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Contents

Foreword

Today's transportation construction programs are constantly affected by the possibility of reduced funding. This situation demands careful attention to effectiveness of methods, efficiency in planning, and innovation in technology to ensure the success of each project. In this Record, various aspects of modern construction techniques and planning practices are considered for the transportation industry.

The first two papers examine concrete pavement construction. Hallin et al. present a performance review of concrete pavement restoration techniques in a sample of 26 projects. The authors conclude that proper preliminary engineering and timing are critical to project performance when these methods are used. Okamoto reports on field work in which two techniques for placing dowels in rigid pavement joints were evaluated by using a commercially available radar system to examine dowel placement within the concrete. The two methods, a dowel bar inserter and a dowel basket assembly, were determined to be similarly effective.

In three papers, the uses of computer and mathematical techniques to increase the efficiency and effectiveness of construction planning and management are considered. Cleveland and Francisco describe a computer-aided design system that can use real-time animation to simulate major construction tasks. They conclude that use of the system can cut reduce costly construction time by allowing planners and workers to "rehearse" a project before work actually starts. Blasko explains the computerized record-keeping and estimation system used by the New Jersey Department of Transportation. The department finds that the system saves a great deal of time in producing status reports and progress estimates for multiple projects. Karshenas and Farid explore a mathematical method for optimal multiloader-truck fleet selection in earth-moving operations. They provide examples that demonstrate how their technique can reduce the time and cost of selecting appropriate equipment for earthwork tasks.

The final paper explores the effect of FHWA's Disadvantaged Business Enterprise program on highway construction in Indiana. Authors Hancher et al. conclude that although the program has been generally successful in allowing disadvantaged business enterprises (DBEs) to take greater part in government-funded highway construction, problems remain. In particular, a few large companies have been winning most of the contracts, and the range of construction activities pursued by DBEs remains narrow.

Performance Review of Concrete Pavement Restoration

JOHN P. HALLIN, DANIEL M. MATHIS, AND ROBERT L. LEE

Concrete pavement restoration (CPR) is a pavement rehabilitation strategy for portland cement concrete (PCC) pavements. The method consists of a number of individual techniques, including slab stabilization (subsealing), full-depth patching, partial-depth patching, load transfer restoration, subdrainage, shoulder restoration, diamond grinding, and joint resealing. These practices are designed to provide additional service life to the existing pavement. The FHWA noted growing concerns that both this entire rehabilitation strategy and the individual techniques were performing below expected levels or were not appropriate for actual project conditions. A plan was developed to conduct detailed reviews of completed CPR rehabilitation projects. In all, 26 CPR projects in 8 states were reviewed. It was found that proper preliminary engineering and timing of the individual techniques are critical to project performance. The reviewers found that when projects are properly designed and constructed, CPR will generally reduce pavement deterioration, thereby prolonging pavement life. Continued maintenance will be required, however, throughout the project design life. In addition, it was noted that pavements that have an accelerated rate of slab cracking will continue to have a high rate of slab deterioration immediately after completion of a CPR project.

One of the pavement rehabilitation strategies for portland cement concrete (PCC) pavements is concrete pavement restoration (CPR). Individual techniques within a CPR project include slab stabilization (subsealing), full-depth patching, partial-depth patching, load transfer restoration, subdrainage, shoulder restoration, diamond grinding, and joint resealing. In the past, these techniques had been used on a limited basis as a maintenance strategy. Very few reliable performance data were available for the CPR techniques.

To assess the effectiveness of the CPR strategies that were being undertaken by state highway agencies, the FHWA conducted a review of selected CPR projects. The review focused on three aspects of CPR work that had been completed on jointed plain and jointed reinforced concrete pavements:

- Expected service life, based on observed performance;
- Variables that significantly affect the performance of individual CPR techniques; and
- Conditions under which each strategy has been used in a cost-effective manner.

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Field reviews were conducted jointly by the FHWA's Pavement Division and Demonstration Projects Division between May and October 1986. Teams composed of an engineer from each division conducted in-depth reviews of 26 CPR projects in eight states. These teams were assisted by engineers from the appropriate FHWA regional and division offices and by state engineers familiar with the design, construction, and maintenance of each project. The states also provided historical and inventory data for each project.

The CPR review provides interim technical guidance. The findings represent the consensus of the FHWA engineers who conducted the reviews, based on their experience, data gathered, field observations, and discussions with field practitioners.

In all, 26 CPR projects were reviewed in 8 states. The projects reviewed and techniques evaluated are listed in Table 1. Pertinent information on each of the pavements rehabilitated is summarized in Table 2.

All the projects evaluated were jointed concrete pavements. Half (13) of the projects were plain concrete pavements with undowelled joints. The remaining 13 projects were reinforced concrete pavements with dowelled joints. The average age of the pavements at the time of rehabilitation was 18 years, with a range of 10 to 38 years.

Very few traffic-loading data were available for most of the projects. However, an attempt was made to classify the current truck loadings on the projects into four groups. The groups are based on daily volume of "five-axle or greater" trucks. This grouping was selected because these trucks generally provide 85 percent or more of the 18-kip equivalent single-axle loadings on rural highways. The following groups were selected:

Loading Class	*Daily Truck Volume (5-Axle or Greater)*
1	>1,500
2	1,001–1,500
3	501–1,000
4	<501

For each major rehabilitation project reviewed, a subjective evaluation of the performance was made. All projects were expected to provide 6 to 10 years' service life. Therefore, if the project required early rehabilitation or major maintenance, it was considered to have been a poor overall candidate for rehabilitation.

In addition, the performance of the individual techniques was evaluated. These techniques included full-depth patching,

TABLE 1 PROJECTS AND REHABILITATION TECHNIQUES REVIEWED

Route	Project Limits	Year Rehabilitated	Pavement Age[a] (yr)	Rehabilitation Techniques: Subseal	Edge Drains	Pressure Relief	Full Depth	Partial Depth	Diamond Grinding	Joint Sealing
California										
I-5	Shasta Co., MP 3.8–14.0	1983	17	Y	Y		Y			Y
I-80	Placer Co., MP 4–11.4	1984	25	Y	Y		Y	Y		
I-5	Yolo Co., MP 23–27.1	1984	18	Y	Y		Y		Y	
Georgia										
I-75	MP 226–232	1981	12	Y					Y	Y
I-475	MP 0–15	1980	13	Y			Y	Y	Y	Y
I-75	MP 64–72	1978	17	Y			Y	Y		Y
I-75	MP 22–59	1978	17	Y			Y	Y		Y
South Carolina										
I-85	MP 21–34	1979	15	Y			Y		Y	Y
I-20	MP 0–6	1984	17	Y			Y	Y	Y	Y
Virginia										
I-81	MP 147.2–161.8 NB	1984	19	Y	Y		Y	Y	Y	Y
I-64	MP 238.4–254	1982	19				Y			Y
I-64	MP 278.7–283.3	1983	16			Y	Y			Y
Minnesota										
I-694	MP 37–46	1981	20				Y	Y		Y
US-10	MP 204–211.6	1981	35						Y	
US-71	MP 124.9–129.2	1983	14						Y	
I-94	MP 81–103	1981	14					Y		Y
Wisconsin										
WI-29	Chippewa Falls to Thorp	1983	16				Y	Y		Y
US-61	Fennimore to Boscobel Rd.	1982	30				Y	Y	Y	
US-151	Columbus–Beaver Dam Rd.	1982	28				Y		Y	
I-90	MP 138–142	1981	21				Y		Y	Y
Michigan										
I-75	MP 64–80	1983					Y			
M-47	Saginaw Co. State Rd to Div.	1983	16					Y		Y
South Dakota										
I-29	MP 27–62	1972	10					Y		Y
I-29	MP 0–15	1980	19			Y	Y	Y		Y
I-90	MP 395.5–412	1985	24			Y	Y	Y		Y
I-90	MP 265–292.2	1982	17					Y		Y

[a] Average Age: 18.76 (Min: 10.00, Max: 35.00).

partial-depth patching, grinding, joint resealing, and subsealing. Very few projects reviewed included pressure relief joints, subdrains, retrofit load transfer devices, and shoulder restoration techniques, so detailed comments on these techniques are not provided. The reviewers also concluded that it is not possible to evaluate subsurface drainage without performing in-depth testing. A separate project has been initiated to evaluate subsurface drainage on a variety of in-service installations. A detailed discussion of the CPR techniques is presented in the following sections.

OVERALL CPR STRATEGY

On many of the projects reviewed, there was very little information available on the condition of the pavement before the rehabilitation project. This lack of data made it difficult to make before and after evaluations of the effectiveness of the CPR techniques. The absence of information on the rate of pavement deterioration before CPR made it difficult to determine whether CPR slowed the rate of deterioration.

Another complication, in addition to the lack of detailed information on the extent and causes of distress, was that the pavement condition on most projects was not formally checked during the latter stages of project development. As a result, several projects experienced overruns that exceeded 500 percent for full- and partial-depth patching quantities. On one project, the quantity of partial-depth patching increased from 11,511 ft^2 to 89,893 ft^2 for an overrun of \$470,292. At least one project was terminated before all CPR work was completed because overruns in quantities exceeded available funds. These findings emphasize the need for detailed monitoring of conditions throughout the preliminary engineering phase of candidate CPR projects.

In retrospect, 4 of the 26 projects reviewed were probably poor candidates for CPR. This judgment was based on the condition of the pavements 5 yr or less after rehabilitation. Three of these projects were in need of major maintenance or

TABLE 2 DESCRIPTION OF THE ORIGINAL PAVEMENT ON EACH PROJECT REVIEWED

Route	Project Limits	Year Opened	Load Class[a]	Pavement Type[b]	Pavement Depth (in.)	Joint Spacing (ft)	Skew ('/12)	Dowels	Climate Zone	Avg. Monthly Temperature Min.	Avg. Monthly Temperature Max.	Freeze Index	Base Material	Subgrade	Year Rehabilitated	Pavement Age[c] (yr)
California																
I-5	Shasta Co., MP 3.8–14.0	1966	2	JPCP	8	12–19	2	N	IIC	37	97	0	CTB	CLY-GR	1983	17
I-80	Placer Co., MP 4–11.4	1959	1	JPCP	8	15	0	N	IIC	39	95	0	CTB	SD-ST	1984	25
I-5	Yolo Co., MP 23–27.1	1966	2	JPCP	8	12–19	2	N	IIC	38	96	0	CTB	ST-CLY	1984	18
Georgia																
I-75	MP 226–232	1969	1	JPCP	10	30	0	N	IC	35	88	0	CTB	ST-CLY	1981	12
I-475	MP 0–15	1967	2	JPCP	9	30	0	N	IC	38	93	0	ATB	Select	1980	13
I-75	MP 64–72	1961	1	JPCP	9	30	0	N	IC	38	93	0	ATB	Select	1978	17
I-75	MP 22–59	1961	1	JPCP	9	30	0	N	IC	38	93	0	ATB	Select	1978	17
South Carolina																
I-85	MP 21–34	1964	1	JPCP	9	25	0	N	IC	35	92	0	Earth	A-7-5 & 6	1979	15
I-20	MP 0–6	1967	2	JPCP	9	25	0	N	IC	35	91	0	Earth	A-2-4	1984	17
Virginia																
I-81	MP 147.2–161.8 NB	1965	3	JRCP	9	61.5	0	Y	IB	29	88	0	Crushed aggregate	A-6 & A-7	1984	19
I-64	MP 238.4–254	1963	2	JRCP	9	61.5	0	Y	IC	32	88	0	Aggregate	A-6 & A-7	1982	19
I-64	MP 278.7–283.3	1967	1	JRCP	9	61.5	0	Y	IC	32	88	0	CTB	A-3 & A-2	1983	16
Minnesota																
I-694	MP 37–46	1961	1	JRCP	10	40	0	Y	IA	1	81	1567	Gravel	A-6	1981	20
US-10	MP 204–211.6	1946	4	JPCP	9–7–9	15	0	N	IA	−2	81	1987	None	A-1-B	1981	35
US-71	MP 124.9–129.2	1969	4	JPCP	8.5	20	2	N	IIA	−1	84	1597	Aggregate	A-4	1983	14
I-94	MP 81–103	1967	3	JRCP	9	39.3	0	Y	IIA	−4	81	2262	Gravel	A-6	1981	14
Wisconsin																
WI-29	Chippewa Falls to Thorp	1967	3	JRCP	9	90	0	Y	IA	3	82	1750	Crushed aggregate	Granular	1983	16
US-61	Fennimore to Boscobel Rd.	1952	4	JPCP	8	20	0	N	IA	9	84	1000	Crushed aggregate	GI = 14	1982	30
US-151	Columbus–Beaver Dam Rd.	1954	4	JPCP	9	80	0	N	IA	8	81	1000	Gravel	A-4	1982	28
I-90	MP 138–142	1960	1	JRCP	9	80	0	Y	IA	8	81	1000	Gravel	N/A	1981	21
Michigan																
I-75	MP 64–80	N/A	1	JRCP	9	99	0	Y	IA	19	83	750	N/A	N/A	1983	–
MI-47	Saginaw Co. State Rd to Div.	1967	4	JRCP	9	71	0	Y	IA	15	81	750	N/A	N/A	1983	16
South Dakota																
I-29	MP 27–62	1962	N/A	JRCP	9	61.5	0	Y	IIA	5	86	N/A	Aggregate	A-7-6-12	1972	10
I-29	MP 0–15	1961	N/A	JRCP	10	61.5	0	Y	IIA	5	86	N/A	Aggregate	A-7-6-12	1980	19
I-90	MP 395.5–412	1961	N/A	JRCP	9	61.5	0	Y	IIA	5	86	N/A	Granular	A-7-6-12	1985	24
I-90	MP 265–292.2	1965	N/A	JRCP	9	46.5	0	Y	IIA	5	86	N/A	Lime/aggregate	A-7-6-12	1982	17

[a] JPCP=jointed plain concrete pavements. JRCP=jointed reinforced concrete pavements.
[b] Load classes are based on the following one-way volumes of five-axle or greater trucks: >1,500=1, 1,001–1,500=2, 501–1,000=3, <501=4.
[c] Average age: 18.76 (Min: 10.00, Max: 35.00)

complete reconstruction. The other project is displaying significant distress less than 2 yr after rehabilitation. The principal type of distress on these projects was the structural failure of the slabs. When these projects were rehabilitated, ~4.7 to 16.3 percent of the pavement in the right lane was replaced by full-depth patching. Generally, additional patching was required, but contract overruns were limited by fiscal constraints. In most cases, full-depth patches were constructed to replace slabs that were breaking up.

Of the remaining 22 projects reviewed, 3 had a significant amount of full-depth patching to correct joint distress. In general, the slabs were in good structural condition other than at the joints. The remaining 19 projects were considered proper candidates for CPR and exhibited satisfactory performance as long as 8 yr. The maximum quantity of full-depth patching on these 19 projects amounted to 2.6 percent of the surface area of the right lane.

The following discoveries on the use and performance of CPR were made:

- Properly designed and constructed CPR techniques can be expected to provide 6 to 10 yr of service life; however, continued maintenance throughout the project's design life will be required.
- The level of performance of each individual CPR technique was highly dependent on the adequacy of design, quality of construction, and the appropriateness of the technique selected to address the cause of distress. Even with high-quality controls, a few early failures of the repairs occurred, and maintenance within 1 yr after completion of CPR is generally required.
- Lack of detailed condition data during project development resulted in major overruns.
- Pavements that have an accelerated rate of slab cracking before rehabilitation had a high rate of slab deterioration immediately after completion of a CPR project. It was found that the percent of the right lane requiring full-depth replacement of cracked slabs appeared to be a good indicator of a project's suitability for CPR. The criteria listed below are based on field observations of the 26 projects:

  - When 5 percent or more of the right lane required full-depth replacement, the project was probably not a suitable CPR candidate.
  - When 2 percent or less of the right lane required full-depth replacement and other forms of distress were within reasonable limits, the project was a suitable CPR candidate.
  - Projects that require between 2 and 5 percent full-depth replacement of the right lane are marginal CPR candidates and require careful monitoring to establish the current rate of pavement deterioration.

FULL-DEPTH PATCHING

Full-depth concrete pavement repairs were reviewed on 19 CPR projects in 8 states. The age of the oldest patches observed was 8 yr, with an average age of 4 yr. The projects reviewed are summarized in Table 3.

Three methods of providing load transfer at the transverse boundary between the patch and the existing concrete were observed. Dowels were used on eight projects, and undercutting (inverted tee) was used on four projects. Load transfer by aggregate interlock only was used for patches on six projects. In addition, all three methods were tried on one project in Wisconsin.

Full-depth patches with dowels used for load transfer provide the best overall performance. Where undercutting was used, a majority of the patches observed exhibited settlement of the patch, faulting at the joint, or both. In many cases, both sides of the patch would be lower than the adjacent slabs. Patches with aggregate interlock had severe faulting, which generally appeared to be greater than the faulting on the original pavement.

Patch cracking was not a major source of distress, although a number of states permitted early opening (48 hr) after concrete placement. Typical concrete mix designs required 3,000 lb/in^2 compressive strength in 24 hr. Reviewers in Georgia noted that patches there were opened to truck traffic after 6 hr at concrete compressive strengths of 1,200 to 1,500 lb/in^2, with no resulting problems.

Of the 19 CPR projects that incorporated full-depth patching, 14 had a minimum patching dimension of one lane width in the transverse direction. The length varied from 2 ft to a full slab length. It was noted that many of the patches that were less than 4 ft long developed longitudinal cracking in the middle third of the patch. Most of the states that were reviewed specify a minimum patch size of a full lane wide by 6 ft long.

The review confirms that full-depth concrete repairs can be constructed to provide satisfactory long-term performance. The additional expense of the dowel bars appears to be very cost-effective in reducing the recurrence of faulting. Patching is a major cost item on most CPR projects, so the rate of continued deterioration of the pavement joints and slabs not repaired must be given careful consideration in the economic (life-cycle cost) analysis of rehabilitation alternatives.

The following findings on full-depth patching were made:

- Dowelled, jointed full-depth concrete patches provide satisfactory long-term performance (as long as 8 yr observed).
- Patches should have a minimum dimension of one lane width in the transverse direction and 6 ft in the longitudinal direction.
- Satisfactory performance was achieved from patches opened to traffic in as little as 4 hr. In these cases, higher cement factors, Type III cement, and as much as 2 percent calcium chloride (by weight of cement) were used to accelerate the strength gain.

PARTIAL-DEPTH PATCHING

Partial-depth patching was performed on 13 CPR projects. Nine of the projects were jointed reinforced pavements with dowelled joints. The remaining four projects were plain pavements with undowelled joints. On all projects reviewed, the partial-depth patches were generally used to correct spalling at transverse contraction joints.

No problems occurred with partial-depth saw cuts and concrete removal. The Georgia reviewers noted excellent results with their procedures. They specify a series of parallel partial-depth saw cuts within patch boundaries to facilitate concrete

TABLE 3 SUMMARY OF FULL DEPTH PATCHING PROJECTS

Route	Project Limits	Year Rehabilitated	Pavement Age (yr)	Patch Age (yr)	Saw Depth (in.)	Minimum size (ft)	Removal Method	Load Transfer	Concrete Mix Strength	Opening Time (hr)
California										
I-5	Shasta Co., MP 3.8–14.0	1983	17	3	3	3 × 3	Break	None	7 bag/2% CaCl	4
I-80	Placer Co., MP 4–11.4	1984	25	2	3	N/A	Break	None	7 bag/2% CaCl	4
I-5	Yolo Co., MP 23–27.1	1984	18	2	3	6 × 6	Break	None	7 bag/2% CaCl	4
Georgia										
I-475	MP 0–15	1980	13	6	Full	Lane width × 15	Lift	Dowels	7.5 bag/Type III/3000 psi/24 hr	6
I-75	MP 64–72	1978	17	6–8	Full	Lane width × 15	Lift	Dowels	7.5 bag/Type III/3000 psi/24 hr	6
I-75	MP 22–59	1978	17	8	Full	Lane width × 15	Lift	Dowels	7.5 bag/Type III/3000 psi/24 hr	6
South Carolina										
I-85	MP 21–34	1979	15	7	Full	Lane width × 6	Break	Undercut 1 side	8 bag/Type III/2% CaCl	N/A
I-20	MP 0–6	1984	17	2	Full	Lane width × 12	Break	Dowels	6.5 bag/Type I	N/A
Virginia										
I-81	MP 147.2–161.8 NB	1984	19	2	Full	Lane width × 2	Lift	Undercut both sides	8.5 bag/Type III/3000 psi/24 hr	48
I-64	MP 238.4–254	1982	19	4	Full	Lane width × 2	Break	Undercut	8.5 bag/Type III/3000 psi/24 hr	6
I-64	MP 278.7–283.3	1983	16	3	Full	Lane width × 2	Lift	None	8.5 bag/Type III/3000 psi/24 hr	N/A
Minnesota										
I-694	MP 37–46	1981	20	5	Full	None specified		Dowels	8.5 bag/Type I/5600 psi/28 days	7
Wisconsin										
WI-29	Chippewa Falls to Thorp	1983	16	3	Full	Lane width × 6	Lift	Dowels	9 bag/Type I/2–4% CaCl	8
US-61	Fennimore–Boscobel Rd.	1982	30	4	Full	Lane width × no min.	Lift	Undercut	9 bag/Type I	8
US-151	Columbus–Beaver Dam Rd.	1982	28	4	Full	Lane width × no min.	Lift	Dowels	9 bag/Type I/2–4% CaCl	8
I-90	MP 138–142	1981	21	5	Full	4 × 4	Lift	Varied	6 bag/Type 1A	N/A
Michigan										
I-75	MP 64–80	1983	N/A	3	Full	Lane width × 6	Lift	Dowels (no grout)	2% CaCl/300 psi/8 hr	8
South Dakota										
I-29	MP 0–15	1980	19	6	8	Lane width × 10	Break	None	N/A	96
I-90	MP 395.5–412	1985	24	1	8	Lane width × no min.	Break	None	N/A	96

removal with lightweight chipping hammers (30-lb maximum size).

The patching materials included "Set 45" on one project in Michigan and high-aluminum cement on one project in California. The remaining projects were patched with PCC, using either Type I or Type III cement. In some of the projects, as much as 2 percent calcium chloride (by weight of cement) was used as an accelerator.

The cement content for the PCC patches ranged from 6.5 to 8.5 bags. Air contents were between 5.5 and 7 percent. A bonding agent was used on all the PCC patches. The most commonly used material was a sand-cement slurry applied to either a dry or damp surface. On several projects, epoxy resin was applied to a dry surface.

The projects reviewed, specifications, and comments on performance are outlined in Table 4. The performance of the partial-depth patching projects is summarized as follows:

Failure Rate (Percent of Patches)	*Number of Projects*
<5	8
15	1
75	2
>90	2

TABLE 4 SUMMARY OF PARTIAL DEPTH PATCHING PROJECTS

Project	Depth of Saw Cut	PCC Removal	Preparation	Patch Material	Bond Agent	Surface Condition	Air Temperature (°F)	Joint Form	Remarks
California									
I-80, MP 4–11.4	1.5 in.	Air hammer	Sand blast	High-aluminum cement	Epoxy	Dry	>45	Styrofoam or cardboard	Less than 5% failure
Georgia									
I-475, MP 0–15	Depth of failure, 2 in. beyond spall	Air hammer	Sand blast	8 bags/Type III/3000 psi/24 hr	Unknown	Unknown		None; saw within 24 hr	Most of the original partial-depth patches have been replaced (>90% failure)
South Carolina									
I-20, MP 0–6.0	2 in. depth, 6 in. beyond spalls	Air hammer; min. length 12 in., min. width 12 in., max. depth 5 in.	Sand blast, air	6.5 bags/Type I/2000 psi/min, to open to traffic	Epoxy resin	Dry		Insert 5 in. deep, 6 in. beyond each side patch	Patches looked good; 1 failure in a 0.5 mi sample (<5% failure)
Virginia									
I-81, MP 147.22–161.77	3 in.	Air hammer, 15-lb max.; min. length 12 in., min. width 12 in., min. depth 3 in., max. depth 4 in.	Water and air blast	8.5 bags/Type III/3000 psi/24 hr	Cement slurry	Damp		Bituminous expansion board	Partial-depth patches were performing well (<5% failure)
Minnesota									
I-694, MP 37–MP 46	1 in.	Air hammer, 30-lb max.; min. depth 1 in., max. depth 5 in.	Sand blast and air	8.5 bags/Type I/5600 psi/24 hr/5.5% air	Equal parts sand and cement; water to produce a stiff slurry	Dry		20 mil. plastic	About 15% have failed; common distress was noted as spalling at edges
I-94, MP 81–MP 103	1 in.	Air hammer, 30-lb max; min. depth 1 in., max. depth 5 in.	Sand blast and air	8.5 bags/Type I/5600 psi/24 hr/5.5% air	Equal parts cement; water to produce stiff slurry	Dry		Compressible materials	Less than 5% showed any distress; none observed had failed completely
Wisconsin									
WI-29, Chippewa Falls–Thorp	2 in.	Air hammer; min. depth 2 in., max. not spec.	Brooming and water pressure	Portland cement concrete Type I	Acryl 60	Dry		Premolded filler strip or sawing	About 75% of patches have failed
U.S.H. 61 Fennimore to Boscobel Rd.	2.5 in.	Air hammer; min. depth 2.5 in., max. depth bottom of slab	Water blasting	7 bags/Type IA	Acryl 60	Dry		None; tooled surface	Most were loose (>90% have failed)
Michigan									
MI-47, Saginaw Co. N58 to US-10	1.75 in.	Air hammer, 15-lb spec. (30-lb actual for some)	Compressed air	Set 45	None	Damp		Polyurethene foam	About 2% of the patches have failed
South Dakota									
I-90 MP265–292.22	1 in.	Light jackhammer	Sand blast	7 bags/Type III		Dry		Joints formed to	0% failure

TABLE 4 *continued*

Project	Depth of Saw Cut	PCC Removal	Prepara-tion	Patch Material	Bond Agent	Surface Condi-tion	Air Tempera-ture (°F)	Joint Form	Remarks
								top of dowels only	
I-29 MP 27–66	–	–	–	7 bags/Type III/ air 7 ± 2	Cement: 1 part sand, 1 part cement, ½ part water	Dry		See above	Bottom of patches were at the dowels or below (75% failure)
I-29 MP 0–15	1 in.	Air hammer, 30-lb max.	–	7 bags/Type III	Cement grout	Dry		See above	less than 5% failure
I-90 MP 395.5–412	1 in.	Air hammer, 30-lb max.	Sand blast	7 bags/Type III		Dry		See above	less than 5% failure

The only consistent difference between the projects with a low failure rate and those with a rate greater than 5 percent was the use of compressible material in the joints. One of the projects with a 75 percent failure rate required a compressible material in the joints, but the depth of many of the patches was reported to be below the depth of the dowel bars. The specifications on the project required the compressible material to be placed to the top of the dowels. A bond breaker was to be used below the dowels.

Problems were observed on several projects where partial-depth patches extended into the dowel bars. It is very difficult to place the compressible material in the joint adjacent to the dowels. Also, the dowel-to-patch contact may result in excessive stresses in the patch and at the interface of the patch and existing concrete. These stresses develop during joint movement or during curling and warping of the slab.

The following findings were made on partial-depth patching:

- A compressible material must be placed in all working joints and cracks within or adjacent to the patch. The compressible material should extend 1 in. below and 3 in. laterally beyond patch boundaries.
- Partial-depth patches should be limited to the top third of the slab and should not extend to a depth that allows the dowel bars to bear directly on the patching material.
- Standard and high–early strength PCC mixes provided satisfactory long-term performance (as long as 6 yr observed).

GRINDING

Of the projects reviewed, 13 included diamond grinding. Of these projects, 11 were on plain undowelled pavements. Grinding was used to improve poor ride quality caused by faulting.

Before and after data on ride or joint faulting were limited. On the basis of the data available and comments by personnel familiar with the projects, grinding appears to provide a significant long-term improvement in ride quality. Continuous grinding of the entire lane achieved uniform ride, friction, and appearance. It was noted that grinding in the either direction—with or against traffic flow—met ride specifications. Several states prefer to grind in the direction of traffic as a safety precaution.

Pavement texture was also discussed. Three of the six states that used grinding require the contractor to adjust the blade spacing to achieve a specified texture. Wisconsin specifies that 95 percent of any 3 × 100–ft section that is ground must meet the texture (depth and spacing) requirements.

A ride or profile equal to or better than new concrete pavement can be obtained through grinding. It appears that specifications for a grinding project could reasonably include profile requirements at least as stringent as those for new PCC pavements. Data on the projects with grinding are summarized in Table 5. Performance to date indicates that 5 to 10 yr of service life can be expected before faulting returns to the condition that existed before grinding. However, grinding is only appropriate if the project meets criteria for CPR, as previously outlined.

On projects where friction data were available, grinding did not provide a long-term increase in pavement friction. On one project in California, the pavement 3 years before grinding had an average skid number at 40 mph (SN 40) of 38, as compared with an average of 35 a year after grinding. Friction data for several projects in Georgia indicated that there is a significant increase in friction number immediately after grinding; however, the friction numbers returned to their pregrinding levels within ~2 yr. Proper blade spacing appears to be a critical factor in maintaining long-term improvements in pavement friction after grinding, particularly if soft coarse aggregates were used in the concrete.

The following findings were made on grinding:

- A significant long-term improvement in ride quality can be obtained on CPR projects by grinding. Performance to date indicates a service life of 5 to 10 yr can be expected before faulting returns to the pregrinding condition.
- Ride specifications were met when grinding was performed in either direction (with respect to the flow of traffic).

JOINT RESEALING

Of the CPR projects examined, 14 included joint resealing. It should be noted that the review concentrated primarily on

TABLE 5 SUMMARY OF GRINDING PROJECTS

	Extent	Friction Before	Friction After	Ride Before	Ride After	Specifications Profile	Specifications Equipment	Comments
California								
I-5, MP 23–27.1	All lanes; entire project	3 yr, 38	1 yr, 35	3 yr: PCA-29, PSI = 2.6	1 yr: PCA-12, PSI = 3.8	California Profileograph, 15 in./mi	None	
Georgia								
I-75, MP 227–232	Outer lane (by maint.)	2 yr, 36	1 yr, 41; 2 yr, 38; 3 yr, 33	1 yr: 10[a]	4 yr, 4[a]	PCA roughness 300 max.; if >300, must meet Rainhart of <7 in./mile		
I-475, MP 0–15	All lanes for entire project by state forces	3 yr, 44; 1 yr, 40	2 yr, 45; 4 yr, 44	0 years[a] (just before), 22	5 yr, 13[a]			Work performed by maintenance
I-75, MP 64–72	Outside lane					PCA <300; Areas not meeting PCA to meet Rainhart 7 in./mi. Diff. at joints shall not exceed 1/6 in.; Cross slope, 1/4 in. in 12′	Self propelled machine; peaks 1/32 higher than bottom 60 grooves/ft 60 grooves/ft	
I-75, MP 22–59	Outside lane				good	As for MP 64–72	As for MP 64–72	
South Carolina								
I-85, MP 21–34	All lanes		N/A		N/A	1/8 in. in 10 ft	Machines using diamond blades	Average faulting 1/16–1/8 in. with areas of 1/4 in.
I-20, MP 0–6.0	All lanes		N/A		N/A	Mayes Meter, <55 in./mi	As for I-20	Diamond grinding saw blade spacing appeared to have been wide, resulting in high fines
Virginia								
I-81, MP 147–160	All lanes	35	N/A			1/8 in. in 10 ft	Power driver, self-propelled; Min wt. 15,000 lbs., Min. HP 200	
Minnesota								
US-10, MP 204–211	All lanes					3/16 in. in 10 ft, parallel to centerline	–	Grooves between 0.097 and 0.128 in. wide, spaced 0.062–0.115 in. apart; Depth = 0.31–0.115 ft.
US-71, MP 124–129	All lanes					1/8 in. in 3 ft at right angle to centerline; 1/16 in. at joints		As for US-10
US-61, Fennimore–Boscobel	All lanes							95 percent of any section 1/16 in. from top to bottom; 50 grooves/ft. min.
US-151, Columbus–Beaver Dam	All lanes					1/8 in. in 10 ft or 0.3 in. in 25 ft	–	As for US-61
I-90, MP 138–142	All lanes					Transverse 1/8 in. in 3	–	As for US-61

NOTE: N/A = not available.
[a] Faulting indices.

resealing of the transverse joints. As such, the following observations and subsequent findings are applicable to transverse joints, unless indicated otherwise.

