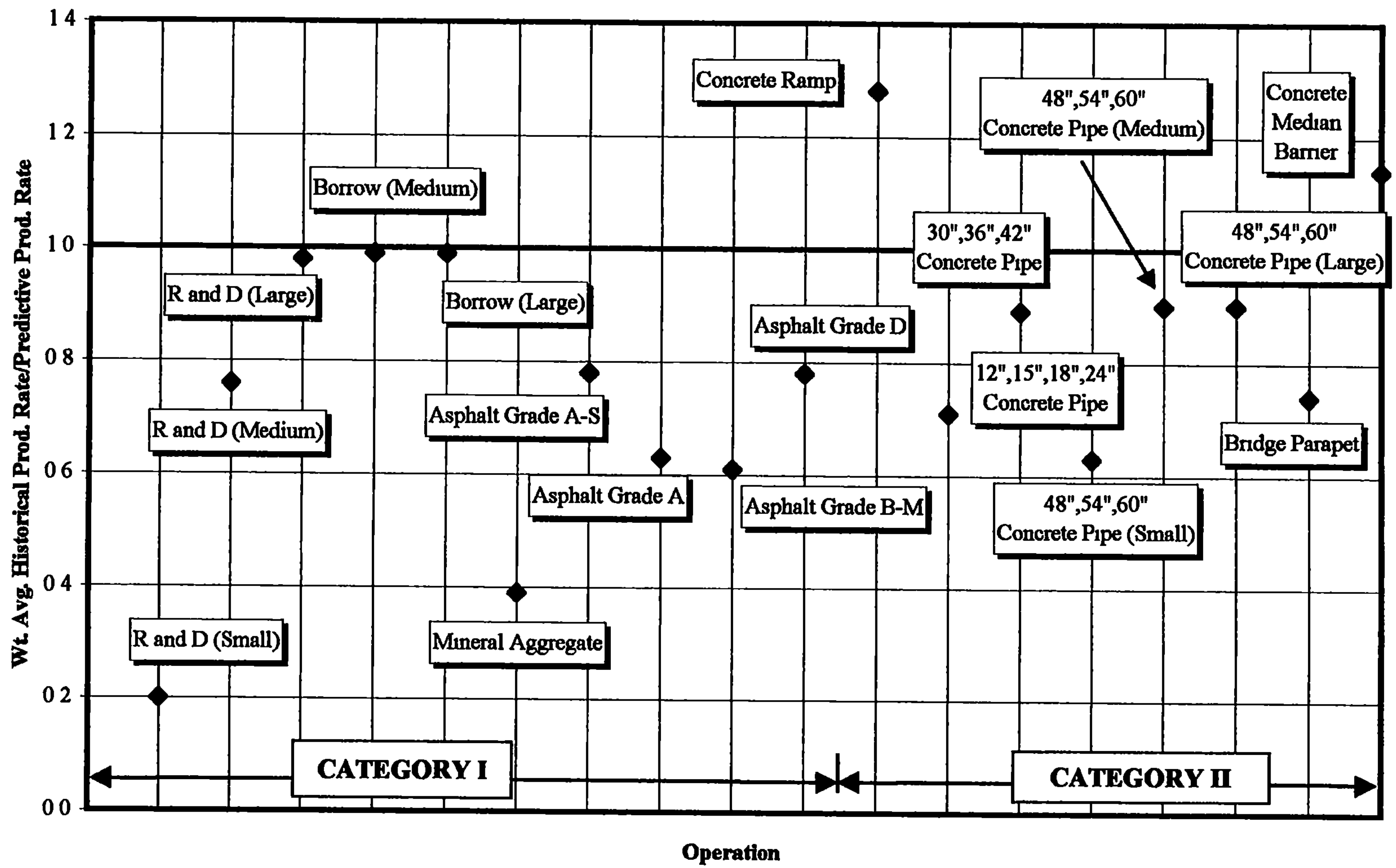

Figure 3-2. Ratio of the Weighted Average Historical Production Rate and the Predicted Production Rate for the Studied Operations

case on a construction project The construction of the catch basin operation involves pouring a footing and bricking the sides Since the operation does not fall on the critical path, the contractor will instruct a couple of men, one man mixing mortar and the other placing bricks, to construct the catch basins Depending on the size of the catch basin, the construction will take about a day to complete

In general there was a large discrepancy between historical production rates and predictive production rates The reason for the difference could be due to the determination of the number of days needed to complete an operation All days listed in the diaries, field books, or asphalt plant books were assumed to be a full day For example, during the collection of data for the mineral aggregate operation, every day that mineral aggregate mix was laid, regardless of quantity, "a day" was recorded Thus, if the contractor had reached full productivity laying mineral aggregate mix on a roadway, "a day" was recorded, however, if the contractor had laid only two truckloads of material on a driveway, "a day" was also recorded This assumption of "full day" for "a day reported" can lead to a lower production rate as not all days reported were fully devoted to that operation. There was no indication in the historical records whether the days reported were full days or half days

3.3 COMPARISON OF RECORDED DURATION AND PREDICTED DAYS FOR AN OPERATION

The last process in validating the predictive production rates was to estimate the operations listed in Table 3-1. According to the assumption of the P_{95} rate, the contractor should meet or exceed the estimated days 95% of the time To develop the maximum number of days needed to complete an operation with a 95% confidence level, the final quantity of each operation for a given contract was divided by the corresponding P_{95} rate Equation 2-8 was utilized in the determination of the maximum number of days needed, t_{MAX} Table 3-4 shows a typical contract (Contract 8402) and the operations studied associated with that contract Each operation has the final quantity, number of days reported by the inspector, predictive production rate, maximum number of days needed to complete the operation (t_{MAX}), and a ratio listed The ratio, r, for each operation was calculated using the following equation

$$r = \frac{Max\ Number\ Of\ Days\ Needed\ At\ 95\%\ Confidence\ Level}{Number\ Of\ Days\ \mathrm{Re}ported\ By\ TDOT\ Inspector} \qquad [\ 3\text{-}4\ ]$$

