Rehabilitation Procedures for Faulted Rigid Pavement

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Faulting of transverse joints in rigid pavements generally has not been a problem in New York, but a change in load-transfer devices (LTDs) between 1960 and 1972 produced significant faulting in pavements with high-volume truck traffic. The results of an 8-year study conducted on Interstate 84 are described. Constructed in the late 1960s, I-84 is a four-lane, 23-cm-thick concrete highway with 18.55-m joint spacing. As a result of failure of LTDs and heavy commercial traffic, faulting became a significant problem in the 1970s. In 1980 a study was begun to determine the most efficient method of removing the faults. After the first 2 years of field study, it was determined that where truck traffic is heavy, it is absolutely necessary to restore load-transfer capability with retrofitted LTDs to minimize pumping and loss of support that result in faulting. In 1983 the study was extended to establish criteria for effective procedures of fault removal and load-transfer restoration. By 1985 the magnitude of faulting at joints not retrofitted was already as great as when faults had been corrected. A second phase of the study thus was initiated to evaluate the effectiveness of LTD replacement in keeping faults from recurring. Two LTDs—the University of Illinois retrofit (the double-V device) and I-beam dowel bars—were installed from 1982 to 1985, retrofitting 289 joints at various locations on I-84. Their performance was evaluated by comparing (a) the rate of faulting return, (b) magnitude of differential joint movement, and (c) distress indexes. Construction and field testing of the LTDs are described, and their effectiveness in removing faulting and restoring load transfer is compared. From the findings, rehabilitation strategies are suggested.

The New York State portion of Interstate 84 was constructed under 16 contracts let between 1962 and 1968. The pavement is 23-cm-thick portland cement concrete with transverse joints spaced at 18.55-m intervals. Each joint had a two-component, malleable-iron load-transfer device (LTD) (Figure 1). The highway is an important connector for traffic flowing to and from New England and the South—the only Interstate route in the area that bypasses the New York City area and thus a heavily used truck route. By the mid-1970s, traffic counts along its length showed annual average daily traffic (AADT) of 8,000 to 17,000 vehicles, with 20 to 32 percent trucks.

In 1976 maintenance personnel observed significant faulting problems at transverse joints in various locations on I-84; in many cases the faulting was more than 2.5 cm. After an average of 10 years of service, faulting had grown so great that trucks were driving in the passing lane to avoid the discomfort of dropping at each faulted joint. The result was a good pavement surface and bad joints.

In 1977 a task force was formed to investigate causes of the transverse joint faulting problem and determine inherent implications for future rehabilitation work. In 1978 they recommended (*1*) that

1. The pavement not be overlaid,
2. The pavement not be "slabjacked" by contract,
3. Faulted joints be milled,
4. All transverse joints be resealed when restoration or alleviation work was done, and
5. Edge drains be designed into all plans for restoration or alleviation work.

In 1980 a study was initiated to determine the most efficient method of removing faults. The first phase investigated two methods of removing faulting at transverse joints: (a) lifting the slabs and then filling the underlying voids in the subbase and (b) grinding the pavement surface. In 1983 the study was extended to evaluate effective fault removal and load-transfer restoration procedures. A total of 289 joints were retrofitted using various LTDs between 1982 and 1985. The restoration methods were evaluated by comparing

1. Rate of faulting return,
2. Magnitude of differential vertical joint movements (DVJMs),
3. Magnitude of differential horizontal joint movements (DHJMs), and
4. Distress indexes.

This paper contains a description of the construction and field testing of those methods, and the performance of each rehabilitation technique is documented. The work is more fully discussed in Research Report 158 of New York's Engineering Research and Development Bureau (*2*).

In jointed reinforced-concrete pavements, LTDs are provided to transfer loads applied by traffic from one slab to the next and to minimize vertical deflection at the joint. Insufficient load transfer at the joint increases the potential for faulting and pumping by magnifying vertical deflections. Because of the importance of LTDs in maintaining pavement service life, their performance has been a major concern in New York State.

Inadequate horizontal slab movement, joint lockup, concrete cracking, and loss of load transfer experienced with steel dowels led in 1960 to introduction of two-component, malleable-iron devices (Figure 1). However, these new devices proved to be less efficient than the dowels, eventually losing metal because of corrosion and wear and thus failing

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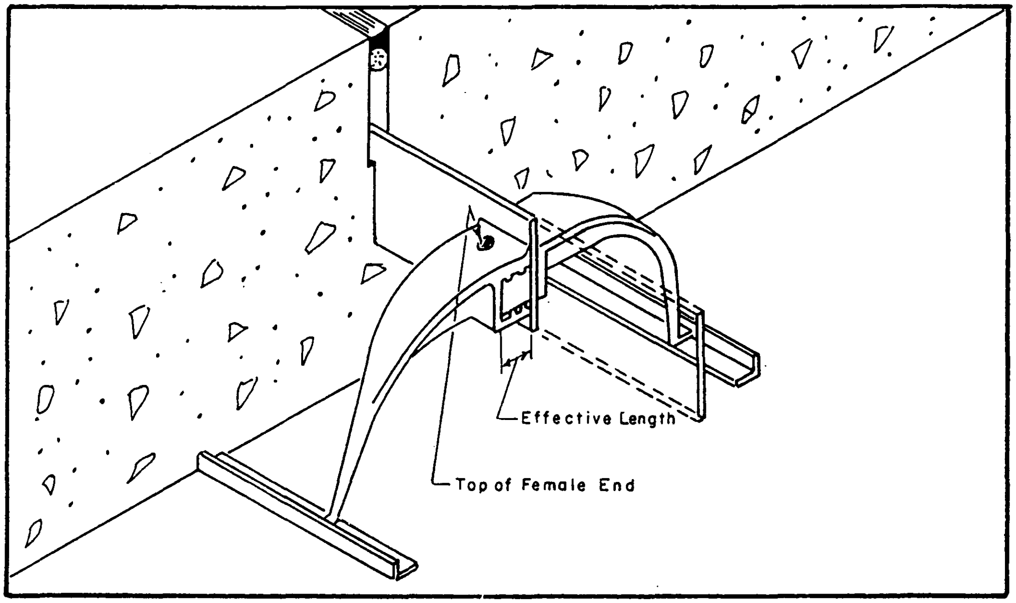

FIGURE 1 **Configuration of two-component load-transfer device.**

in load-transfer capability. As these problems became apparent, use of these devices was discontinued and plastic-coated or epoxy-coated dowels and I-beams were substituted. The problem now was how to restore load-transfer capability to the two-component devices that were reaching the stage at which they became ineffective, resulting in severe faulting and related distress.