The projects reviewed are summarized in Table 6. In 11 of the projects, a single type of sealant material was used exclusively. The sealant used was silicone in six projects, hot-poured sealant in four, and neoprene in one. The remaining three projects used two sealant materials.

On the projects that were inspected, the hot-poured joint seals experienced adhesion failures, generally within 2 years after construction. Preformed neoprene seals appear to be better suited to new construction. Because minor joint spalling is generally present in rehabilitation projects, the full bearing required for preformed seals to remained compressed and in place may not be achieved.

A majority of projects that had joints resealed with silicone material are providing good performance. Periodic maintenance is required, however, to cut out and repair isolated failures. In those cases for which field personnel had mentioned that the manufacturer's guidance for installation was not followed explicitly, significant failures (as much as 75 percent) were observed. Procedures such as refacing the joint to allow for the proper shape of the joint sealant material, providing a clean and dry bonding surface, and inspecting the application and tooling of this sealant closely are critical to performance.

Several projects included sealing of the longitudinal PCC pavement/asphalt concrete (AC) shoulder joint with hot-poured sealants. This material appears to be effective for about 2 yr before maintenance is required.

The following findings were made on joint resealing:

- Preformed neoprene joint seals are generally not suitable for rehabilitation projects because even a small amount of spalling in the existing joint can result in failure of the seal.
- The hot-poured sealants were observed to experience significant adhesion failure, generally within 2 yr.
- Silicone, when properly installed, provided good performance. In all cases, however, maintenance was required after 1 to 2 yr to correct construction deficiencies.
- Hot-poured sealants used in the longitudinal PCC pavement/AC shoulder joint requires maintenance on a ~2-yr cycle.

SLAB STABILIZATION (SUBSEALING)

Subsealing as a rehabilitation technique was reviewed in eight projects, located in four states. Criteria for subsealing ranged from blanket subsealing of all faulted slabs to subsealing only those slabs that exceeded a minimum specified deflection under loading. The projects reviewed are summarized in Table 7.

It was difficult to evaluate the effectiveness of the technique visually, but an attempt was made to determine whether the subsealing appeared to have any detrimental effects. Slabs were closely observed for cracks that passed through or radiated from the subsealing holes. No distress of this type was observed. One project had a high level of slab breakup after a CPR project that included subsealing. A review of the project records and discussion with project personnel, however, revealed that there was a high rate of deterioration before the CPR project.

The review of subsealing indicated that although the benefits of subsealing could not be readily observed, there appeared to be no adverse effect to pavement performance on the projects inspected. Further research in this area appears warranted.

COST DATA

The available cost data for the rehabilitation techniques used on each project are listed in Table 8. The planned and final quantities are also presented. The data are presented by project to give the reader a "feel" for the total scope of each project.

SUMMARY

In all, 26 completed CPR projects in 8 states were reviewed. The reviewers found that proper preliminary engineering and timing of the individual techniques are critical to project performance. It was found that if CPR projects are properly designed and constructed, they will generally reduce pavement deterioration, thereby prolonging pavement life. Properly designed and constructed CPR techniques can be expected to provide 6 to 10 yr of service life, but continued maintenance throughout the project design life will be required. On most projects, a follow-up maintenance effort was needed within 1 yr of project completion.

Like that of any other pavement rehabilitation strategy, the overall effectiveness of CPR techniques is highly dependent on design adequacy, construction quality, and maintenance practices. The available preliminary engineering data developed for each CPR project were reviewed. On many projects, very little detailed information on the causes and extent of distress had been assembled. Some projects experienced large overruns in quantities, and at least one project was terminated because of cost overruns before all the CPR work could be completed. The lack of timely, detailed condition data probably contributed to the major overruns.

The individual CPR techniques that were reviewed included subsealing, full-depth patching, partial-depth patching, grinding, and joint resealing. Very few of the projects reviewed included pressure relief joints, subdrains, retrofit load transfer devices, and shoulder restoration techniques. It was concluded that proper evaluation of subdrainage is not possible without performing in-depth testing. A separate project has been initiated to evaluate subsurface drainage on a variety of in-service installations.

On the basis of the review of these 26 projects, the following conclusions were drawn:

- When 5 percent or more of the right lane required full-depth replacement, the project was probably not a suitable CPR candidate.
- When 2 percent or less of the right lane required full-depth replacement, and other forms of pavement distress were within reasonable limits, the project was a suitable CPR candidate.
- Projects that required between 2 and 5 percent full-depth replacement of the right lane were marginal CPR candidates. In these cases, pavement deterioration should be more closely monitored and evaluated. This analysis will assist in determining whether to undertake CPR.

TABLE 6 SUMMARY OF JOINT RESEALING PROJECTS

Route	Project Limits	Year Rehabilitated	Pavement Age (yr)	Type of Joint	Sealant Material	Sealant Reservoir Shape: Width (in.)	Depth (in.)	Top Below Surface	Backer Rod	Comments
California										
I-5	Shasta Co. MP 3.8–14.0	1983	17	Transverse	Rubber-asphalt	½	1¼	N/A	Not required	
				Longitudinal	Rubber-asphalt	½	1¼	N/A	Not required	
Georgia										
I-75	MP 226–232	1981	12	Transverse	Low-mod. silicone (Dow)	⅜–⅝	1½	½	Polyethylene	Minor failures at 25–50% of joints
				Longitudinal	Low-mod. silicone (Dow)	⅜–⅝	1½	½	Polyethylene	Minor failures at 25–50% of joints
I-475	MP 0–15	1980	13	Transverse	Low-mod. silicone (Dow)	⅜–⅝	1½	½	Polyethylene	Joints regularly maintained; most in good condition
				Longitudinal	Low-mod. silicone (Dow)	⅜–⅝	1½	½	Polyethylene	Joints regularly maintained; most in good condition
I-75	MP 64–72	1978	17							Construction data not available
I-75	MP 22–59	1978	17							Construction data not available
South Carolina										
I-85	MP 21–34	1979	15	Transverse	Hot-poured ASTM D3405	⅜–⅓	1¼–1½	N/A	Upholstery chord	
				Long. (ctrline)	Not sealed					
				Shoulder	Hot-poured ASTM D3405	¾	¾			Sealants failed in adhesion
I-20	MP 0–6	1984	17	Transverse	Low-mod. silicone (Dow)	–[a]	–[a]	–[a]	Polyethylene	
				Longitudinal	Low-mod. silicone (Dow)	–[a]	–[a]	–[a]	Polyethylene	
				Shoulder (Long.)	Low-mod. silicone (Dow)	¼	¼	½		
				Shoulder (Trans.)	Low-mod. silicone (Dow)	⅜–½	2½	Flush		25% of sealant failed due to construction issues
Virginia										
I-81	MP 147.2–161.8 NB	1984	19	Trans. <1–⅛ in.	Low-mod. silicone (Dow)	Varied	Varied	¼	Polyethylene	Numerous adhesion failures, possibly due to aggregate incompatibility
				Trans. >1–⅛ in.	Pref. compression seal					Seals looked to be in good conditon

				Long. <1–⅛ in.	Low-mod. silicone (Dow)	Varied	Varied	¼	Polyethylene	
				Long. >1–⅛ in.	Pref. compression seal					
I-64	MP 238.4–254	1982	19	Transverse	Hot-poured elastomeric	½	½	Flush		All failed in adhesion
				Longitudinal	Hot-poured elastomeric	½	½	Flush		All failed in adhesion
I-64	MP 278.7–283.3	1983	16	Transverse	Rubber-asphalt	¾	¾	Flush		Adhesion failures were noted
				Longitudinal	Rubber-asphalt	¾	¾	Flush		Adhesion failures were noted
Minnesota										
I-694	MP 37–46	1981	20	Transverse	Rubber-asphalt	¾	¾	0–⅛		Sealants failed in adhesion
				Longitudinal	Rubber-asphalt	¾	¾	0–⅛		Sealants failed in adhesion
I-94	MP 81–103	1981	14	Transverse	Rubber-asphalt	¾	¾	0–⅛		Sealants failed in adhesion
				Longitudinal	Rubber-asphalt	¾	¾	0–⅛		Sealants failed in adhesion
Wisconsin										
WI-29	Chippewa Falls to Thorp	1983	16	Transverse	Hot-poured elastomeric	½	½	⅛–¼		All failed in adhesion
				Longitudinal	Hot-poured elastomeric	½	½	⅛–¼		All failed in adhesion
I-90	MP 138–142	1981	21	Transverse	Low mod. silicone (Dow)	⅜	½	⅛	Polyethylene	75% had failed in adhesion
				Longitudinal	Hot-poured ASTM D3405	(Exist.)	¾	¼		
Michigan										
MI-47	Saginaw Co. State Rd. to Div.	1983	16	Transverse	Neoprene	(Exist.)	(Exist.)	¼	N/A	
				Longitudinal	Sof Seal	¼–⅜	1–1¼	⅛	Polyurethane	50% had failed in adhesion
South Dakota										
I-29	MP 27–62	1972	10	Transverse	Neoprene					Construction data not available
I-29	MP 0–15	1980	19	Transverse	Low-mod. silicone (Dow)	⅞	½	¼	Polyethylene	
				Longitudinal	Not sealed					
I-90	MP 395.5–412	1985	24	Transverse	Low-mod. silicone (Dow)	⅞	½	⅛	Polyethylene	
				Longitudinal	Hot rubber-asphalt	⅞	1⅞	⅛		
I-90	MP 265–292.2	1982	17	Transverse	Low-mod. silicone (Dow)	N/A	N/A	N/A	Polyethylene	

[a] Manufacturer's recommendation.

TABLE 7 SUMMARY OF SUBSEALING PROJECTS

Project	Deflection	Grout	Hole Pattern	Pressure	Depth of Hole	Minimum Air Temperature (°F)	Holes Plugged	Lift	Comments
California									
I-5, MP 23–27.1	None available	2.5 parts pozzolan, 1 part cement, time efflux 10–16	3–5 in leave slab	None specified	15 in.	45	Wooden pegs	First movement	No deterioration that could be related to subsealing noted
I-80, MP 4.0–11.4	See remarks	As for I-5	3–4 in leave slab	None specified	15 in.	45	Wooden pegs	First movement	Deflections were taken before and after subsealing. When taking deflections, the difference between the deflection of loaded and unloaded side was measured: before 0.007 in., after 0.008 in.
I-5, MP 3.8–14	Load transfer only	3 parts pozzolan, 1 part cement, time efflux, 11–16 spec., 10–11 actual; comp. strength spec. 750 psi/7 days, actual 1430 psi/7 days	3–4 in leave slab	None specified	15 in. Nozzle not to extend below bottom of slab			First movement but not monitoried in all slabs	
Georgia									
I-75, MP 227–232	Min 0.025 in.								No deflection >0.025 in., so subsealing was deleted.
I-475, MP 0–15	Min 0.005 in.	3 parts limestone, 1 part cement, time efflux 16–22 sec	2 holes 18 in. from leave, 4 additional along outer edge		8 in. below bottom of slab	No	⅛ in.		
South Carloina									
I-85, MP 21–34	Tested under 18-kip axle; if movement visually was observed, pavement was subsealed	3 parts ag. lime, 1 part type III cement; water content to give slurry apearance of thick cream	1 hole on approach side, 4 on leave side	None specified	Bottom of slab	35 and rising, 40 and falling	Wooden pegs	When dial indicates movements, max. ⅛ in.	Slabs retested and regrouted as necessary
I-20, MP 0–6	Min 0.020 in.	3 parts ag. lime, 1 part cement; time efflux 14–22 sec	2 holes on approach, 4 on leave	None specified	8–10 in. below slabs	35 and rising	Wooden pegs	⅛ in.; any slab raised more than ⅛ in. replaced	Slabs retested, and any with movement >0.020 in. were regrouted
Virginia									
I-81, MP 147–161 NB	Not performed; all slabs in rt lane were subsealed.	3 parts pozzolan, 1 part cement; time of efflux 10–16; sec; mean compressive strength: 1 day, 300 psi; 3 days, 620 psi; 7 days, 1,000 psi	7 holes per slab	200 psi max.	Bottom of slab	35	Wooden pegs	0.125 in. per hole; many holes pumped to max.	

TABLE 8 SUMMARY OF QUANTITIES AND BID PRICES

Route	Limits	Year Rehabilitated	Technique	Units	Bid Price($)	Quantities Plan	Final	Comments
California								
I-5	Shasta Co., MP 3.8–14.0	1983	Slab replacment	yd²	36.27	8,970	11,307	No load transfer
			Corner patch	yd²	214.33	45	45	
			Subseal hole	each	4.50	21,600	32,521	
			Grout	cwt.	15.00	11,000	19,562	
I-80	Placer Co., MP 4–11.4	1984	Full-depth patches	yd²	63.95	2,340	2,588	No load transfer
			Partial-depth patches	yd²	250.00	210	191	
			Subseal hole	each	4.50	14,200	13,181	
			Grout	ton	320.00	230	222	
I-5	Yolo Co., MP 23–27.1	1984	Full-depth patches	yd²	73.33	2,073	2,706	No load transfer
			Subseal hole	each	5.50	6,318	5,813	
			Grout	ton	1,600.00	158	52	
			Grinding	yd²	2.99	95,000	N/A	
Georgia								
I-75	MP 227–232	1981	Subseal hole	each	3.00	2,500	0	
			Grout	bags cement	27.50	600	0	
			Subseal pre. test	mi	1,200.00	12	12	
			Subseal stab. test	joint	600.00	800	0	
			Grinding	yd²	4.04	80,800	80,761	Includes traffic control
			Joint seal	linear ft	0.64	167,000	133,826	Low-mod silicone
			Sawing joints	linear ft	0.50	167,000	133,826	
I-475	MP 0–15	1980	Slab replacement	yd³	90.00	240	457	Dowelled load transfer
			Slab removal	yd²	70.00	600	1,259	
			Partial-depth patches	ft²	19.50	4,000	7,869	
			Subseal hole	each	4.42	5,300	4,678	
			Grout	bags cement	19.50	1,100	494	
			Subseal pre. test	mi	1,050.00	28	28	
			Subseal stab. test	joint	556.00	890	820	
			Grinding	yd²				Done by maintenance forces
			Saw and reseal	linear ft	1.61	92,300	80,742	Existing joints were uni-tube; low-mod silicone
			Saw and reseal	linear ft	1.48	154,200	154,309	Other joints and cracks; low-mod silicone
I-75	MP 64–72	1978	Grinding	yd²	3.49	N/A	126,900	
I-75	MP 22–59	1978	Grinding	yd²	3.07	N/A	232,600	
South Carolina								
I-85	MP 21–34	1979	Full-depth patches	yd²	N/A	3,800	N/A	No load transfer
			Subseal hole	each	N/A	2,375	N/A	
			Grout	bags cement	N/A	1,068	N/A	
			Grinding	yd²	N/A	361,891	N/A	Continuous grinding
I-20	MP 0–6	1984	Full-depth patches	yd²	110.80	750	2,155	Dowelled load transfer
			Partial-depth patches	ft²	24.00	1,000	9,555	
			Subseal hole	each	4.00	12,240	12,459	
			Grout	bags cement	22.00	4.080	1,472	
			Grinding	yd²	2.48	217,621	183,551	Continuous grinding
			Joint sealing	linear ft	1.53	170,311	171,136	Existing joints were uni-tube; low-mod silicone
			PCC shoulder 4 ft	yd²	14.75	36,448	34,431	Full-depth retrofit shoulders
			PCC shoulder 6 ft	yd²	14.05	8,548	9,142	Full-depth retrofit shoulders
			PCC shoulder 10 ft	yd²	13.55	70,757	61,984	Full-depth retrofit shoulders
Virginia								
I-81	MP 147.2–161.8 NB	1984	Full-depth slab rep.	yd²	100.00	1,884	3,502	Final quantities represent only half of entire project; other half was readvertised. Inverted tee if patch 2–42 ft, dowelled if longer
			Partial-depth patches	yd²	80.00	0	87	
			Subseal hole	each	2.00	9,885	10,956	
			Grout (cement)	ft³	25.00	2,275	10,809	
			Grinding	yd²	2.00	202,611	108,851	
			Joint sealing	linear ft	1.30	104,985	61,988	Silicone

TABLE 8 *continued*

Route	Limits	Year Rehabilitated	Technique	Units	Bid Price($)	Quantities Plan	Quantities Final	Comments
			Joint sealing (2 in. pref.)	linear ft	12.00	7,001	888	Neoprene compression seal
			Joint sealing (3 in. pref.)	linear ft	20.00	1,046	871	Neoprene compression seal
			Joint sealing (3.5 in. pref.)	linear ft	40.00	38	234	Neoprene compression seal
			Edge drains	linear ft	10.00	16,685	8,835	
I-64	MP 238.4–254	1982	Full-depth patches	yd^2	109.00	2,300	2,721	Final quantities represent only half of entire project; project was terminated. Inverted tee load transfer
			Joint sealing	linear ft	0.55	174,010	79,644	Hot-poured elastomeric
I-64	MP 278.7–283.3	1983	Full-depth patches	yd^2	89.00	9,323	8,221	No load transfer
			Joint sealing	linear ft	0.65	96,222	150,516	Rubber-asphalt joint sealant
			Pressure relief joint	linear ft	25.00	2,300	2,044	
Minnesota								
I-694	MP 37–46	1981	Full-depth patches	N/A				Full- and partial-depth patch quantities were intermixed; partial depth patch boundaries are tapered; dowelled load transfer
			Partial-depth patches	N/A				
US-10	MP 204–211.6	1981	Grinding	yd^2	2.88	59,269	N/A	
US-71	MP 124.9–192.2	1983	Grinding	N/A				Quantities and costs not available
I-94	MP 81–103	1981	Partial-depth patches	ft^3	N/A	580	4,421	Boundaries are tapered
			Joint sealing	linear ft	N/A	271,787	278,508	Hot-poured rubber
			Crack sealing	linear ft	N/A	6,275	2,864	
Wisconsin								
WI-29	Chippewa Falls to Thorp	1983	Full-depth patch 6 × 12 ft	yd^2	47.00	14,136	16,448	Dowelled load transfer
			Full-depth patch 8 × 12 ft	yd^2	42.84	960	1,397	Dowelled load transfer
			Full-depth patch 10 × 12 ft	yd^2	39.37	440	733	Dowelled load transfer
			Full-depth patch 12 × 12 ft	yd^2	37.81	176	416	Dowelled load transfer
			Full-depth patch 16 × 12 ft	yd^2	35.64	427	1,024	Dowelled load transfer
			Full-depth patch 20 × 12 ft	yd^2	34.50	720	347	Dowelled load transfer
			Partial-depth patches	ft^2	9.00	2,000	4,154	
			Longitudinal joint sealing	linear ft	0.85	167,000	152,898	Hot-poured elastic
			Transverse joint sealing	linear ft	0.90	40,000	37,807	Hot-poured elastic
US-61	Fennimore to Boscobel Rd.	1982	Full-depth patches	yd^2	30.60	7,981	7,197	Inverted tee (6 × 6 in.) load transfer
			Partial-depth patch	ft^2	16.00	1,000	1,392	
			Grinding	yd^2	2.50	77,500	77,460	
US-151	Columbus–Beaver Dam Rd.	1982	Full-depth patches	yd^2	68.00	700	1,172	Inverted tee (6 × 6 in.) load transfer
			Grinding	yd^2	2.55	97,350	89,759	
I-90	MP 138–142	1981	Full-depth full-lane patch	yd^2	40.00	4,074	7,866	Dowelled and no load transfer methods used
			Full-depth corner patch	yd^2	42.00	475	800	No load transfer
			Full-depth inverted tee patch	yd^2	50.00	210	416	
			Grinding	yd^2	2.92	41,710	41,674	
			Longitudinal joint sealing	linear ft	0.70	28,785	30,156	Hot-poured elastic meeting ASTM D3405
			Transverse joint sealing	linear ft	1.25	48,722	64,941	Low-mod. silicone (Dow 888)
Michigan								
I-75	MP 64–80	1983	Full-depth patches	yd^2	N/A	23,532	26,481	Dowelled load transfer
			Pressure relief joints	each	N/A	0	864	
MI-47	Saginaw Co. State Rd. to Div.	1983	Joint spall repair	linear ft	16.00	7,750	10,918	
			Patching material	ft^3	42.00	930	1,032	
			Sealing transverse cracks	linear ft	1.75	10,960	16,514	Sealtight Sof-Seal (hot poured)
			Replace neoprene seals	linear ft	3.10	N/A	28,940	
			Exp. joint removal and reseal	linear ft	4.25	N/A	7,512	Sealtight Sof-Seal (hot poured)

TABLE 8 *continued*

Route	Limits	Year Rehabilitated	Technique	Units	Bid Price($)	Quantities Plan	Final	Comments
South Dakota								
I-29	MP 27–62	1972	Partial-depth patch (Type B)	ft^2	17.50	364	568	
			Partial-depth spall repair	ft^2	5.79	24,337	105,336	
			Joint sealing	linear ft	1.01	117,481	118,223	Neoprene
I-29	MP 0–15	1980	Full-depth repair	yd^2	60.00	N/A	800	No load transfer
			Partial-depth patch (Type B)	ft^2	40.00	255	255	
			Partial-depth patches	ft^2	6.40	127,653	109,193	
			Joint sealing	linear ft	2.00	65,424	67,765	Silicone (Dow 888)
			Pressure relief joints	each	800.00	107	106	
I-90	MP 395.5–412	1969	Partial-depth patch (Type A)	ft^2	N/A	8,268	21,381	Type A patch >0.4 ft wide
			Partial-depth patch (Type B)	ft^2	N/A	690	1,890	Type B patch ≤0.4 ft wide
			Remove unitube	linear ft	0.80	62,425	60,304	
			Install neoprene	linear ft	1.10	62,425	60,304	No pavement/shoulder joint sealing setup in contract
			Seal w/hot rubber-asphalt	linear ft	0.30	11,016	8,622	
		1985	Full-depth patches	yd^2	60.00	636	1,581	Dowelled load transfer
			Partial-depth patch (Type A)	ft^2	6.00	11,511	89,893	
			Joint sealing (silicone)	linear ft	1.68	77,712	74,981	No pavement/shoulder joint sealing setup in contract
			Pressure relief joints	each	400.00	32	32	
I-90	MP 265–292.2	1982	Partial-depth patch (Type A)	ft^2	6.87	36,806	32,547	Type A patch >0.4 ft wide
			Partial-depth patch (Type B)	ft^2	N/A	72	181	Type B patch ≤0.4 ft wide
			Joint sealing	linear ft	1.59	6,094	6,094	Silicone sealant
			Pressure reflief joints	each	695.00	45	45	

- The minimum length for a full-depth patch in the longitudinal direction should be 6 ft to prevent longitudinal cracking.
- Full-depth patches with dowelled joints provided satisfactory long-term performance. However, patches placed with the inverted tee method or those that depended on aggregate interlock for load transfer did not provide satisfactory performance.
- High cement factors (seven bags or more), Type III cement, and as much as 2 percent calcium chloride (by weight of cement) were used to accelerate the concrete mix strength in the full-depth patching projects. These projects were opened to traffic in as little as 4 hr and were performing satisfactorily after 8 yr.
- Partial-depth patching was performed on 13 CPR projects. On eight of these projects, less than 5 percent of the total number of patches had failed.
- Field inspections of completed patches and discussions with state engineers demonstrated that a compressible material must be placed in all working joints and cracks within and adjacent to the patch to obtain satisfactory performance from partial-depth patches.
- Field observations also confirmed that partial-depth patches should be limited to the top third of the slab and should not extend to a depth that allows the dowel bars to bear directly on the patching material.
- Satisfactory long-term performance (as long as 6 yr observed) of partial-depth patches was achieved with standard and high–early strength PCC mixes.
- Grinding resulted in a ride or profile equal to or better than that of a new concrete pavement. Specifications for a grinding project should include profile requirements at least as stringent as those for new PCC pavements.
- Of the reviewed CPR projects, 17 included joint resealing. Hot-poured transverse joint sealants were used on seven projects. Those sealants experienced adhesion failure, which generally occurred within 2 yr after construction.
- Silicone sealants provided generally good performance. Minor adhesion failures were noted in ~25 percent of the joints inspected. Many of these failures appeared to be due to improper cleaning of the joints before resealing.
- The benefits of subsealing could not be readily determined. Field reviews on eight projects in four states indicated there was no apparent visual difference in pavement performance between states that had subsealed as part of CPR and those that did not. Where recommended procedures were followed, subsealing did not appear to have any adverse effects on pavement performance. Further research is needed to refine the correct procedures and to define the benefits of subsealing.

The contents and opinions presented in this paper reflect the views of the authors, who are responsible for the facts presented and the accuracy of the data. The contents do not necessarily reflect the views of the FHWA.

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Field Evaluation of Dowel Placement Along a Section of Interstate 45 in Texas

PAUL A. OKAMOTO

The results of a field investigation conducted to determine the effectiveness of an automatic dowel bar inserter at properly placing dowel bars in rigid pavements are presented. The study, which was sponsored by the FHWA Demonstration Projects Division, was conducted during February and March 1987 along a section of I-45, south of Dallas, Texas. A commercially available radar system, capable of quickly and easily locating reinforcing bars and other embedded steel in concrete, was used to examine the experimental dowel placement. This system produces a real-time graphic recording that gives both location and relative depth of the embedded steel. Cores were taken to calibrate the graphic recordings so that the actual embedded depths of the steel bars could be obtained. Along one portion of the test section, a dowel bar inserter was used to place dowel bars in the plastic concrete. For the remainder of the project, dowel basket assemblies were used to place dowels at transverse joints. The radar system was then used to evaluate dowel placement along 51 basket assembly and 52 inserter joints. Results indicate that dowel bar alignment at inserter joints is as good as or better than that at the basket assembly joints.

The results of a field investigation that was conducted to determine the effectiveness of a radar technique for measuring dowel bar misalignment in the field and to evaluate the effectiveness of an automatic dowel bar inserter at properly placing dowel bars in rigid pavements are presented in this paper. The current practice is to use round steel dowel bars for load transfer at rigid pavement joints. The bar diameter is generally ⅛ the slab thickness, with dowel spacing at 12 in. and dowel length 18 in. Dowel bars are placed at pavement mid-depth, and care in placement is required to minimize the detrimental effects of misalignment.

Dowels may be placed by using wire basket assemblies, or they may be inserted directly into plastic concrete by an automatic dowel bar inserter (implanter). Use of the inserter has not been widespread because of concerns about whether properly aligned dowels in rigid pavement joints can be obtained with this method. Recently, several new dowel bar inserters have been introduced. The manufacturers claim that these new inserters are capable of both accurate dowel placement and proper concrete finishing after insertion, without disturbing the inserted dowels.

For satisfactory long-term performance in rigid pavements, dowel bars must be placed as parallel as is practical to the longitudinal axis and the horizontal plane of the pavement. In the United States, limits on permissible tolerances are generally specified by the individual state highway agencies. The different categories of dowel misalignment and their possible effects on pavement behavior are illustrated in Figure 1.

In the past, a maximum allowable alignment error of ¼ in. per 18 in. length of the dowel was specified. Recently, many state agencies have been revising the allowable tolerance levels. For example, the Georgia Department of Transportation specifies an allowable tolerance of ⅜ in./ft in both the horizontal and vertical directions, and several other state agencies specify an allowable tolerance of ¼ in./ft in both the horizontal and vertical directions.

It should be noted that no clear consensus exists about the level of practical limits on dowel placement tolerances (*1*). In addition, determination of levels of misalignment after pavement construction is complete has typically been an extremely slow process. In the past, dowel bar misalignment was measured by using a pachymeter and taking partial-depth or full-depth cores near the ends of the dowel. Recently, ground-penetrating radar devices have been used to determine dowel placement accuracy (*2*).

OBJECTIVES

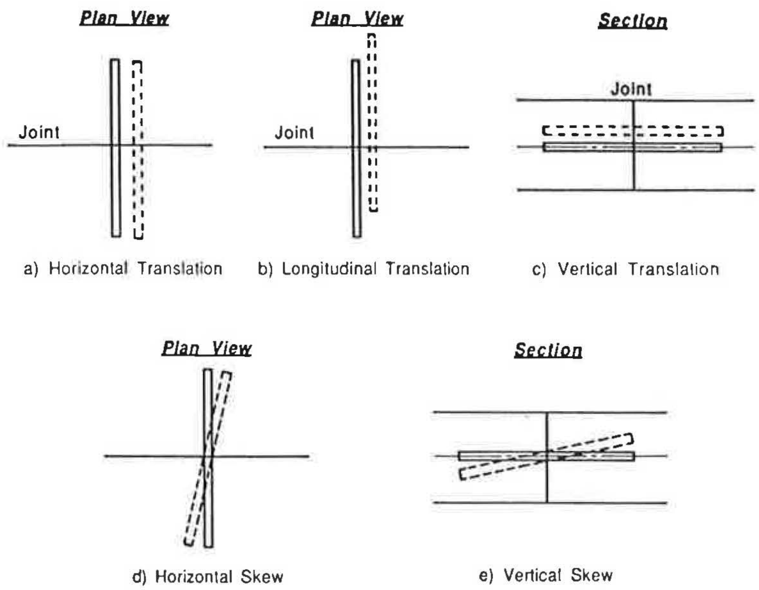
An investigation of dowel bar placement was sponsored by the FHWA Demonstration Projects Division. The objectives of the investigation were as follows:

- Measure dowel alignment by using ground-penetrating radar equipment at joints along two sections of pavement: one in which dowel baskets were used and one in which a dowel bar inserter was used;
- Demonstrate the effectiveness of the radar technique for measuring dowel bar misalignment in the field; and
- Evaluate the effectiveness of an automatic dowel bar inserter at properly placing dowel bars in rigid pavements.

FIELD EVALUATION

The radar technique for locating dowel bar position was used in a field evaluation of the automatic dowel bar inserter that was conducted during the last week of February and first week of March, 1987. The investigation site was along a section of I-45, south of Dallas, Texas.

Construction Technology Laboratories, Inc., 5420 Old Orchard Road, Skokie, Ill. 60077.



Type of Misalignment	Effect on		
	Spalling	Cracking	Load Transfer
a	-	-	Yes*
b	-	-	Yes*
c	Yes	-	Yes*
d	Yes	Yes	Yes
e	Yes	Yes	Yes

*Effect will depend on amount of translation

FIGURE 1 Effects of dowel misalignment.

Construction Project Details

The investigation site was a 6.2-mi section of I-45 pavement that was replaced during winter 1986–1987. This plain jointed concrete pavement is for the most part 10.0 in. thick. Near bridge approaches, underpasses, and so on, the nominal thickness was increased to 12 in.

