INNOVATIVE CONCRETE PAVEMENT DOWEL DESIGN GUIDELINES
November 2008

Introduction

For nearly one hundred years, dowel bars have been used in concrete pavements as a means to bridge vehicle loads across adjacent slabs. It is commonly known that dowels can increase pavement performance considerably, particularly in circumstances where heavy traffic or poor soils are present.

However, while many facets of pavement engineering have advanced in recent years, dowel design continues to be conducted as it has for decades. Although modern analytical methods now allow us to optimize the shape, size, and spacing of dowels to accommodate site-specific conditions, highway engineers and specifiers continue to employ “standards and specifications” that have been repeatedly demonstrated to be overly conservative in most cases.

Given the increasing cost of construction materials – including steel – seemingly small measures such as the reduction of even one dowel per joint can compound into significant cost savings overall. As long as measures are taken to ensure that pavement performance is not compromised, these cost savings can benefit the owner-agency as they seek out the most efficient use of their budgets.

The purpose of this document is to demonstrate how rational analysis techniques can be used to better understand the response of concrete pavements that employ alternative dowel designs. To facilitate implementation of these techniques, a simple software tool has been developed and described herein. The software is termed Dowel Comparison Analysis and Design or DowelCAD.

DowelCAD 2.0 Software

Version 2.0 of DowelCAD was developed for ACPA and is built off an application previously developed for American Highway Technology.

The DowelCAD software consists of two modules that work independent of each other. The first assists the pavement engineer with determining various joint responses to varying dowel size. As illustrated in Figure 1, there are seven inputs: dowel spacing, concrete elastic modulus, slab thickness, slab support reaction modulus (k-value), joint opening, wheel load, and tire pressure. Each of these inputs is used in a series of calculations previously derived by Timoshenko, Westergaard, Skarlatos, Friberg, Colley & Humphrey, and Ioannides. The result are predictions of various load transfer efficiency metrics, along with the predicted dowel bearing stress at both the critical corner and edge dowels. Predicted values are updated in real time and presented in the format of a table that cross-references a range of round and elliptical dowels.