In the past, faulting occurred slowly and coincided with other forms of distress; the general remedy was to overlay the pavement with asphalt concrete. More recently, however, the combination of relatively rapid loss of LTD efficiency and increasingly heavy truck traffic—both in volume and in weight—led to earlier and more severe faulting. Frequently the concrete slabs remained in fairly good condition, but the faulting appeared relatively early in life of the pavement. The New York State Department of Transportation (NYSDOT) began considering alternatives to overlaying the concrete. Two problems were involved: (a) repairing distress to restore riding quality and (b) developing procedures to retard recurrence of the distress.

INVESTIGATION

First-Phase Evaluations (1977)

In 1977 the task force formed to investigate I-84 pavement condition began collecting data. Several indexes of deterioration were measured—faulting, differential vertical and horizontal movements, and pavement cracking. Truck traffic data were also collected.

Faulting Measurements

All faulting data were collected in the travel lane, because field inspection showed little or no faulting in the passing lane. Faulting was measured to the nearest 1.6 mm and joint sealer condition was recorded for both lanes at more than 700 joints. Previous work had shown that faulting became noticeable to the motorist when it averaged 3.2 mm and objectionable at 4.8 to 6.4 mm. Faulting measurements are given in Table 1,

TABLE 1 **1977 Condition Survey of I-84 Transverse Joints**

Range of Faulting, 1/16 in.	Total Readings (two/joint)	Actual Average Faulting, 1/16 in.	% of Readings Showing Faulting	% of Joints With Faulting ≥ Range Shown
1.1-2.0	111	1.5	7.85	100.00
2.1-3.0	243	2.6	17.20	92.15
3.1-4.0	603	3.3	42.60	74.95
4.1-5.0	24	4.8	1.70	32.30
5.1-6.0	330	5.3	23.30	30.60
6.1-7.0	17	6.2	1.20	7.30
>7.1	86	10.3	6.10	6.10

(1 mm = 0.04 in.).

where it can be noted that 92 percent of the readings were over 3.2 mm by 1977, putting the faulting in the noticeable range and 75 percent were greater than 4.8 mm, making the faulting objectionable.

Differential Vertical Joint Movements

DVJMs of adjacent slabs across a transverse joint were measured using a truck with a 100-kN axle load, which was then the legal maximum single-axle load in New York State. Table 2 summarizes results of measuring DVJMs across transverse joints for four different faulting ranges to the nearest 25.4 μm. None of these movements were large (over 0.5 mm). Weather records showed no appreciable rainfall for nearly 2 weeks before these measurements, which meant that the pavement sections had received little infiltration of surface water. Table 2 data showed no trend between average faulting and DVJMs.

TABLE 2 Effects of Faulting on DVJM

Range of Faulting, 1/16 in.	Average Faulting, 1/16 in.	DVJMs, mils
1.1-2.0	1.7	0.3
3.1-4.0	3.5	0.3
6.1-7.0	6.6	12.1
>10.0	10.5	2.5

(1 mm = 0.04 in.).

Pavement Cracking

The number of slabs with transverse, longitudinal, and corner cracks was recorded for the faulted sections. Table 3 is a summary of the number of slabs having such cracking and corresponding ranges of joint faulting. The most prevalent type is transverse cracks, appearing in close to 25 percent of the slabs in two of the faulting ranges. No trend appears between transverse faulting magnitude and percent of slabs with transverse cracking. However, a trend is evident between faulting and years of service (Table 4). A linear relationship appears between the first three faulting ranges and years of service of about 1.6 mm of faulting annually, but for the last two ranges the relationship is nonlinear with a higher rate of deterioration.

Truck Traffic

The most important and most difficult data to obtain concern traffic to which the pavement is subjected. Performance of a pavement such as I-84 with a high volume of trucks greatly depends on that traffic; that is, the number and configuration of axle loads that the pavement experiences will control its service life. A Viatec axle-weight analyzer was used to measure traffic loading. This device determines weights of moving axles and classifies them in 900-N categories. Measurements were made at several locations where significant changes in traffic volume were expected; counts were taken for 18 to 22 hr. The data were then converted to 24-hr periods and numbers of 80-kN equivalent single-axle loads (ESALs). Total ESALs for the years in service was determined with the following equation: ESAL = number of 80-kN ESALs/truck × total truck traffic + number of 80-kN ESALs/car × (total traffic − truck traffic). Table 4 summarizes these counts and gives faulting averages. A trend appears between faulting and total axle loads, but it seems less significant than that for increased faulting with age.

Visual Inspection from Test Pit

Once faulting begins, erosion of material under the slabs and inadequate load transfer across the joint contribute to a faster rate of faulting. Deflections induced by heavy wheel loads continue to increase faulting unless corrective measures are taken. To investigate magnitude of the settlement under the slab and corrosion of the LTDs, visual inspection was attempted from a test pit. At six locations, joint assemblies were removed from the right edge of the travel lane adjoining the shoulder. Pavements were sawcut and 60- by 90-cm rectangles were removed across transverse joints to include bearing portions of the LTDs. The test showed that at joints with little or no faulting, bearing surfaces remained in good-to-excellent condition. Otherwise, either or both portions of the sleeve-and-butt devices were corroded or sheared away, eliminating part or all of the load-transfer capability. In all instances, a ridge of soil material was found directly below the joint assembly, suggesting that pumping had occurred. The neoprene joint sealers were compressed and had lost much of their original shape.

TABLE 3 Faulting, Cracking, and Years in Service

Range of Faulting, 1/16 in.	Total Slabs	% of Slabs Having Transverse Cracks	Years in Service	Total Slabs With Cracks		
				Transverse	Longitudinal	Corner
1.1-2.0	99	25	7	25	2	1
2.1-3.0	247	19	8	47	1	4
3.1-4.0	98	12	9	12	3	4
4.1-5.0	659	8	11	49	9	25
5.1-6.0	120	24	13	29	0	10

(1 mm = 0.04 in.).

TABLE 4 Faulting, ESALs, and Years in Service

Range of Faulting, 1/16 in.	Actual Average Faulting, 1/16 in.	18-kip ESALs, millions	Years in Service
1.1-2.0	1.9	4.1	7
3.1-4.0	3.8	5.0	9
4.1-5.0	4.3	6.7	11
5.1-6.0	5.9	5.2	13
6.1-7.0	6.2	7.8	13

(1 mm = 0.04 in., 1 N = 0.225 lbf).