This ratio shows whether the contract was behind or ahead of schedule If the ratio was less than 1.0, the contract was behind schedule The project was ahead of schedule if the ratio was greater than 1 0 A ratio of 1 0 reflected a contract concurrent with the schedule

The historical time duration of an operation was estimated using the predictive production rates and then compared to the actual time recorded by the contractor for completion of the project By making this comparison, it could be determined if the contractor had been allotted enough days for construction of the operations For example, 72% of the operations took 50% longer to complete and approximately 39% of the contracts took 70% longer to complete All of the major operations like road and drainage excavation, borrow excavation, mineral aggregate, and asphalt operations, were 50% or more behind schedule according

Table 3-4. Comparison of the Number of Days Reported and the Maximum Number of Days Reported at a 95% Confidence Level for Contract 8402

Task	Unit of Measure	Final Quantity	# of Days Reported	Predictive Prod. Rate	Max # Day Needed at 95%	Difference	Percent	Ratio
Road & Drainage Excavation	CY	666668	212	3461	193	-19	-10	0.91
Borrow Excavation	CY	178768	70	2324	77	7	9	1.10
Mineral Aggregate Mix	TONS	457979	232	2800	164	-68	-41	0.71
Asphalt Grade A.S.	TONS	47694	27	1560	31	4	13	1.15
Bituminous Plant Mix Grade A	TONS	59205	27	1808	33	6	18	1.22
Bituminous Plant Mix Base Grade B-M	TONS	36924	29	1400	27	-2	-7	0.93
Asphalt Grading D	TONS	21829	19	1176	19	0	0	1.00
18" Concrete Pipe Culvert	LF	7370	36	225	33	-3	-9	0.92
24" Concrete Pipe Culvert	LF	286	2	225	2	0	0	1.00
30 " Concrete Pipe Culvert	LF	592	7	146	5	-2	-40	0.71
36" Concrete Pipe Culvert	LF	1297	5	146	9	4	44	1.80
42" Concrete Pipe Culvert	LF	382	6	146	3	-3	-100	0.50
48" Concrete Pipe Culvert	LF	297	7	85	4	-3	-75	0.57
Concrete Parapet	LF	913	6	350	3	-3	-100	0.50

to the analysis. These major operations usually fall on the critical path, which affects the total project duration and the total project cost An operation estimated to take 20 days to complete was taking the contractor a minimum of 30 actual days to complete Again, the predictive production rates were based on the contractor allocating the appropriate amount of resources to perform the operations There is insufficient information recorded in the inspector's diaries indicating whether this large discrepancy was due to an error in the predictive production model or the contractor's failure to allocate sufficient resources for the operations.

The road and drainage operation was the only operation studied that had enough data to develop predictive production rates and historical production rates for the three contract classifications. Figure 3-3 is a graphical representation of all road and drainage operations studied for this thesis. Thirteen contracts were studied and 77% of the contracts were found to be behind schedule Since this operation usually falls on the critical path, the proper allocation of resources is crucial to the project being completed on schedule

Since the mineral aggregate operation always falls on the critical path, it is important that the estimation of this operation be within 10% of the actual time needed for completion Figure 3-4 lists the results of the mineral aggregate mix analysis The results indicate that for the thirty-six contracts examined, 98% of the operation's time duration were underestimated. Thirteen contracts took at least twice the allotted time to complete the operation This large discrepancy might