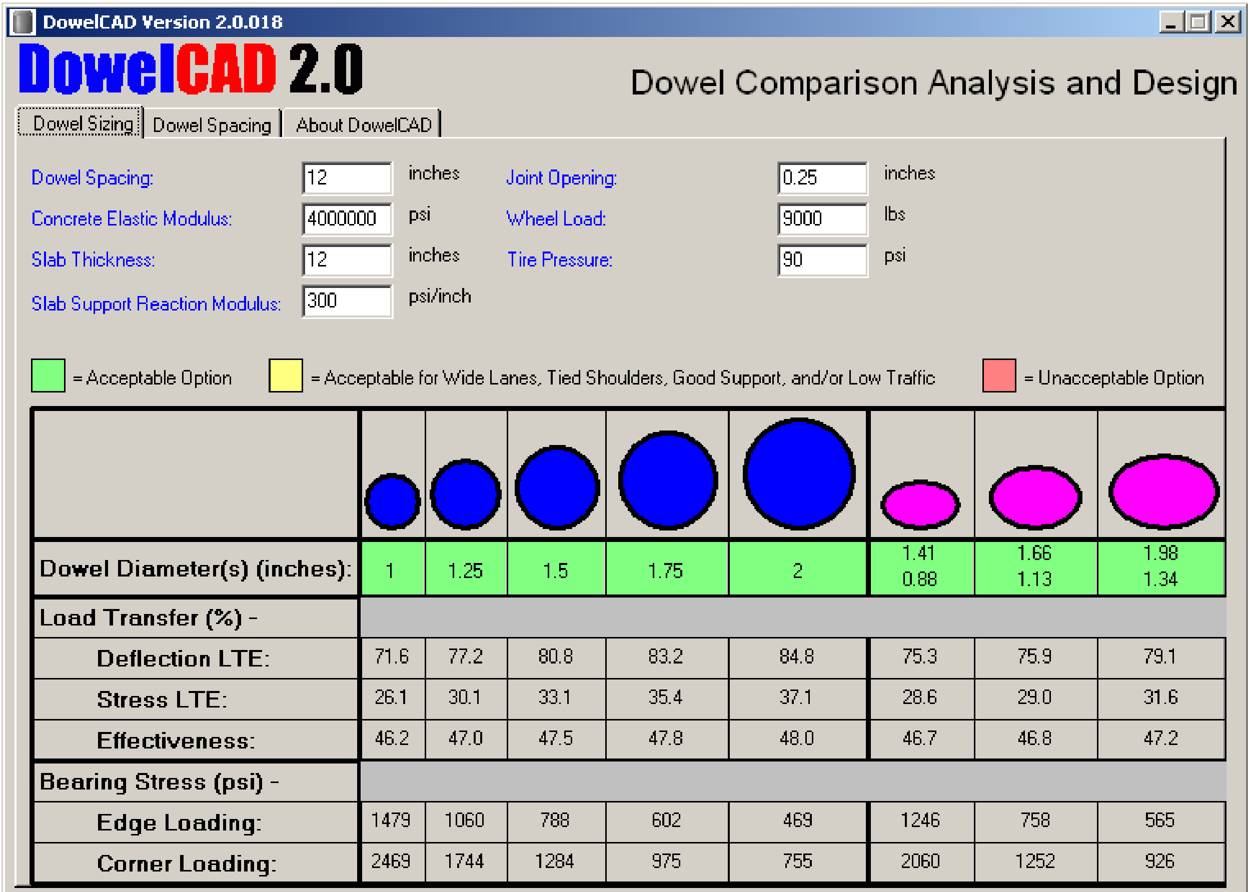


Figure 1. Screen Capture of the Dowel Sizing Module in DowelCAD.

To further assist the user in interpreting the results, a color-coded system was adopted for identifying three levels of risk. In developing this system, guidance for acceptable, marginal, and unacceptable levels of deflection load transfer efficiency were derived from the 1993 AASHTO Guide for Design of Pavement Structures. Similar guidance for bearing stress was based on work published by ACI Committee 325. The resulting a red-yellow-green classification system is defined as follows:

- GREEN – dowel size/shape options that are acceptable based on criteria for both deflection load transfer and dowel bearing stress.
- YELLOW – a combination of dowel size/shape where the deflection load transfer is within the range of 50 to 70% and/or the bearing stress is in the range of 3000 to 4500 psi. In either case, the selected dowel size/shape can still be deemed acceptable if one or more of the following is true:

1. The traffic loads are away from the pavement edge or have improved edge support (either by a widened lane, use of tied shoulders, or tied curb & gutter);
2. Support beneath the slab is stable and of high quality; and/or
3. Truck traffic levels are low.

- RED – deflection load transfers that are below 50% and/or bearing stresses in excess of 4500 psi will trigger this condition; the corresponding dowel size/shape is not recommended.

The second module in DowelCAD 2.0 assists the user in assessing the impact of dowel spacing. The theoretical basis is described later in this document. As illustrated in Figure 2, the user is presented with the various options for dowel spacing as described in this report. After selecting the dowel size of interest, calculations are made of the various pavement responses including peak dowel bearing stress, slab edge stress and deflection, and slab corner stress. These are listed and plotted on the screen, along with an indication of the difference relative to the baseline case. To assist the user in interpreting the results, a graphical representation of the various spacings are shown on the screen, and updated in real-time. A simple calculation of the percentage of steel (dowels) that are reduced by the alternate design is also provided.