Second-Phase Evaluations (1979–1991)

Project Contracts

Test sections for this later study involved 116 km of I-84, covering 232 lane-km of the eastbound and westbound driving lanes (Figure 2). The project was divided into five contracts:

1. Contract 1 was located near Port Jervis, in Orange County, and had a total length of 7.4 km, including 3.5 km in the town of Deer Park and 3.9 km in the town of Greenville. Rehabilitation began in June 1979 because the I-84 task force survey had previously shown that joints in the driving lane were badly faulted over most of the highway in both directions. The cause was determined to be the malleable-iron LTDs used from 1960 to 1972, the period during which most of I-84 was built. To correct the faulted pavement, various rehabilitation techniques were attempted, including full-width, full-length grinding of slabs, mechanical lifting and pump grouting, edge drains, resealing, and subsealing.
2. Contract 2 was located near Fishkill in Dutchess County on 7.66 km in the town of Fishkill. It called for a full-width, full-length grinding and subsealing with a fly-ash grout.
3. Contract 3, near the village of Ludingtonville in Putnam County, was awarded in May 1983, including 5.8 km eastbound in the towns of Kent and Patterson. It called for partial-length slab grinding at the rate of 38 cm/mm of faulting, edge drains, crushed-stone weeps, and resealing. The pavement was retrofitted with I-beam dowels and University of Illinois (UI) LTD devices (to be discussed later).
4. Contract 4 was called the "Penn-Conn" (Pennsylvania to Connecticut) contract. Awarded in May 1983, it covered all of I-84 from the western to eastern state lines, a length of 63.6 km in Orange County, 27.55 km in Dutchess County, and 15.10 km in Putnam County, with a total contract length of 106.25 km.
5. Contract 5 was used for administrative convenience to describe installation and monitoring of a group of improved mechanically precompressed retrofit LTDs supplied by the Dayton-Superior Corporation (manufacturer of the Illinois LTDs). As a result of early failure of previous retrofit LTDs

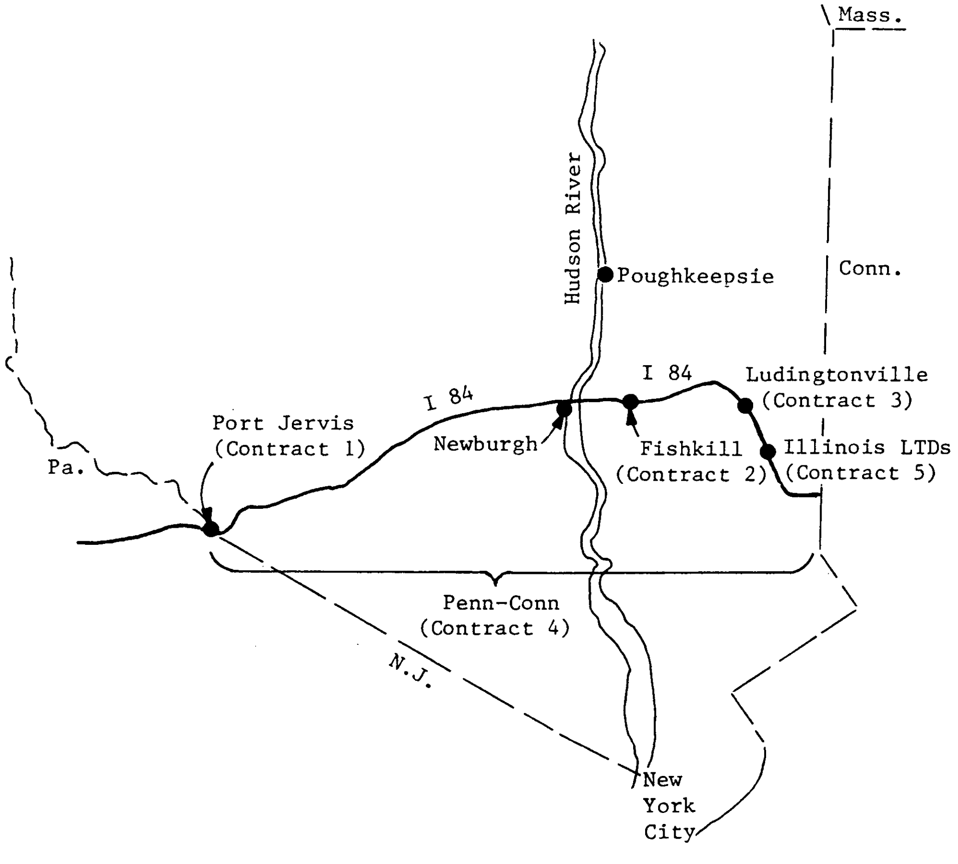

FIGURE 2 Locations of I-84 contracts and test sections.

of the Illinois design, the manufacturer developed a mechanically compressed version to replace it, which was to compensate for the wide joint openings experienced in winter. In 1985, 100 of these factory-compressed LTDs were installed, four per joint.

Rehabilitation Procedures

Fault Removal Without Restoration of Load Transfer For the first part of this later study two procedures were used to remove faulting at transverse joints without trying to restore load transfer across the joints: (a) lifting the slabs and then filling the underlying voids in the subbase and (b) grinding the pavement surface. The first method was achieved by lifting the slabs mechanically using several lifting procedures tested in the field. After the slabs were raised to the height of the adjoining slabs, a cement grout was pumped beneath them (*1*). The second method was grinding the pavement surface with a drum consisting of closely spaced diamond sawblades. The desired longitudinal profile was maintained by carrying the drum in an extended wheelbase. A vacuum-collecting device picked up the cooling water and fine particles during grinding. These two methods effectively reduced the magnitude of faulting without attempting to treat its cause. One problem encountered using lifting was that the slabs settled below the desired level when the jacks were released, forcing grout (thought to have set) from beneath them along the sides and into the transverse joint. Experience also showed that when grout is used to jack slabs, it is difficult to determine when all voids are filled and support is adequate.