Dowels were used for load transfer at right-angle transverse joints spaced every 15 ft. Project specifications required use of lead-painted 22-in.-long, 1¼-in.-diameter bars spaced at 12 in. The outside lane (truck lane) is 14½ ft wide, and the inside lane (passing lane) is 12½ ft wide. The full 27-ft-wide section was laid in a single pass by a Guntert & Zimmerman paver.

In one portion of the project, dowel basket assemblies were used to place dowels. The specified dowel basket assembly used wire gauge No. 1/0 (0.306 in. diameter), with bars alternately welded on one end. For the remainder of the project, a Guntert & Zimmerman dowel bar inserter was used to place dowels in the plastic concrete.

Radar Location of Rebar

Dowel alignment was measured at joints along both sections of pavement. The ground-penetrating radar device used to locate and measure the depths of the dowel bars was a commercially available unit owned and operated by Construction Technology Laboratories, Inc. (CTL). The radar unit itself was the SIR System-4R, sold by Geophysical Survey Systems, Inc. (GSSI). It allows quick and easy location of reinforcing bars (rebar) and other embedded steel in concrete. The radar system included the following components:

- Radar control unit,
- Transducer,
- Graphic recorder,
- Transducer control cable, and
- Remote marker switch.

High-frequency electromagnetic pulses are sent into the concrete by a hand-held transducer. The pulses are reflected by the reinforcing bars (or other embedded steel) back to the transducer, which sends the signals to the radar control unit for signal processing and feeding to a line scan graphic recorder. While the transducer is being moved along the concrete surface, a graphic recording that depicts the location and relative depths of all the steel bars along the transect line is automatically generated. Cores or known steel bar depths are used to calibrate the graphic recordings and obtain the actual embedded depths of the steel bars.

By measuring the depths near the ends of the dowels with the radar unit, the magnitude and direction of vertical misalignment can be accurately determined. The dowel bars can also be located in the horizontal plane so that any horizontal skewness can be detected. Longitudinal displacement relative to the joint centerline can also be qualitatively evaluated by using the graphic recordings.

Test Procedure

To compare the inserter and dowel basket placement procedures, 51 joints in the basket portion and 52 joints in the inserter portion were evaluated, along ~9,300 ft lengths of each type of dowel placement. To eliminate any pavement thickness influences, only 10-in.-thick pavement was examined. The joints selected for evaluation in the basket assembly portion were uniformly spaced at ~150 ft. The evaluated inserter length consisted of two segments. In one, the selected joints were uniformly spaced at ~225 ft, and in the other, the spacing was uniformly 75 ft. Both outside and inside lane joints were evaluated at each test site.

At each selected joint, the evaluation procedure was to make a pass with the radar transducer 6 in. away from each side of the joint, as shown in Figure 2. The output for each pass was simultaneously recorded in graphic form for future interpretation. The transducer was passed along the top of a ⅜-in.-thick Plexiglas™ guide, which was used to

- Allow dowel depths to be determined at a constant offset distance from the joint,
- Facilitate uniform travel rate rates along the joint surface to allow for horizontal skewness estimation, and
- Provide a template for triggering reference marks on radar output.

Initially, the transducer was passed along a line offset 8 in. from the joint. This procedure was meant to maximize the total distance between readings on each side of the joint. However, because of longitudinal translations of the dowels relative to the joint, the radar output signal at many joints was weak, making interpretation quite subjective. To eliminate any additional source of variation in the interpretation, the offset distance was reduced to 6 in.

To estimate horizontal dowel skewness, a triggering device that printed a reference mark on the radar recording was assembled. Metal rivets mounted on the plastic guide at uniform 4-in. spacings triggered the marker. The guide was always placed in the same position on each side of the joint to allow estimation of horizontal misalignment levels.

When the transducer passed near or over the end of the dowel, a weak return signal was received, giving a lighter recording. In these cases, the test was repeated at a 4-in. offset to eliminate additional subjective variance in interpolating output. This repetition also allowed for qualitative verification that the dowel embedment lengths were at least 4 in.

FIGURE 2 Radar test setup at transverse joint.

DATA ANALYSIS

During the radar evaluation, 32 cores were obtained at dowel bar locations identified by the radar. Cores were obtained from both the dowel basket and inserter sections. Dowel depths (to top of steel) ranged from 4.0 to 6⅛ in. The average dowel depth for the 32 cores was 5.1 in. These cores and core holes were used to measure the depth of dowel bars from the pavement surface. By using the core data, the graphic recordings could be calibrated to obtain the actual dowel bar depths (to top of steel). A typical graphic output is presented in Figure 3.

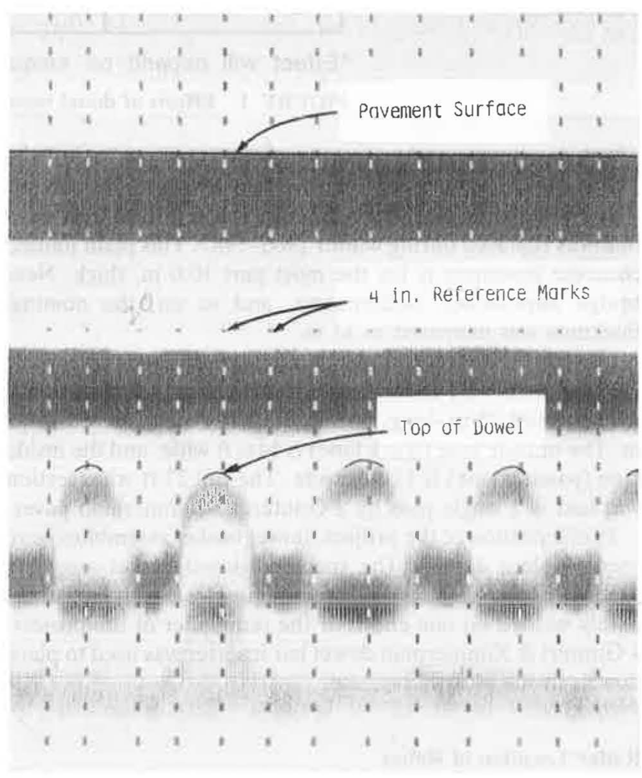


FIGURE 3 Typical graphic output of a pass of the radar transducer.

Previous laboratory testing had indicated that the degree of influence that the plastic guide exerted on the test results was proportional to the depth of the dowel, rather than constant. To reduce any proportional influence of the plastic guide, a calibration factor that was dependent on the depth of steel was developed for the study. A simple least squares linear regression analysis was performed on the transformed core data. The regression equation of actual depth on chart depth is

$$D^2 = -38.148 + 57.586 \ln(P) \qquad R^2_{\text{adj}} = 87.5 \text{ percent}$$

where D is the actual dowel depth (in.) and P is the paper depth on output (in.). The data and regression line are given in Figure 4.

The depth of the dowel was determined by measuring the distance on the graphic output from slab surface to peak of dowel signal. This paper depth was input into the regression equation to determine the estimated dowel depth.

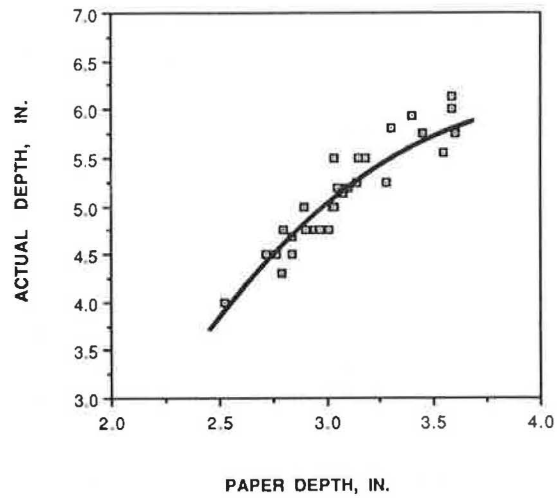


FIGURE 4 Scatter plot of actual dowel depth versus graphic output paper depth.

TABLE 1 TYPICAL DATA, BASKET JOINT

JT. B-19 DOWEL NO.	AVERAGE DOWEL DEPTH, IN.	VERT. MISALIGN. IN./FT.	HORIZ. MISALIGN. IN./FT.	LONG. DISPL.
1	5.01	-0.11	-0.25	
2	5.20	0.11	0.00	
3	5.05	-0.15	-0.50	
4	5.01	-0.11	0.25	
5	5.33	0.15	-0.25	
6	5.50	-0.83	-0.50	
7	5.96	0.43	0.00	L
8	4.40	0.27	-0.50	
9	5.79	0.61	0.50	L
10	4.82	-0.06	-0.50	
11	4.86	-0.14	0.25	
12	5.09	0.00	-0.50	
C.L.	5.11	-0.07	-0.50	
14	5.14	0.00	0.25	
15	4.97	-0.12	0.00	
16	5.01	-0.04	0.50	
17	4.83	-0.04	0.00	
18	4.65	0.02	0.00	
19	4.54	0.21	0.50	
20	4.49	0.26	0.25	
21	4.39	0.15	0.00	
22	4.43	0.33	0.00	
23	4.35	0.27	0.00	
24	4.47	0.07	0.50	
25	4.41	-0.05	0.50	
26	4.44	0.19	0.00	
27	4.66	0.04	0.00	
MINIMUM	4.35	0.00	0.00	
MAXIMUM	5.96	0.83	0.50	
AVERAGE	4.89	0.18	0.26	
STD. DEV.	0.44	0.19	0.23	

Notes:

1. Dowel No. 1 is located approximately 6 in. from inside (passing) lane shoulder
2. Vertical and horizontal misalignment given is over a distance of 12-in..
3. Negative vertical misalignment indicates that the approach slab end of dowel is lower than leave end.
4. Negative horizontal misalignment indicates that the leave slab dowel end is skewed toward the inside lane shoulder.
5. The letter "L" indicates that the dowel is displaced backward from the leave slab and the letter "A" indicates that the dowel is displaced forward away from the approach slab relative to the joint.
6. Minimum, maximum, average, and standard deviation statistics describe the magnitudes of misalignment.

Summary of Data

A detailed summary of estimated dowel placement data for each joint evaluated for joints with dowel baskets and for joints with inserted dowels is available elsewhere (*3*). Typical data are presented for a basket joint in Table 1 and for an inserter joint in Table 2.

Average Depth

Calculations of the average depth to the top of each dowel at the 51 basket and 52 inserter joints involved data obtained from both sides of the joint. Dowel depths for basket joints ranged from 3.7 to 6.2 in. and averaged 5.0 in. For dowel inserter joints, average dowel depths ranged from 4.2 to 6.1 and averaged 5.1 in. Statistics of average dowel depths are summarized by joint in Tables 3 and 4 for basket and inserter joints, respectively.

Generally, the average dowel depths determined for both types of joints are similar. At each joint the range in individual dowel depths varied from 0.2 to 1.6 in. for basket assembly joints and from 0.2 to 1.4 in. for dowel inserter joints. The average range at individual joints was 0.8 in. for basket joints and 0.6 in. for inserter joints. These values represent the variation in dowel bar depths within joints.

Vertical Misalignment

By using the data obtained from both sides of the joint, the vertical misalignment across 12 in. was calculated for all 103 sample joints. The maximum misalignments calculated for individual dowels were 1.1 in. for basket joints and 0.6 in. for inserter joints. Overall, the individual dowel misalignment averaged 0.1 in. for both joint types. Statistics of individual dowel vertical misalignments are summarized by joint in Tables 5 and 6 for basket and inserter joints, respectively. The summary statistics refer to the magnitudes of vertical misalignment.

TABLE 2 TYPICAL DATA, INSERTER JOINT

JT. I-12 DOWEL NO.	AVERAGE DOWEL DEPTH, IN.	VERT. MISALIGN. IN./FT.	HORIZ. MISALIGN. IN./FT.	LONG. DISPL.
1	4.92	-0.10	-1.00	
2	5.16	-0.07	0.00	
3	5.12	-0.07	0.50	
4	5.11	0.11	-1.00	
5	5.21	0.04	0.00	L
6	5.18	-0.04	0.00	
7	5.18	-0.04	0.00	
8	5.11	0.07	0.50	
9	5.23	0.18	-0.25	L
10	5.25	0.18	0.25	L
11	5.25	-0.07	0.00	L
12	5.27	0.03	0.75	L
C.L.	5.01	0.00	0.25	L
14	5.21	0.00	0.00	
15	5.18	0.04	0.00	
16	5.09	0.15	-1.00	
17	5.34	0.03	0.00	
18	5.34	0.07	0.00	L
19			0.00	L
20			0.00	L
21	5.16	0.04	-0.50	
22	5.19	0.09	-0.25	
23	5.15	0.13	-0.50	
24	5.14	0.07	0.25	
25	5.03	0.00	0.25	
26	5:03	0.04	0.00	
27	4.90	0.22	0.00	
MINIMUM	4.90	0.00	0.00	
MAXIMUM	5.34	0.22	1.00	
AVERAGE	5.15	0.07	0.27	
STD. DEV.	0.11	0.06	0.34	

Notes:

1. Dowel No. 1 is located approximately 6 in. from inside (passing) lane shoulder.
2. Vertical and horizontal misalignment given is over a distance of 12-in..
3. Negative vertical misalignment indicates that the approach slab end of dowel is lower than leave end.
4. Negative horizontal misalignment indicates that the leave slab dowel end is skewed toward the inside lane shoulder.
5. The letter "L" indicates that the dowel is displaced backward from the leave slab and the letter "A" indicates that the dowel is displaced forward away from the approach slab relative to the joint.
6. Minimum, maximum, average, and standard deviation statistics describe the magnitudes of misalignment.

TABLE 3 SUMMARY OF AVERAGE DOWEL DEPTH, BASKET JOINTS

JOINT NUMBER	AVERAGE DEPTH, IN.	STD. DEV. DEPTH, IN.
B-1	5.07	0.47
B-2	5.21	0.12
B-3	4.92	0.27
B-4	5.04	0.13
B-5	4.83	0.28
B-6	5.01	0.23
B-7	4.67	0.42
B-8	4.79	0.35
B-9	5.37	0.26
B-10	5.37	0.28
B-11	4.87	0.24
B-12	5.34	0.19
B-13	5.11	0.10
B-14	5.04	0.11
B-15	5.20	0.20
B-16	5.16	0.17
B-17	4.85	0.34
B-18	4.81	0.12
B-19	4.89	0.43
B-20	4.34	0.21
B-21	5.31	0.34
B-22	4.84	0.43
B-23	5.91	0.20
B-24	5.30	0.34
B-25	5.72	0.38
B-26	5.34	0.16
B-27	5.68	0.34
B-28	5.04	0.29
B-29	5.04	0.22
B-30	4.09	0.16
B-31	4.98	0.25
B-32	4.50	0.19
B-33	4.57	0.27
B-34	4.60	0.34
B-35	5.18	0.13
B-36	4.73	0.18
B-37	5.06	0.16
B-38	4.73	0.43
B-39	4.39	0.33
B-40	4.32	0.14
B-41	4.51	0.12
B-42	5.15	0.46
B-43	4.51	0.16
B-44	4.49	0.42
B-45	5.12	0.06
B-46	4.72	0.13
B-47	5.24	0.17
B-48	5.14	0.10
B-49	5.37	0.25
B-50	4.82	0.19
B-51	5.21	0.20
MINIMUM	4.09	0.06
MAXIMUM	5.91	0.47
AVERAGE	4.97	0.25

The range of vertical misalignment at individual joints varied from 0.2 to 1.0 in. for basket joints and 0.1 to 0.6 in. for inserter joints. The range in vertical misalignment at each joint averaged 0.5 for the basket joints and 0.3 in. for the inserter joints. This indicates that although both joint types had the same average misalignment magnitude (0.1 in.), the variation of estimated misalignment within joints was larger for the basket joints than for the inserter joints.

To evaluate the within-joint average vertical alignment in detail, the degree of misalignment was summarized by dowel location (Table 7, basket joints; Table 8, inserter joints). Misalignment was categorized by magnitude as well as by sign. Negative misalignment means that the dowel depth is greater on the approach-joint side than on the leave-slab side. The paving sequence was in the direction of traffic. Dowel 1 is located ~6 in. from the inside lane shoulder, and Dowel 27 is located ~6 in. from the outside lane shoulder. Dowel 13 was located at the longitudinal joint between lanes.

For both joint types the majority of the dowels were misaligned between −0.20 and +0.20 in. Of the 1,367 dowels evaluated at basket joints, only 53 had vertical misalignments greater than 0.50 in. Of these 53 dowels, only 16 dowels evaluated had misalignments greater than 0.70 in. None of the 1,329 inserter dowels were found to have vertical misalignments greater than 0.70 in., and only 4 dowels evaluated at inserter joints had misalignments exceeding 0.50 in. The

TABLE 4 SUMMARY OF AVERAGE DOWEL DEPTH, INSERTER JOINTS

JOINT NUMBER	AVERAGE DEPTH, IN.	STD. DEV. DEPTH, IN.
I-1	5.71	0.27
I-2	5.16	0.10
I-3	5.32	0.12
I-4	5.12	0.15
I-5	5.15	0.15
I-6	5.34	0.19
I-7	5.13	0.14
I-8	5.15	0.13
I-9	5.38	0.20
I-10	5.16	0.11
I-11	5.18	0.09
I-12	5.15	0.11
I-13	5.20	0.10
I-14	5.15	0.20
I-15	5.26	0.20
I-16	4.94	0.13
I-17	4.99	0.12
I-18	4.95	0.13
I-19	5.12	0.17
I-20	4.94	0.14
I-21	4.93	0.12
I-22	5.04	0.16
I-23	5.54	0.24
I-24	5.24	0.23
I-25	5.22	0.09
I-26	5.24	0.15
I-27	4.87	0.20
I-28	5.01	0.14
I-29	5.01	0.14
I-30	5.25	0.32
I-31	5.02	0.13
I-32	5.00	0.10
I-33	5.28	0.20
I-34	4.94	0.12
I-35	4.98	0.11
I-36	5.11	0.12
I-37	4.89	0.11
I-38	5.03	0.15
I-39	4.93	0.13
I-40	4.82	0.17
I-41	4.68	0.18
I-42	4.47	0.17
I-43	4.86	0.15
I-44	4.89	0.09
I-45	5.01	0.13
I-46	4.72	0.15
I-47	4.80	0.11
I-48	5.09	0.07
I-49	4.87	0.14
I-50	5.02	0.16
I-51	5.08	0.26
I-52	4.76	0.15
MINIMUM	4.47	0.07
MAXIMUM	5.71	0.32
AVERAGE	5.06	0.15

TABLE 5 SUMMARY OF VERTICAL DOWEL MISALIGNMENT, BASKET JOINTS

JOINT NUMBER	AVERAGE MISALIGN., IN./FT	STD. DEV. MISALIGN., IN./FT
B-1	0.20	0.18
B-2	0.12	0.19
B-3	0.16	0.12
B-4	0.44	0.20
B-5	0.17	0.13
B-6	0.11	0.10
B-7	0.28	0.25
B-8	0.11	0.09
B-9	0.13	0.09
B-10	0.11	0.10
B-11	0.25	0.27
B-12	0.09	0.06
B-13	0.12	0.14
B-14	0.14	0.11
B-15	0.12	0.10
B-16	0.09	0.07
B-17	0.13	0.12
B-18	0.12	0.08
B-19	0.18	0.19
B-20	0.15	0.17
B-21	0.17	0.18
B-22	0.11	0.09
B-23	0.07	0.10
B-24	0.11	0.16
B-25	0.07	0.11
B-26	0.11	0.07
B-27	0.13	0.14
B-28	0.06	0.07
B-29	0.06	0.05
B-30	0.25	0.20
B-31	0.11	0.08
B-32	0.13	0.12
B-33	0.11	0.08
B-34	0.14	0.12
B-35	0.09	0.06
B-36	0.13	0.13
B-37	0.09	0.07
B-38	0.14	0.10
B-39	0.20	0.17
B-40	0.16	0.11
B-41	0.10	0.09
B-42	0.14	0.08
B-43	0.16	0.10
B-44	0.12	0.14
B-45	0.08	0.09
B-46	0.14	0.12
B-47	0.16	0.18
B-48	0.08	0.05
B-49	0.27	0.23
B-50	0.09	0.07
B-51	0.09	0.09
MINIMUM	0.06	0.05
MAXIMUM	0.44	0.27
AVERAGE	0.14	0.12

NOTE: Misalignment statistics refer to magnitudes of misalignment

TABLE 6 SUMMARY OF VERTICAL DOWEL MISALIGNMENT, INSERTER JOINTS

JOINT NUMBER	AVERAGE MISALIGN., IN./FT	STD. DEV. MISALIGN., IN./FT
I-1	0.11	0.10
I-2	0.06	0.04
I-3	0.18	0.15
I-4	0.06	0.05
I-5	0.07	0.07
I-6	0.17	0.12
I-7	0.04	0.04
I-8	0.07	0.05
I-9	0.09	0.07
I-10	0.05	0.04
I-11	0.05	0.03
I-12	0.07	0.06
I-13	0.08	0.05
I-14	0.08	0.08
I-15	0.14	0.11
I-16	0.08	0.08
I-17	0.08	0.07
I-18	0.06	0.06
I-19	0.10	0.08
I-20	0.08	0.06
I-21	0.07	0.05
I-22	0.06	0.04
I-23	0.07	0.05
I-24	0.13	0.09
I-25	0.10	0.04
I-26	0.08	0.06
I-27	0.07	0.05
I-28	0.05	0.03
I-29	0.06	0.04
I-30	0.10	0.09
I-31	0.12	0.08
I-32	0.15	0.13
I-33	0.08	0.07
I-34	0.07	0.06
I-35	0.06	0.05
I-36	0.06	0.04
I-37	0.09	0.06
I-38	0.09	0.08
I-39	0.09	0.08
I-40	0.10	0.08
I-41	0.10	0.06
I-42	0.11	0.11
I-43	0.09	0.07
I-44	0.05	0.04
I-45	0.08	0.07
I-46	0.12	0.09
I-47	0.07	0.04
I-48	0.06	0.06
I-49	0.08	0.07
I-50	0.10	0.07
I-51	0.20	0.15
I-52	0.09	0.06
MINIMUM	0.04	0.03
MAXIMUM	0.20	0.15
AVERAGE	0.09	0.07

NOTE: Misalignment summary statistics refer to magnitudes of misalignment.

TABLE 7 NUMBER OF DOWELS VERTICALLY MISALIGNED, BY LOCATION, BASKET JOINTS

BASKET DOWEL NO.	NO.	MIN. IN./FT	MAX. IN./FT	AVE. IN./FT	VERTICAL MISALIGNMENT, IN./FT > -1.0	-1.0 to -0.9	-0.9 to -0.8	-0.8 to -0.7	-0.7 to -0.6	-0.6 to -0.5	-0.5 to -0.4	-0.4 to -0.3	-0.3 to -0.2	-0.2 to -0.1	-0.1 to 0.0	zero
1	48	-0.80	0.51	-0.02	0	0	1	0	0	0	1	0	0	10	11	4
2	51	-0.45	0.40	0.03	0	0	0	0	0	0	1	0	1	8	8	4
3	51	-0.22	0.44	0.01	0	0	0	0	0	0	0	0	1	9	11	7
4	51	-0.83	0.23	0.02	0	0	1	0	0	0	0	0	1	5	9	4
5	51	-0.32	0.42	-0.01	0	0	0	0	0	0	0	1	2	8	12	7
6	51	-0.96	1.02	0.04	0	1	1	0	1	2	2	1	1	5	5	3
7	51	-0.43	0.61	-0.02	0	0	0	0	0	0	1	2	1	10	15	4
8	51	-0.61	0.56	0.03	0	0	0	0	1	0	0	0	3	2	9	9
9	51	-0.56	0.74	0.01	0	0	0	0	0	1	0	0	2	8	14	8
10	51	-1.05	0.70	0.01	1	0	0	0	0	0	0	0	1	11	9	3
11	51	-0.31	0.52	-0.01	0	0	0	0	0	0	0	1	4	10	13	1
12	51	-0.54	0.46	-0.02	0	0	0	0	0	1	0	1	5	8	12	2
C.L.	50	-0.43	0.39	-0.06	0	0	0	0	0	0	1	2	5	8	14	6
14	50	-0.45	0.56	0.05	0	0	0	0	0	0	2	0	1	4	8	4
15	51	-0.55	0.52	-0.05	0	0	0	0	0	1	2	4	4	7	11	3
16	51	-0.36	0.60	0.07	0	0	0	0	0	0	0	2	1	6	6	0
17	51	-0.65	0.42	-0.02	0	0	0	0	1	0	0	3	2	7	15	6
18	51	-0.38	0.59	0.07	0	0	0	0	0	0	0	1	2	3	8	1
19	51	-0.51	0.69	-0.01	0	0	0	0	0	1	0	2	6	6	14	3
20	51	-0.48	0.63	0.09	0	0	0	0	0	0	1	0	2	3	7	3
21	51	-0.57	0.60	0.02	0	0	0	0	0	1	1	1	1	7	12	5
22	51	-0.40	0.73	0.12	0	0	0	0	0	0	0	1	2	1	7	2
23	51	-0.70	0.51	-0.01	0	0	0	1	0	0	1	1	3	9	14	3
24	50	-0.50	0.72	0.07	0	0	0	0	0	1	0	0	1	5	6	3
25	50	-0.59	0.60	-0.06	0	0	0	0	0	1	0	0	6	18	11	3
26	49	-0.60	0.84	0.04	0	0	0	0	1	0	0	0	3	2	10	3
27	50	-0.58	0.72	-0.09	0	0	0	0	0	1	0	4	6	13	10	1
				TOTAL	1	1	3	1	4	10	13	27	67	193	281	102

NOTE: Negative misalignment indicates that the dowel depth is greater on the approach joint side than the leave slab side.

TABLE 7 *continued*

BASKET DOWEL NO.	NO.	MIN. IN./FT	MAX. IN./FT	AVE. IN./FT	VERTICAL MISALIGNMENT, IN./FT zero	0.0 to 0.1	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 0.6	0.6 to 0.7	0.7 to 0.8	0.8 to 0.9	0.9 to 1.0	> 1.0
1	48	-0.80	0.51	-0.02	4	13	6	0	1	0	1	0	0	0	0	0
2	51	-0.45	0.40	0.03	4	12	12	4	0	1	0	0	0	0	0	0
3	51	-0.22	0.44	0.01	7	12	7	3	0	1	0	0	0	0	0	0
4	51	-0.83	0.23	0.02	4	17	9	5	0	0	0	0	0	0	0	0
5	51	-0.32	0.42	-0.01	7	14	3	2	1	1	0	0	0	0	0	0
6	51	-0.96	1.02	0.04	3	11	6	2	3	1	2	0	1	2	0	1
7	51	-0.43	0.61	-0.02	4	8	7	1	0	1	0	1	0	0	0	0
8	51	-0.61	0.56	0.03	9	14	7	5	0	0	1	0	0	0	0	0
9	51	-0.56	0.74	0.01	8	8	6	0	1	0	1	1	1	0	0	0
10	51	-1.05	0.70	0.01	3	13	8	4	0	0	0	1	0	0	0	0
11	51	-0.31	0.52	-0.01	1	13	5	3	0	0	1	0	0	0	0	0
12	51	-0.54	0.46	-0.02	2	12	6	1	2	1	0	0	0	0	0	0
C.L.	50	-0.43	0.39	-0.06	6	11	2	0	1	0	0	0	0	0	0	0
14	50	-0.45	0.56	0.05	4	16	7	6	0	1	1	0	0	0	0	0
15	51	-0.55	0.52	-0.05	3	9	5	3	0	1	1	0	0	0	0	0
16	51	-0.36	0.60	0.07	0	15	15	1	3	1	0	1	0	0	0	0
17	51	-0.65	0.42	-0.02	6	10	1	2	3	1	0	0	0	0	0	0
18	51	-0.38	0.59	0.07	1	13	16	4	2	0	1	0	0	0	0	0
19	51	-0.51	0.69	-0.01	3	10	1	3	2	1	1	1	0	0	0	0
20	51	-0.48	0.63	0.09	3	14	8	8	0	3	1	1	0	0	0	0
21	51	-0.57	0.60	0.02	5	7	9	3	2	0	2	0	0	0	0	0
22	51	-0.40	0.73	0.12	2	13	11	4	5	3	0	0	2	0	0	0
23	51	-0.70	0.51	-0.01	3	8	4	3	0	2	2	0	0	0	0	0
24	50	-0.50	0.72	0.07	3	17	8	5	2	0	0	1	1	0	0	0
25	50	-0.59	0.60	-0.06	3	5	2	2	1	0	1	0	0	0	0	0
26	49	-0.60	0.84	0.04	3	14	11	2	2	0	0	0	0	1	0	0
27	50	-0.58	0.72	-0.09	1	12	2	0	0	0	0	0	1	0	0	0
				TOTAL	102	321	184	76	31	19	16	7	6	3	0	1

TABLE 8 NUMBER OF DOWELS VERTICALLY MISALIGNED, BY LOCATION, INSERTER JOINTS

INSERT DOWEL NO.	NO.	MIN. IN./FT	MAX. IN./FT	AVE. IN./FT	VERTICAL MISALIGNMENT, IN./FT											
					> -1.0	-1.0 to -0.9	-0.9 to -0.8	-0.8 to -0.7	-0.7 to -0.6	-0.6 to -0.5	-0.5 to -0.4	-0.4 to -0.3	-0.3 to -0.2	-0.2 to -0.1	-0.1 to 0.0	zero
1	51	-0.24	0.36	0.02	0	0	0	0	0	0	0	0	2	2	14	4
2	51	-0.12	0.31	0.02	0	0	0	0	0	0	0	0	0	2	22	4
3	51	-0.18	0.36	0.03	0	0	0	0	0	0	0	0	0	5	13	4
4	51	-0.07	0.33	0.07	0	0	0	0	0	0	0	0	0	0	7	8
5	51	-0.18	0.36	0.08	0	0	0	0	0	0	0	0	0	1	10	4
6	51	-0.22	0.36	0.01	0	0	0	0	0	0	0	0	1	4	20	1
7	51	-0.21	0.45	0.04	0	0	0	0	0	0	0	0	1	4	9	6
8	51	-0.24	0.34	0.03	0	0	0	0	0	0	0	0	1	4	13	4
9	49	-0.37	0.27	0.05	0	0	0	0	0	0	0	1	0	1	9	8
10	50	-0.35	0.37	0.04	0	0	0	0	0	0	0	1	0	9	7	2
11	51	-0.41	0.50	0.03	0	0	0	0	0	0	1	0	0	8	12	1
12	51	-0.19	0.26	0.01	0	0	0	0	0	0	0	0	0	7	15	4
C.L.	51	-0.10	0.57	0.06	0	0	0	0	0	0	0	0	0	1	11	7
14	48	-0.14	0.29	0.01	0	0	0	0	0	0	0	0	0	4	16	7
15	49	-0.46	0.40	0.01	0	0	0	0	0	0	1	0	2	2	14	3
16	49	-0.28	0.36	0.04	0	0	0	0	0	0	0	0	2	3	9	6
17	49	-0.30	0.25	0.03	0	0	0	0	0	0	0	0	2	4	10	1
18	47	-0.18	0.55	0.03	0	0	0	0	0	0	0	0	0	4	13	2
19	46	-0.13	0.61	0.07	0	0	0	0	0	0	0	0	0	1	11	5
20	47	-0.22	0.32	0.04	0	0	0	0	0	0	0	0	1	3	13	2
21	47	-0.12	0.21	0.05	0	0	0	0	0	0	0	0	0	1	9	6
22	48	-0.28	0.22	0.06	0	0	0	0	0	0	0	0	1	0	6	5
23	48	-0.34	0.16	0.02	0	0	0	0	0	0	0	1	1	2	9	7
24	48	-0.34	0.14	-0.02	0	0	0	0	0	0	0	1	1	10	12	3
25	48	-0.33	0.30	-0.04	0	0	0	0	0	0	0	2	0	11	15	3
26	47	-0.30	0.28	-0.03	0	0	0	0	0	0	0	1	3	6	19	2
27	48	-0.30	0.37	-0.02	0	0	0	0	0	0	0	1	2	10	13	4
				TOTAL	0	0	0	0	0	0	2	8	20	109	331	113

NOTE: Negative misalignment indicates that the dowel depth is greater on the approach joint side than the leave slab side.