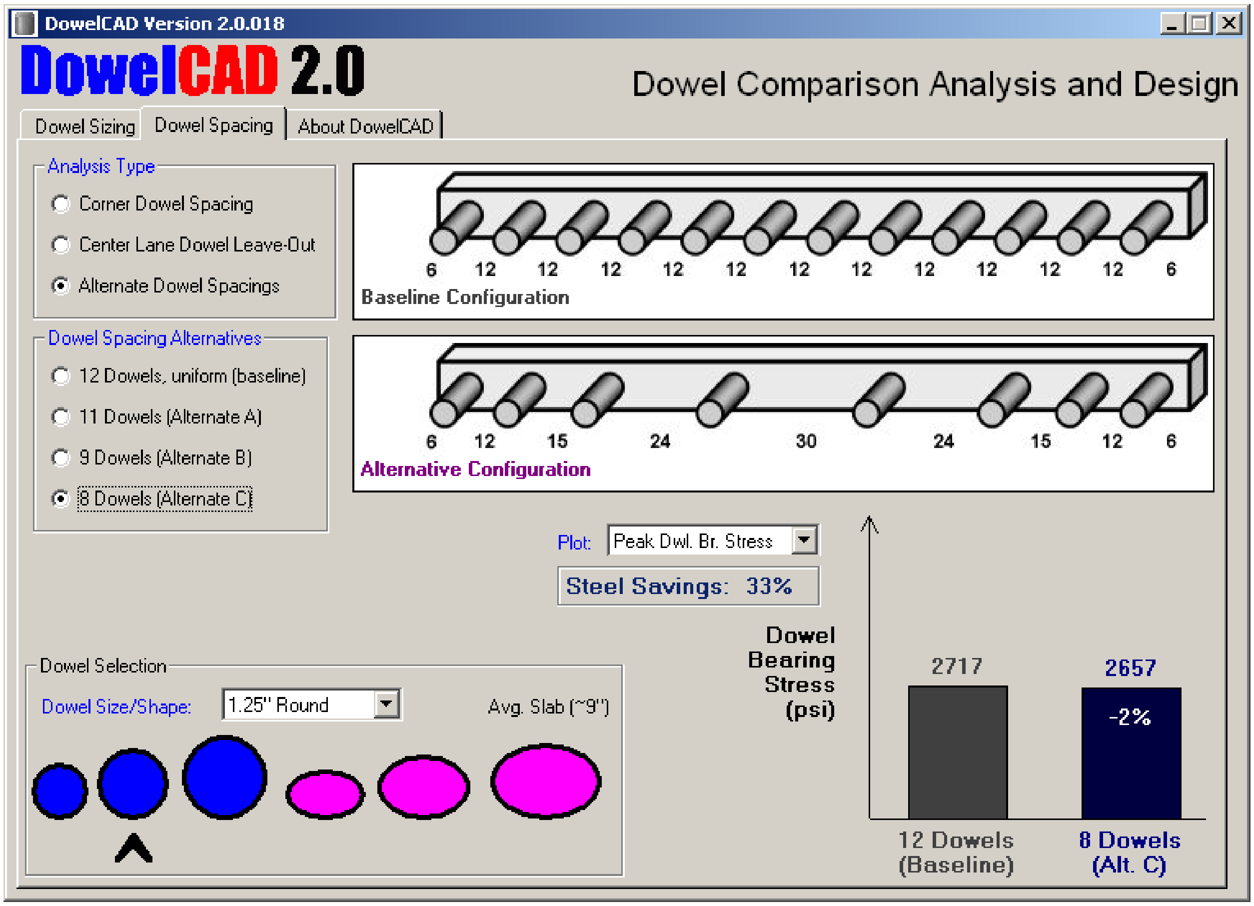


Figure 2. Screen Capture of the Dowel Spacing Module in DowelCAD.

It is recommended that emphasis be given to the *relative* change in the pavement responses (in terms of percent deviation from baseline). However, *absolute* values of the pavement responses can also be used as an indicator of risk, as long as the user recognizes that the prediction is based on a number of key assumptions (found in the "About DowelCAD" tab). Dowel Bearing Stress, for example, can be assessed using the same Red-Yellow-Green thresholds described previously. Predicted slab stresses can also be used with any number of fatigue models that are commonly used to predict pavement life.