Retrofitted LTDs In the second part of the study, two devices were installed and evaluated: University of Illinois (IU) LTDs [epoxy-coated (E), stainless steel (S), and precompressed (C)] and epoxy-coated I-beam dowel bars. The Illinois devices (Figure 3) were placed either three or four per joint. The retrofitted I-beam dowel bars (Figure 4) were in two configurations, four or eight per joint. Installation of the Illinois devices involved drilling a 15.25-cm core hole across the joint, applying polymer primer, inserting the device, and backfilling the hole with polymer concrete; the transverse joints were sawcut to remove the fiberboard bond breaker and form a sealer reservoir. The procedure for the I-beams consisted of making longitudinal grooves (slots) at least 7.6 cm wide and 46 cm long, preparing the slots using the same procedures as for the Illinois devices, installing the I-beams,

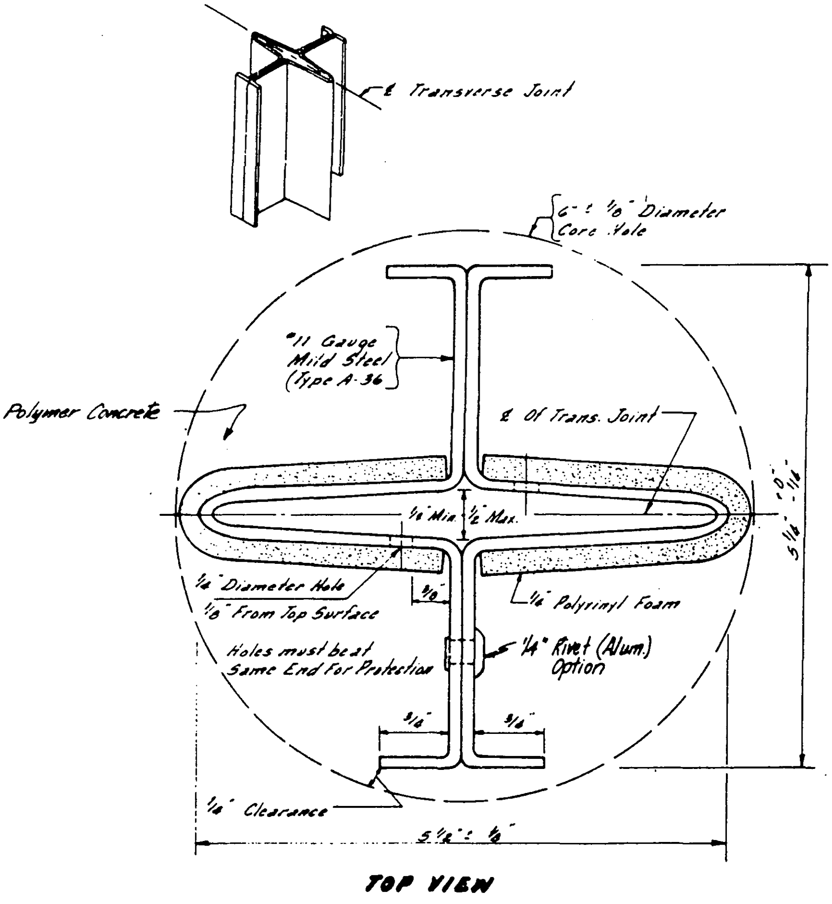

FIGURE 3 Configuration of University of Illinois double-V retrofit LTD (1 mm = 0.04 in.).

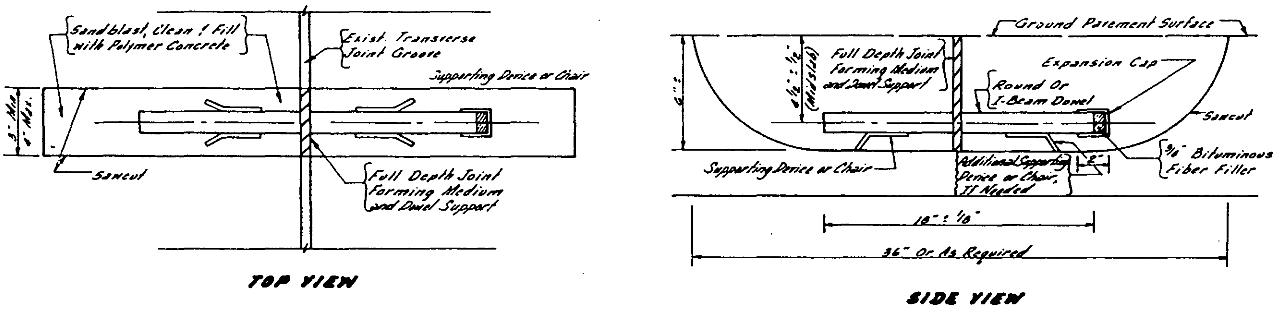

FIGURE 4 Configuration of I-beam retrofit LTD (1 mm = 0.04 in.).

filling the slots with polymer concrete, and sawcutting the transverse joints. Construction for these two LTDs followed two NYSDOT specification items [Contract for F.A. Project I-84-1 (I-84), March 3, 1983, Items 18502.3401 and 18502.3402] and was documented by Bernard (*3*). Spacing and orientation of the double-V and I-beam devices as used in this study are shown in Figure 5. They were installed while traffic was maintained in adjacent lanes, and the retrofitted lanes were opened to traffic after the polymer concrete cured for about 2 hr.

RESULTS AND DISCUSSION

Faulting

Because faulting was the major cause for the poor functional performance of I-84, all rehabilitation techniques studied were focused on its correction. Because of concern that too much concrete would be removed by grinding, it was decided to limit grinding to sections where average faulting was less than 2.5 cm and to lift joints that had greater faulting. However, for some joints exceeding this limit, grinding was permitted for uniform sections. Grinding and lifting effectively reduced the magnitude of faulting but failed to restore load transfer. Figure 6 shows faulting from 1980 to 1987 before and after grinding. Grinding removed all faulting in 1980, but by 1985 average faulting was larger than before grinding. Fault return at joints that were lifted was about equal to that at joints that were ground. Final faulting at lifted joints was greater than that at ground joints, lifting having left some faulting (both positive and negative) that contributed to greater fault return.

Epoxy-coated Illinois (IUE) retrofit LTDs were installed in four joints in August 1982, an operation that was labor-intensive and time-consuming. It was hoped to gain experience installing the new devices and then monitor their performance. Average faulting for three- and four-Illinois-LTD installations (3UI and 4UI) was compared using a *t*-test; no significant difference was found. Thus, 3UI and 4UI were combined into a single Illinois group. Figure 6 compares these three approaches and shows the effectiveness of LTDs in retarding fault recurrence.