TABLE 8 *continued*

INSERT DOWEL NO.	NO.	MIN. IN./FT	MAX. IN./FT	AVE. IN./FT	VERTICAL MISALIGNMENT, IN./FT zero	0.0 to 0.1	0.1 to 0.2	0.2 to 0.3	0.3 to 0.4	0.4 to 0.5	0.5 to 0.6	0.6 to 0.7	0.7 to 0.8	0.8 to 0.9	0.9 to 1.0	> 1.0
1	51	-0.24	0.36	0.02	4	19	8	1	1	0	0	0	0	0	0	0
2	51	-0.12	0.31	0.02	4	16	4	2	1	0	0	0	0	0	0	0
3	51	-0.18	0.36	0.03	4	18	8	1	2	0	0	0	0	0	0	0
4	51	-0.07	0.33	0.07	8	22	9	4	1	0	0	0	0	0	0	0
5	51	-0.18	0.36	0.08	4	18	11	5	2	0	0	0	0	0	0	0
6	51	-0.22	0.36	0.01	1	14	9	1	1	0	0	0	0	0	0	0
7	51	-0.21	0.45	0.04	6	22	5	3	0	1	0	0	0	0	0	0
8	51	-0.24	0.34	0.03	4	21	5	2	1	0	0	0	0	0	0	0
9	49	-0.37	0.27	0.05	8	13	12	5	0	0	0	0	0	0	0	0
10	50	-0.35	0.37	0.04	2	13	14	3	1	0	0	0	0	0	0	0
11	51	-0.41	0.50	0.03	1	15	8	3	2	0	1	0	0	0	0	0
12	51	-0.19	0.26	0.01	4	19	4	2	0	0	0	0	0	0	0	0
C.L.	51	-0.10	0.57	0.06	7	16	12	3	0	0	1	0	0	0	0	0
14	48	-0.14	0.29	0.01	7	14	5	2	0	0	0	0	0	0	0	0
15	49	-0.46	0.40	0.01	3	18	6	2	0	1	0	0	0	0	0	0
16	49	-0.28	0.36	0.04	6	16	10	0	3	0	0	0	0	0	0	0
17	49	-0.30	0.25	0.03	1	19	8	5	0	0	0	0	0	0	0	0
18	47	-0.18	0.55	0.03	2	17	9	1	0	0	1	0	0	0	0	0
19	46	-0.13	0.61	0.07	5	13	14	1	0	0	0	1	0	0	0	0
20	47	-0.22	0.32	0.04	2	12	12	3	1	0	0	0	0	0	0	0
21	47	-0.12	0.21	0.05	6	15	15	1	0	0	0	0	0	0	0	0
22	48	-0.28	0.22	0.06	5	19	16	1	0	0	0	0	0	0	0	0
23	48	-0.34	0.16	0.02	7	16	12	0	0	0	0	0	0	0	0	0
24	48	-0.34	0.14	-0.02	3	16	5	0	0	0	0	0	0	0	0	0
25	48	-0.33	0.30	-0.04	3	15	1	0	1	0	0	0	0	0	0	0
26	47	-0.30	0.28	-0.03	2	13	2	1	0	0	0	0	0	0	0	0
27	48	-0.30	0.37	-0.02	4	12	4	1	1	0	0	0	0	0	0	0
				TOTAL	113	441	228	53	18	2	3	1	0	0	0	0

TABLE 9 SUMMARY OF HORIZONTAL DOWEL MISALIGNMENT, BASKET JOINTS

JOINT NUMBER	AVERAGE MISALIGN., IN./FT	STD. DEV. MISALIGN., IN./FT
B-5	0.44	0.47
B-6	0.43	0.34
B-7	0.25	0.27
B-8	0.39	0.35
B-9	0.29	0.26
B-15	0.31	0.27
B-19	0.26	0.22
B-23	0.36	0.33
B-26	0.23	0.22
B-29	0.36	0.26
B-30	0.54	0.36
B-33	0.31	0.31
B-36	0.44	0.36
B-39	0.44	0.40
B-42	0.21	0.18
B-45	0.38	0.33
B-48	0.31	0.31
B-50	0.28	0.24
B-51	0.14	0.24
MINIMUM	0.14	0.18
MAXIMUM	0.54	0.47
AVERAGE	0.34	0.30

NOTE: Misalignment summary statistics refer to the magnitudes of misalignment.

TABLE 10 SUMMARY OF HORIZONTAL DOWEL MISALIGNMENT, INSERTER JOINTS

JOINT NUMBER	AVERAGE MISALIGN., IN./FT	STD. DEV. MISALIGN., IN./FT
I-1	0.36	0.47
I-3	0.20	0.22
I-8	0.32	0.32
I-10	0.31	0.21
I-12	0.27	0.34
I-15	0.32	0.31
I-18	0.41	0.32
I-21	0.39	0.35
I-24	0.25	0.22
I-27	0.23	0.22
I-30	0.31	0.30
I-34	0.43	0.33
I-37	0.25	0.29
I-40	0.32	0.22
I-44	0.60	0.39
I-47	0.54	0.55
I-51	0.19	0.26
MINIMUM	0.19	0.21
MAXIMUM	0.60	0.55
AVERAGE	0.33	0.31

NOTE: Misalignment summary statistics refer to the magnitudes of misalignment.

TABLE 11 NUMBER OF DOWELS HORIZONTALLY MISALIGNED, BY LOCATION, BASKET JOINTS

BASKET DOWEL NO.	NO.	MIN. IN./FT	MAX. IN./FT	AVE. IN./FT	HORIZONTAL MISALIGNMENT, IN./FT > -1.0	-1.0 to -0.5	-0.5 to 0.0	zero	0.0 to 0.5	0.5 to 1.0	> 1.0
1	19	-1.25	1.00	-0.09	2	3	3	6	2	1	2
2	19	-2.00	1.00	-0.06	1	4	2	7	0	4	1
3	19	-0.50	1.00	0.10	0	3	4	4	3	4	1
4	19	-1.00	0.50	-0.09	1	3	3	7	3	2	0
5	19	-0.50	0.50	0.06	0	2	3	6	4	4	0
6	19	-0.50	0.75	0.17	0	3	2	4	2	8	0
7	19	-0.75	0.75	0.12	0	3	1	6	3	6	0
8	19	-0.75	1.25	0.03	0	6	1	3	5	3	1
9	19	-1.00	0.75	0.08	1	2	4	3	2	7	0
10	19	-0.75	1.00	0.04	0	4	2	5	5	1	2
11	19	-0.75	1.00	0.06	0	3	2	5	6	2	1
12	19	-0.75	0.75	0.01	0	3	3	6	4	3	0
C.L.	19	-1.00	0.75	-0.11	2	3	2	6	5	1	0
14	19	-0.50	0.75	0.14	0	2	1	8	2	6	0
15	19	-0.25	1.50	0.26	0	0	3	6	2	7	1
16	19	-1.00	1.25	0.00	1	4	3	5	2	2	2
17	19	-0.90	0.50	-0.03	0	5	1	6	3	4	0
18	19	-1.00	0.50	0.09	1	0	2	7	5	4	0
19	19	-0.50	1.00	0.16	0	3	2	4	3	6	1
20	19	-1.50	0.75	0.07	2	0	4	3	3	7	0
21	19	-1.25	1.00	0.13	1	1	0	8	4	3	2
22	19	-0.50	0.75	0.12	0	2	3	7	1	6	0
23	19	-0.50	1.00	0.21	0	1	1	7	4	5	1
24	19	-0.75	1.50	0.17	0	1	3	6	5	2	2
25	19	-0.30	1.50	0.13	0	0	6	8	1	2	2
26	19	-0.75	0.50	-0.03	0	3	5	3	6	2	0
27	19	-1.00	0.50	-0.03	1	1	4	7	4	2	0
				TOTAL	13	65	70	153	89	104	19

NOTE:

Negative misalignment indicates the leave slab dowel end is skewed toward the inside lane.

percentage of dowels with less than 0.25-in. estimated vertical misalignment across 12 in. was 85 percent for basket joints and 96 percent for inserter joints.

Overall, there was no trend in the direction of misalignment for basket joints. Individual dowel locations did exhibit evidence of dowels misaligned in one direction, but these locations appeared to be randomly dispersed along the joint profile. At Dowel Location 6 (basket joints), the spread in misalignment was large in comparison with other dowel locations.

Overall, the dowels in the inserter sections tended to be misaligned slightly downward in the leave-slab direction. Of the 1,329 dowels tested, 35 and 56 percent were misaligned downward in the approach-slab and leave-slab direction, respectively. The number of misaligned dowels appeared to be uniformly distributed across the joint.

Horizontal Misalignment

Horizontal misalignment across 12 in. was calculated for 19 basket and 17 inserter joints by using data from both sides of the joint. The horizontal position was estimated by interpolating dowel location relative to the reference marks on the

TABLE 12 NUMBER OF DOWELS HORIZONTALLY MISALIGNED, BY LOCATION, INSERTER JOINTS

INSERT DOWEL NO.	NO.	MIN. IN./FT	MAX. IN./FT	AVE. IN./FT	HORIZONTAL MISALIGNMENT, IN./FT						
					> -1.0	-1.0 to -0.5	-0.5 to 0.0	zero	0.0 to 0.5	0.5 to 1.0	> 1.0
1	17	-1.00	1.00	-0.10	1	4	3	4	3	1	1
2	17	-0.75	1.00	-0.02	0	3	2	8	1	2	1
3	17	-2.25	0.50	-0.04	1	1	3	5	3	4	0
4	17	-1.00	1.00	-0.08	1	4	1	6	3	1	1
5	17	0.00	0.75	0.26	0	0	0	8	3	6	0
6	17	-0.50	0.75	0.17	0	1	4	3	4	5	0
7	17	-0.50	0.75	0.15	0	2	2	4	4	5	0
8	17	-0.50	0.50	0.08	0	2	3	3	5	4	0
9	17	-0.75	1.00	0.19	0	1	3	5	3	2	3
10	17	-0.56	1.00	0.14	0	3	1	5	3	4	1
11	17	-0.25	1.00	0.15	0	0	3	8	3	1	2
12	17	-0.50	1.25	0.29	0	1	0	7	3	5	1
C.L.	17	-0.25	1.75	0.20	0	0	3	6	5	2	1
14	17	-0.75	1.00	0.15	0	3	0	7	3	1	3
15	17	-2.00	0.75	-0.23	2	4	1	5	3	2	0
16	17	-1.00	0.50	-0.06	2	2	2	3	7	1	0
17	17	-0.50	0.75	0.23	0	1	2	4	3	7	0
18	17	-0.50	0.75	0.07	0	1	2	8	4	2	0
19	17	-1.00	0.50	0.07	1	0	1	8	5	2	0
20	17	-0.75	1.00	0.33	0	1	0	5	3	7	1
21	17	-1.00	1.00	0.06	1	3	1	3	5	3	1
22	17	-1.00	1.00	0.14	1	1	3	4	3	2	3
23	17	-0.50	1.00	0.08	0	4	0	6	3	3	1
24	17	-0.75	0.50	0.01	0	4	1	5	4	3	0
25	17	-0.75	1.00	0.07	0	3	2	5	4	2	1
26	17	-0.75	0.75	0.06	0	3	1	7	3	3	0
27	17	-2.00	0.75	-0.08	2	1	3	6	1	4	0
				TOTAL	12	53	47	148	94	84	21

NOTE:

Negative misalignment indicates the leave slab dowel end is skewed toward the inside lane.

recordings. These reference marks, automatically printed on the radar output, represented an actual spacing of 4 in.

The maximum estimated horizontal misalignment was 2 in. for the basket joints and 2.25 in. for the inserter joints. Overall, individual dowel horizontal misalignment averaged ~⅓ in. for both types of joints. Horizontal misalignments are summarized by joint in Tables 9 and 10 for basket and inserter joints, respectively.

So that the within-joint average horizontal alignment variation could be evaluated in detail, the degree of misalignment was summarized by dowel location (Table 11, basket joints; Table 12, inserter joints). Because of limitations of precision in interpreting horizontal dowel position, the degree of misalignment was categorized in ½-in. ranges. Given this limitation on precision (to be discussed more extensively later in the paper), the estimates of horizontal misalignment distribution should be considered only rough approximations.

In general, the basket and inserter joints exhibited similar distributions of horizontal misalignment levels both in magnitude and dowel position. On average, basket joint dowel locations 15 and 23 exhibited a slightly higher misalignment average (magnitude and direction) relative to other dowel locations. Inserter joint dowel locations 5, 12, 15, 17, and 20 also exhibited higher average misalignments.

TABLE 13 SUMMARY OF LONGITUDINAL DOWEL DISPLACEMENT, BASKET JOINTS

JOINT NUMBER	LONGITUDINAL DISPLACEMENT	JOINT NUMBER	LONGITUDINAL DISPLACEMENT
B-1	A	B-27	
B-2		B-28	
B-3	A	B-29	
B-4		B-30	
B-5		B-31	
B-6		B-32	
B-7		B-33	
B-8		B-34	
B-9		B-35	
B-10		B-36	
B-11		B-37	
B-12		B-38	
B-13		B-39	
B-14	L	B-40	
B-15	L	B-41	
B-16		B-42	
B-17	L	B-43	
B-18	L	B-44	
B-19	L	B-45	L
B-20		B-46	L
B-21		B-47	L
B-22		B-48	
B-23		B-49	A
B-24		B-50	
B-25		B-51	L
B-26			

NOTE: The letter "L" indicates that one or more dowels are displaced backward from the leave slab and the letter "A" indicates that one or more dowels are displaced forward from the approach slab relative to the joint.

Longitudinal Displacement

Longitudinal displacement was qualitatively evaluated on the basis of output signal strength. When the relative signal strength was weaker, the dowel embedment length was considered to be less than the optimal 11 in. To verify that longitudinal displacement could be qualitatively evaluated, eight cores were selected on the basis of relatively weak radar output signals. In all cases the cores revealed that the transducer had passed over the dowel end.

Longitudinal displacement was qualitatively evaluated at all 103 joints. A summary of joints that exhibited weak radar output signals is given for basket joints in Table 13 and for inserter joints in Table 14. Of the 51 basket joints evaluated, 9 joints exhibited some weak signals on the leave-slab side and 3 exhibited weak signals on the approach side. For the inserter joints, 20 exhibited some weak signals on the leave side of the joint and only 3 joints exhibited weak signals on the approach side. In the majority of the cases in which weak signals were observed, the joint was retested at a 4-in. offset. In almost every retested joint, a stronger signal was observed. For a few joints, the test was repeated over the joint to verify the presence of dowels.

TABLE 14 SUMMARY OF LONGITUDINAL DOWEL DISPLACEMENT, INSERTER JOINTS

JOINT NUMBER	LONGITUDINAL DISPLACEMENT	JOINT NUMBER	LONGITUDINAL DISPLACEMENT
I-1		I-27	
I-2		I-28	
I-3		I-29	
I-4		I-30	
I-5	L	I-31	
I-6		I-32	
I-7		I-33	L
I-8		I-34	L
I-9		I-35	L
I-10		I-36	
I-11	L	I-37	A
I-12	L	I-38	L
I-13	A	I-39	L
I-14	A,L	I-40	L
I-15	L	I-41	L
I-16	L	I-42	L
I-17		I-43	L
I-18		I-44	
I-19	L	I-45	L
I-20		I-46	
I-21		I-47	L
I-22	L	I-48	L
I-23		I-49	
I-24		I-50	
I-25		I-51	
I-26		I-52	

NOTE: The letter "L" indicates that one or more dowels are displaced backward from the leave slab and the letter "A" indicates that one or more dowels are displaced forward from the approach slab relative to the joint.

SUMMARY

On the basis of the available core data, it is concluded that radar can be an effective tool for evaluating dowel bar misalignment. The statistical reliability of vertical depth measurements was verified by the linear least squares regression of core data on radar output (paper depth).

The need for improvement in the current technique for estimating horizontal alignment is apparent. In the present study, it was assumed that the traverse speed between the 4-in. reference marks was constant so that linear interpolation of radar output could be performed. The precision of the estimate of the degree of horizontal misalignment in this study was ~½ in.

Longitudinal displacement relative to the joint was estimated qualitatively. Because of the variability in radar output interpretation and operator experience, only the presence of displacement, as opposed to its degree or magnitude, can be estimated. Any longitudinal displacement that is detected is not necessarily caused by the dowel placement techniques used. Displacement can be introduced if the joint location is not marked correctly for sawing or if the saw cut does not follow the marked joint location.

On the basis of 103 joints tested in sections of pavement where basket assemblies were used and where the Guntert & Zimmerman dowel implanter was used, the average dowel depths appeared to be uniform for both types of construction. The inserter performance was somewhat better than that of the basket in terms of both the degree of vertical misalignment and the variability of vertical misalignment within each joint. On the basis of the 36 joints evaluated for horizontal misalignment, the basket and inserter joints appeared to exhibit similar trends in horizontal misalignment.

Longitudinal displacement was examined at all 103 joints tested. On the basis of signal strength and the evaluation of dowel embedment (based on cores), it was demonstrated that radar can be used qualitatively to detect longitudinal displacement relative to the joint. Given that there are other sources of variability, such as accuracy of joint locating and sawing, any comparisons between basket and inserter construction should be approached cautiously. If other sources of variability for both construction methods are assumed to be constant, it appears that more longitudinal displacement was detected in the dowel inserter sections than in the basket assembly sections. The number of occurrences of longitudinal displacement detection, however, was small in comparison with the number of dowels evaluated. This small percentage of detected longitudinal displacement may not be significant in evaluating the two methods.

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Use of Real-Time Animation in the Construction Process

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Recent advances in computer workstation performance and the increasing functionality of computer-aided design (CAD) software make it possible for today's engineers and constructors to interact with and animate complex three-dimensional computer models in real time. This makes the computer model not only a tool to be used in the design process but also a planning device that can be used during the construction of facilities. Major construction tasks can now be simulated routinely with real-time computer animation, allowing construction plans to be developed and verified so that the problems areas can be identified and corrected before the actual task is undertaken. In this paper, a description of Bechtel's real-time animation system, WALKTHRU, will be presented, and methods for application of the model to the construction process will be given.

Productivity in engineering and construction has become an increasingly important and critical issue. Reduced business, the declining U.S. world market share, and intense foreign competition have all contributed to elevating the importance of productivity in the construction industry. A traditional U.S. strength in this ongoing battle to improve productivity is the development, if not application, of new technologies. In engineering and construction, one of the most visible technologies in recent years has been computer-aided design, or CAD.

The engineering and construction industry often appears to lag behind the manufacturing industries (e.g., automotive and aerospace) in the integrated use of CAD technology. There are a number of important reasons for this. With few exceptions, the engineering and construction industry has traditionally lacked two important characteristics that are common in the manufacturing industries and that make it much easier to implement the integrated use of CAD technology cost effectively. These factors are mass production and vertical integration.

The primary use of CAD in manufacturing is the design of mechanical parts, mechanisms, assemblies, and so on. In the construction industry, there is little, if any, design of parts. A typical design consists of assembling and managing an extremely large number of parts, and nearly every project is unique, with little opportunity to reduce unit costs significantly through the use of mass production alone. Every bridge is different, every highway overpass has slightly different dimensions, and every subway station must satisfy a different set of spatial and service requirements. These types of projects are almost always constructed in a location different from that in which they are engineered. The "manufacturing" equipment and personnel are moved to the site and not vice versa. Finally, it is typical of engineering and construction projects that the owner, architect, engineer, and constructor are often different companies. If these different entities ever apply automation to the same degree, with compatible technologies, it is usually only coincidence.

In spite of these disadvantages, it is possible to apply CAD technology to engineering and construction projects in significant and cost-effective ways, over and above the use of CAD as an electronic drafting board. This technology, although often viewed strictly as an engineering tool, presents a tremendous opportunity for streamlining and integrating the entire engineering and construction process. In fact, the argument can be made that in the final analysis, the use of CAD in engineering will provide more benefits to the construction process than it does to the engineering itself. This paper will highlight just a few of the areas in which CAD has helped to enhance the productivity of the overall process and, in particular, construction. Specifically, the application of three-dimensional computer modeling and real-time computer animation in support of engineering and construction will be addressed.

BACKGROUND

The use of computers in the engineering and construction industries has been fairly commonplace for more than 20 yr. In engineering, the early applications of computing were mostly very specific point solutions to well-defined problems. Typically, these applications fell into the category of engineering analysis. Structural analysis, for example, was one of the very first engineering computing uses. Large engineering analyses involved an incredibly large number of calculations that were impractical, if not impossible, to perform by hand. As such, they were very amenable to the batch-processing nature of the computer technology of the day. Other applications were data base operations, such as tracking bulk quantities, materials management, and project management. Again, this use of computing was effective because it involved a well-defined problem in which large amounts of data had to be manipulated.

In nearly all these early uses of computing in engineering

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and construction, real-time interaction with the computer was either limited to the data input process or totally nonexistent. Likewise, graphics were seldom used except to represent the results of the analysis pictorially.

Computer-aided design was one of the first computing applications that was both highly interactive and made extensive use of computer graphics. These early CAD systems were developed for mainframe computers and were thus expensive, a characteristic that limited their application to very specialized and usually repetitive tasks. The advent of the minicomputer and the subsequent development of turnkey CAD systems, based on these less expensive computers, paved the way for more widespread use of CAD.

Although there were some notable applications of CAD that were truly design applications, most of the early usage of CAD in the engineering and construction area was purely as a drafting tool. Two major impediments held back the expansion of CAD use beyond drafting: a lack of software and the limited power of the early minicomputers. Typically, engineering and construction projects must include large amounts of data about the physical geometry of the project. Thus any software that is used to manage these data must be very efficient at generating data and maintaining data integrity. The computer must be able to manage these large amounts of data and still maintain its interactive quality. It was the introduction of the 32-bit minicomputers, with their increased processing power, that opened the door for design applications of CAD in engineering and construction. Ultimately, this led to a number of design systems supporting interactive three-dimensional (3-D) computer modeling.

The use of 3-D computer models has become an integral part of the Bechtel Eastern Power Corporation's activities in the design, construction, and retrofit of process and power plants. These computerized models are extremely economical to develop, enhance, and maintain. The conventional construction drawings and related documents (e.g., bills for material) are extracted automatically and are consistent in style, accuracy, and quality. The electronic model makes it possible for all members of the engineering and construction team to have immediate access to the current design data. It is also possible to link the electronic model to standard computer-aided engineering (CAE) analysis programs and data base management applications. For review purposes, these 3-D models can be downloaded to personal computers, where they can be interactively reviewed, queried, and color shaded. After the design and construction phase of a project is complete, the electronic model remains an important tool for subsequent operation and maintenance of the facility.

WALKTHRU

The effectiveness of 3-D computer modeling has eliminated our use of the plastic model as a design tool. There are a number of very good reasons for this. The computer model is more accurate, it is portable, and the data can be extracted automatically. Also, the computer model is not an "extra." By this, we mean that the 3-D computer model is a natural byproduct of the design process. However, we did pay a price for the demise of the plastic model: reduced visibility of the physical design. In spite of all its advantages, the full-scale use of 3-D computer modeling has limited routine access to the "live" design data to those who are trained to use CAD workstations and who use them on a daily basis, in other words, the physical designers. Those involved with project management, construction, and ownership were restricted to infrequent drawing extractions or looks over a designer's shoulder for their "view" of the physical design. In contrast, when physical models were used, anyone could walk up to the model and get an immediate appreciation for the plant configuration. The viewer did not require a CAD training course to change views, walk around the model, or examine the project design in some other way.

In an attempt to recapture electronically what was lost by giving up the plastic model, we developed WALKTHRU™, a real-time 3-D animation system. It allows users to interact with existing 3-D computer models in much the same way that they would with a real-world model. With this system, the user sits at a color graphics workstation and, with the use of a control panel to control "body" and "head" motion, moves through the 3-D computer model, observing physical objects much as he or she would in the real world.

To take full advantage of the benefits of real-time animation in an engineering and construction environment, a number of criteria were established before the development of WALKTHRU. These will be examined in the next sections.

Use of Existing Three-Dimensional Geometry Data

Unlike manufacturing projects that use CAD with computer-aided manufacturing (CAD/CAM), the projects performed in engineering and construction are typically "one off" projects. That is, after the project is designed, it is constructed only once. For routine visualization, construction simulation, and so on, it is therefore not practical to build a model because it would only be used for a single application. For WALKTHRU to be cost-effective for routine use, the system must be able to accept the 3-D geometry data directly and completely from the design models.

Real-Time Interaction

To be a truly effective simulation tool, WALKTHRU must be able to simulate motion of both the viewer and any object in the 3-D model. Also, the user must have precise control over his own position and the position of the 3-D objects. Thus the system must display at least several "frames" per second, even for complex models. A "freeze" frame every couple of seconds would not be acceptable.

Large Models with Arbitrary Geometry

It is not uncommon for plant design 3-D models to be made up of hundreds of thousands of polygons. The system must therefore have mechanisms for displaying models of this size and still maintain real-time interaction. Also, the system cannot be designed to take advantage of the 3-D model geometry to gain speed. It must be able to handle totally arbitrary geometry, including open surfaces, nonconvex polygons and solids, and other unusual forms.

Sufficient Visual Realism

Because many of the users of WALKTHRU will not be CAD-trained designers, the system must be able to display the model images with sufficient visual realism to be accurately interpreted by casual users. This visual realism includes such features as perspective, color, and smooth shading.

Stand-Alone Workstation

Not all users of WALKTHRU will be located in the design office with direct access to either a mainframe or minicomputer, such as a VAX. WALKTHRU must therefore function on a workstation that can operate in a completely stand-alone environment. Cost considerations are associated with this. We believed that it was appropriate to target the system for stand-alone workstations that cost less than $75,000 each.

Capabilities of the WALKTHRU Workstation

The workstation used for WALKTHRU is a Silicon Graphics IRIS workstation. This workstation uses specialized processors that are specifically designed for the high-speed graphics manipulations required for real-time simulation. The software that actually performs the walk-through functions runs as a stand-alone on the Silicon Graphics workstation, independent of the mainframe, manipulating 3-D data downloaded from the CAD system. The primary input/output device that is used during performance of the walk-through is a "button/dial" box. This device, which interacts with the workstation through an RS-232 interface, has 8 input dials and 32 push buttons. The dials are used to control the viewer motion, and the push buttons are used to invoke a number of functions. Other functions are controlled by the mouse and the keyboard. Some of the basic capabilities incorporated into the WALKTHRU system are summarized in the next sections.

View Control

Direction of Travel

Two of the dials are used to control the direction of travel through the model. One turns the body left and right, and the other controls the up and down inclination of travel. The user can travel both forward and backward.

Travel Speed

Another dial controls the travel speed. Turning the dial clockwise increases the travel speed, and turning it counterclockwise decreases speed.

Head Orientation

The user can also control the orientation of his head independently of the travel direction. One dial pans the head left and right, and the other pans the head up and down. This allows the user to travel in one direction while looking over his shoulder, up at the ceiling, or in any other real world direction.

Zoom

By using another dial, the user can interactively zoom in and out in much the same way that a zoom lens on a camera can go from wide angle to telephoto.

Initial Position

If the user wishes to position herself in a specific position without "walking" to that position, he can specify the position either by keying in *x-y-z* coordinates or by using the mouse and a pop-up map on the screen. To use the mouse and map, the user graphically specifies his position and viewing direction and is subsequently positioned there.

View Clipping

By using two of the dials, the user can interactively change the near- and far-view clipping planes as he is walking.

Perspective

The default display mode is with perspective display on. With one of the push buttons, the display can be toggled between perspective display and a parallel projection display. The parallel projection is the same type of display that is used on traditional CAD systems for wire frame images.

Display Control

Shaded Images

During the real-time walk-through, images are displayed in wire frame. At any time, the user can render a shaded image by using a push button. When the "shade" button is pressed, the motion is frozen and the image is shaded. The shading process uses user-defined color tables. These color tables allow the user to specify specular reflection characteristics for each color.

Location Map

During the walk-through, the user can toggle a location map on and off. The map displays plan and elevation views that give the range cube of the model. The user's position within the model is displayed with two direction vectors, one of which provides the direction of travel and the other the orientation of the head. As the user's position and view direction changes, the direction vectors also move.

Control Panel

In addition to the location map, the user can "pop up" a control panel display that provides a numerical readout of the user's *x-y-z* position, direction of travel, head orientation, and travel speed.

Record/Playback

Record

The user can record "key frames" that save the current view parameters, object positions and orientation, and delta time (from last save frame). These parameters are saved on a disk file with a name specified by the user.

Replay

Any "record" file created with the "record" option or by other software can be recalled. The software interpolates between the key frame parameters and replays the saved sequence in real time. In this mode, the user's travel and the motion of the objects is controlled by the record file.

Object Motion

The user has a number of options for moving and positioning individual objects within the model. Object hierarchy can be defined such that the motion of one or more objects is dependent on the motion of another object. The hierarchy can be defined to an unlimited number of levels.

Constant Motion

The user can assign a constant motion to any object in the model. Both delta translations and rotations can be specified. Once the object is set in motion, the user can continue the walk-through while the object is moving.

Moving Objects

The user can select an object in the model and interactively move (translate, rotate, or both) the object to another position.

Replay Motion

With the "record" option, the user can record the position of the objects at different times and then replay their motion, as in the "replay" function described earlier. However, in this mode, only the motion of the objects is controlled by the software. The user retains full control over travel and viewing parameters while the objects are moving.

Interference Detection

While system is in the interactive object mode, the user can ask that the active object be checked against the other objects in the model to determine if there are any interferences with the active object. The interferences that are detected are highlighted on the screen.

Measure

In the parallel projection mode, the user can invoke the "measure" command from the button box. This function allows use of the mouse to specify an "anchor point" in the view. Then, as the mouse is moved, an instantaneous readout is given, displaying the distance, delta *x*, delta *y*, and angle between the anchor point and the current cursor position. The anchor point may be moved by simply positioning the cursor and pressing a mouse button.

Shaded Image Animation

The number of polygons associated with computer models, particularly nuclear plant models, can easily range in the hundreds of thousands. The sheer volume of model data makes it impractical to perform real-time motion in shaded image. However, WALKTHRU has the capacity to replay the viewer and object motion one frame at a time, shading each frame and outputting the shaded frame to a video recorder. This option is executed as a batch process, in which motion that was recorded as described previously is replayed. The final product is a videotape of the recorded motion, displayed entirely in shaded image.

WALKTHRU Compared with Other Systems

WALKTHRU differs from commercial video-animation systems in a number of significant ways. The most important is that it uses geometry data directly from the 3-D design models and therefore a special model need not be developed strictly for the animation. Second, even though WALKTHRU can produce a shaded animation video, its focus is real-time interaction and not output to videotape, as in the case of commercial animation systems. Finally, the user interface for the real-time interaction is designed to allow the user to interact with the plant geometry as a designer or engineer would, as opposed to as a film director.