Dowel Spacing Analysis Methodology

This section reports on the development of three analysis methods that describe the impact of using non-traditional dowel spacings. These include:

1. Alternate *corner dowel* spacings. As illustrated in Figure 3, this is defined as the distance between the center of the dowel closest to the slab corner, and the edge of the slab. Typical practice today is to specify this dimension as 6 in. (152 mm); however, alternate corner dowel spacings have been analyzed in terms of the potential impacts to pavement response.
2. Removal of *centerline dowels*. These dowels are located in the center of the lane (along the transverse joint), as illustrated in Figure 4. Traditionally, pavement engineers include dowels at equal spacings across the lane width. However, the majority of the wheel loading straddles the center of the lane, thus leading to an overly conservative design. The question addressed here is what the effect on pavement response would be if a number of dowels are removed from the center of the lane.
3. Alternative dowel designs – more specifically, *alternative spacings* along the transverse joint. Traditionally, pavement engineers specify dowels at equal spacings across the lane width. However, wheel loading is typically channelized in the lane, which leads to inherent inefficiencies with this approach. With alternative designs, some dowels are removed, while others are redistributed along the joint. Three such alternatives are shown in Figure 5.

The intent of this discussion is to present the results of a series of engineering analyses that illustrate the influence that spacing can have on various pavement responses that are commonly of interest to the pavement engineer. It will be demonstrated that as long as a dowel of proper shape and size is selected, dowels can be removed from the lane and/or redistributed without significantly affecting pavement responses of interest. Where an additional factor of safety is desired, small adjustments in thickness or strength can typically be used. The net result can be a cost savings without compromising performance.

An analytical technique termed the *finite element method (FEM)* was used to determine the impact of different corner dowel spacings. Using FEM, a variety of pavement and dowel configurations were evaluated efficiently and accurately. Similar techniques are in use today as part of *mechanistic-empirical (M-E)* pavement design methods.

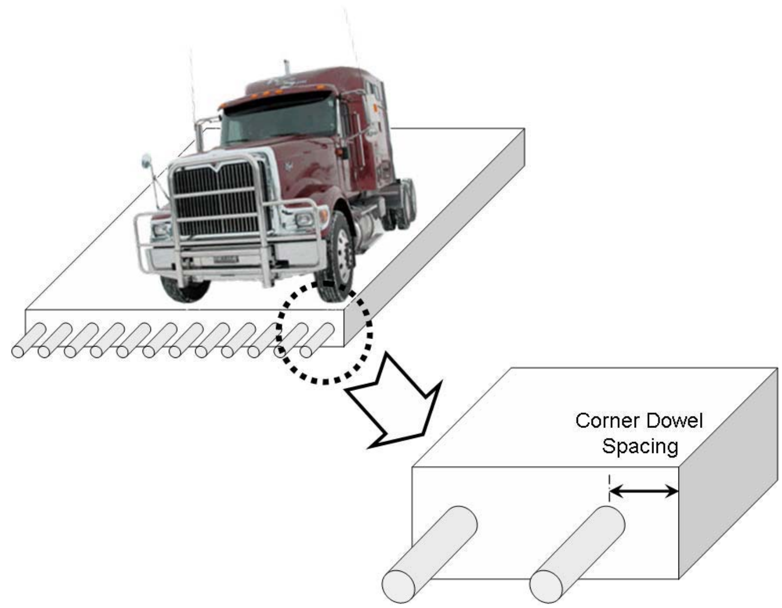


Figure 3. Corner Dowel Spacing.

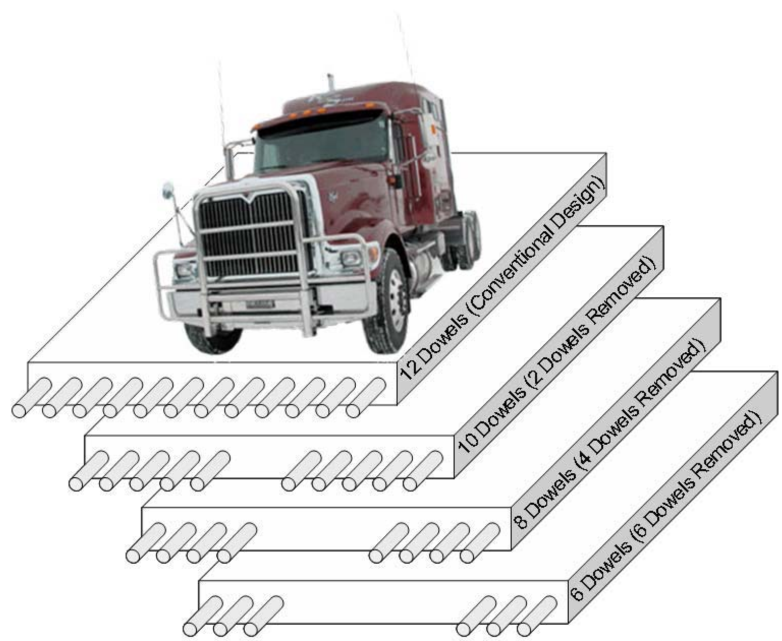


Figure 4. Removal of Centerline Dowels.