The Ludingtonville project (Contract 3) was specifically designed to solve the long-term faulting problem. To do this, the project scope was changed on the basis of information obtained during construction as well as postconstruction evaluation of the first two projects and availability of funds. The first two projects had included grinding the entire pavement, subsealing, underdraining, and sealing joints. In contrast, this contract called for partial grinding in the passing and driving lanes, selective subsealing, selective underdraining, sealing

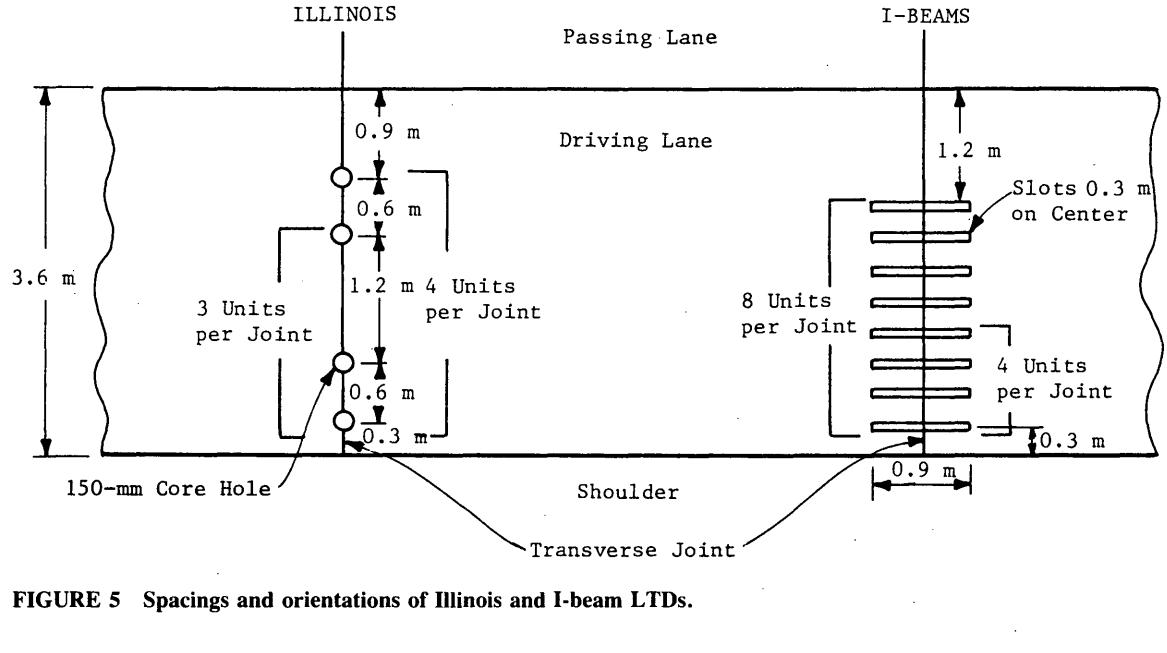

FIGURE 5 Spacings and orientations of Illinois and I-beam LTDs.

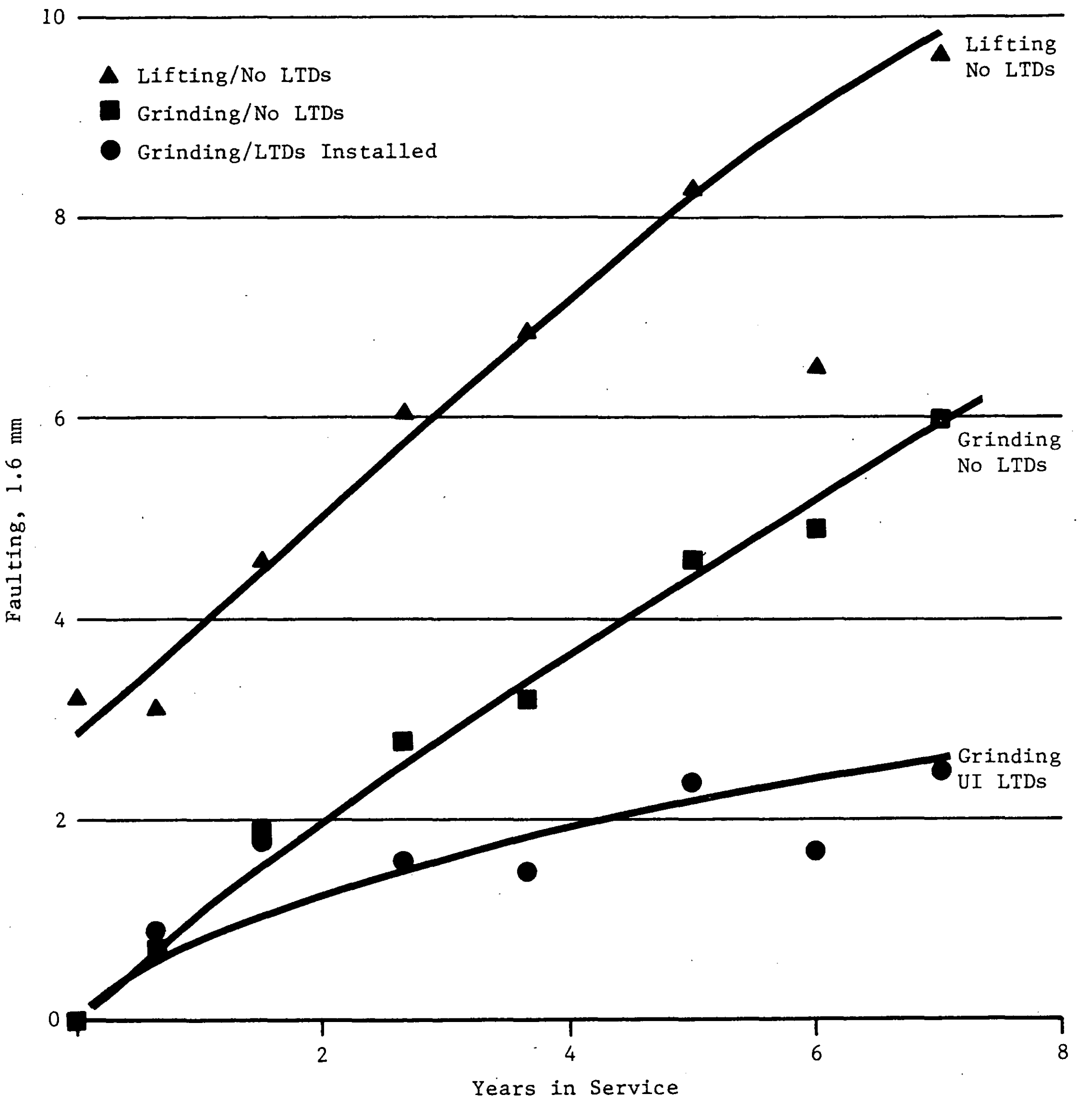

FIGURE 6 Contract 1 faulting with and without LTDs.

joints, and retrofitting LTDs. As in the previous two projects, construction was very difficult and labor-intensive.