The current capabilities of WALKTHRU reflect a balance between our desire to maximize real-time interaction with the 3-D model and the realities of current workstation technology. Many of the features of WALKTHRU were developed in direct response to feedback from project applications. Future enhancements will focus on increasing the functionality of WALKTHRU as a construction planning and simulation tool.

APPLICATIONS

Although WALKTHRU was initially conceived simply as a visualization tool, it has been effective for a wide range of activities, particularly in support of the construction process. Some of the more significant applications are described in the following sections.

Visualization

The importance and value of the ability to quickly and accurately convey the physical configuration of the construction project cannot be overemphasized. The current format and content of many of the traditional construction drawings have evolved as much from the limitations of the manual drafting process as they have from the need to convey design information. As a result, there is a significant amount of symbolic and shorthand notation on these drawings that does not necessarily look like the configuration that is being constructed. This notation has been adopted to streamline the drafting process, but the resulting drawings require some degree of experience to interpret. By using 3-D modeling and a tool such as WALKTHRU, the physical configuration can be conveyed graphically in a form that appears very much like the real thing. Also, views are not limited to a few orthographic projections. The ability to view any portion of the project dynamically in all three dimensions significantly enhances the user's ability to interpret the final configuration.

Construction Planning

In the design office, the use of a 3-D computer model will prove that a design has no interferences and will fit together, but it will not necessarily prove that the design can be built. The construction engineers must deal with a very dynamic situation. They must visualize and plan for a large amount of material, equipment, and personnel working in harmony, all in the same place and at the same time. The problem of scheduling multiple activities in congested areas is difficult at best. Installation and manipulation of large pieces of equipment also require precise planning. Construction simulation is a tool that can streamline this process.

The use of real-time animation for construction simulation in support of construction planning provides an excellent opportunity to significantly reduce construction costs, as evidenced by two examples. The first is that in power plant construction, studies have indicated that construction personnel spend only 35 percent of their time performing actual, direct construction activities. The rest of their time, outside of the normal personal time for coffee breaks and so on, is spent in planning, preparing, getting material, waiting for material, and similar activities. The second is that on a recent large project involving construction of three similar nuclear power plant units, construction costs on the second and third units were reduced by 15 percent and 25 percent, respectively.

In both of these cases, the figures are from power plant construction, but they are likely to be similar for other types of construction projects. Essentially, what the figures indicate is that a lot of time is spent figuring out what to do and getting ready to do it, and that it's easier to do it the second time. Because nearly every construction project is, at the detailed level, a unique effort, the conclusions for the use of 3-D modeling are fairly obvious. The 3-D model aids in visualization of the available work area and planning the sequence of construction activities to allow the most productive work effort in that area. Work crew activities can be scheduled to minimize personnel and equipment congestion in an area, thus improving crew productivity. Also, in simplest terms, real-time animation allows the project to be built once in the computer before it is built in the field.

Training

A natural byproduct of the visualization and planning applications is an effective training tool. The capability to produce videotapes as a result of a planning session makes it possible to inform an entire construction crew of the exact plan to be executed. Videotape provides a very portable and graphic tool for this type of training, bringing the benefits of construction simulation to a very large audience.

CONCLUSION

Almost every aspect of engineering and construction is being affected by automation. Many of the more recent applications have been made practical by the use of 3-D computer models in the initial design phase. In engineering and construction applications, the use of 3-D animation to simulate construction activities is a very powerful planning and training tool. As is well known, mistakes in the field are very costly to correct. This type of avoided cost is difficult to measure but very real.

The use of construction simulation allows the rapid development and rehearsal of plans and the graphical demonstration of those plans to others. We have used the WALKTHRU software for reviewing designs, simulating major construction activities, and training. The capabilities provided by WALKTHRU enable the 3-D computer model to be much more accessible to project and owner personnel. WALKTHRU also increases the value of the 3-D computer model in engineering, construction, and operation by giving it a means to provide an immediate and animated visual impact.

Perhaps the most effective role of WALKTHRU to date has been in support of construction planning. This type of simulation is an excellent planning and training tool. The animation can include not only the individual components being installed but also such construction equipment as cranes, rigging, and so on. Some recent applications have included the following:

- Planning for the replacement of the tube bundles in some large heat exchangers in a nuclear power plant,
- Planning for the complete replacement of the steam generators in a nuclear plant,
- Review of a petrochemical facility for maintenance operations, and
- Several visualization applications for review of both conceptual and detailed plant designs.

This type of simulation has also been used to educate construction personnel about the exact plan for the job. The result is that the supervisor can plan work activities with confidence that the work can be completed according to the plan with a minimum amount of errors and rework.

Publication of this paper sponsored by Committee on Construction Management.

New Jersey Department of Transportation Automated Construction Estimate System

EUGENE K. BLASKO

In this paper, the New Jersey Department of Transportation's computerized construction estimate program is described from the user's perspective. This personal computer–based system is used by resident engineers for inputting daily inspection data, information on materials received, and field personnel data. From these data the program produces various documents, including daily reports, weekly reports, item and materials status reports, and monthly progress estimates.

Construction record keeping is a complicated task that is vital to the efficient management of New Jersey Department of Transportation (NJDOT) highway and bridge projects. These record-keeping responsibilities rest are entrusted to the resident engineer and the inspection staff assigned to the particular construction project.

In 1984, at the request of the Division of Construction and Maintenance, computer programmers assigned to the Department of Transportation from the Office of Telecommunications and Information Systems (OTIS) of the New Jersey Department of Treasury assisted construction personnel in the development of a personal computer (PC) data base management system. This system, known as the Automated Construction Estimate System (ACES), has been specifically tailored to meet existing NJDOT procedures for construction documentation and estimate preparation. The field-based system was initially installed December 1985 on the I-195 project in Trenton.

PROJECT DOCUMENTATION: GENERAL INFORMATION

Forms DC-29-A, B, C and D (Figures 1–4) are the source documents that are prepared and submitted by the field inspector. These forms contain specific information about a contract item work activity, progress or as-built quantities, the contractor's work force and equipment, and weather conditions. The field inspector's signature is required on the DC-29 document package. Under the New Jersey Department of Transportation Project Documentation and Estimate System, information from the DC-29 reports is entered on daily reports, weekly reports, item summary reports, and monthly estimates (Figure 5).

Currently, the computerized system is being used on nine projects. The present policy is to provide personal computers and related equipment for projects with budgets of $16,000,000 or greater. Eventually, it is expected that virtually every project will use the computer-based system.

New Jersey Department of Transportation, Division of Construction and Maintenance, 1035 Parkway Avenue, Trenton, N.J. 08625.

SYSTEM

The system employs a IBM personal computer (IBM PC) and a Bernoulli box with two 10-megabyte drives. ACES is written in dBASE III, compiled with Clipper. The dBASE III software, 92 dBASE III programs, and the data base files are maintained on one 10-megabyte Bernoulli cartridge. The report files are maintained on another 10-megabyte Bernoulli cartridge. Various programs written in dBASE III produce input panels that allow the user to enter data on the screen for daily construction quantities, materials received on site, and personnel data. The system stores the input information and uses it to produce various reports, including item quantity summaries, materials received reports, daily reports, weekly reports, and monthly progress estimates.

INSTALLATION

The computer and related hardware are included as part of the equipment required for the field office specified in the contract. The contractor is responsible for supplying and installing the computer system at the resident engineer's field office site. At the end of the project, the equipment remains the property of the contractor. The Bernoulli cartridges containing the ACES programs and data bases become the property of NJDOT. The following is a sample specification:

105.15 Field Office

The contractor shall supply the field office with a computer configuration as follows:

Hardware

1 IBM/PC or IBM/XT with two 360K disk drives and 256K memory (without hard disk)
1 Quadram board with 384K memory
1 Hayes 1200-baud modem without Smartcom
1 Princeton Graphics color RGB monitor or equivalent
1 graphics monitor adapter
1 Epson LQ-1000 printer or equivalent with tractor feed
1 printer cable
1 printer stand

Form DC-29(a) 4/80

NEW JERSEY DEPARTMENT OF TRANSPORTATION
DAILY INSPECTOR'S REPORT

(h) AS–BUILT QUANTITY

(a) Route ______ Section ______ Structure ______ Day and Date ______

(b) Item No. ______ Item ______ (e) Inspector Worked: ______ A.M. to ______ P.M.

(c) Plan Sheet No. ______ (d) Inspector's Signature(s) ______ Man Hours This Item →

(f) Location (Station to Station) (Structure – Description)	(g) Offset	(h) Quantity	(i) Concrete Req.	(i) Concrete Used	(j) Contractor Worked AM to PM (k) Labor & Equipment	(l) Hrs.

Weather and Air Temperature

(m) REMARKS: (Ground conditions, materials used, etc.):

(n) Use reverse side for sketches and calculations

FIGURE 1 Form DC-29-A.

Form DC-29 (b) 4/80

NEW JERSEY DEPARTMENT OF TRANSPORTATION

DAILY INSPECTOR'S REPORT – BITUMINOUS CONCRETE PAVEMENT

(a) Route ______ Section ______ Day and Date ______

(b) Item No. ______ Item ______ (e) Inspector Worked: ______ A.M. to ______ P.M.

(c) Plan Sheet Nos. ______ (d) Inspector's Signature(s) ______ Total Man Hours This Item →

Mix No (f)	Lot No (g)	Location Baseline & Station to Station (h)	Lane (i)	Lift (j)	Thickness (k)	Pounds Received (l)	Pounds Laid (m)	S.Y. Laid (n)	Lbs S.Y. (o)

(p) Progress Quantity → ______ Tons or ______ S.Y.

(q) Producer of Material

Weather & Temperatures

(t) Remarks (Base Conditions, etc.)

Mixture Temperature (r)	Mix No	Highest	Lowest	Ave for Day
		°F	°F	°F
		°F	°F	°F

(s) Contractor Worked AM to PM

(s) Labor & Equipment	(s) Hours

Type of Automatic Controls Used

(u) Use Reverse Side for Sketches, Calculations and Additional Remarks

FIGURE 2 Form DC-29-B.

Form DC-29 (c) 4/80

NEW JERSEY DEPARTMENT OF TRANSPORTATION

DAILY INSPECTOR'S REPORT – APPLICATION OF BITUMINOUS MATERIALS

(a) Route ______ Section ______ Day and Date ______

(b) Item No. ______ Item ______ (e) Inspector Worked: ______ A.M. to ______ P.M.

(c) Plan Sheet Nos. ______ (d) Inspector's Signature ______ Man Hours This Item ______

(f) Grade of Material Applied ______ | (g) Producer and Location | (h) Hauler and Location

(i) Location Station to Station	Lane or Side (j)	Lot No (k)	Tank No (l)	Date Material Inspt. (m)	Delivery Slip No. (n)	Truck No (o)	Gauge on Truck Start (p)	Gauge on Truck Finish (q)	Temp. of Mat'l. (r)	Conversion Factor (s)	GALLONS APPLIED Gross (t)	GALLONS APPLIED @60° F (u)	Number of S Y Covered (v)	Rate G/S.Y. @ 60° F (w)

(x) Specified Temperature range of material ______ ° F to ______ ° F

(x) Specified rate of application ______ G/S.Y to ______ G/S Y

Weather and Air Temperature

(z) Remarks (Base Condition, Stability, etc.)

(y) Contractor Worked ______ AM to ______ PM

(y) Labor and Equipment Used | Hours

USE REVERSE SIDE FOR SKETCHES, CALCULATIONS, AND ADDITIONAL REMARKS.

FIGURE 3 Form DC-29-C.

1 Iomega Bernoulli box with two 10-MEG drives; the driver will be IDRIVE 4.11 and the board will be PC2B, self-booting

Software

1 DOS Version 3. 1
1 Multimate
1 Lotus 1-2-3

Accessories and Supplies

1 surge protector with a minimum of six outlets
1 surge protector for the modem phone line
1 static mat—floor type, 4′ × 5′
1 desk or work station to set computer on
15 cartridges for the Bernoulli box
48 cartons of paper (9½ × 11″, 1 part, blank, approximately 3,000 sheets per carton, medium weight)
10 printer ribbons
4 boxes diskettes (10 per box)
1 diskette holder (holds 50 diskettes), dust covers for Bernoulli box, PC CPU, keyboard, monitor, and printer
1 Bernoulli box head cleaner kit

Any accessories for the computer must be able to be used with the computer.

The contractor will not be permitted to use this computer equipment at any time as it is being supplied for the Department's use.

The contractor shall forward all manuals, instructions, or literature received with the computer package to the engineer. The contractor is also responsible to keep the computer equipment in good working condition and is also responsible for all maintenance and repairs.

The contractor is responsible to install the computer system at the field office site. At the time of setup, the contractor shall ensure that the system is in operating condition. In addition, the computer system shall be removed and shall become the property of the contractor when no longer required. The Bernoulli cartridges containing the ACES programs and data bases shall become the property of the State.

A designated OTIS representative is responsible for loading the operating system and data base files onto the Bernoulli cartridges. The data for item numbers, item descriptions, quantities, and bid prices are downloaded from the NJDOT mainframe data base file, so the resident engineer's staff need not input this information.

OPERATING THE SYSTEM

ACES is written so that the user does not need much knowledge of or experience with the IBM PC or dBASE III to operate the system. An office worker or secretary assigned to the project is responsible for entering data.

To start up the system, the program and data base file Bernoulli cartridge is inserted into the Bernoulli box C drive, and the report file cartridge is inserted into the Bernoulli box D drive. When the computer is turned on, the program is automatically loaded into memory.

Form DC-29 (d) 4/80

NEW JERSEY DEPARTMENT OF TRANSPORTATION
DAILY INSPECTORS - REPORT - PILE DRIVING

DAILY INSPECTOR'S REPORT – PILE DRIVING

Route	Section	Structure	Location	Day and Date

Type Hammer	Blows/Min.	Inspector's Signature	Inspector Worked AM to PM	Man hours This item

Pile * No	Order Length	Actual Length	Timber Pile Dia		Splice Data		Penetration **	Cutoff **	Blows Last 5 Feet					Blows Last Inch	NOTES
			Tip	Butt	Length	From			5	4	3	2	1		

Weather & Air Temperature:

REMARKS:

ITEM NO.	DESCRIPTION	QUANTITY

* See Pile Numbering on Pile Plan
* * Indicate (A) for Actual Length or (E) for Estimated Length to be Corrected later

Contractor Worked AM to PM

Labor & Equipment	Hours

FIGURE 4 Form DC-29-D.

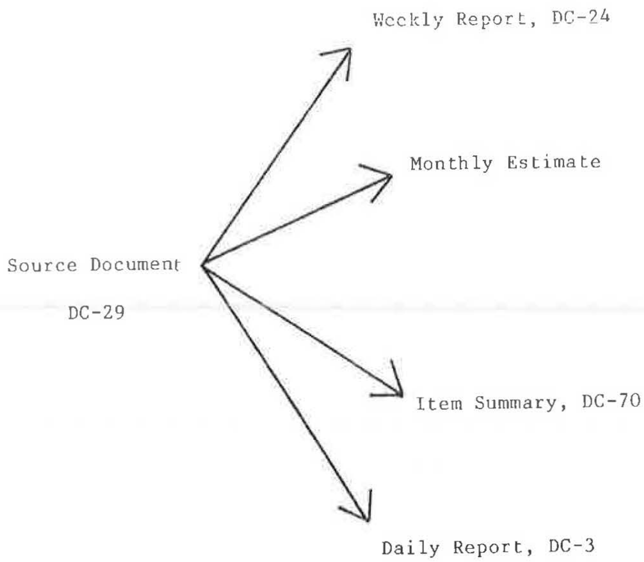

FIGURE 5 Reports produced from the information supplied by the DC-29 forms.

ACES is menu driven. An option is chosen from a menu by simply typing the number or letter that corresponds to the option. The user does not have to press any other key. The system provides a main menu and several submenus that are accessible from the main menu. Submenu selections allow the user to modify display colors, reset the system clock, and change personnel data, in addition to operating the data entry and report functions.

Main Menu

The Main Menu (Figure 6) allows the user to enter the rest of the menus in the system or to exit the system. Options are as follows:

Selection 0: Exit the Program Return to DOS.

Selection 1: Input Inspection Data Display the Inspection Menu (Figure 7). This submenu, from which daily inspection information is entered, is the most frequently used.

Selection 2: Generate Reports to Disk Allow the user to write various reports to disk.

Selection 3: View Reports on Disk Allow the user to view or print the reports written to disk.

Selection 4: Project Setup Program Enable the user to enter or change various particulars, such as project description, completion dates, personnel information, and human resources data for the project.

Selection 5: Disk Utilities Display the utilities submenu so that the user may perform various utilities functions (backup of the current data files is one of the most important).

Selection 6: Send Reports Over the Phone Lines Permit the user to send reports already on the cartridge to another PC or allow the user to receive reports from another PC to the user's PC through the telephone lines.

Inspection Menu

This submenu (Figure 7) provides the following options:

Selection 0: Return to Main Menu

Selections 1–4: Input Inspection Data Permit entry of progress quantities and related information reported by inspectors on the daily inspection report (DC-29-A, -B, -C, or -D).

Selection 5: DC-12-A Allow entry of change order data into the system.

Selection 6: Manpower Input Provide opportunity to input or change data on personnel work hours.

Selection 7: DC-70 Materials Received Input Permit logging of materials received.

Selection 8: Materials on Jobsite Input Allow user to input or change the data on the materials on the job site.

Selection 9: DC-29 Edit Existing Data Permit user opportunity to edit data previously entered from the daily inspection report.

```
PMEMAIN        06/04/86        NJDOT CONSTRUCTION                    09:54:00
                        RESIDENT ENGINEER FORMS AND REPORTS
                                    MAIN MENU

        SELECTION           DESCRIPTION
            0               EXIT PROGRAM

            1               INPUT INSPECTION DATA

            2               GENERATE REPORTS TO DISK

            3               VIEW REPORTS ON DISK

            4               PROJECT SET-UP PROGRAMS

            5               DISK UTILITIES

            6               SEND REPORTS OVER PHONE LINE

                      CHOOSE A SELECTION BY NUMBER

        *
       [1] <======
```

FIGURE 6 ACES Main Menu. Number in brackets is entered by user.

```
PMEINSP          06/04/86                 NJDOT CONSTRUCTION                 12:24:00
                                 RESIDENT ENGINEER FORMS AND REPORTS
                                           INSPECTION MENU

         SELECTION                 DESCRIPTION
             0         EXIT        RETURN TO MAIN MENU

             1         DC-29-A     DAILY INSPECTIONS REPORT (QUANTITIES)
             2         DC-29-B     DAILY INSPECTIONS REPORT (PAVING)
             3         DC-29-C     DAILY INSPECTIONS REPORT (OIL)
             4         DC-29-D     DAILY INSPECTIONS REPORT (PILES)

             5         DC-12-A     CHANGE ORDER
             6                     MANPOWER INPUT
             7         DC-70       MATERIAL RECEIVED INPUT
             8                     MATERIALS ON JOB SITE INPUT
             9         DC-29       EDIT EXISTING DATA

                     CHOOSE A SELECTION BY NUMBER

         [1] <======
```

FIGURE 7 ACES Inspection Menu. Number in brackets is entered by user.

PRINCIPAL FEATURES

Inspection Data Input

Daily inspection reports DC-29-AD are used as source documents for reporting progress quantities and related information. Pertinent details, including inspection date, item number, item description, location of work, weather, progress quantity, or as-built quantity, are provided on these inspection documents. To input these data, the user chooses Selection 1 on the Main Menu, followed by selection 1, 2, 3, or 4 on the Inspection Menu to reach the new data input screen for item number and inspection date (Figure 8). The "page down" (PGDN) key is used to move to the next screen, allowing entry of the weather conditions, location, and pay quantity or as-built quantity (Figure 9).

```
PMEITEM          06/04/86                 NJDOT CONSTRUCTION                 12:25:00
                                 RESIDENT ENGINEER FORMS AND REPORTS
                                  ITEM NUMBER AND DATE FOR NEW DATA

                      ENTER ITEM NUMBER TO ADD DATA FOR: [103]*

                        ENTER DATE TO ADD DATA FOR: [06/04/86]

    USE ARROW KEYS TO MOVE AROUND ON SCREEN

    PRESS THE "PGDN" KEY TO MOVE TO THE NEXT SCREEN
```

FIGURE 8 Input screen for contract item number and date. Items in brackets are entered by user.

```
PME29A_2         06/04/86                 NJDOT CONSTRUCTION                 12:26:00
                                 RESIDENT ENGINEER FORMS AND REPORTS
                                 DAILY INSPECTOR REPORT ON QUANTITIES

    RETURN TO MAIN MENU (Y/N)    [N]    RECORD NUMBER 3277

    ITEM NO.:103                     INSPECTION DATE:06/04/86
    DESCRIPTION: 15" REINFORCED CONCRETE CULVERT PIPE STRUCTURE:
    WEATHER:[SUNNY]                  TEMPERATURE AM:     [66]       PM:     [80]
        LOCATION                                 PAY QUANTITY   AS-BUILT QUANTITY
         FROM RELOC. ARENA DR.                      [20.00]           [0.00]

     * TO ENTER DATA - PRESS ENTER KEY, THEN ENTER DATA
     * TO STOP ENTERING DATA - PRESS THE "PGDN" KEY
     * TO CANCEL THIS ENTRY - MOVE CURSOR UP TO TOP
          OF SCREEN AND TYPE "Y" AND PRESS THE "PGDN' KEY
```

FIGURE 9 Input screen for daily inspector's report data. Items in brackets are entered by user.

Material Received Input

From the Material Received Menu (Figure 10), the user can

Selection 0: Exit to Inspection Menu
Selection 1: Add New Material Description
Selection 2: Change Existing Material Description
Selection 3: Add Material Delivery Record That is, add the actual dates of delivery to the project.

To input material received, the user chooses selection 1 on the Main Menu, then Selection 7 on the Inspection Menu, then Selection 3 on the Material Received Menu. The appropriate record is obtained by inputting the item number for the material (Figure 11). Information entered includes the description of the material, quantity, source of supply, date of inspection or certification, and date that the material was received at the project site.

Supplementary Items and Changes to Existing Item Quantities

Screens are provided for adding supplementary item data, including item number, item description, quantity, and price. A screen is also provided for changing contract quantities of existing items (Figure 12).

Personnel Information

The system maintains data on each employee. Each day, the employee work hours are charged to specific activities by using the input screen shown in Figure 13. The source document for the information is the DC-29 Daily Inspector's Report. This human resources information is used by the NJDOT Construction Engineering Manpower Management (CEMM) System.

The CEMM System provides the estimated human resources needs for the project before construction. Actual human resources usage is later compared with the original estimate. The comparison provides a means for adjusting the human resources factors for future projects, if necessary.

Reports

One of the powerful features of ACES is its capacity to produce the many reports required on a construction project. The menu for printing reports is given in Figure 14. As an example

```
PMEMATIN        06/04/86             NJDOT CONSTRUCTION                  12:58:00
                             RESIDENT ENGINEER FORMS AND REPORTS
                                   MATERIAL RECEIVED MENU


                SELECTION         DESCRIPTION
         0      EXIT          EXIT TO INSPECTION MENU

         1      ADD           ADD NEW MATERIAL DESCRIPTION
         2      CHANGE        CHANGE EXISTING MATERIAL DESCRIPTION
         3      DETAIL        ADD MATERIAL DELIVERY RECORD


               CHOOSE A SELECTION BY NUMBER

      [3]<======
```

FIGURE 10 Material Received Menu. Number in brackets is entered by user.

```
PREMATDL        06/04/86             NJDOT CONSTRUCTION                  13:05:57
                             RESIDENT ENGINEER FORMS AND REPORTS
                                ADD MATERIAL DELIVERY RECORD

                             MATERIAL NUMBER:  01

      MATERIAL DESCRIPTION: POROUS FILL (A)      ITEM NUMBER: [345]   UNITS: CY

  SOURCE OF SUPPLY #1: TELFORD SOIL       DATE QUESTIONNAIRE SUBMITTED: 03/29/86

  RECORD NUMBER: 255

  MATERIAL       REC'D       CERTIFICATION        INSPECTION REPORT
  RECEIVE        QUANT
  DATE           TODAY      DATE     QUANT    DATE       QUANT   RSLT FORM    REMARKS
  [06/04/86]   [30.00]    /   /     0.00   [06/04/86]  [30.00]


   ARE YOU FINISHED ENTERING DATA ON THIS SCREEN?  (Y/N): [Y]

                      USE ARROW KEYS TO MOVE AROUND ON SCREEN
```

FIGURE 11 Input screen for material delivery. Items in brackets are entered by user.

```
PME12A_2         06/04/86            NJDOT CONSTRUCTION                 12:48:00
(CHANGE)                       RESIDENT ENGINEER FORMS AND REPORTS
                                 CHANGE TOTAL CONTRACT QUANTITY

   CHANGE ORDER NUMBER: [003]
   DATE INITIATED: [04/12/86]
   APPROVAL DATE : 05/01/86
   ITEM NO.: [063]
   ITEM DESCRIPTION: BORROW EXCAVATION, BRIDGE FOUNDATION ROAD OR BRIDGE
   UNIT OF MEASURE: CY              UNIT PRICE: 10.00
   CURRENT CONTRACT QUANTITY:    24510.00
   ADD OR SUBTRACT          :     [10.00]
   NEW CONTRACT QUANTITY         24520.00

   IS THIS QUANTITY OK (Y OR N) ?  [Y]
   USE ARROW KEYS TO MOVE AROUND ON THE SCREEN

   PRESS THE "PGDN" KEY TO MOVE TO THE NEXT SCREEN
```

FIGURE 12 Input screen for changing contract quantities. Items in brackets are entered by user.

```
PMEMANIX         06/04/86            NJDOT CONSTRUCTION                 12:55:00
                               RESIDENT ENGINEER FORMS AND REPORTS
                                 DAILY MANPOWER DATA - INDIVIDUAL

NAME: FALVO, S.            TITLE: SENIOR ENGINEER            DATE: [06/04/86]

REGULAR    OVERTIME                              OTHER TIME
 [8.0]        0.0  RESIDENT ENGINEER                 0.0  VACATION
  0.0         0.0  NON RESIDENT ENGINEER             0.0  SICK
  0.0         0.0  OFFICE WORK                       0.0  ADMINISTRATION
  0.0         0.0  AS-BUILT                          0.0  OTHER LEAVE
  0.0         0.0  GENERAL                           0.0  WITHOUT PAY
  0.0         0.0  EARTH                             0.0  WITH PAY
  0.0         0.0  DRAINAGE                          0.0  TRAINING OFF PROJ
  0.0         0.0  AGGREGATES                        0.0  LOANED OFF PROJ
  0.0         0.0  CURB & S WALK
  0.0         0.0  PAVING
  0.0         0.0  STRUCTURES
  0.0         0.0  UTILITIES
  0.0         0.0  ELECTRICAL
  0.0         0.0  MISCELLANEOUS
  0.0         0.0  SPECIAL CATEGORY

                        PRESS THE "PGDN" KEY TO CONTINUE
```

FIGURE 13 Input screen for daily human resources data. Items in brackets are entered by user.

```
PMEREPT          06/04/86            NJDOT CONSTRUCTION                 13:38:20
                               RESIDENT ENGINEER FORMS AND REPORTS
                                  GENERATE REPORT TO DISK MENU

      SELECTION             DESCRIPTION
          0        EXIT     RETURN TO MAIN MENU

          1        DC-3B    PRINT QUANTITIES OF WORK BY ITEM
          2        DC-70    PRINT ITEM BOOK PAGE
          3                 PRINT CONTRACT SUMMARY
          4                 PRINT CHANGE ORDER HISTORY BY ITEM

          5        DC-24    PRINT WEEKLY ESTIMATE
          6                 PRINT MONTHLY ESTIMATE
          7        DC-70    PRINT MATERIALS RECEIVED
          8                 PRINT ITEMS OVER SPECIFIED CONTRACT LIMIT
          9                 PRINT MATERIAL ON JOB SITE EXCEEDING 85% CONTRACT
                            AMOUNT
          A                 PRINT WEEKLY DETAIL TIME REPORT

                   CHOOSE A SELECTION BY NUMBER

      [1]<======
```

FIGURE 14 Menu for printing reports. Number in brackets is entered by user.

of ACES output, a weekly report is presented in Figures 15 and 16.

ADVANTAGE OF THE ACES SYSTEM

The calculation and report production capabilities of ACES are a great improvement over the manual system in terms of time saved. Table 1 presents the average times required to produce various reports for a manual system versus the time needed for use of ACES.

TRAINING

Training personnel to use ACES is extremely important to the success of the program. After a project has been selected to use the system, the resident engineer and staff receive 3 days of training. A Bureau of Construction liaison is available to assist with additional training and to help throughout the duration of the project.

The trainees are provided with a user's manual that includes detailed instructions for using the system. As stated previously, the system menus and input screens are designed to

PME24PR NJDOT - AUTOMATED CONSTRUCTION ESTIMATE SYSTEM SHEET 1
DC-24 WEEKLY PROGRESS REPORT REPORT NO. 175
PRELIMINARY RUN

MAN HOURS USED BY ACTIVITY GROUP	SAT	SUN	MON	TUE	WED	THU	FRI	WEEKLY USE TODATE	TOTAL USED	TOTAL PLANNED MAN HOURS
RESIDENT ENGINEER	0.0	0.0	8.0	8.0	8.0	8.0	8.0	40.0	5913.5	5792
NON RESIDENT FIELD SUPERVISION	0.0	0.0	1.0	7.0	3.0	5.0	7.0	23.0	5380.5	5106
FIELD INSPECTION	0.0	0.0	47.0	41.0	41.0	19.0	9.0	157.0	35178.5	30450
OFFICE WORK - EEO	0.0	0.0	8.0	8.0	8.0	8.0	0.0	32.0	10113.0	8977
AS-BUILTS	0.0	0.0	0.0	0.0	0.0	24.0	32.0	56.0	4933.5	4164
GENERAL	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1569.0	2615
PROJECT TOTALS	0.0	0.0	64.0	64.0	60.0	64.0	56.0	308.0	63088.0	57104
INSPECTION ACTIVITIES										
EARTH WORK	0.0	0.0	0.0	0.0	0.0	16.0	8.0	24.0	9084.5	9141
DRAINAGE	0.0	0.0	16.0	14.0	16.0	0.0	0.0	46.0	4687.5	2372
AGGREGATES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2326.0	1373
CURB & SIDEWALK	0.0	0.0	0.0	2.0	0.0	0.0	0.0	2.0	1780.0	834
PAVING	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2259.5	2074
STRUCTURES	0.0	0.0	12.0	8.0	8.0	2.0	0.0	30.0	11288.0	9446
UTILITIES	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	935.0	1152
ELECTRICAL	0.0	0.0	2.0	0.0	0.0	0.0	0.0	2.0	201.0	872
MISCELLANEOUS	0.0	0.0	16.0	16.0	16.0	0.0	0.0	48.0	1980.0	998
SPECIAL	0.0	0.0	1.0	1.0	1.0	1.0	1.0	5.0	637.0	2188
INSPECTION SUBTOTAL	0.0	0.0	47.0	41.0	41.0	19.0	9.0	157.0	35178.5	30450

NUMBER OF EMPLOYEES ASSIGNED TO THIS PROJECT

PROJ ENGR	0.0	ASST. ENGR (INCL CET)	0.0	HWY INSP	2.0
PRIN ENGR	1.0	PRIN INSP	0.0	CLERICAL (INCL CO-OP'S)	1.0
SR ENGR	2.0	SR INSP	3.0	OTHER (INCL SUMMERHELP)	0.0

PERCENTAGE OF MANPOWER USAGE
(MUST BE COMPLETED BY ALL PROJECTS)

TOTAL PROJECT = 63088.0 / 57104 = 110 .%

FIELD INSPECT = 35178.5 / 30450 = 116 .%

STATE EMPLOYEES & TITLE	DEPT CAR	THIS WEEK	NEXT WEEK	HOURS WORKED	OVERTIME WORKED	LEAVE TIME
ABATTO, A. SR INSP	-			40.0	0.0	0.0
DAMIANO, J. CLERICAL	-			32.0	0.0	0.0
DOLCI, W. SR INSP	-			40.0	0.0	0.0
FALVO, S. PRIN ENGR	TD-918			40.0	0.0	0.0
GALLO, P. HWY INSP	-			40.0	0.0	0.0
KAFER, W. SR ENGR	-			40.0	0.0	0.0
LOGAN, D. HWY INSP	-			40.0	0.0	0.0
MISNER, E. SR ENGR	TD-396			36.0	0.0	4.0
THOMPSON, F. SR INSP	-			0.0	0.0	40.0
TOTALS				308.0	0.0	44.0

WORK PLANNED BY CONTRACTOR NEXT WEEK OR OTHER APPLICABLE REMARKS INCLUDING MANPOWER NEEDS AND EXCESSES.
CONTRACTOR PLANS TO CONTINUE WORKING ON LANDSCAPE ITEMS AND CORRECTIVE ACTION LIST.