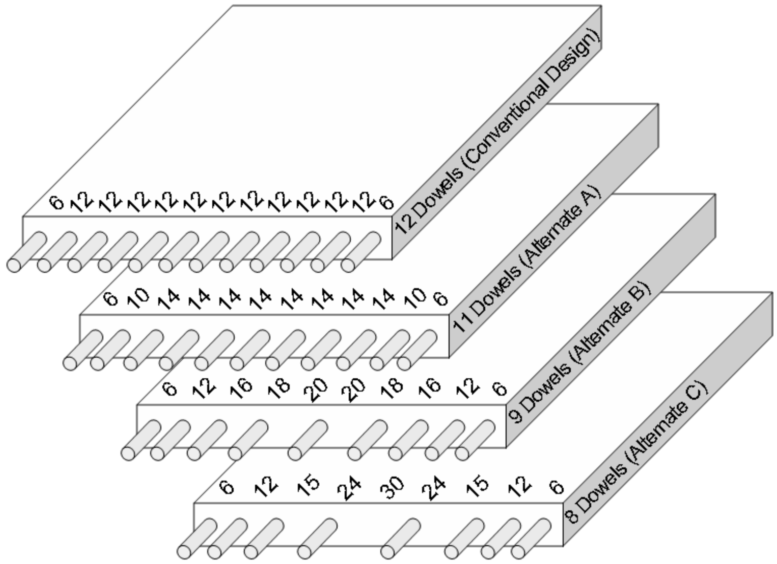


Figure 5. Alternative Dowel Spacings.

To evaluate the effects of varying the dowel spacings, a relative approach was adopted herein. To begin, a number of *analysis constants* were defined including material properties and other parameters. As shown in Figure 6, these parameters are reasonable and typical for many pavement engineering designs. In adopting a relative approach, a *baseline* pavement must be defined, which in this case includes "typical" dowel spacings in use today. This begins with a dowel at 6 in. (152 mm) from the edge, and proceeds with uniformly spaced dowels every 12 in. (305 mm) across the lane width.

Deviations from this baseline were defined for each of the three analysis types as follows:

1. Corner dowel spacings of 8, 10, and 12 in. (203, 254, and 305 mm). This dimension is illustrated in Figure 3. In all cases, the remaining dowels are spaced at 12 in. (305 mm).
2. Removal of 2, 4, and 6 dowels at the centerline, leaving a "gap" between the centerline dowels of 36, 60, and 84 in. (0.91, 1.52, and 2.13 m), respectively. This is illustrated in Figure 4.
3. Three alternatives termed A, B, and C that include 11, 9, and 8 dowels, respectively. The individual spacings for each of the dowels in these alternatives are illustrated in Figure 5.

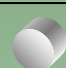
Analysis Constants	
Concrete properties:	Elastic Modulus: 4 Mpsi (28 GPa)
	Poisson's Ratio: 0.15
Dowel properties:	Elastic Modulus: 29 Mpsi (200 GPa)
	Poisson's Ratio: 0.3
Slab dimensions:	Width: 12 ft. (3.66 m)
	Length: 15 ft. (4.57 m)
Joint:	Opening: 0.1 in. (2.5 mm)
	Aggregate Interlock: None
Loading:	Load: 18 kips (80 kN) single axle
	Pressure: 100 psi (690 kPa)
	Axle Length: 87 in. (2.21 m) c-c
	Position: Outside tire adjacent to slab edge
Slab support:	Modulus of Reaction: 200 psi/in. (5500 g/cm³)
Shoulder:	None (free edge condition)

Figure 6. Analysis Constants.