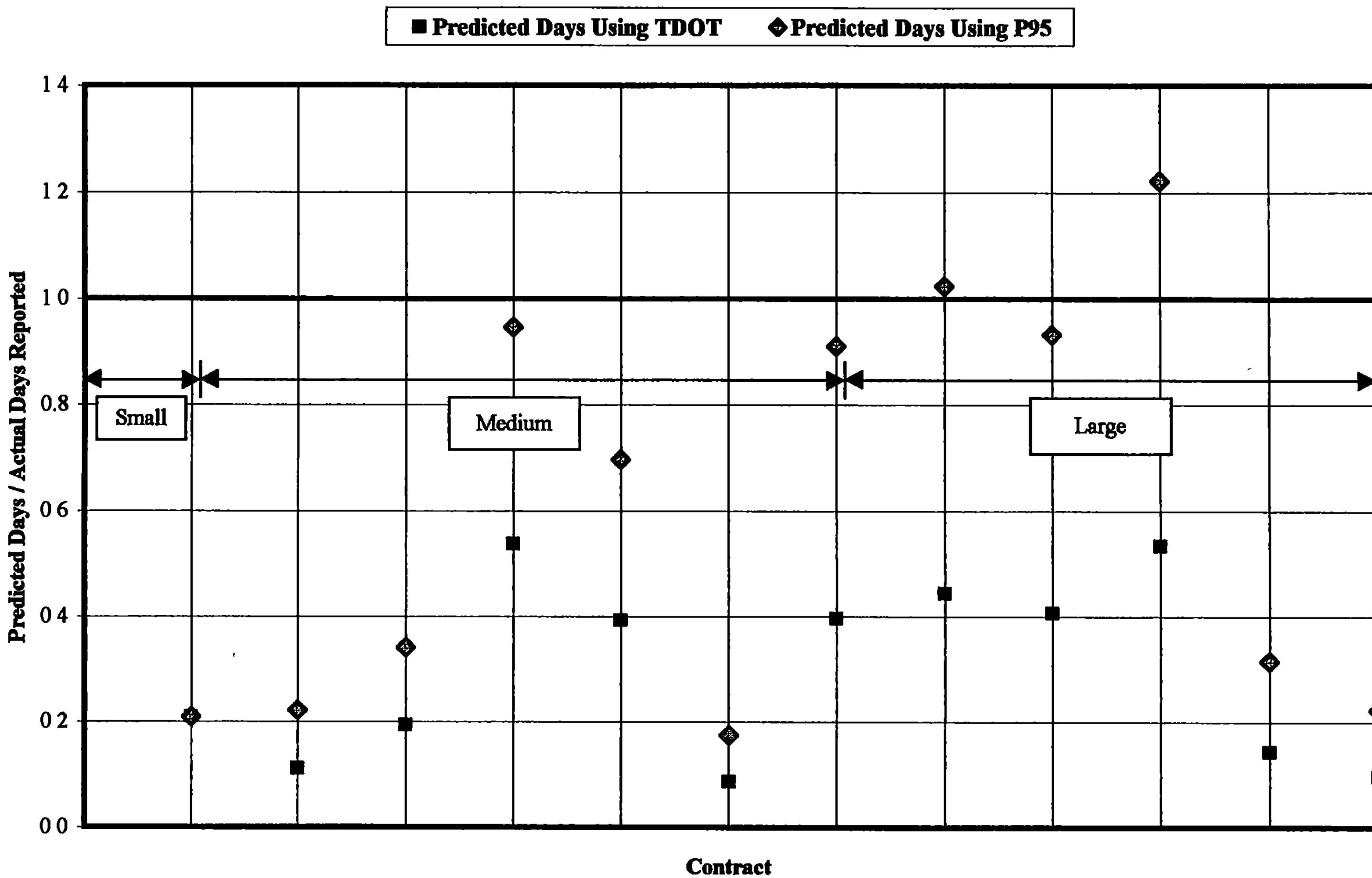

Figure 3-3. Ratio of Predicted Days and Number of Days Reported for All Road and Drainage Excavation Operations

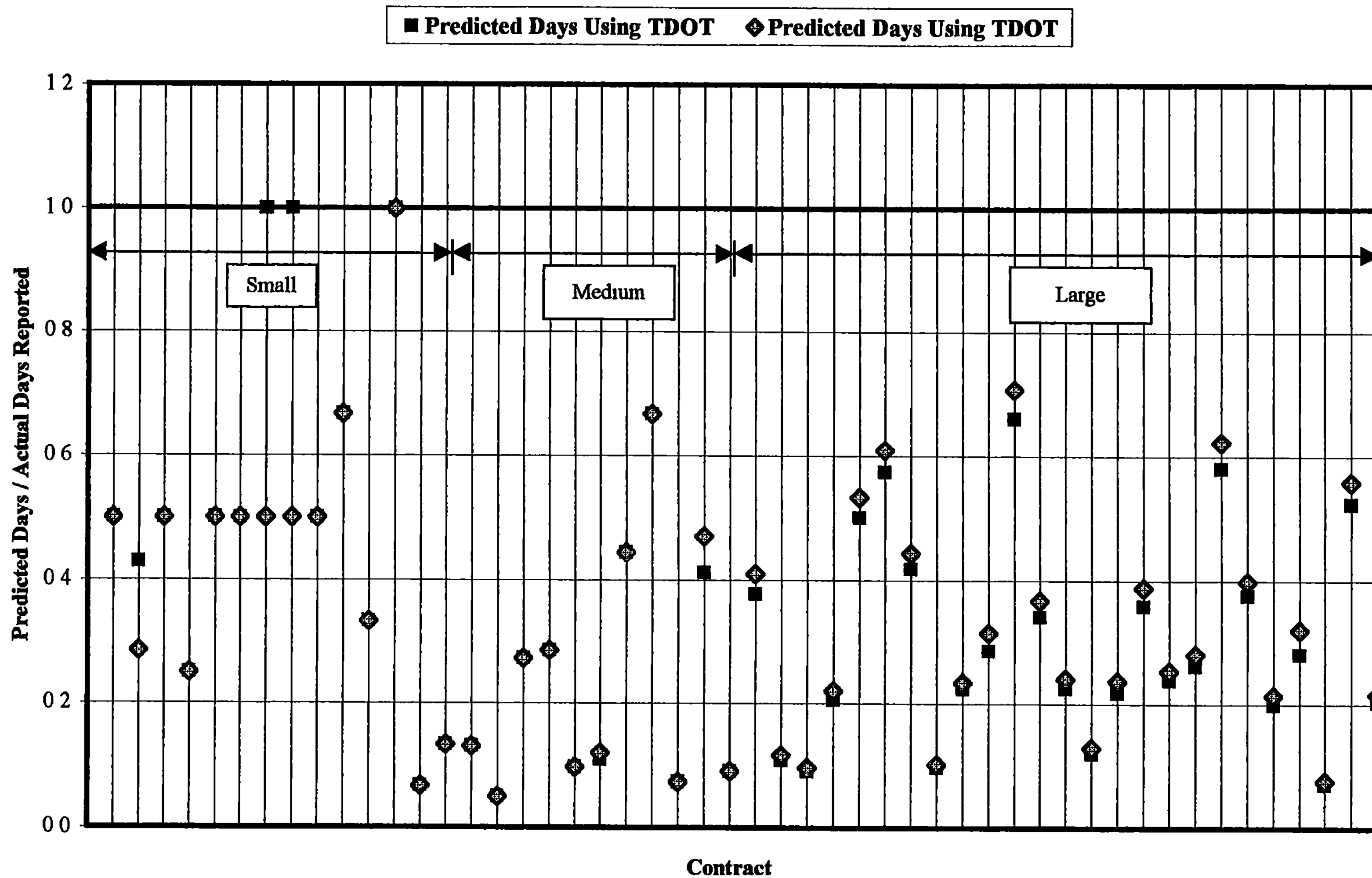

Figure 3-4. Ratio of Predicted Days and Number of Days Reported for All Mineral Aggregate Mix Operations

not be due entirely to TDOT's production rates Historical data collection for this item was difficult The determination of a full day or a half-day could not be made, therefore, each day recorded was taken as a full day An error was introduced upon making this assumption Without the proper documentation needed for determining the historical production rates accurately, the assumption had to be made just to get an idea of how well the production rates compared