BY:FRED THOMPSON / SR. HWY INSPECTOR / ______________
PRINT NAME PRINT TITLE SIGNATURE

FIGURE 15 Sample of ACES output: a weekly progress report (page 1).

TABLE 1 AVERAGE TIME TO PRODUCE REPORTS

Report	Time to Produce Report	
	Manual System	ACES
Daily report, DC-3	1.5 hr	10 min
Weekly report, DC-24	1.5 hr	15 min
Monthly estimate	4.0 hr	20 min

provide instructions to the new user. Directions in clear, plain English are included at the bottom of each screen to guide the user through the system. Constant reference to the user's manual is therefore not necessary.

IMPLEMENTATION AND SYSTEM IMPROVEMENT

A coordinating team has been established to handle all aspects of implementation and improvement to the system. The ACES Coordinating Team consists of two members from each of the four regional construction offices plus three members from the Bureau of Construction. One of the Bureau of Construction team members serves as team leader. Representatives of OTIS also attend each of the team meetings, which are held every 2 months. Before each meeting, an agenda is prepared and distributed to each member:

ACES MEETING AGENDA—JUNE 29, 1987

I. Current Status of ACES System at the Field Office's New Site—Route 38, Mount Holly
II. Technical Update
   A. Communications between Field Offices and Regional Office, Discuss BITCOM
   B. Hardware—OTIS will begin testing ACES on other brands of microcomputers once the current version is completed
III. Priority List Review
   A. Third Priority List—Currently Being Programmed
      1. Progress Report on Items 19

```
PME24PR                          NJDOT - AUTOMATED CONSTRUCTION ESTIMATE SYSTEM                  SHEET   1
DC-24                                        WEEKLY PROGRESS REPORT                              REPORT NO. 175
                                                                                                 WEEK ENDING : 08/28/87
ROUTE: 195          SECTION: 1A, 1E, 10D     FEDERAL PROJ : I-195-8(14)60                         RESION NO: III
LOCAL NAME : ROUTE 195 SECTION 1A,1E & 10D, FROM EAST OF WATSON CREEK TO EAST OF                 DP FILE NO:  752
CONTRACTOR : HESS BROTHERS, INC.          PROJ ENGINEER : LOUIS PAPP        RES ENGINEER : SANTE FALVO

ITM ITEM                 22       23       24       25       26       27        28                     UNIT     AMOUNT THIS
NO. DESCRIPTION         SAT      SUN      MON      TUE      WED      THU       FRI       TOTAL         PRICE    WEEK ($)

003 TRAFFIC DIRECT      0.00     0.00     6.00     0.00     0.00     0.00      0.00       6.00 MH      14.00        84.00
072 RIPRAP SLOPE P      0.00     0.00     0.00    52.40     0.00     0.00      0.00      52.40 SY      15.00       786.00
171 CONCRETE SIDEW      0.00     0.00     0.00     2.70     0.00     0.00      0.00       2.70 SY      19.00        51.30
181 24" CORRUGATED      0.00     0.00     1.00     0.00     0.00     0.00      0.00       1.00 U      130.00       130.00
231 1.5 INCH RIGID      0.00     0.00    88.00     0.00     0.00     0.00      0.00      88.00 LF       8.50       748.00
238 18 IN X 36 IN       0.00     0.00     1.00     0.00     0.00     0.00      0.00       1.00 U      625.00       625.00
271 4 INCH TOPSOIL      0.00     0.00     0.00     0.00     0.00     0.00   6021.00    6021.00 SY       0.80      4816.80
273 FERTILIZING AN      0.00     0.00     0.00     0.00     0.00     0.00  13919.00   13919.00 SY       0.25      3479.75
277 STRAW MULCHING      0.00     0.00     0.00     0.00     0.00     0.00  13919.00   13919.00 SY       0.25      3479.75
319 CORE STONE          0.00     0.00     0.00    81.00     0.00     0.00      0.00      81.00 CY      45.00      3645.00

                                                          (B) AMOUNT OF WORK COMPLETED THIS WEEK         17845.60
      CALCULATION OF COMPLETION PERCENTAGES. NOTE: ALL PERCENTAGES WERE CALCULATED USING LATEST ADJUSTED CONTRACT AMOUNTS.

                                              CO# 1 TO 030 EXCEPT

   (A) AMOUNT PREVIOUS  $ 25,449,402.73                   ORIGINAL CONTRACT AMOUNT       $ 25,978,212.98
   (B) AMOUNT THIS WEEK $     17,845.60                   TOTAL EXTRAS & SUPPLEMENTALS $  1,665,501.94
                                                          TOTAL REDUCTIONS             $  1,903,676.43
   (C) AMOUNT TO DATE   $ 25,467,248.33
                                                          ADJUSTED CONTRACT AMOUNT     $ 25,740,038.49

                                     (C)                 $  25,467,248.33          9 9 . %
        % TO DATE  =   --------------------------   =   ----------------   =     +-+-+-+
                       ADJUSTED CONTRACT AMOUNT      $  25,740,038.49

                                 TIME USED                    1223                 1 0 3 . %
                   =   --------------------------   =   ----------------   =     +-+-+-+
                                TIME ALLOWED                  1193

   ENGINEERS' ESTIMATE OF PROJECT COMPLETION DATE   =  07/29/87

   ESTIMATED PROJECT FULL OPENING DATE              =  08/15/87

   DAILY AVERAGE NUMBER OF CONTRACTOR EMPLOYEES   27             ASBUILT WORK     3 0 .
   DAILY AVERAGE NUMBER OF CONTRACTOR ACTIVITIES   6             COMPLETED      +-+-+-+
                                                                       TO DATE
```

FIGURE 16 Sample weekly progress report (page 2).

2. Handouts for Change Orders and Fuel Price Adjustments
   - B. Fourth Priority List
     1. Review the Two Items
     2. Discuss Any Proposed Items

IV. Miscellaneous Discussion, New Topics

V. Visit to the Microcomputer Store at OTIS Central, Bear Tavern Road

ACES Team meeting discussions are divided into four areas:

- *Discussion of Current Sites* Projects using ACES are discussed. Any problems that have occurred are examined, along with the status of each site.
- *Technical Updates* Items such as new hardware or software are either demonstrated or discussed. The team may vote on any choices that are presented. Normally, OTIS personnel have the responsibility of recommending changes in hardware.
- *Review of the Priority Lists* Additions to the ACES software are discussed. Proposed additions are ranked and placed on a priority list. The higher-priority items are placed on the higher-priority lists. As of August 1987, the First and Second priority lists had been completed, and OTIS was working on the Third Priority List. The Fourth Priority List was still pending. During this portion of the meeting, OTIS also demonstrates the programs that are in progress. The team reviews the work and either accepts it or recommends changes to it. All new programs must be accepted by a majority vote of the team before being included in the ACES program.
- *Miscellaneous Discussion* Computer applications outside of ACES are discussed, along with other topics of general interest.

IN THE FUTURE

There are plans to include automatic change order generation among the menu selections. The ACES team is exploring the use of electronic signatures for monthly estimate approvals. Currently, estimates produced by the system must be processed manually because approval signatures are required. An electronic signature system would speed the processing of estimates and payment to the contractor considerably.

CONCLUSIONS

ACES has proven to be a valuable tool for the NJDOT field forces. Resident engineers have always complained about the volume of paperwork generated by construction projects and the time required to produce it. ACES substantially reduces the time needed to produce reports and related documents. The system is flexible, and additional features can be added without a complete redesign. Its ease of use has converted the noncomputer users into computer enthusiasts.

Publication of this paper sponsored by Committee on Construction Management.

Multiloader-Truck Fleet Selection for Earth Moving

SAEED KARSHENAS AND FOAD FARID

Loaders and trucks are often used in earthwork projects. In major earth-moving operations, careful selection of the number of machines used and the size of the equipment can produce substantial savings in both time and cost. Currently, the only method available for determining the optimum size-number combination for loaders is comparison of all possible alternatives. This is a tedious and time-consuming task, especially if a large volume of soil must be hauled, requiring several loading units. In this study, optimal multiloader-truck fleets are investigated, and sensitivity of the production cost to the key variables is analyzed. The cost-capacity and capacity-horsepower relationships for trucks and loaders are investigated by using published equipment specifications and cost data.

In planning an earthwork operation, the number and size of the loading units are usually determined on the basis of the productivity required and the equipment already on hand. Use of equipment on hand can give satisfactory results for small projects. However, careful selection of an equipment fleet for a major earth-moving operation can produce substantial savings in both time and cost.

For a given loader, the optimal number of trucks may be obtained by using queuing theory (*1, 2*). However, the questions of what size of loader and how many loaders must be used to minimize the total production cost remains unresolved. To answer these questions, a mathematical model representing multiloader-truck system production will be presented, and solutions of the model for various project conditions are given as examples.

FORMULATION OF MULTILOADER-TRUCK FLEET PRODUCTION

The steady state expected production per hour, Q, of an earth-moving fleet consisting of a number of loading units and trucks is

$$Q = T \cdot Q_l \tag{1}$$

T is the production factor, which takes into consideration the fact that loaders and trucks may not be busy all the time. Q_l is average productivity of a loading unit if there is always a truck available to be loaded.

Q_l and T in Equation 1 can be calculated as follows:

$$Q_l = \frac{f \cdot q_l \cdot b_f}{t_c} \tag{2}$$

$$T = \sum_{n=1}^{N_l} n \cdot P_n + \sum_{n=N_l+1}^{N_t} N_l \cdot P_n \tag{3}$$

where

f = operating efficiency of loading unit,
q_l = rated bucket capacity of loading unit,
b_f = bucket fill factor of loading unit,
t_c = average cycle time of loading unit (hr),
N = total number of loading units,
N_t = total number of trucks, and
P_n = the steady state probability of exactly n trucks being loaded or waiting to be loaded.

Substitutions for Q_l and T in Equation 1 from Equations 2 and 3 yield

$$Q = \left(\sum_{n=1}^{N_l} nP_n + N_l \sum_{n=N_l+1}^{N_t} P_n\right) \frac{f \cdot q_l}{t_c} \tag{4}$$

By using the assumptions of exponential interarrival and loading time distributions, Taha (*3*, p. 616–617) developed the following equations for calculating P_n:

$$P_n = \binom{N_t}{n} r^n \cdot P_0 \qquad 0 \le n \le N_l \tag{5a}$$

$$P_n = \binom{N_t}{n} \frac{n! \cdot r^n}{N_l! \cdot N_l^{n-N_l}} \cdot P_0 \qquad N_l \le n \le N_t \tag{5b}$$

where r is the ratio of average loading time to average interarrival time (i.e., time between two consecutive arrivals of the same truck, excluding loading and queue time) of a given truck. The probability of an empty system, P_0, is calculated as follows (*3*, p. 616):

$$P_0 = \left[\sum_{n=0}^{N_l} \binom{N_t}{n} r^n + \sum_{n=N_l+1}^{N_t} \binom{N_t}{n} \frac{n! r^n}{N_l! \cdot N_l^{n-N_l}}\right]^{-1} \tag{6}$$

Thus the estimation of production, Q, from Equation 4 requires the calculation of r first, then calculation of P_0 (using Equation 6), and then P_n (Equation 5). By using $N_l = 1$ in

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these equations, the loader-truck production equations developed by O'Shea et al. (*4*) can be obtained.

The average loading time of a truck with a volume capacity equal to q_t is

$$t_l = \frac{q_t \cdot t_c}{q_l \cdot b_f} \qquad (7)$$

The average truck travel time (excluding loading and queue time) is the sum of the haul, dump, and return times. It can be calculated as

$$t_t = \frac{L}{\overline{V}_h} + \frac{L}{\overline{V}_r} + t_d \qquad (8)$$

where

L = length of the haul and return roads,
$\overline{V}_h$ = average haul speed,
$\overline{V}_r$ = average return speed, and
t_d = dump time.

According to the principles of engineering mechanics, the power required to move an object with a constant speed of V while overcoming a constant resisting force of F is

$$\text{power} = F \cdot V \qquad (9)$$

For a truck, in terms of engine horsepower, Equation 9 would be

$$\text{hp} \cdot \alpha \cdot k = F \cdot V \qquad (10)$$

in which hp is the rated engine horsepower and α is the mechanical efficiency of a truck. The mechanical efficiency of most trucks ranges from 80 to 85 percent (*2*). The unit conversion factor, k, is 16.5 ft-ton/min when V is expressed in feet per minute and F is in tons; in metric units, k = 746 N-m/sec when V is in meters per second and F is in Newtons.

The total resistance against the movement of a piece of equipment on a road consists of rolling and grade resistances. The rolling resistance may be expressed in terms of equipment weight as

$$F_r = W \cdot R \qquad (11)$$

where

F_r = rolling resistance,
W = equipment weight, and
R = rolling resistance factor, expressed as a fraction of equipment weight.

For small grades, it can be demonstrated (*1, 2*) that grade resistance is equal to the product of equipment weight and grade:

$$F_s = W \cdot S \qquad (12)$$

where

F_s = grade resistance,
W = equipment weight, and
S = absolute value of the haul road grade.

Grade resistance may be zero, positive, or negative, depending on the haul road grade. If $F = F_r + F_s$ in Equation 10, the maximum haul and return speeds may be calculated as follows:

$$V_h = \frac{\text{hp} \cdot \alpha \cdot k}{(W_t + W_w)(R \pm S)} \leq V_l \qquad R \pm S > 0 \qquad (13)$$

$$V_r = \frac{\text{hp} \cdot \alpha \cdot k}{W_t\,(R \mp S)} \leq V_l \qquad R \mp S > 0 \qquad (14)$$

where

V_h = maximum haul speed,
V_r = maximum haul return speed,
V = truck speed limit,
W_t = net truck weight,
W_w = truck weight capacity, and

$R \pm S$ is the total road resistance (effective grade).

Equations 13 and 14 can be used to calculate the maximum speed of trucks as long as the truck's retarder is not applied, that is, the total road resistance is positive. When the total road resistance is positive, the maximum speed of off-highway trucks is limited by the engine's governor to about V_l = 40 mph (64.4 km/hr). To ensure that the maximum speeds calculated from Equation 13 do not exceed the truck's speed limit, $R \pm S \geq 2$ percent must be used in Equation 13. In other words, when the total resistance of a portion of a haul load is between 0 and 2 percent, $R \pm S = 0.02$ must be used to calculate the maximum truck speed for that portion of the road from Equation 13. For calculating return speeds from Equation 14, a minimum resistance of 5 percent must be used. Therefore, if the total resistance of a portion of return road is between 0 and 5 percent, $R \pm S = 0.05$ must be used in Equation 14. Speeds calculated from Equations 13 and 14 in this way are close to those that can be determined from the charts provided by truck manufacturers.

If the average truck speeds are represented as percentages of the maximum speeds, the average truck travel time can be calculated from Equation 8 after substituting for travel and return speeds from Equations 13 and 14:

$$t_t = \frac{L(W_t + W_w)(R \pm S)}{\text{hp} \cdot \alpha \cdot k \cdot \beta} + \frac{L \cdot W_t \cdot (R \mp S)}{\text{hp} \cdot \alpha \cdot k \cdot \beta'} + t_d \qquad (15)$$

where β and β' are speed factors for converting the maximum haul and return speeds to average speeds. Estimates of β and β' are given elsewhere (*5*). For a haul road consisting of m sections with different grades and rolling resistance factors, Equation 15 can be modified as

$$t_t = \sum_{i=1}^{m}\left[\frac{W_t + W_w}{\text{hp}} \cdot \frac{L_i(R_i \pm S_i)}{\alpha \cdot k \cdot \beta_i} + \frac{W_t}{\text{hp}} \cdot \frac{L_i(R_i \mp S_i)}{\alpha \cdot k \cdot \beta_i'}\right] + t_d \qquad (16)$$

The scatter diagram of $W_t + W_w$ versus horsepower for the trucks listed in Table 1 is presented in Figure 1. As this figure

TABLE 1 PRIMARY SPECIFICATIONS AND HOURLY OWNING AND OPERATING COSTS OF TRUCKS (*6*)[a]

Model[b]	Flywheel Horsepower hp (k watt)	Capacity, $yd^3(m^3)$ Heaped (SAE)	Net weight lb. (kg)	Cost[c] Dollars/hr
Caterpillar				
769C	450 (336)	30.8 (23)	69,100 (31344)	88
773B	-650 (485)	44.6 (34)	86,630 (39295)	114
777	870 (649)	67. (51)	127,100 (57653)	156
DJB				
D25B	260 (194)	18.3 (14)	40,800 (18507)	60
D445	450 (336)	31.1 (24)	61,600 (27942)	102
Cline				
A22-R	235 (175)	20 (15)	35,000 (15876)	55
235R	400 (298)	25.5 (19)	52,260 (23705)	78
Euclid				
R25	220 (164)	19.5 (15)	39,200 (17781)	55
R35	450 (336)	29 (22)	58,300 (26445)	89
R50	608 (429)	41.4 (31)	77,100 (34963)	109
R75	755 (563)	60 (45.6)	101,000 (45814)	140
R85	818 (563)	66.5 (50.5)	117,100 (35117)	149
International-Hough				
350B	607 (453)	41.8 (32)	71,800 (32568)	111
WABCO				
35D	441 (313)	29 (22)	61,140 (27733)	93
50B	577 (429)	40 (30)	77,240 (35036)	119
60B	651 (474)	48 (36.5)	85,000 (38556)	129
75C	694 (506)	57 (43)	91,500 (41504)	144
85D	818 (610)	67 (51)	120,100 (54114)	165
TEREX				
33-03B	215 (160)	18.3 (14)	38,000 (17237)	52.5
33-05B	321 (239)	24.6 (19)	49,500 (22453)	74
33-07	493 (367)	31.9 (24)	71,600 (32478)	93
33-09	624 (465)	47.5 (36)	93,200 (42275)	115
33-11C	840 (626)	63.7 (48)	124,900 (52481)	158

[a] Adapted from "Contractor's Equipment Cost Guide" (6)
[b] All trucks are off highway, diesel powered
[c] Operator cost is not included

shows, $(W_t + W_w)$/hp is roughly constant for the various makes and sizes of trucks listed in Table 1. The average value of $(W_t + W_w)$/hp is 0.163 ton/hp (0.146 metric ton/hp), with a coefficient of variation (COV) of 0.076. Figure 1 also shows the curve $(W_t + W_w)/\text{hp} = 0.163$ for comparison with the data. A plot of truck weight, W_t, versus horsepower revealed that W_t/hp is roughly constant, with an average value of 0.071 ton/hp (0.063 metric ton/hp) and a COV of 0.087.

If 16.5 ft-ton/min were substituted for K, 0.163 ton/hp for $(W_t + W_w)$/hp, and 0.071 ton/hp for W_t/hp in Equation 16, the average truck travel time would be

$$t_t = \left\{ \sum_{i=1}^{m} \left[0.011 \frac{L_i(R_i + S_i)}{\alpha \cdot \beta_i} + 0.004 \frac{L_i(R_i + S_i)}{\alpha \cdot \beta_i'} \right] \right\} + t_d \quad (17)$$

In this equation, when L_i is in feet, the calculated t_t is in minutes. Equation 17 expresses the truck travel time independent of the truck's horsepower or size. This simplifies loader-truck fleet analysis considerably.

If $\lambda = b_f \cdot t_t$, λ would be a function of the characteristics of the haul road, the material to be hauled, and the trucks

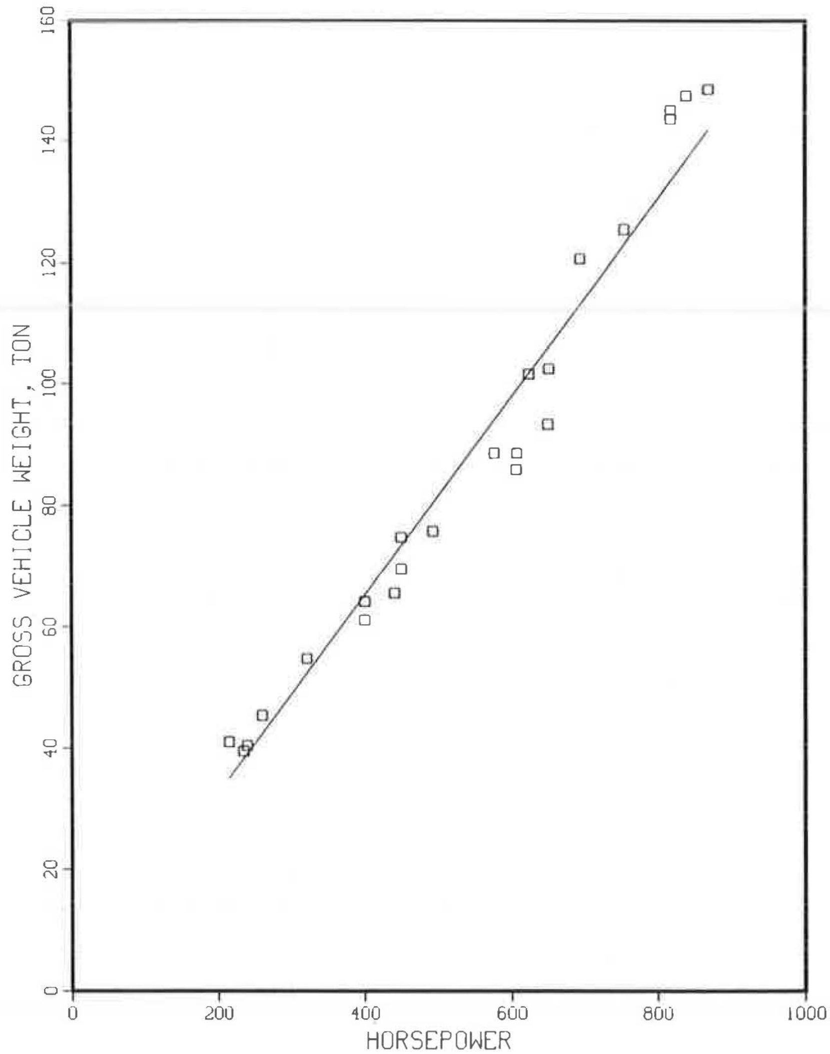

FIGURE 1 Scattergram of gross weight versus power for trucks.

used. Hereafter, λ will be referred to as the project factor. By using Equations 7 and 17, the ratio of loading to travel time, r, can be calculated as follows:

$$r = \frac{q_t \cdot t_c}{q_l \cdot \lambda} \qquad (18)$$

MULTILOADER-TRUCK FLEET PRODUCTION COST

The cost per unit volume of production, C, for a fleet consisting of N_l loading units and N_t trucks is

$$C = \frac{N_t \cdot C_t \cdot N_l \cdot C_l}{Q} \qquad (19)$$

where C_t and C_l are average truck and loader owning and operating costs, respectively, per hour (the rest of the variables in Equation 19 were defined previously). To reduce the number of variables in Equation 19, the equipment costs can be expressed in terms of equipment capacities. This procedure requires an estimate of the owning and operating costs of various sizes of trucks and front-end loaders. The equipment owning and operating costs from the 1986 edition of the *Contractor's Equipment Cost Guide* (*6*) are used here. Costs published in this manual are based on average working conditions. These include depreciation, insurance, facilities capital, storage, license fee, record keeping, overhaul, field repair, lubrication, and fuel ($0.96 per gallon for diesel fuel) costs. Costs published in this guide are not the actual equipment costs but are approximate national averages. For a comparative study of equipment production costs, such as the current study, these figures are sufficient.

The monthly equipment cost provided by the *Contractor's Equipment Cost Guide* is calculated by multiplying the hourly owning and operating cost of the equipment by 176. Therefore, to determine the hourly costs presented in Table 1, the published monthly equipment costs were divided by 176.

The cost data used to investigate the truck cost-capacity relationship are presented in Table 1. The owning and operating costs given in Table 1 do not include any sales or property taxes, freight costs, main office overhead, or profit. These costs, however, are usually expressed as percentages of equip-

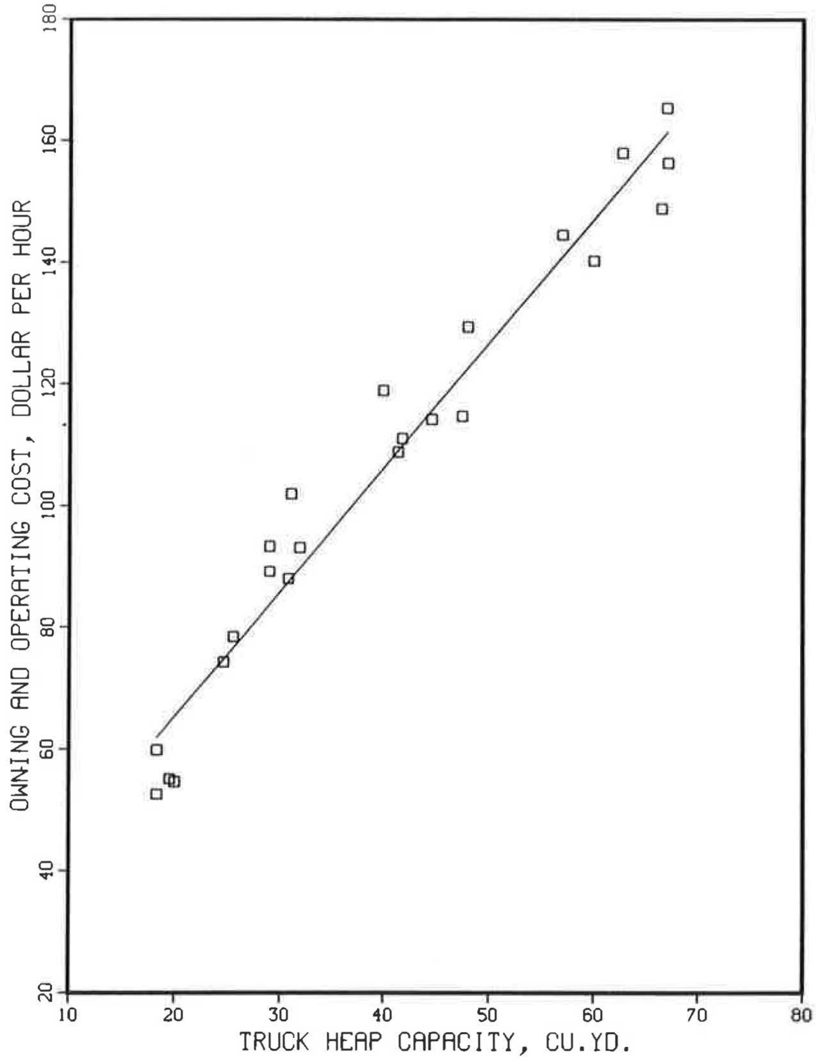

FIGURE 2 Cost-capacity scattergram for trucks.

ment direct costs, so such costs do not influence the optimal equipment fleet design.

Figure 2 shows a scattergram of the heaped capacities (SAE) versus the hourly owning and operating costs of trucks listed in Table 1. The method of least squares was used to obtain the following relationship between the cost and heaped capacity of various trucks:

$$C_t = 2.04\ q_t + 24.6 \tag{20}$$

This equation is plotted in Figure 2. Because the published equipment costs do not include operator cost, \$20 per hour should be added to account for the hourly cost of an equipment operator. Thus the total truck owning and operating cost would be

$$C_t = 2.04\ q_t + 44.6 \tag{21}$$

By applying the same methodology, the cost capacity relationship of front-end wheel-loaders was also investigated. The data used for this investigation are given in Table 2. All loaders were assumed to be equipped with their standard bucket sizes. The owning and operating costs of loaders listed in Table 2 are also from the 1986 cost guide (*6*). The cost equation obtained by the least squares method for front-end loaders is

$$C_l = 11.19\ q_l - 6.82 \tag{22}$$

After adding \$20 per hour for the loader operator cost,

$$C_l = 11.19\ q_l + 13.18 \tag{23}$$

By substitution for C_t, C_l, and Q in Equation 19, the unit production cost can be expressed in terms of loader and truck bucket sizes, number of loaders and trucks in the fleet, loader cycle time, and haul road characteristics:

$$C = \frac{(2.04\ q_t + 44.6)N_t + (11.19\ q_l + 13.18)N_l}{\left[\sum_{n=1}^{N_l} nP_n + N_l \sum_{n=N_l+1}^{N_t} P_n\right] \cdot f \cdot q_l \cdot b_f/t_c} \tag{24}$$

TABLE 2 PARTIAL SPECIFICATIONS AND HOURLY OWNING AND OPERATING COSTS OF FRONT-END LOADERS (*6*)[a]

Model[b]	Rated Bucket Capacity (heaped, SAE) yd^3 (m^3)	Cost[c] Dollars/hr
Case		
W24C	2.5 (1.9)	24.5
W26B	3 (2.29)	23
W36	3.5 (2.67)	31
Caterpillar		
936	2.5 (1.9)	23
950B	3 (2.29)	27.8
966D	4 (3.0)	41
980C Hi-Lift	5 (3.8)	56.5
980C	5.25 (4)	54
988B	7 (5.3)	76
988B Hi-Lift	6.5 (5)	78
992C Hi-Lift	12 (9.2)	154
Clark		
55C	2.5 (1.9)	21
75C	3 (2.29)	27.5
125C	4 (3.0)	40
175C	5 (3.82)	51
275C	7 (5.35)	72
475C	12 (9.2)	131
475C Turbo	12 (9.2)	140
Dresser		
550	5.25 (4.)	53
560B	7.5 (5.7)	76
570	12 (9.2)	131
644D	3 (2.29)	24
844	4.5 (3.4)	68.35
Fiat-Allis		
605B	2.5 (1.9)	18.5
645B	3 (2.29)	24
FR20	4.5 (3.4)	41
International-Hough		
H80B	3.5 (2.67)	27
H100C	4.5 (3.4)	46
560	6.5 (5)	65
H400C	11 (8.5)	108.5
TEREX		
72-31B	3 (2.29)	26.5
72-61	5.5 (4.2)	53
90B	8 (6.1)	75
72-71B	8 (6.1)	73
72-81	9 (6.88)	95
Trojan		
5500	6 (4.6)	52
7500	7.5 (5.8)	69

[a]Adapted from "Contractor's Equipment Cost Guide" (6)
[b]Diesel powered, wheel loaders
[c]Operator cost is not included

Thus an estimation of the unit production cost, C, from Equation 24 will first require calculation of r from Equation 18, then determination of P_0 by using Equation 6, followed by P_n from Equation 5.