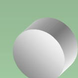
Six different slab thickness/dowel designs were analyzed in order to gauge the effect of dowel spacing on pavements that range from local roads to heavy-duty highways. These are shown in Figure 7, and include three commonly specified round dowels, along with three innovative dowels of elliptical cross sections. Unique baseline cases were defined for each slab thickness/dowel design. It should be noted that while slab curling and warping was evaluated during these analyses, it was dropped as a variable when it was found to have a negligible effect on the relative results. Dowel length was also not considered in this analysis.

Slab Thickness / Dowel Designs

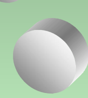
❶ 7 in. (178 mm) Thickness
1-in. (25-mm) Round Dowel



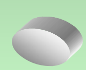
❷ 9 in. (229 mm) Thickness
1¼-in. (32-mm) Round Dowel



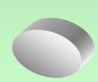
❸ 14 in. (356 mm) Thickness
1½-in. (38-mm) Round Dowel



❹ 7 in. (178 mm) Thickness
Small Elliptical Dowel (1.41/0.88 in. – 36/22 mm)



❺ 9 in. (229 mm) Thickness
Medium Elliptical Dowel (1.66/1.13 in. – 42/29 mm)



❻ 14 in. (356 mm) Thickness
Large Elliptical Dowel (1.98/1.34 in. – 50/34 mm)

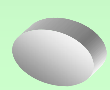


Figure 7. Slab Thickness / Dowel Cross-Section Combinations.

For each of the three analysis types, a structural analysis using the FEM model was conducted on each of 24 unique combinations of the thickness/dowel designs and dowel spacings. In each case, the pavement was loaded by a single axle with both wheels directly adjacent to the transverse joint, and one of the two wheels directly adjacent to the longitudinal joint (atop the slab corner). Figure 8 illustrates this, which represents a worst-case scenario since rarely will wheel loads coincide with the slab corner in practice. Peak stresses at the slab edge, deflections at the slab corner and edge, and the peak dowel bearing stress were all noted, as illustrated in Figure 8.

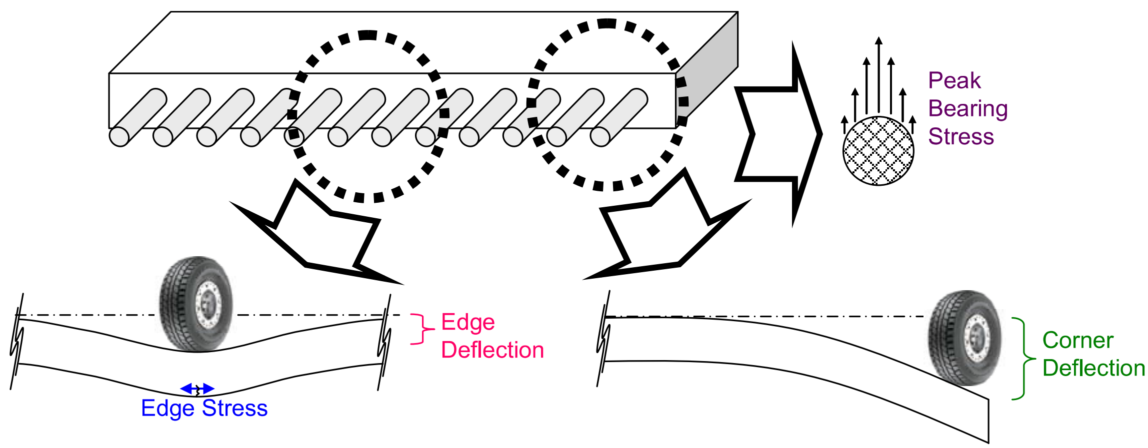


Figure 8. Slab Responses noted in Analysis.

Findings

The three analyses resulted in a number of interesting findings. The following sections highlight some of the more relevant ones.