Statistical analysis of Contract 3 faulting data showed no significant difference between 3UIE and 3UIS joints, which were thus combined for analysis into a single 3UI group. Four LTD groups could then be compared: 3UI, 4UI, four I-beam, and eight I-beam. Figure 7 summarizes faulting before and after grinding. In a comparison of the 3UI and 4UI joints, the former performed better, with an annual fault return of less than 0.8 mm. Paradoxically, the 4UI performed worse, with an annual fault return of 1.9 mm. Inadequate compaction of polymer concrete and improper aggregate gradation were two construction and materials problems noted, which caused poor performance of the 4UI joints.

The Penn-Conn project (Contract 4) had the same objectives as Contract 3, including partial slab grinding (38 cm horizontally per millimeter of fault), joint sealing, and retrofitting Illinois and I-beam LTDs along the entire highway length (except the road near Ludingtonville treated under Contract 3). Driving and passing lane joints with more than 4.8 mm of faulting were to be ground. To preserve earlier test sections at Port Jervis and Fishkill, several groups of joints were not to be ground even if faulting equaled or exceeded 4.8 mm. Annual survey results showed that performance of joints with retrofitted LTDs varied significantly from joints without them. In general, faulting of joints without LTDs had an annual return of about 2.4 mm compared with less than 1.6 mm for those with LTDs.

In Penn-Conn Contract 4, as at Ludingtonville (Contract 3), no significant difference was observed between the epoxy and steel Illinois LTDs, and they were combined into a single 3UI group. Penn-Conn faulting data for 3UI and 4UI were compared using a *t*-test; no significant difference was found. These two types had annual fault returns of about 1 mm after more than 3 years of service. Penn-Conn faulting data are shown in Figure 8.

In a comparison of the performance of the four and eight I-beam joints, the latter performed better, but the results also showed no proportionality between number of LTDs and annual fault return values. At Ludingtonville, increasing the

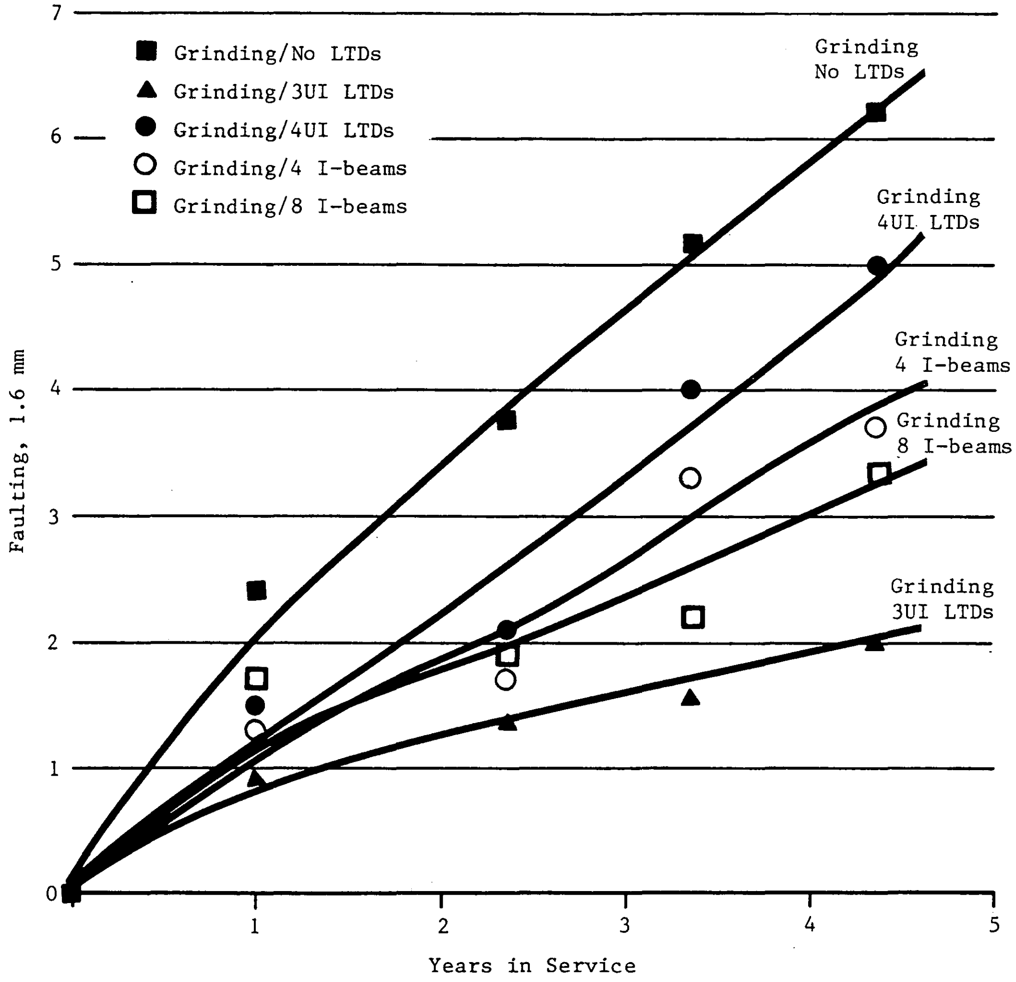

FIGURE 7 Contract 3 faulting with and without LTDs.

number of LTDs by 100 percent (from four to eight I-beams) improved performance by only 7 percent, from an annual fault return of 1.36 mm to 1.2 mm. In Contract 4 the same increase in total LTDs accounts for a 33 percent improvement, from an annual fault return of 1.06 to 0.67 mm. For the Illinois devices, the 33 percent increase in number of LTDs (from three to four) had no noticeable effect on performance. Quality of the patching material seemed to have the greatest effect on performance of Illinois LTDs.

In 1985, 100 factory-compressed Illinois LTDs were installed, four each in 25 joints in the eastbound lanes just east of Ludingtonville. Overall, this device performed better than any other tested, with an annual fault return of 0.42 mm, although only the first 2½ years of service was monitored.