Figure 3-5 shows the summary of all asphalt grade D operations As can be seen, the majority of the contracts underestimated the construction duration according to the number of days reported. This underestimation is the case for all asphalt operations studied. Only a few contracts were able to meet the predictive production rates and finish the operation on or ahead of schedule. In general, the asphalt operations indicated that more time was needed to complete the operations

The item having the largest discrepancy between the historical production rate and TDOT's production rate was the concrete ramp pavement operation Figure 3-6 represents the summary of all concrete ramp pavement operations TDOT currently uses a production rate of 10,000 sy/day Gatlin (1998) and Brown (1999) developed a P_{95} rate of 536 sy/day Based on the P_{95} rate, 40% of the historical contracts were ahead of schedule by at least 30% All of the contracts were 600% or more behind schedule when TDOT's production rate was used. According to these results, adjustments should be made to TDOT's

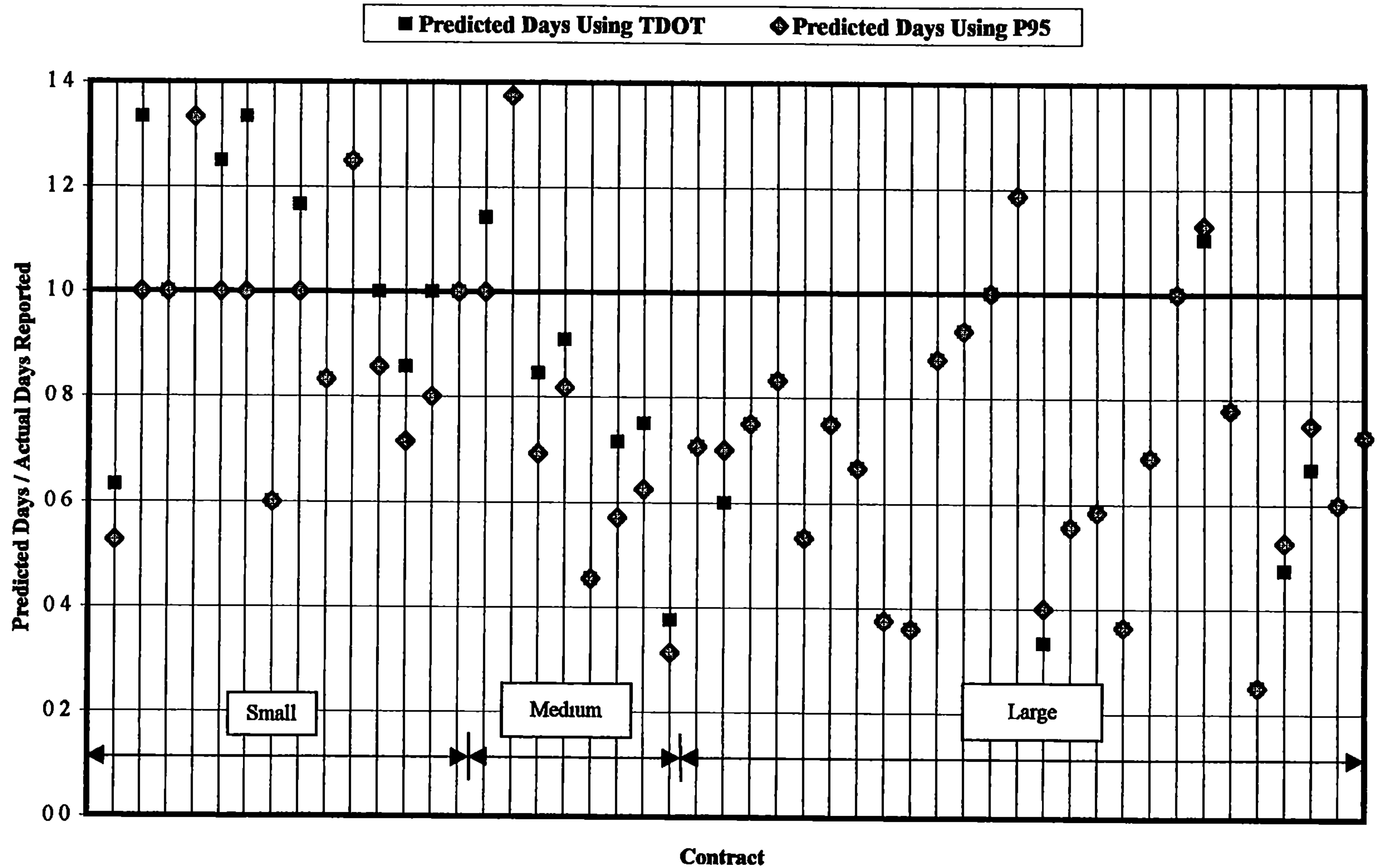

Figure 3-5. Ratio of Predicted Days and Number of Days Reported for All Asphalt Grade D Operations