ANALYSIS OF MULTILOADER-TRUCK FLEET PERFORMANCE

To get a general picture of the multiloader-truck fleet design problem and to examine the sensitivity of the optimal solution to variations in the key variables, optimal loader-truck combinations for various project conditions will be investigated. The optimal loader-truck combination for a given project is defined as the combination that minimizes Equation 24 and in which the dump clearance of the loaders at full lift is greater than the loading height of the trucks selected.

In the following analysis, f and b_f in Equation 24 are assumed to be equal to 1. The results can be adjusted easily for other values of f and b_f. To calculate the productivity and unit cost of production for various loader-truck fleets, the following basic loader cycle times are used:

Rated Bucket Capacity [yd³ (m³)]	*Basic Cycle Time (min)*
1–2 (0.76–1.5)	0.50
3–4 (2.3–3.0)	0.55
5–6 (3.8–4.6)	0.60
7–8 (5.3–6.1)	0.65
9–10 (6.9–7.6)	0.70

The basic loader cycle time includes loading, dumping, maneuvering, full cycle of hydraulics, and minimum travel.

The effect of the size and number of loaders on the production cost of a multiloader-truck fleet will be examined first. Figure 3 shows contours of minimum cost per cubic yard of production for various bucket sizes for a number of loaders used in an example project. The project layout is given in Figure 4. If it is assumed that $\alpha = 0.8$, $t_d = 1.1$ min, and $b_f = 1$ and that the following speed factors are used (*5*):

	Speed Factors	
Section	*Hauling* (β_i)	*Returning* (β_i')
1	0.90	0.95
2	1.00	0.93
3	0.93	0.90

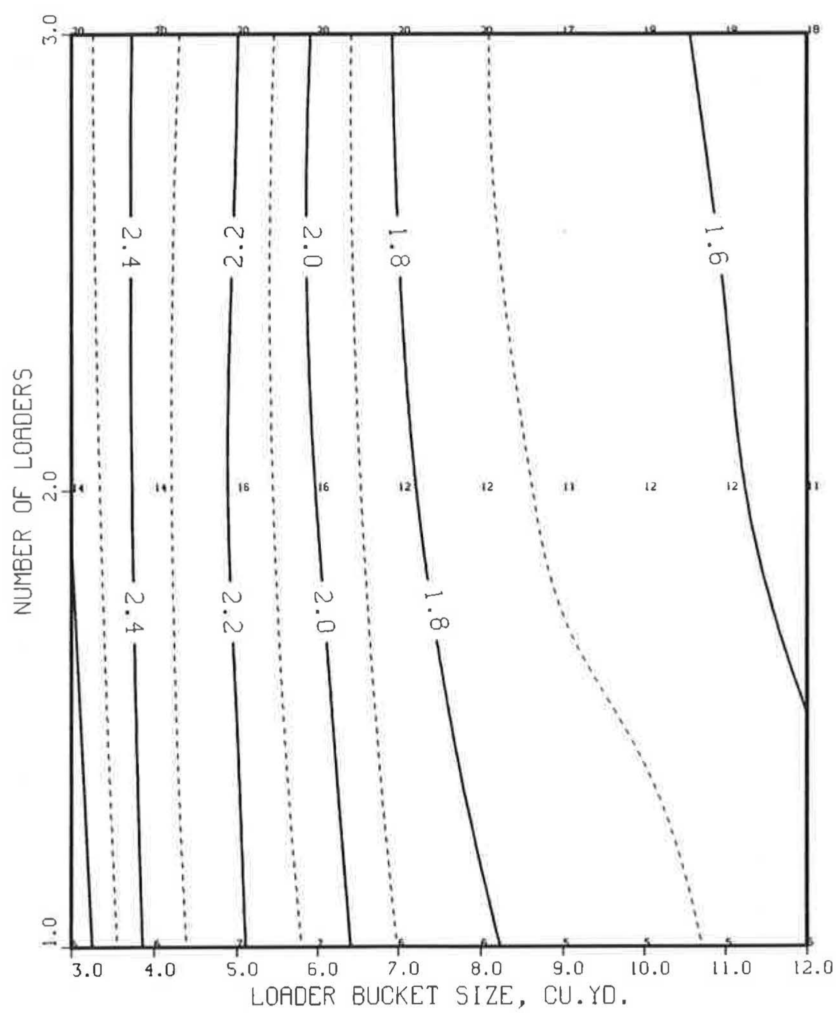

FIGURE 3 Optimal number of trucks (small integers) and contours of minimum unit cost ($/yd³) for example project.

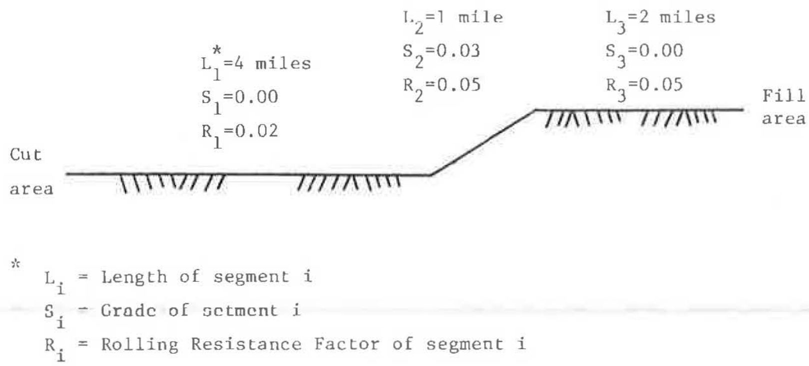

FIGURE 4 Layout of haul and return road for example project.

then the project factor, λ, for this project is about 25 min.

Figure 3 shows that both the bucket size and the number of loaders used affect the cost of production. However, the effect of loader bucket size is more significant than the effect of the number of loaders used. The cost per cubic yard of production decreases as the bucket size or number of loaders increases. Figure 3 also gives the optimal number of trucks (small integers in the background) that should be used with various number of loaders for the example project shown in Figure 4.

Figure 5 depicts the productivity variation for various loader bucket size and number combinations. This figure also gives the optimal truck capacity (small integers) that should be used with each loader combination for the example project.

To examine the effect of haul road characteristics on the

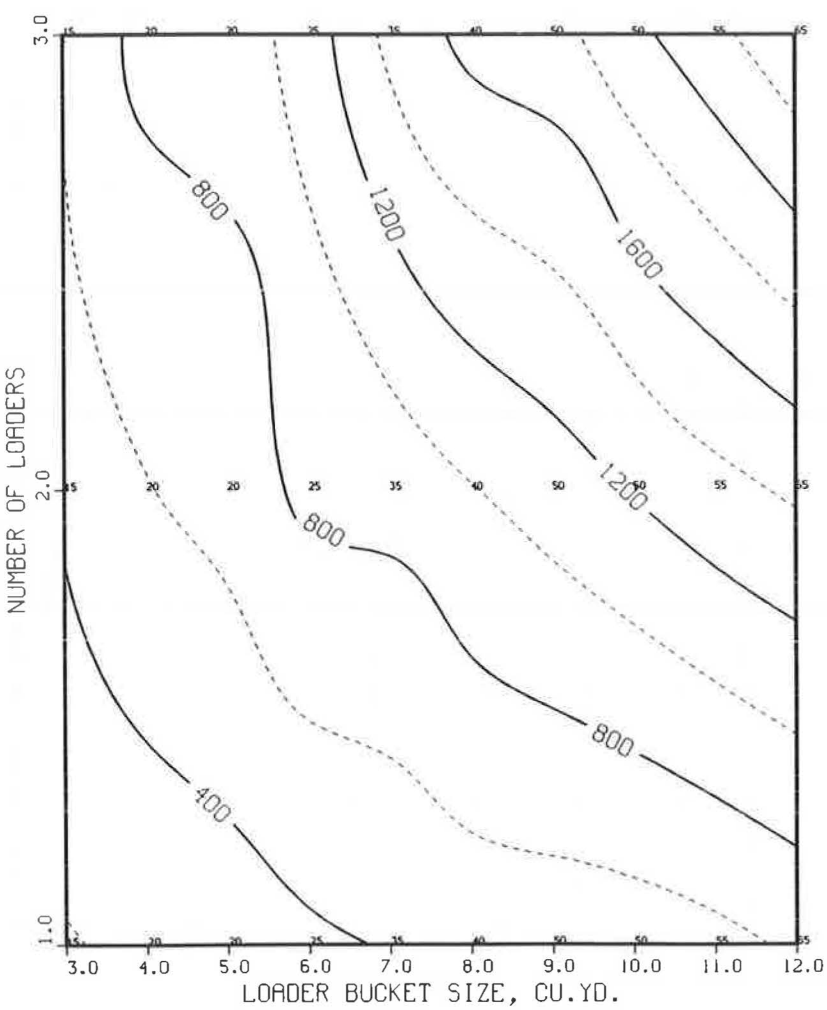

FIGURE 5 Optimal truck capacities (small integers; yd³) and contours for hourly productions (yd³) for example project.

production cost, Equation 24 was used to plot contours of minimum unit costs of production for various combinations of project factors and loader bucket sizes. Figure 6 shows such a contour map for a fleet consisting of one loader and several trucks. The optimal truck sizes for various combinations of project factors and loader bucket sizes are also given. Figure 6 confirms that the conclusion drawn for the example project in Figure 4 is valid for various road characteristics. That is, in general, the unit production cost decreases as the loader bucket size increases.

The production for each combination of project factor and loader bucket size is given (in cubic yards per hour) in Figure 7. This figure also shows the optimal number of trucks (small integers in the background) that should be used with each loader bucket size in a project.

Hourly productions and minimum unit costs for a fleet consisting of two loaders and several trucks are shown in Figures 8 and 9. The same information for three loaders and a number of trucks is given in Figures 10 and 11. A comparison of Figures 6, 8, and 10 confirms that the optimum truck capacity is independent of the number of loaders used in a project. That is, the optimum truck capacity is mostly a function of the loader size. These figures demonstrate that to reduce unit production cost, the largest practical size loaders must be used.

DESIGNING A MULTILOADER-TRUCK FLEET

Figures 6 through 11 can be used in designing optimum loader-truck fleets for projects with positive road resistance. The design process is demonstrated by the following examples.

Example 1

Problem

What is the optimal truck fleet to be used with a single 4-yd^3 (3.1-m^3) front-end loader for loading and hauling material with a bucket fill factor of 0.8 in the example project presented in Figure 4? A 0.83 job efficiency is assumed.

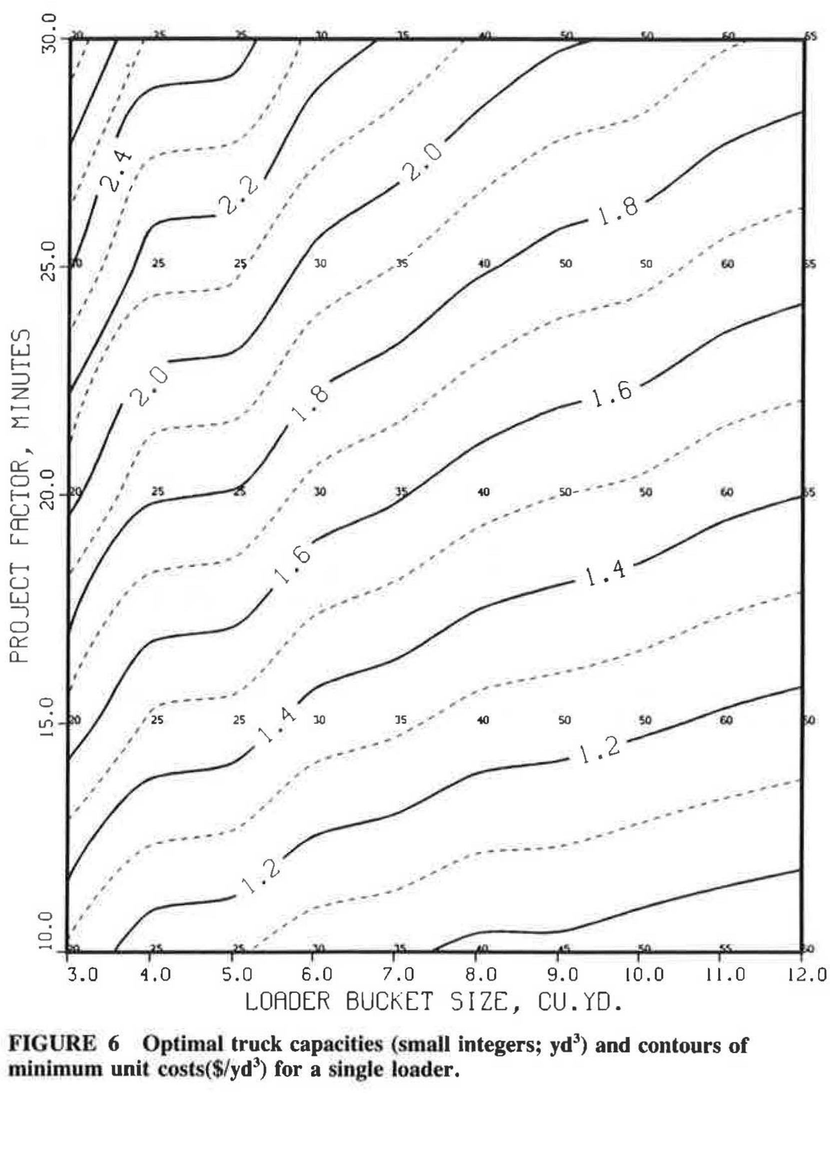

FIGURE 6 Optimal truck capacities (small integers; yd^3) and contours of minimum unit costs($/yd^3) for a single loader.

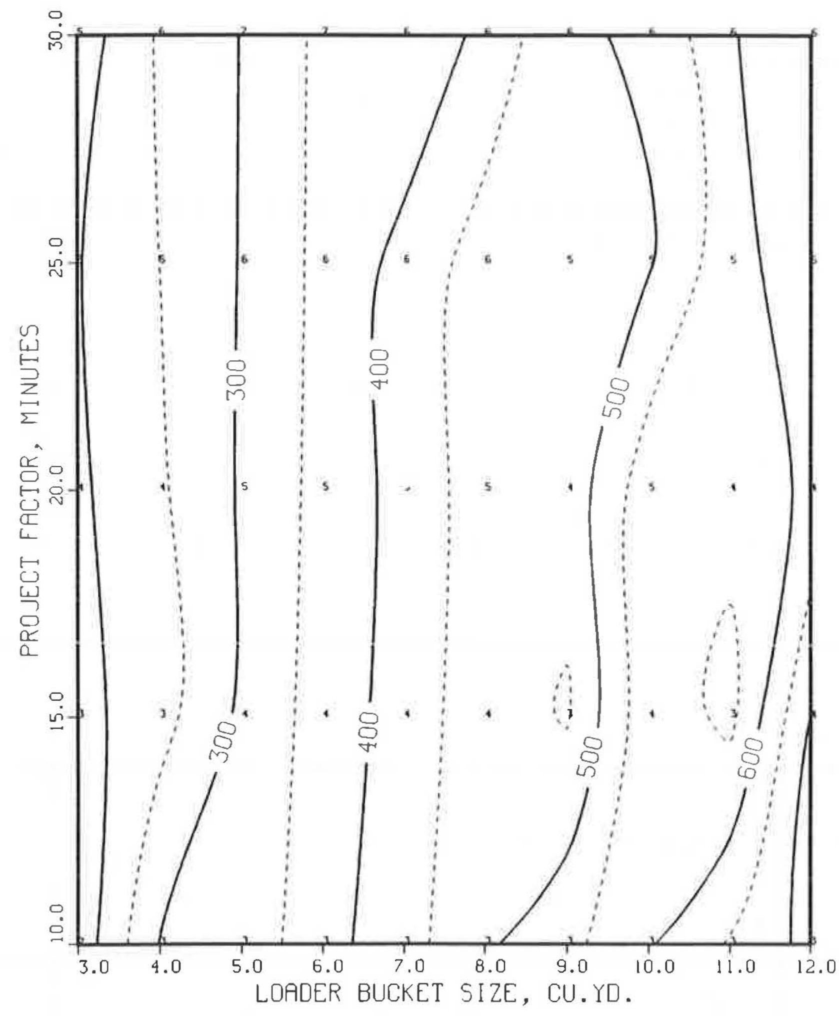

FIGURE 7 Optimal number of trucks (small integers) and contours of hourly productions (yd³/hr) for a single loader.

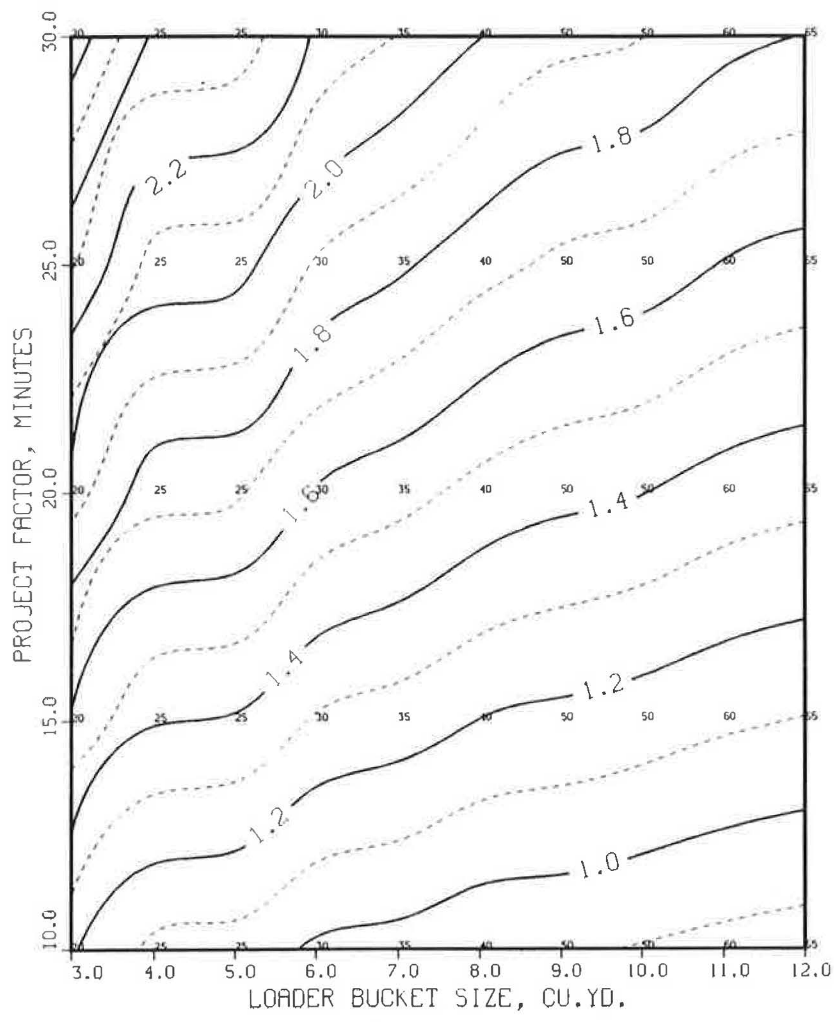

FIGURE 8 **Optimal truck capacities (small integers; yd³) and contours of minimum unit costs ($/yd³) for two loaders.**

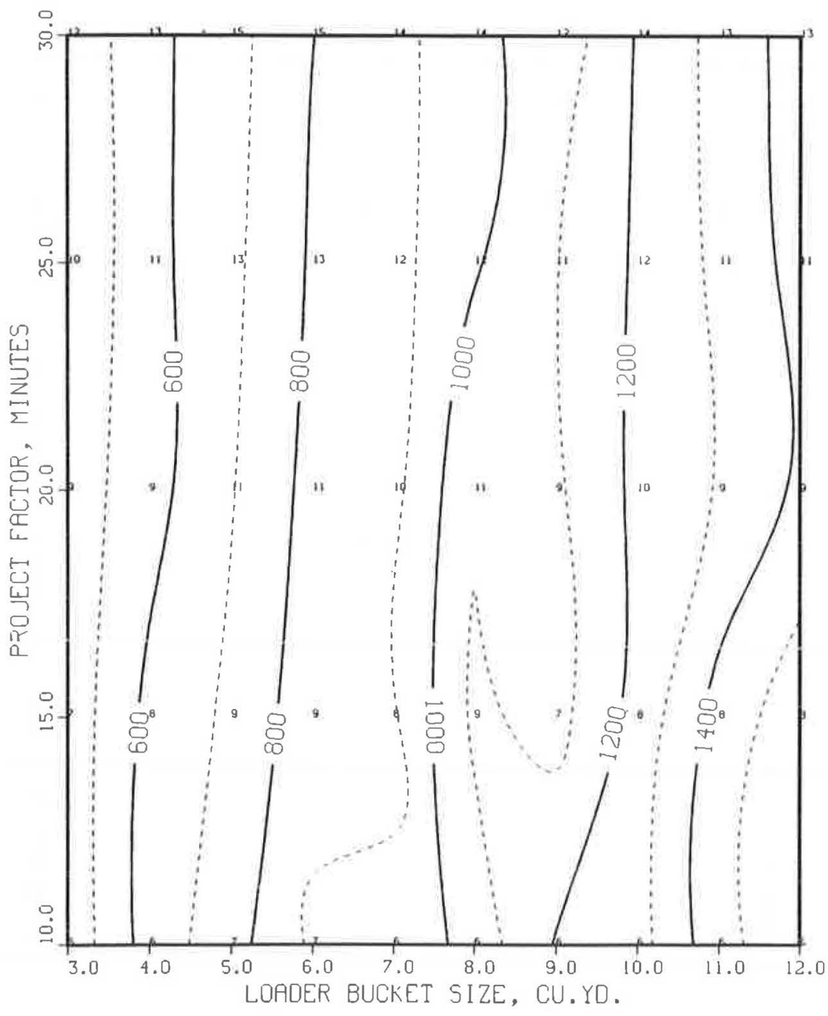

FIGURE 9 Optimal number of trucks (small integers) and contours of hourly productions (yd^3/hr) for two loaders.

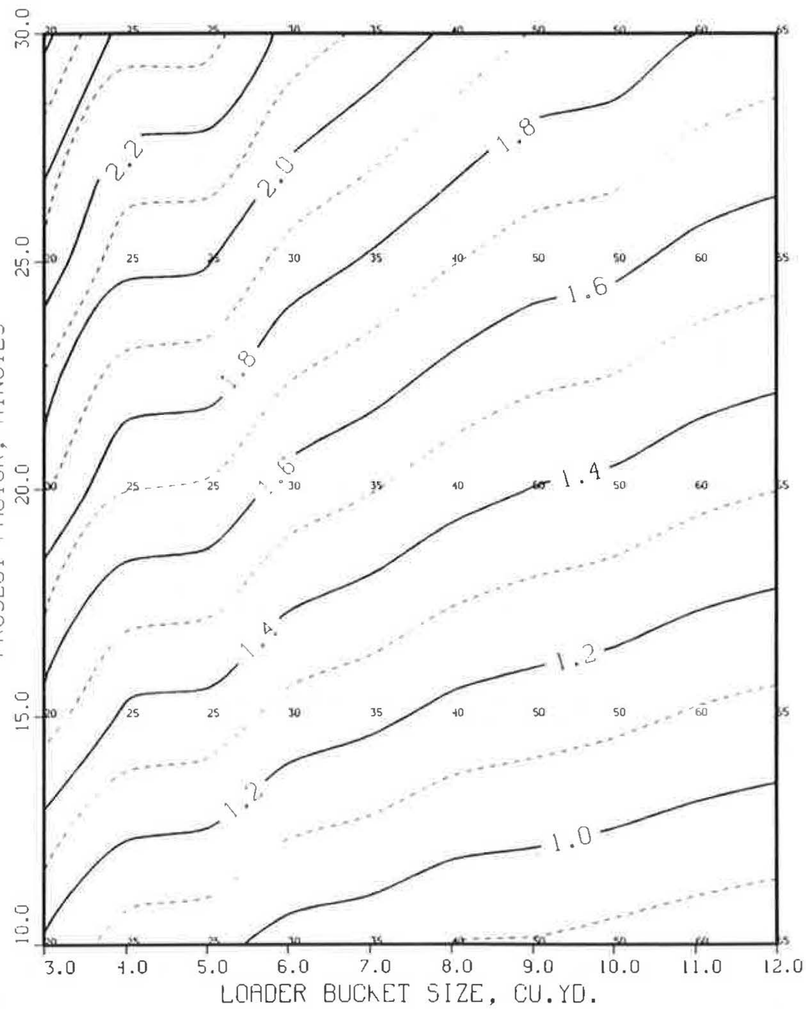

FIGURE 10 Optimal truck capacities (small integers; yd³) and contours of minimum unit costs ($/yd³) for three loaders.

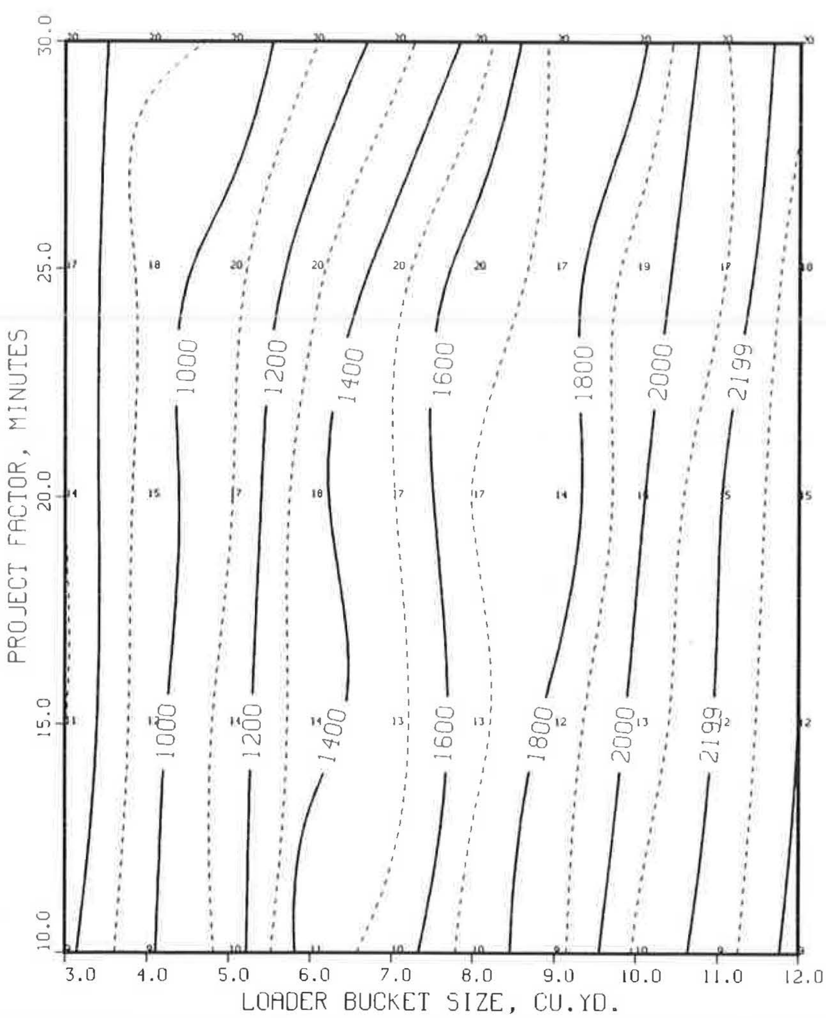

FIGURE 11 Optimal number of trucks (small integers) and contours of hourly productions (yd³/hr) for three loaders.

Solution

The project factor for this project is 20 min. For a 4-yd³ bucket, Figures 6 and 7 show that four 25-yd³ (18.8-m³) trucks should be used in this project. For $f = 1$ and $b_f = 1$, the fleet production would be about 250 yd³/hr (191 m³/hr) and the cost per cubic yard of production would be about \$1.82 (\$2.38/m³). After adjusting for project efficiency and bucket fill factor, fleet production and unit production cost would be 166 yd³ (127 m³) and \$2.74/yd³ (\$3.58/m³), respectively.

Example 2

Problem

Determine the optimal loader-truck fleet for an 800-yd³/hr (612-m³/hr) production for the example project depicted in Figure 4. It is assumed that $f = b_f = 1$.

Solution

From Figures 8 and 9, a production of at least 800 yd³/hr (612 m³/hr) in a project with a project factor equal to 25 min requires two 6-yd³ (4.5-m³) loaders with thirteen 30-yd³ (22.6-m³) trucks. The unit cost of production would be about \$1.9/yd³ (\$2.5/m³). Figures 10 and 11 demonstrate that the same 800-yd³ production can be accomplished with three 4.0-yd³ (3.06-m³) loaders and eighteen 25-yd³ (19.4-m³) trucks. The unit production cost, however, will be increased to about \$2.02/yd³ (\$2.64/m³). Thus this example also verifies that it is more economical to use the largest loaders that are practical for the given job conditions.

SUMMARY AND CONCLUSIONS

The 1986 owning and operating costs and specifications for several front-end loaders and off-highway trucks were used to develop an optimum multiloader-truck fleet design approach for earth moving. The trucks used were off-highway, rear-dump, diesel-powered vehicles. The loaders are front-end wheel-loaders equipped with the standard buckets. The approach developed here is applicable to projects with positive road resistance. The main conclusions of the study can be summarized as follows:

- Given the current cost-capacity relationships for loaders and trucks, the largest practical loader sizes must be used to minimize the cost of earth-moving projects.
- The optimum truck capacity is mostly a function of the loader size and is almost independent of the number of loaders used: the larger the loader size, the larger the optimum truck capacity.
- The optimum truck capacity is not affected significantly by the project factor.

The graphical solutions presented provide a general picture of the multiloader-truck combination problem and make design of the optimal multiloader-truck fleet for a project simple and fast. The main conclusions drawn remain generally valid as long as there is not a substantial change in truck and loader specifications and as long as the costs of trucks and loaders change proportionally. The minimum unit cost curves must be updated regularly by using the latest equipment owning and operating costs.

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Impact of the DBE Program on Indiana Highway Construction

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The Disadvantaged Business Enterprise (DBE) program has been a controversial and fiercely debated topic since the January 1983 passage of the Surface Transportation Assistance Act. Strong opinions on this subject, combined with a shortage of relevant data, have increased the program's vulnerability to criticism. A quantitative view of the impact of the current DBE program is provided to help give an understanding of the program's strong points and weaknesses. In addition, results of a study conducted at the Indiana Department of Highways (IDOH) are presented. The study demonstrates that the IDOH DBE program has increased minority participation in the Indiana highway construction industry in terms of dollar volume and that the number and dollar volume of DBE subcontract awards have been reasonably distributed throughout the six Indiana districts. Also, DBE firms are being awarded an increasing number of large contracts each year, and repeat award-winning DBE firms in Indiana have consistently been awarded the majority of DBE dollars. A large percentage of the minority work in Indiana is being performed by a small group of DBE contractors, and a majority of the work performed by DBEs in Indiana is in low-capital, intensive specialty areas.

In the years since the passage of the Surface Transportation Assistance Act of 1982 and the implementation of the Disadvantaged Business Enterprise (DBE) program, the DBE program has become a highly controversial and political topic throughout the United States. Contractor organizations have debated fiercely with FHWA about the effects of the program on the nation's highway construction programs. To address this issue, a study was conducted in Indiana for the Indiana Department of Highways (IDOH). The intent of the study was not to take any one side in the debate but instead to examine IDOH fiscal data and use them to evaluate the impact of the current DBE program. It was hoped that an understanding of both the strong points and the weaknesses of the program would be gained through this procedure.