Life-Cycle Cost Analysis

A simplified analysis compared cost-effectiveness of Illinois devices and I-beams. Five treatments were considered: joints with three or four epoxy-coated or stainless steel Illinois devices, joints with four precompressed Illinois devices, and joints with four or eight I-beams. A 4 percent discount rate was used to compute life-cycle cost, using the following costs associated with rehabilitation work:

Retrofit (per mile)	*Cost/Lane-Mile ($)*
Illinois device (each)	13,840
Dowels (each)	17,300
Grinding	23,252
Resealing	43,306

Life-cycle costs reported here were based on two failure criteria: faulting index and distress index. These were selected on the basis of the assumption of a proportionality between (a) faulting and performance and (b) distress and performance. For faulting it was assumed that a joint failed when average faulting reached 6.2 mm. For distress, if 50 percent of the LTD system showed such distress as cracking or debonding, the joint was considered to have failed. A rating scale from 0 to 100 (with 100 a perfect pavement) was used in computing faulting and distress indexes. Threshold values for both indexes were set at 70. The equations are as follows:

$$\text{FI} = 100 - 30 \times (\text{millimeters of faulting} \div 6.4)$$

$$\text{DI} = 100 - 30 \times (\text{percent cracked area} \div 50)$$

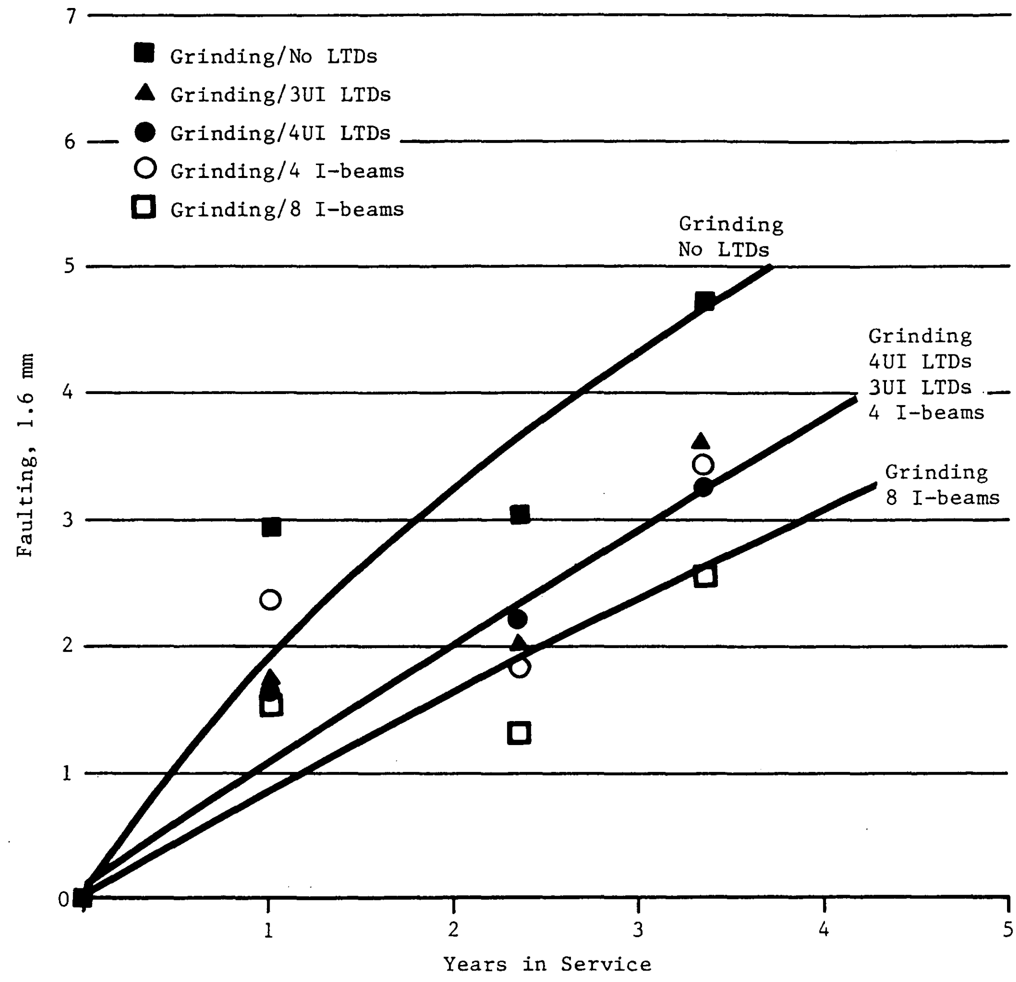

FIGURE 8 Contract 4 faulting with and without LTDs.

Contract 3 (Ludingtonville)

For Contract 3, faulting and distress indexes were used to determine the life of the various treatments. Based on the field data, the estimated life associated with the four treatments (*2*) for an FI of 70 was as follows (each treatment type includes grinding and subsealing):

Treatment Type	*Years in Service*
3UI	8
4UI	3
Four I-beams	5
Eight I-beams	6

Using the present worth method and the costs shown in the previous section, the results indicated that 3UI was the most cost-effective treatment, followed by four and eight I-beams, with 4UI last.

For a DI of 70, the years in service were as follows (each treatment type includes grinding and subsealing):

Treatment Type	*Years in Service*
3UI	3.5
4UI	2
Four I-beams	4
Eight I-beams	6

Using the present worth method and the same costs, the results again indicated that 3UI was the most cost-effective treatment, followed by four and eight I-beams, with 4UI last.

Contracts 4 and 5

For Contracts 4 and 5, faulting was the only factor used in determining the life of the various treatments. Besides the four treatments discussed for Contract 3, a fifth, the precompressed Illinois device (UIP), was included for the faulting analysis. Estimated years of service associated with those five treatments were as follows (each treatment type includes grinding and subsealing):

Treatment Type	*Years in Service*
3UI	4
4UI	4
4UIP	6
Four I-beams	4
Eight I-beams	5

The results indicated that 4UIP was the most cost-effective, followed by 3UI, 4UI, and four I-beams, with eight I-beams last.

Subsealing

This procedure restores the structural integrity of slab support by filling voids and providing an even surface. In Contract 1 (Port Jervis), subsealing with limestone grout was inadequate. Angularity of the limestone increased the mixture's viscosity, reducing its ability to flow freely beneath the slabs. This could have caused uneven support for the slabs, resulting in poor performance. Contract 2 (Fishkill) called for subsealing the entire project with a fly-ash grout, which flowed more freely than the limestone grout at Port Jervis and consequently performed far better.