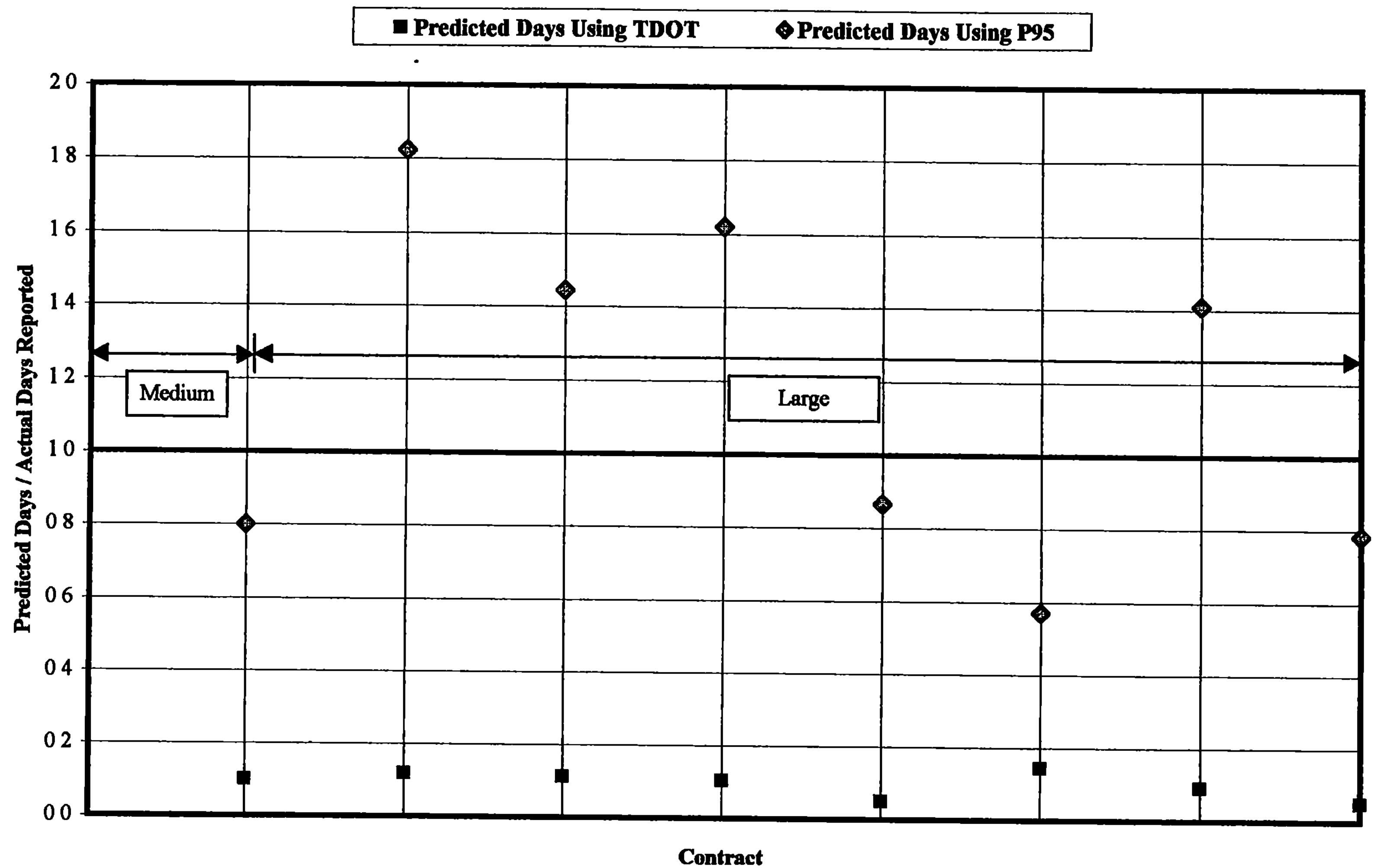

Figure 3-6. Ratio of Predicted Days and Number of Days Reported for All Concrete Ramp Pavement Operations

production rate to prevent this huge underestimation of time required for concrete ramp pavement construction

The results of the analysis showed that the concrete pipe culvert operations were generally allotted enough days for completion Sixty-seven percent of the concrete pipe culvert operations were estimated to be 65% or more ahead of schedule. This item does not usually have a great impact on the overall duration of a project because it is not on the critical path. Therefore, the data indicated that the production rates currently being used by TDOT would be sufficient in the estimation of the time duration for the concrete pipe culvert operation

Even though the results indicate that the contractor typically needed more time to complete the operations, the historical data showed that some contractors were capable of meeting the predictive production rates. Since some contractors met the P_{95} rate, it can be assumed that all contractors should be capable of meeting the P_{95} rate The misallocation of resources could be the main reason for not finishing the operation on schedule.

CHAPTER 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS

The goal of this research project was to collect historical data, determine historical production rates, and compare these rates with the predictive production rates developed by Gatlin (1998) and Brown (1999). Comparisons were made to determine the validity of the predictive production rates. The results for the operations indicate, typically, that there was not enough time appropriated for the contractor to complete the operations on schedule. However, a look at the historical data and the number of days meeting or exceeding the P_{95} rate shows that the contractors were able to match the predictive production rate some of the time during construction. This fact would indicate that the contractor might not have the appropriate amount of resources allotted to the operations. Failure to have enough resources available can lead to contract overruns, cost overruns, and ultimately claims.

The mineral aggregate operation was the only operation studied where 98% of the contracts had more days reported to complete the operation than the number of days estimated using the predictive production rates. The reason for the large discrepancy between actual days and estimated days was due primarily to record keeping. Days were recorded when mineral aggregate mix was laid; however, no details as to the location of placement were recorded in the historical records. A differentiation could not be made between a "day recorded" and a "full day of work"; therefore, an assumption had to be made. The assumption was that each day recorded would be counted as a "full day". This assumption can lead to a large underestimation of operation productivity, since there was no indication in the historical records whether the days reported were full days or half days. Although it is not as evident in the results of the asphalt operations, the same problem occurred in record keeping.