The purpose of this paper is to report the study results and present the methods used for assessing the impact of the DBE program on the Indiana highway construction industry. It has become evident that the DBE program is going to be a part of the highway construction industry for the next several years. It is time for all parties involved to recognize this fact and try to execute the DBE programs in the best manner possible.

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BACKGROUND

On January 6, 1983, President Ronald Reagan signed into law the Surface Transportation Assistance Act (STAA) of 1982. Section 105(f) of the STAA stated that

> . . . except to the extent that the Secretary determines otherwise, not less than 10 percentum of the amounts authorized to be appropriated under this Act shall be expended with small business concerns owned and controlled by socially and economically disadvantaged individuals as defined by Section 8(d) of the Small Business Act and relevant subcontracting regulations promulgated pursuant thereto.

The small business concerns mentioned in the act are more commonly referred to as Disadvantaged Business Enterprises, or DBEs, and the program assembled by the Federal Highway Administration (FHWA) to fulfill the requirements of section 105(f) has become known as the DBE program.

The DBE program was announced on February 18, 1983, in a memorandum from FHWA to the FHWA Regional Administrators. Rules and regulations for implementing the individual DBE programs were published in July 1983 and became effective on August 22, 1983. Thus the first full fiscal year of program implementation in Indiana under these regulations was fiscal year (FY) 1984 (October 1983 to September 1984).

Since the passage of the STAA, each state has established its own goals for DBE participation. In FY 1986, five states had received approval of goals less than 10 percent, and four states submitted goals greater than 10 percent. All other states followed the 10 percent goal (*1*).

After a goal has been set by a state, it is the state's responsibility to meet or exceed this goal by implementing its own DBE program within the guidelines issued by FHWA. This means that the overall federal DBE program is actually a combination of 52 separate programs that are operated by the states plus the District of Columbia and the Commonwealth of Puerto Rico. Each of these jurisdictions is responsible for most of the important dimensions of the program, including certification processes, prequalification and licensing procedures, project monitoring, and enforcement of regulations.

Although each state has a considerable amount of independence in establishing its own DBE program, there are some specific regulations developed by the U.S. Department of Transportation that must be followed when a state is determining the eligibility of a firm to participate (*2*). For a firm to be recognized as a legitimate DBE, it must meet three basic qualifications:

- It must be owned and controlled by individuals who are socially disadvantaged.
- It must be owned and controlled by individuals who are economically disadvantaged.
- It must be a small business, as defined by Section 3 of the Small Business Act.

Usually, an individual's racial or ethnic heritage is the key to meeting the socially or economically disadvantaged qualification. By law, members of the following groups automatically have such eligibility if they are proven to be economically disadvantaged:

- Black Americans,
- Hispanic Americans (Mexicans, Puerto Ricans, Cubans, Central or South Americans, or others of Spanish culture),
- Native Americans (American Indian, Eskimos, Aleuts, and native Hawaiians),
- Asian Pacific Americans (Japanese, Chinese, Taiwanese, Koreans, Vietnamese, Laotians, Cambodians, Filipinos, Samoans, Guamanians, Northern Marianans, and individuals from the U.S. Trust Territory of the Pacific Islands), and
- Asian Indian Americans (individuals from India, Pakistan, and Bangladesh).

In addition, recent legislative amendments specify that women are also to be considered socially disadvantaged individuals (*3*).

The definition of a small business varies according to the type of business, such as general contractor, consultant, vendor, or supplier. Each business category is measured by different criteria, such as dollar receipts or number of employees. Generally, a company would be eligible for certification as a DBE if it meets the following standards:

- For subcontracts of $10,000 or less, a company is determined to be small if it does not have more than 500 employees, including employees at all affiliates.
- For subcontracts of $10,000 or more and for all prime contracts, a firm is classified as small under the following circumstances:
  - –For general construction work, if the firm's average receipts have not exceeded $14 million over the previous three fiscal years;
  - –For special trade construction work, if the firm's average receipts have not exceeded $5 million dollars for each of the last 3 years;
  - –For manufacturing plants and suppliers, a firm must have no more than 500 employees, including all affiliates;
  - –For all other contractor categories (such as architects, engineers, janitorial firms, etc.), details on size limitations are specified by the Small Business Administration.

In addition to meeting these qualifications, a firm must also be certified. To become a certified DBE firm, at least 51 percent of the business must actually and legally be owned by a socially and economically disadvantaged individual or individuals. Finally, the active management and daily operations of the firm must be controlled by one or more of those individuals.

As stated previously, these are the specific guidelines set by the U.S. Department of Transportation. It is the responsibility of each individual state to follow these guidelines in developing or amending its own DBE programs.

DATA AND ANALYSES

The increase in DBE participation in response to the STAA is the key measure of the short-term effectiveness and impact of the program. The results presented here are from an analysis that focused on the impact of DBE participation during FY 1983–FY 1986 in Indiana. The changes during this time in the type of work performed by DBEs are also examined, in terms of both contract size and function. Readers should be advised that the dollar amounts described throughout this paper are real value. Inflation was low during FY 1983–FY 1986, and its impact was therefore minimal. It is the changes in the parameters and their combinations that permit an assessment of the full short-term impact of Section 105(f).

Are DBEs becoming more involved in heavy highway and bridge construction, or has their apparent increase in participation been confined to the less capital-intensive specialty areas? Are their average contract sizes growing, indicating an ability to perform and manage larger jobs? Are certain areas of the state being used to meet the majority of the 10 percent minority goal? These were the sort of questions that this study was intended to answer.

OVERALL DBE PARTICIPATION IN INDIANA

Table 1 presents the number of DBE subcontract awards from FY 1983 through FY 1986. In the first fiscal year of the current program, 221 subcontracts to DBEs were approved. It should be recalled that the DBE program was not formally implemented until June 1983; therefore these 221 contracts were approved in a span of only 4 months (June to September).

In FY 1984, 657 subcontracts to DBEs were approved. This was the largest number of subcontracts approved in the 4 years analyzed, and it represented an increase over the previous fiscal year. In FY 1985, the number of subcontracts approved to DBEs decreased 10 percent, from 657 to 591, and in FY 1986, the number again increased, to 624 subcontracts—a 6 percent increase.

Although the number of DBE subcontract awards has fluctuated since the program's first year, the dollar volume of these same awards has steadily increased over the same period (Table 1). In FY 1983, DBE subcontracts totaled $5,805,000. This represented a 178 percent increase in DBE participation over FY 1982, which was the last full fiscal year before the program's implementation. In FY 1984, which was the first

TABLE 1 NUMBER AND DOLLAR VOLUME OF DBE SUBCONTRACTS

Fiscal Year	Number of Awards	Volume ($)
1983	221	5,805,000
1984	657	24,820,000
1985	591	27,382,000
1986	624	28,853,000

full fiscal year of the program, the dollar volume of DBE subcontracts rose by a dramatic 328 percent to $24,820,000. The next year (FY 1985) the total value of DBE subcontract awards again rose, this time by 10 percent, to $27,382,000. In FY 1986 this figure was increased by another 5 percent to $28,853,000.

In terms of increasing minority participation in the highway construction industry, there is no doubt that the DBE program in Indiana has had an impact. In FY 1982, the total value of DBE subcontracts was $2,086,859; by FY 1986, this number had risen to $28,853,000. Although the amount of Federal Aid highway dollars available to states during this time had also increased, the tremendous rise in DBE dollars is primarily due to the implementation of the DBE program.

DBE SUBCONTRACT DISTRIBUTION BY INDIANA DISTRICT

This portion of the analysis had three objectives. The first was to determine whether any specific location in the state was receiving a disproportionate amount of DBE subcontract awards. The second was to calculate the actual dollar volume of the subcontracts for each district and compare it with the number of awards for that district. This information was then used to satisfy the third objective, which was to compute the average subcontract size for each of the six districts for FY 1983–FY 1986. Table 2 summarizes the information from this analysis.

As may be observed in Table 2, the distribution of DBE subcontract awards throughout the districts in the state has been relatively uniform, except for one particular district. This is the Greenfield district (including Indianapolis), which over the past 3 fiscal years has received from 5 to 10 percent more DBE awards than the next closest district.

In general, however, the IDOH DBE program has been distributing the DBE subcontracts quite evenly throughout the state. This point is also made evident in Table 2 by the distribution of the dollar volume of these subcontracted awards throughout the six districts in Indiana. Although the Greenfield district still has higher percentages of DBE dollars, the percentages are much closer to those of the other five districts. The only district that consistently had a low percentage of DBE subcontract dollars was the Seymour district, which has never had more than 10 percent of the total DBE subcontract dollar volume.

Table 3 presents the average of DBE subcontract size for each district for the same period. During the 4 years analyzed, the LaPorte district had the largest average subcontracts for 2 years. In fact, in FY 1986, the average subcontract size in the LaPorte district was almost 60 percent larger than in the next nearest district. In general, however, the fluctuation in average contract size for every district was substantial, which indicates that no district in particular has received inordinately large subcontracts.

TABLE 3 AVERAGE DBE AWARD BY DISTRICT

	Average Award ($)			
District	FY 1983	FY 1984	FY 1985	FY 1986
Crawfordsville	18,700	44,000	51,400	48,300
Fort Wayne	28,500	34,400	54,100	53,800
Greenfield	30,900	42,000	43,700	34,500
LaPorte	25,800	50,900	49,900	85,700
Seymour	21,200	25,600	33,100	24,800
Vincennes	32,900	22,900	48,800	48,600

DBE PARTICIPATION BY CONTRACT SIZE

Table 4 lists DBE participation by subcontract size in each of 10 different contract size categories. The average DBE subcontract size for each fiscal year and the percentage increase or decrease from the previous fiscal year were as follows:

TABLE 2 DISTRIBUTION OF SUBCONTRACT AWARDS AND DOLLAR VOLUME BY DISTRICT

	Subcontract Awards								Dollar Volume $(000's)							
	FY83		FY84		FY85		FY86		FY83		FY84		FY85		FY86	
District	%	#	%	#	%	#	%	#	%	#	%	#	%	#	%	#
Crawfordsville	21.7	48	16.7	110	17.9	106	17.0	106	15.5	898	19.5	4842	19.9	5453	17.8	5124
Fort Wayne	22.6	50	14.6	96	12.4	73	15.2	95	24.6	1426	13.3	3306	14.4	3947	17.7	5110
Greenfield	18.6	41	22.8	150	29.6	175	26.8	167	21.8	1268	25.4	6293	27.9	7649	20.0	5763
LaPorte	12.2	27	17.7	116	12.2	72	10.4	65	12.0	696	23.8	5905	13.1	3590	19.3	5573
Seymour	11.3	25	13.4	88	14.0	83	13.5	84	9.1	529	9.1	2250	10.0	2744	7.2	2082
Vincennes	13.6	30	14.8	97	13.9	82	17.1	107	17.0	988	9.0	2224	14.6	3999	18.0	5201
Totals	100	221	100	657	100	591	100	624	100	5805	100	24820	100	27382	100	28853

TABLE 4 DBE PARTICIPATION BY CONTRACT SIZE, FY 1983–FY 1986

Subcontract Size	FY 83				FY 84				FY 85				FY 86			
	#	%	Value (000's)	%	#	%	Value (000's)	%	#	%	Value (000's)	%	#	%	Value (000's)	%
>$1,000,000	0	0	0	0	0	0	0	0	1	0.2	1050	3.8	0	0	0	0
750000-999999	0	0	0	0	1	0.2	965	3.9	0	0	0	0	1	0.2	852	2.9
500000-749999	0	0	0	0	3	0.5	1814	7.5	2	0.3	1286	4.7	4	0.6	2336	8.1
250000-499999	0	0	0	0	7	1.1	2270	9.0	16	2.7	5112	18.7	12	1.9	4064	14.1
100000-249999	13	5.9	1751	30.2	39	5.9	5506	22.2	46	7.8	6616	24.2	48	7.7	7756	26.9
150000-99999	17	7.7	1103	19.0	85	12.9	6118	24.6	84	14.2	6048	22.1	84	13.5	6118	21.2
25000-49999	39	17.7	1340	23.1	108	16.4	3713	15.0	95	16.1	3453	12.6	118	18.9	4187	14.5
10000-24999	67	30.3	1151	19.8	192	29.2	3371	13.6	173	29.3	2982	10.9	153	24.5	2539	8.8
5000-9999	33	14.9	300	5.2	101	15.4	705	2.8	74	12.5	526	1.9	98	15.7	667	2.3
<$5000	52	23.5	160	2.8	121	18.4	358	1.4	100	16.9	309	1.1	106	17.0	334	1.2
Totals	221	100.0	5805	100.0	657	100.0	24820	100.0	591	100.0	27382	100.0	624	100.0	28853	100.0

	Average Contract Size ($)	*Increase/Decrease from Previous Year (%)*
FY 1983	26,300	–
FY 1984	37,800	+43.7
FY 1985	46,300	+22.5
FY 1986	46,200	−0.2

If this information is examined alone, it suggests that DBEs have been taking on larger jobs because the average subcontract size has grown significantly since 1983. Nevertheless, further analysis of the data presented in Table 4 reveals that in each of the past 4 fiscal years, between 57 and 69 percent of all DBE subcontract awards were less than $25,000. This fact suggests that the majority of DBE subcontracts are still small, and that in general, DBEs do not have the ability to obtain and manage larger jobs. In the first year of the DBE program, there were no approved DBE subcontracts over $250,000. In FY 1986, there were 17. It is more important, however, to note that this figure represented 25 percent of all DBE subcontracted work for that year. This demonstrates that well-established DBEs are benefiting from the program and are beginning to undertake larger contracts.

Although an examination of the total subcontracts approved is interesting, it tends to understate the gains made by some of the more well-established minority firms. Much of the increase in DBE participation has come from new and relatively small firms that are not capable of performing and managing a large contract. This condition does not hold, however, for all DBEs in the program. Some of these companies have grown rapidly and are successfully undertaking larger projects. This growth and development was one of the objectives of the DBE program, and the data presented in this section suggest that this objective might have been met.

In summary, the average size of the DBE subcontract award has increased since FY 1983. Although a large percentage of these awards are less than this average figure, the increase in larger awards and the continued decrease in awards of less than $25,000 suggest growth in the capacity of the average DBE firm in Indiana.

DBE SUBCONTRACTS DISTRIBUTION BY CONTRACTOR

The data presented in the previous section indicated that some minority firms have grown substantially since the DBE program was implemented. These firms have experienced a dramatic increase in their annual volume of work and are continually being awarded larger contracts. Although one objective of the program was to develop DBEs into large contracting firms, a major concern throughout the country has been that the major DBE firms will become so large that in some states they will be used almost exclusively to meet the 10 percent minority goal. Opponents of the DBE program add that several minority firms across the country are getting rich, whereas the majority of DBEs are struggling to survive. Since the DBE program became fully operational in 1983, there have been at any one time some 100 firms certified by IDOH to do work on federally funded highway projects. The number of certified firms has gone above and below 100, but on average the figure has remained at or near this level. This number also includes Indiana-certified DBEs and minority firms from other states.

Table 5 gives the percentage of DBE subcontract work performed by various numbers of minority contractors in Indiana, FY 1983 to FY 1986. The data presented in this table definitely support the claim that a small percentage of DBE firms are performing most of the minority work in the state. For example, in each of the four fiscal years analyzed, 30 percent of the total DBE subcontract volume was performed by 3 minority contractors. In fact, in FY 1985, this number reached 40 percent.

TABLE 5 DBE SUBCONTRACT DISTRIBUTION BY CONTRACTOR

Number of Contractors (Cum.)	FY83		FY84		FY85		FY86	
	* %	$(000's)	* %	$(000's)	* %	$(000's)	* %	$(000's)
3	29.5	1712	32.3	8010	39.9	10920	32.2	9303
5	41.8	2428	44.7	11085	57.7	15806	42.3	12214
10	63.4	3681	67.2	16682	77.5	21223	60.4	17426
15	76.9	4462	77.8	19322	88.1	24126	76.2	20835
20	87.0	5053	83.8	20788	93.6	25630	79.6	22960
25	93.8	5445	88.2	21901	96.7	26482	83.6	24116
35	98.5	5717	94.0	23329	99.7	27303	89.1	25715
50	100.0	5805	98.0	24319	100.0	27382	93.3	26925

* Percentages and Dollar Amounts Shown are Cumulative

Closer examination of Table 5 reveals that the top 5 minority contractors have performed more than 40 percent of the DBE subcontract volume for the past 4 years, and the top 10 have performed more than 60 percent. This means that of all the DBE-approved subcontract work, considerably more than 60 percent of it has gone to 10 percent of the eligible firms. Further analysis of the information presented in Table 5 reveals that since FY 1983, 90 percent of the dollar volume of DBE subcontracts has been performed by 35 or fewer minority firms. Of this volume of work, 80 percent has been performed by 20 of fewer firms.

As mentioned previously, much of the increase in Indiana DBE participation has come from small firms that are incapable of handling larger projects. Perhaps these firms would have been able to develop and take on larger contracts if it were not for the dominance of the larger DBE firms. It appears that the existence of these large firms can make it difficult for companies that are younger and smaller (or both) to be competitive. It is important that DBEs develop and grow into successful contracting firms, but it is equally important that all minority firms have the same opportunities to grow. This does not appear to be the current situation, given that a few firms can control such a large percentage of the work. It is obvious that the DBE program has been of help to several minority firms in Indiana, but the program has met a large percentage of its goal through a rather small number of successful firms.

DBE REPEAT AWARD WINNERS

One indicator of the stability of DBE firms and markets is the degree to which DBE firms that won awards in an early fiscal year continue to win awards in later fiscal years. Another good indicator of a program that is stimulating increased participation is the degree to which increased numbers of DBE firms are being awarded contracts each year. Also of interest are the average number of subcontracts per firm and the average dollar volume per firm on an annual basis. These indicators, for all approved DBE subcontracts from FY 1983 to FY 1986, are given in Table 6.

The number of approved DBE subcontracts fluctuated considerably over the past 4 fiscal years. In FY 1983, 42 minority firms were awarded subcontracts, which averaged out to 5.3 subcontracts per firm. In FY 1984, 67 DBE firms were awarded subcontracts. On the average, each firm therefore received 9.8 awards. This dramatic increase occurred partially because FY 1983 was not a complete program year. In FY 1985, the number of DBE firms that received subcontracts dropped by 30 percent, to 47 firms. This decrease was probably due, at least in part, to the 10-percent decrease in number of DBE subcontract awards for that year. Although the number of firms that received awards dropped in FY 1985, the average number of awards per firm increased by nearly 29 percent, to 12.6 awards per firm. In FY 1986, 60 DBE firms were awarded subcontracts, representing a 28-percent increase over the previous year. However, the increased number of award-winning firms also decreased the average number of awards per firm by 17 percent, to 10.4 awards per firm.

The best indication of the stability of a DBE firm is probably its ability to win awards year after year. Although there is variation between states, the general logic is that states and general contractors cannot and usually will not make awards to firms that have previously proved to be incapable of performing the desired work. Firms that win highway awards for successive years are considered to be more qualified than firms that do not, and usually these firms perform a large percentage of the minority work done in the state. Table 6 presents the number and dollar volume of subcontract awards received by firms that won awards in any of the four fiscal years analyzed (FY 1983 to FY 1986). In FY 1983, 19 of the 42 award-winning firms (45 percent) also won awards in FY 1984, 1985, and 1986.

The significance of these data is that these 19 firms accounted for 67, 66, 65, and 52 percent of the total DBE subcontract work over the next 4 fiscal years. Also, the awards to these repeating firms increased in size during subsequent year. For

TABLE 6 DBE REPEAT AWARD WINNERS, FY 1983–FY 1986

Firms Winning	FY 83				FY 84				FY 85				FY 86			
D.B.E. Awards in:	No.	%	$(000's)	%	No.	%	$(000's)	%	No.	%	$(000's)	%	No.	%	$(000's)	%
FY 83, 84, 85, 86	19	45.2	3908	28.4	19	28.4	16437	66.2	19	40.4	17815	65.1	19	31.7	15121	52.4
FY 83, 84, 85	3	7.1	561	9.7	3	4.5	478	1.9	3	6.4	470	1.7	0	0	0	0
FY 84, 85, 86	0	0	0	0	9	13.4	3325	13.4	9	13.4	4225	15.4	9	15.0	3433	11.9
FY 83, 84, 86	3	7.1	259	4.5	3	4.5	691	2.8	0	0	0	0	3	5.0	900	3.1
FY 83, 85, 86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FY 83, 84	1	26.2	926	16.0	11	16.4	2183	8.8	0	0	0	0	0	0	0	0
FY 83, 85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FY 83, 86	1	2.4	30	0.5	0	0	0	0	0	0	0	0	1	1.7	105	0.4
FY 84, 85	0	0	0	0	3	4.5	369	2.6	3	6.4	639	2.3	0	0	0	0
FY 84, 86	0	0	0	0	1	1.5	29	0.1	0	0	0	0	1	1.7	39	0.1
FY 85, 86	0	0	0	0	0	0	0	0	8	17.0	3994	14.6	8	13.3	5547	19.2
FY 83 only	5	11.9	121	2.1	0	0	0	0	0	0	0	0	0	0	0	0
FY 84 only	0	0	0	0	18	26.9	1038	4.2	0	0	0	0	0	0	0	0
FY 85 only	0	0	0	0	0	0	0	0	5	10.6	239	0.9	0	0	0	0
FY 86 only	0	0	0	0	0	0	0	0	0	0	0	0	19	31.7	3708	12.9
Totals	42	100.0	5805	100.0	67	100.0	24820	100.0	47	100.0	27382	100.0	60	100.0	28853	100.0

example, firms that won awards in all 4 successive fiscal years averaged $206,000 per firm in FY 1983, $865,000 per firm in FY 1984, and $938,000 per firm in FY 1985. However, this figure did decrease to $796,000 per firm in FY 1986. The decrease in dollar volume per firm in FY 1986 was largely due to the increases in dollar volume experienced by repeating firms that began business in FY 1985.

The information presented in Table 6 clearly demonstrates that in Indiana, repeat award-winning DBE firms are doing nearly all the minority work. Firms that have only existed for 1 year have never done more than 4.2 percent of the total volume of subcontract work for a year. This analysis excludes FY 1986 because it is almost certain that many of the firms in this subgroup will receive awards in future years.

These data indicate that the positive impact of the DBE requirement on DBEs can be measured by factors other than the impressive growth in the number of DBE awards and volume of highway construction dollars going to DBEs that participate in the program. The data suggest that, in general, the majority of DBE firms that win awards in one fiscal year are likely to win awards in future years.

DBE SUBCONTRACT DISTRIBUTION BY TYPE OF WORK

One of the strongest complaints registered against the DBE program is that DBE firms are only entering into specialty trades that are not capital intensive. It has also been claimed that these firms are not growing and are subsequently not taking on any other type of highway work. Because the objective of the DBE program is to develop these DBE firms into successful highway contractors, this is a serious claim.

The specialty trade most frequently mentioned in discussions of new DBE entrants is guardrails. If the data presented in Table 7 are reviewed, it is obvious that this is a valid complaint in Indiana. In every fiscal year since the DBE program was implemented, more than 15 percent of all work subcontracted to minority firms has been for guardrails. In the past 2 fiscal years, this figure has grown to more than 20 percent.

The dollar volume of these awards has increased significantly over this period as well. Table 7 gives the percentage increase or decrease in the dollar volume of awards of each of the 17 categories. From FY 1983 to FY 1984, the dollar volume of guardrail awards increased by more than 40 percent. It is clear that most of this increase was due to the large increase in total dollars awarded to DBEs, but this is still a significant increase. From FY 1984 to FY 1985, the dollar volume again increased by 36 percent, and from FY 1985 to FY 1986, the volume essentially leveled off and increased by less than 1 percent. An interesting note about the volume of guardrail work is that it has increased every year since the program's inception. Further examination of Table 7 reveals that most categories of work have experienced a decline in volume at one time or another. This is not the case in the guardrail area, indicating that this is a popular task among DBE firms in Indiana.

Another common specialty performed by the minority firms is miscellaneous concrete and concrete finishing, which consists of curb and gutter work, sidewalks, slope and head-

TABLE 7 DBE SUBCONTRACT AWARDS DISTRIBUTION AND CHANGES IN DOLLAR VOLUME BY TYPE OF WORK

Type of Work	Subcontract Award Number & Dollar Volume								% Change in $ Volume		
	FY 83		FY 84		FY 85		FY 86		FY 83-84	FY 84-85	FY 85-86
	%	$(1,000)	%	$(1,000)	%	$(1,000)	%	$(1,000)			
Guardrail	14.5	840	17.2	4261	21.1	5777	20.1	5798	407.3	35.6	0.4
Misc. Conc. & Conc. Fin.	19.2	1112	12.6	3125	6.5	1784	13.1	3770	181.0	-42.9	111.3
Constr. Signs	11.6	673	8.8	2174	9.1	2481	6.1	1750	223.0	14.1	-29.5
Pavement Marking	5.0	293	5.5	1359	5.3	1443	4.0	1151	363.8	6.2	-20.2
Pipes, Sewers & Drains	3.9	225	6.1	1525	9.5	2599	10.6	3059	577.8	70.4	17.7
Bridge Work	2.8	162	3.7	924	4.5	1241	3.8	1097	470.4	34.3	-11.6
Constr. Eng.	1.5	87	1.5	364	1.5	416	2.6	745	318.4	14.3	79.1
Excavation	2.3	132	5.5	1372	3.5	959	2.6	742	939.4	-30.1	-22.6
Hauling	15.1	878	6.4	1579	6.7	1841	6.0	1745	79.8	16.6	-5.2
Reinforcing Steel	2.3	134	2.1	524	5.2	1412	9.3	2686	291.3	169.5	90.2
Seed/Sod Landscaping	3.0	174	6.3	1560	4.3	1176	2.4	691	796.6	-24.6	-41.2
Traffic Contr.	3.5	206	2.7	665	1.5	415	2.8	816	222.8	-37.6	96.6
Undersealing	0	0	9.9	2467	11.0	3017	0.2	66	---	22.3	-97.8
Conc. Mbrs. Str. Steel	4.3	250	4.2	1049	2.8	769	5.2	1492	319.6	-26.7	94.0
Fence	1.6	90	0.6	141	2.4	661	1.5	149	56.7	368.8	-77.5
Conc. Pvmnt.	1.1	66	1.7	417	1.0	274	2.9	824	531.8	-34.3	200.7
Other	8.3	483	5.3	1314	4.1	1117	7.9	2272	172.0	-15.0	103.4
Totals	100.0	5805	100.0	24820	100.0	27382	100.0	28853	427.6	110.3	105.4

walls, and other small concrete items. In FY 1983, DBEs performed more of this type of work than any other, including guardrail. The dollar volume awarded in this category has fluctuated considerably during the past 4 years, but in FY 1986, the volume was definitely higher than in any other year. In 3 of the 4 fiscal years analyzed, this specialty area has either been the first- or second-largest dollar volume business among minority subcontracted work.

Construction signs are another type of work frequently performed by DBE firms. This task has accounted for 6 to 12 percent of the total volume of minority subcontracted work during the past 4 fiscal years. As was the case for miscellaneous concrete work, dollar volume in this category has varied greatly through the years. In FY 1986, the volume decreased by 30 percent, representing the lowest level since the beginning of the DBE program.

Hauling has been a fairly stable business for minority firms throughout the past 4 years. Although hauling currently does not account for as large a percentage of total dollar volume as it did in FY 1983, its volume has leveled off and has not varied appreciably. Several firms are well established in this business and do the majority of this work.

Pavement marking is similar to the hauling business in that its total dollar volume has not fluctuated much since the second year of the program. This work has consistently accounted for some 5 percent of the total DBE work volume for each of the past 4 fiscal years. Marking is another area of construction in which there are a few firms that do the majority of the work.

Seed and sod, also known as landscaping, is another type of work frequently mentioned as being flooded with new minority firms. In Indiana, however, large volumes of work have not generally been awarded to DBEs for landscaping, except during FY 1984. Even in this peak year, the volume accounted for only 6 percent of the total amount of work. In the past 2 fiscal years, the volumes of work awarded to DBEs for landscaping have decreased by 25 percent and 41 percent, respectively.

Other categories of work listed in Table 7, such as bridge work, excavation, the placing of concrete and structural steel members, traffic control, piping, placement of sewers and drains, construction engineering, placing of reinforcing steel, fencing, and concrete pavement, have consistently accounted for the rest of total dollar volumes. The information presented in Table 7 suggests that the claim that most DBE work is performed in functions that don't require much capital is valid to some extent. Jobs such as guardrail, construction signs, and miscellaneous concrete have, in fact, made up a large percentage of the minority work performed in Indiana.

It must be noted, however, other areas of highway construction not usually associated with DBEs have displayed considerable increases in dollar volume and participation. In particular, pipe, drain, and sewer work; construction engineering; and placement of reinforcing steel have had tremendous increases in dollar volume of awards. This information suggests that some minority firms have truly benefited from the program and are learning to manage and perform larger more difficult jobs, even though many firms are content to stay specialized and perform in their traditional highway construction tasks.

CONCLUSIONS

The DBE program has been a controversial and fiercely debated topic since the January 1983 passage of the STAA. Strong opinions on this subject, combined with a shortage of relevant data, have increased the program's vulnerability to criticism. It is hoped that this paper has presented a quantitative view of the positive and negative impacts of the IDOH DBE program, with the result that the temptation to make unwarranted claims for or against the program has been reduced.

The findings of this study can be summarized as follows:

- The IDOH DBE program has increased minority participation in the Indiana highway construction industry in terms of dollar volume. In FY 1982, before implementation of the current DBE program, the total value of DBE subcontracts was a little more than $2 million. By FY 1986, this figure had increased to more than $28 million. There is no doubt that this increase in minority participation is largely due to the DBE program.
- The number and dollar volume of DBE subcontract awards have been reasonably distributed throughout the six Indiana districts.
- DBE firms are being awarded an increasing number of large contracts each year. This rise in awards suggests that the capacity of the average DBE firm is increasing. The average size of the subcontract awarded to a DBE has significantly increased.
- Repeat award-winning DBE firms in Indiana have consistently been awarded the majority of DBE dollars.
- A large percentage of the minority work in Indiana is being performed by a small group of DBE contractors. The data demonstrate that during each fiscal year from 1983 to 1986, at least 30 percent of the total DBE subcontract volume was performed by three minority contractors. Also, the top 10 minority contractors have performed more than 60 percent of the minority work over the same period. Considering that some 100 firms have been certified for minority work in Indiana at any given time in the DBE program's existence, it can be observed that 10 percent of the eligible firms, on the average, are performing more than half of the available work.
- A majority of the work performed by DBEs in Indiana is in non-capital-intensive specialty areas.
- The types of work performed by DBEs in Indiana has for the most part varied from year to year, but DBE participation in guardrail, miscellaneous concrete, and construction sign jobs has been consistently high since the program began. Recently, however, there have been dollar volume and participation increases in highway construction tasks not usually associated with DBEs.

Finally, although Section 105(f) was only one small aspect of the STAA, it has become an extremely large and complex issue in the highway construction industry; much more complex, in fact, than can be reflected in this paper. The authors believe that an individual's judgment of the DBE program depends on that person's attitude toward history and beliefs about the appropriate role of government, as well as on whether that person is a member of a group that is involved with or affected by the DBE program itself. The authors hope that the information presented in this paper will help those who must make or influence decisions on the future of the DBE program.

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