Fishkill faulting data (grinding and subsealing without retrofitting LTDs) were compared with Penn-Conn data (grinding without LTDs) to investigate effectiveness of subsealing in retarding faulting recurrence. Since construction and material qualities were adequate at Fishkill and both contracts were without LTDs, the comparison is technically correct. At Fishkill after 6 years of service, the magnitude of faulting was 7.85 mm, with an annual fault return of 1.32 mm versus Penn-Conn with 7.6 mm of faulting and an annual fault return of 2.16 mm after almost 3½ years. This indicates that subsealing, done properly, does reduce fault return.

Differential Vertical Joint Movements

In this study DVJM values were directly measured using a truck with a 100-kN single-axle load. Since with this method the deflections of the approach and leave slabs are unknown, load-transfer efficiency could not be computed. The magnitude of the DVJM values thus may result from such other factors as humidity, temperature, and aggregate interlock, but not necessarily from load-transfer efficiency. DVJM values were used here to compare degree of load transfer between adjacent slabs for the different procedures tested, using engineering judgment to account for environmental conditions.

At Port Jervis (Contract 1), DVJM was measured at transverse joints before and after LTD installation. On the average, DVJM values changed from 660 μm at 19 C without retrofitted LTDs to 162 μm at 12 C with them, indicating good load transfer.

Distress Survey and Construction Problems (Contract 3)

During the surveys each LTD system was visually inspected after installation. The concern was to establish whether LTD system performance was affected solely by the devices themselves or by other factors (such as quality control during construction and quality of patching material). The types of distress recorded were circle and hairline cracks, crushing of the patch over the retrofit device, and debonding between patching material and old concrete.

Polymer primer and polymer concrete were used to bond the retrofitted Illinois and I-beam devices to the concrete slab. Dowel performance in bonding was good, with no I-beam debonding found 10 months after installation. A 16 percent debonding rate, however, was recorded for the Illinois devices. After a review of construction procedures, it was determined that poor polymer concrete consolidation and insufficient primer adhesion were the primary reasons for the high debonding rate. It was concluded that under no circumstances should polymer primer should be used on a wet concrete surface.

A field inspection on October 19, 1983, showed that 8 of 85 Illinois LTDs were displaying cracks at joints between polymer and old concrete. By October 26, the number had increased to 24. A follow-up inspection on November 14 indicated that about 40 were showing cracks. Coring revealed that the polymer concrete was not consolidated and that many voids existed between LTD flanges and the core hole walls. In 1984 a condition survey reported that 46 of 304 Illinois LTDs were showing cracks, with 44 of these 46 failing on the leave slab. Thirty of those 46 had been placed on the first day, the same day that wrong aggregate size and wrong type of primer application brush were noted.

To compare effectiveness of the LTD systems in preventing fault recurrence, it was necessary to include in the analysis the quality of construction materials and quality control during construction. The latter was assessed by computing the percent of LTDs showing distress. If quality control and material quality are the same for both LTD types, it thus is technically correct to compare them on the basis of fault return alone. Figure 7 shows faulting for the 4UI and 3UI LTDs. An erroneous conclusion could be drawn from this graph if distress is not considered. It is reasonable to expect that 4UI LTDs will perform far better than 3UI LTDs if both are subjected to the same number of stress repetitions. However, looking at the fault return rate, the 4UI has a higher rate than the 3UI but more failures, reflected by their poor performance. Data collected for the 4UI thus cannot be used to quantify effectiveness of only the LTD, but rather the entire LTD system, since poor construction practices and material quality were found to control its behavior.

Long-term performance of a load-transfer system depends on adequate performance of all its components. For retro fitting, these include

1. Construction quality control,
2. Good patching material quality,
3. Sound concrete slabs, and
4. Adequate load-transfer devices.

The system can be represented by a series of models. Failure of any component causes the system to fail. This model is a reasonable and convenient approximation of actual performance of a load-transfer system. For example, the patching material component has the reliability function *Ri*(*t*). Then the probability that the system will survive to time *t* is the probability that all the components simultaneously will survive to time *t*. Probability of system survival is the product of the individual probabilities of survival. The reliability function of the system is

$$R_{\text{system}} = R_{\substack{\text{construc-}\\\text{tion}\\\text{quality}\\\text{control}}} \times R_{\substack{\text{good}\\\text{patching}\\\text{material}}} \times R_{\substack{\text{sound}\\\text{concrete}\\\text{slabs}}} \times R_{\substack{\text{adequate}\\\text{LTDs}}}$$

Differential Horizontal Joint Movements

For a joint to perform adequately, its LTDs should accommodate expansion and contraction movements due to temperature change. If horizontal movement is restricted, slabs may crack. In this study, DHJMs were measured to determine if LTDs under consideration allowed horizontal expansion and contraction at joints. DHJM data (*2*) indicate that all LTDs in this experiment did permit horizontal movement.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations can be drawn from these results:

1. Interstate 84 restoration proved that concrete pavement joint retrofitting is appropriate when slabs are in good-to-excellent condition and distress is mostly due to LTD deficiencies at the joints. On the other hand, when a pavement has lost its structural integrity, retrofitting is not recommended.
2. Total traffic loading is the major factor that accelerates or decelerates failure. This study proved that retrofitting is essential to retard fault recurrence when a pavement is subjected to such heavy traffic loading as there is on I-84.
3. The faulting mechanism implies that voids are present under the leave slab. Thus, if there is faulting, subsealing is recommended before any LTDs are placed, to prevent a rapid breakup of the slab. However, careful attention to construction practice is important because insufficient grout may not reduce deflections and too much grout could easily result in more broken slabs by providing an uneven support. Excessive grout also fills the transverse joints, which may cause blowups.
4. Other researchers (*4*) have indicated that at least four dowels should be used in each wheelpath for adequate load transfer between slabs. However, results from this study indicate that using fewer than four dowels in each wheelpath may be satisfactory. The gain in performance by using four rather than two dowels per wheelpath was not significant. Additional field experimentation is needed to determine the optimum combination of size and spacing.
5. Patching material for the I-beams was found to be less critical than for the Illinois shear devices.
6. Results of life-cycle cost analyses indicate that Illinois LTDs are the most cost-effective method of load-transfer restoration if good construction quality control and good quality patching material are provided.

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