Many factors influence production rates. For example, project management is one of the most influential factors affecting final completion of a project. Project managers determine how many resources should be used. The production rates were developed on the assumption that enough resources will be available for construction. When equipment or personnel are inappropriately allocated, a reduction in productivity occurs. Another factor influencing project duration is the arrival time of material. Delays occur if the materials do not arrive on the project site when they are needed. The bunching together of haul trucks during the hauling or dumping of materials, also known as the bunching effect, causes a reduction in productivity. The processor has to wait for trucks to arrive, and then the trucks are bunched together. Trucks have to wait in a queue to be loaded and then delays occur.

4.2 RECOMMENDATIONS

Descriptive record keeping would help in the improvement of production rates. A researcher must rely on the documents of the past to provide information for future changes in productivity calculations. Many problems in record keeping were noted during this research. When referring back to field books, dates of construction and placement of materials were often difficult to find or not found at all. For example, dates for placement of the mineral aggregate mix and asphalt were most always noted; however, the location of placement was never noted. It is important to the researcher to know where the material was being laid. If only two truckloads of material were laid on a driveway, the proper adjustments need to be made to account for the low daily production. Also, when the contractor is at full production laying material on the roadway, a note needs to be made so that a full day would be interpreted.

Information needed from inspector's field diaries was also hard to collect. Historical data for the box culvert, box bridge, bridge deck, and steel bar reinforcement operations could not be collected because of poor record keeping. To make a proper assessment of these operations, the inspector must keep detailed notes. The amount of time needed to dig footings, to lay the steel, to form the foundation, walls, and top, to cure, and to strip the forms should all be noted for the box culvert and bridge operations. Since the inspector cannot oversee everything on a project without missing something during the construction process, an approximate time would be sufficient. The amount of time needed to tie steel bars on a bridge deck is also very important to research. This item is on the critical path for bridge construction. Work cannot proceed until the reinforcement is placed and tied. Accurate production rates need to be determined in order to predict the amount of days needed for this operation.

The future of an organization depends greatly on learning and improving on the progress of the past. Proper record keeping would help to improve on future construction. By keeping proper records, contract overruns, dispute resolution, and total project cost can be better defended. The record keeping process should be uniform across the state, thereby reducing the possible misinterpretation of contract documents. Training seminars would be one step in assuring appropriate recording of events occurring on projects. By taking a little more time and making the proper notes, production rates can be determined for any of the construction processes.

LIST OF REFERENCES

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Adrian, James J. Construction Productivity Improvement Elsevier Science Publishing Co , Inc. New York, New York, 1987

Brown, E R "Factors Affecting Productivity of Highway Construction Operations " M S. thesis presented to the University of Tennessee, Knoxville 1998

Gatlin, R L. "Productivity Analysis for Highway Excavation Operations " M S thesis presented to the University of Tennessee, Knoxville 1998

APPENDIX

A step by step analysis of an operation studied.

Contract 2476

Final Contract Amount = $2,511,506 28 > $2,500,000

Therefore, this contract falls into the large contract classification

For Asphalt Grade A-S

Final Quantity = 11019 tons

Average P_{95} Production Rate = 1560 tons/day

TDOT Production Rate = 2000 tons/day

Data collected from historical records (See Figure A-1)

Number of Days Reported for Completion of Operation = 7 days

Number of Days Meeting or Exceeding TDOT Production Rate = 2 days

Number of Days Meeting or Exceeding P_{95} Production Rate = 3 days

Analysis

$$Max\ Number\ of\ Days\ Needed\ According\ to\ TDOT = \left(\frac{Final\ Quantity}{TDOT\ \mathrm{Pr}oduction\ Rate}\right)$$

$$Max.\ Number\ of\ Days\ Needed\ According\ to\ TDOT = \left(\frac{11019 tons}{2000 tons / day}\right) = 6\ days$$

$$Max.\ Number\ of\ Days\ Needed\ at\ 95\% = \left(\frac{Final\ Quantity}{\mathrm{Pr}edictive\ \mathrm{Pr}oduction\ Rate}\right)$$

$$Max.\ Number\ of\ Days\ Needed\ at\ 95\% = \left(\frac{11019 tons}{1560 tons / day}\right) = 8\ days$$

Figure A-1. Contract 2476 Historical Data for Asphalt Grade A-S

ITEM 307-0103 AGGREGATE (APMB-HM) GRDG. A-S MIX

DATE	DAILY TONS MIX	ACC TONS MIX	DAILY TONS AGG.	ACC TONS AGG.	% AC.	
9-27-93	1433.560	1433.560	1387.650	1387.650	3.2	NON-POLYMER
10-17-94	1973.850	3407.370	1910.688	3298.338	3.2	
10-18-94	2464.510	5871.880	2385.648	5683.985	3.2	
10-20-94	871.500	6743.380	843.612	6527.597	3.2	
12-15-94	1075.450	7818.830	1041.032	7568.629	3.2	
5-5-95	2447.000	10,265.830	~~2368.896~~ 2363.803	9932.432	3.2	
5-3-15	753.000	11,018.830	727.398	~~9664.965~~ 10,659.830	3.4	

FINAL PAY QUANTITY ~~10,664.7~~ 10,659.8

MEAS./INSP./COMP. BY Vance M. Toomey

CHECKED BY R. [illegible] 3-16-96

ITEM 307-0104

ASPHALT CEMENT (APMB-HM) GRDG A-S MIX

NET TONS A.C.	ACC TONS A.C.	307.01
45.870	45.870	9/92
63.163	109.032	
78.863	187.895	
27.888	215.783	10/94 169
104.032	250.198 / 251.815	11/94
81.591 / 83.577	333.374	
25.602	358.698 / 358.976	5/95

FINAL PAY QUANTITY ~~358.110~~ 359.00

$$D_{TDOT} = Max\ Number\ of\ Days\ Needed\ According\ to\ TDOT - Number\ of\ Days\ Reported$$

$$D_{TDOT} = 6 days - 7 days = -1 day$$

$$D_{P95} = Max\ Number\ of\ Days\ Needed\ at\ 95\% - Number\ of\ Days\ Reported$$

$$D_{P95} = 8 days - 7 days = 1 day$$

$$Percent\ TDOT = \left(\frac{D_{TDOT}}{Max\ Number\ of\ Days\ Needed\ According\ to\ TDOT} \right) * (100)$$

$$Percent\ TDOT = \left(\frac{-1 day}{6 days} \right) * (100) = -17\%$$

$$Percent\ P_{95} = \left(\frac{D_{P95}}{Max.Number\ of\ Days\ Needed\ at\ 95\%} \right) * (100)$$

$$Percent\ P_{95} = \left(\frac{1 day}{8 days} \right) * (100) = 13\%$$

$$Ratio\ TDOT = \left(\frac{Max\ Number\ of\ Days\ Needed\ According\ to\ TDOT}{Number\ of\ Days\ Reported} \right)$$

$$Ratio\ TDOT = \left(\frac{6 days}{7 days} \right) = 0.86$$

$$Ratio\ P_{95} = \left(\frac{Max\ Number\ of\ Days\ Needed\ at\ 95\%}{Number\ of\ Days\ Reported} \right)$$

$$Ratio\ P_{95} = \left(\frac{8 days}{7 days} \right) = 114$$

$$Contribution\ to\ Wt.\ Avg = \left(\frac{Final\ Quantity}{Number\ of\ Days\ Reported} \right) * \left(\frac{Final\ Quantity}{\sum of\ All\ Final\ Quantities} \right)$$

$$Wt\ \ Avg\ \ Historical\ \mathrm{Prod}\ \ Rate = \left(\frac{11019tons}{7days}\right) * \left(\frac{11019tons}{516419tons}\right) = 34\,tons\,/\,day$$

$$Wt\ \ Avg = \sum\left[\left(\frac{Final\ Quantity}{Number\ of\ Days\ \mathrm{Re}ported}\right) * \left(\frac{Final\ Quantity}{\sum of\ Final\ Quantities}\right)\right]$$

$$Wt\ \ Avg = \sum\left[\left(\frac{Final\ Quantity}{Number\ of\ Days\ \mathrm{Re}ported}\right) * \left(\frac{Final\ Quantity}{\sum of\ Final\ Quantities}\right)\right]$$

The analysis was performed on all other contracts containing the asphalt grade A-S operation and then summarized in Table A-1. Figure A-2 is a graphical representation of the summary Table A-2

Table A-1. Summary of All Asphalt Grade A-S Operations

#	Region	Contract Number	County	Contract Size	Final Quantity	# of Days Reported	TDOT Prod Rate	Max # of Days Needed According to TDOT	Predictive Prod Rate	Max # of Days Needed at 95%	DTDOT	DP95	Percent TDOT	Percent P95	Ratio TDOT	Ratio P95	Weighted Prod Rate
1	1	Contract 2417	Knox	Large	17971	6	2000	9	1560	12	3	6	33	50	1.50	2.00	104
2	1	Contract 2452	Anderson	Large	23865	32	2000	12	1560	16	-20	-16	-167	-100	0.38	0.50	34
3	1	Contract 2476	Knox	Large	11019	7	2000	6	1560	8	-1	1	-17	13	0.86	1.14	34
4	1	Contract 2483	Unicoi	Large	11354	6	2000	6	1560	8	0	2	0	25	1.00	1.33	42
5	1	Contract 2962	Unicoi	Large	18642	26	2000	10	1560	12	-16	-14	-160	-117	0.38	0.46	26
6	1	Contract 7361	Washington	Medium	6730	8	2000	4	1560	5	-4	-3	-100	-60	0.50	0.63	11
7	1	Contract 8787	Sullivan	Medium	9031	14	2000	5	1560	6	-9	-8	-180	-133	0.36	0.43	11
8	2	Contract 2867	Hamilton/Sequatchie	Large	39872	28	2000	20	1560	26	-8	-2	-40	-8	0.71	0.93	110
9	2	Contract 7511	Hamilton	Large	6905	19	2000	4	1560	5	-15	-14	-375	-280	0.21	0.26	5
10	2	Contract 8124	Marion	Large	15080	21	2000	8	1560	10	-13	-11	-163	-110	0.38	0.48	21
11	2	Contract 8392	Coffee	Large	883	15	2000	1	1560	1	-14	-14	-1400	-1400	0.07	0.07	0.1
12	2	Contract 8402	Coffee/Franklin/Grundy	Large	47694	27	2000	24	1560	31	-3	4	-13	13	0.89	1.15	163
13	2	Contract 8436	Warren	Large	33378	28	2000	17	1560	22	-11	-6	-65	-27	0.61	0.79	77
14	2	Contract 8490	Hamilton	Large	20158	35	2000	11	1560	13	-24	-22	-218	-169	0.31	0.37	22
15	3	Contract 2730	Montgomery	Large	19636	30	2000	10	1560	13	-20	-17	-200	-131	0.33	0.43	25
16	3	Contract 2749	Sumner	Large	13721	16	2000	7	1560	9	-9	-7	-129	-78	0.44	0.56	23
17	3	Contract 3556	Davidson	Large	26490	25	2000	14	1560	17	-11	-8	-79	-47	0.56	0.68	54
18	3	Contract 4017	Davidson	Large	21102	27	2000	11	1560	14	-16	-13	-145	-93	0.41	0.52	32
19	3	Contract 4251	Williamson	Large	96682	62	2000	49	1560	62	-13	0	-27	0	0.79	1.00	292
20	4	Contract 2674	Weakley	Large	20035	23	2000	11	1560	13	-12	-10	-109	-77	0.48	0.57	34
21	4	Contract 2739	Shelby	Large	8820	20	2000	5	1560	6	-15	-14	-300	-233	0.25	0.30	8
22	4	Contract 2780	Gibson	Medium	4658	12	2000	3	1560	3	-9	-9	-300	-300	0.25	0.25	4
23	4	Contract 2825	Weakley	Large	24371	25	2000	13	1560	16	-12	-9	-92	-56	0.52	0.64	46
24	4	Contract 2967	Weakley	Large	18320	16	2000	10	1560	12	-6	-4	-60	-33	0.63	0.75	41

Average Weighted Historical Production Rate = 1218 tons/day

r = 0.78

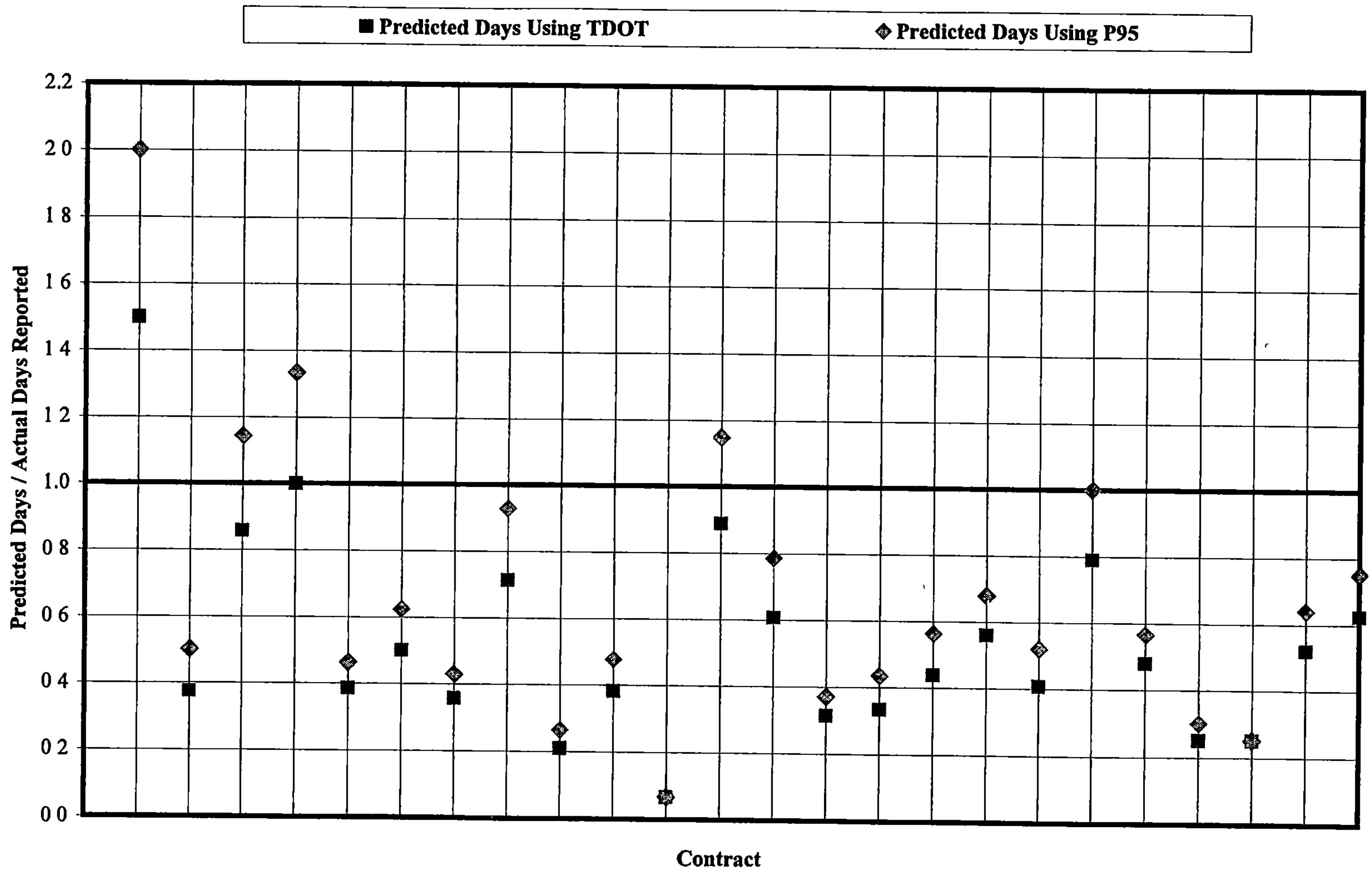

Figure A-2. Ratio of Predicted Days and Number of Days Reported for All Asphalt Grade A-S Operations

VITA

Brent Alan Thornton was born in Union City, Tennessee on January 4, 1975 He attended schools in the Gibson County School System, where he spent kindergarten through fifth grade at Kenton Elementary School, sixth grade through eighth grade at Rutherford Junior High School, and graduated from Gibson County High School in May, 1993 He entered The University of Tennessee at Martin during August of 1993 After attending UTM for two years, he transferred to The University of Tennessee at Knoxville during August of 1995 where in December, 1998 he received the Bachelor of Science in Civil Engineering January 1999, he began his graduate studies and received his Master of Science in Civil Engineering in May, 2000