Corner Dowel Spacing

As illustrated in
Table 1 and Figure 9, there appeared to be little effect on slab behavior as a result of repositioning the dowel away from the slab corner. Stresses at the slab edge did not increase more than 1% as the dowel spacing increased. Furthermore, the maximum slab deflection at the corner changed 2% or less compared to the baseline case of a 6 in. (152 mm) edge spacing. For thicker slabs, this change did not exceed 1%. From a pavement performance standpoint, even the most significant of these changes could be compensated for with a nominal increase in slab thickness of only 0.125 in. (3 mm), or an increase in flexural strength of 15 psi (0.1 MPa). It should be further noted that most slabs are designed with thicknesses "rounded up", and thus this compensation may already be present.

The bearing stress at the dowel-concrete interface did change, however. As expected, when the corner dowel spacing increased, it was accompanied by an increase in the peak dowel bearing stress. In all instances, the *critical dowel* – that with the highest bearing stress – was located at the corner. Compared to the baseline case, the peak bearing stresses increased 8 to 10% for an 8-in. (203-mm) spacing, 16 to 21% for a 10-in. (254-mm) spacing, and 24 to 32% for a 12-in. (305-mm) spacing. The increase in bearing stress was greater on the thicker slabs with larger dowels.

Slightly larger increases are also evident for round dowels as compared to those with an elliptical section. To compensate for increases in dowel bearing stress, a larger dowel or those with an elliptical cross section can be used. However, a slight increase in concrete strength might often yield a more economical approach.

Centerline Dowel Removal

Not surprisingly, there appeared to be little effect on slab behavior at the corner as a result of removing centerline dowels. As shown in Table 2 and Figure 10, the maximum increase in corner deflection was found to be only 2% compared to the baseline case. However, stresses and deflections at the slab edge did change more significantly. This too was not surprising since the location of the critical edge condition coincides with the location of the dowels that are removed. When two dowels were removed (leaving 10 remaining), edge stresses increase 2 to 4%, and deflections, 1 to 2%. With only eight dowels remaining, the stresses and deflections changed by 5 to 9% and 2 to 5%, respectively. If half of the dowels are removed, leaving only six remaining, the edge stresses increase from 9 to 16%, while the deflections increase 3 to 10%. For thicker slabs, the increases in slab responses did not change as much as for thinner sections. Again, small increases in thickness or strength can also be used to compensate for increases in slab response.

Along with the slab edge responses, the bearing stresses at the dowel-concrete interface also changed. The increase in these stresses was found not to be significant for the 10 or 8 dowel scenarios. However, at 6 dowels, the position of the critical dowel changes from the slab corner to the slab edge. It is at this point that the bearing stresses begin to increase more considerably. Compared to the baseline case, the peak bearing stresses with 8 or 10 dowels increase only 1 to 2%. However, with six dowels remaining, the bearing stress was found to increase up to 16% when compared to the baseline case. This effect was found to be more evident with the thicker slabs with larger dowels.

Alternative Dowel Bar Spacings

As with the previous analyses, there appeared to be little effect on slab behavior at the corner due to alternative dowel bar spacings. The corner dowel spacing remained at 6 in. (152 mm) for all of the designs, and therefore the maximum increase in corner deflection was found to be only 2% compared to the baseline case. This is shown in Table 3 and Figure 11. What may be less intuitive at first, however, was that the stresses and deflections at the slab edge did not change significantly either. The reason is that although the critical edge condition coincides with the location of where dowels are removed, those that remain have been redistributed in such a fashion to bridge and transition the loading imparted by the axle. Under Alternative A (using 11 dowels), edge stresses increased only 1%, and deflections, 1% or less. With Alternative B, including only nine dowels, the stresses and deflections only changed by 3 to 4% and 1 to 2%, respectively. Even Alternative C with only eight dowels had an increase of edge stresses ranging from 4 to 7%, while the deflections increase 2 to 3%. For thicker slabs, the increases in slab responses did not change as much as for thinner sections.

The bearing stresses at the dowel-concrete interface also changed for each of the alternative dowel spacing designs. However, of interest is that the peak bearing stresses actually decreased for each of the alternatives when compared to the baseline. It should be noted though that while the peak stress at the position of the critical dowel may have decreased, stresses in most of the remaining dowels did increase. In other words, the stresses along the joints simply redistributed. Compared to the baseline case, the peak bearing stresses in Alternative A decreased by 6 to 8%, with 1 to 5% decreases for the remaining two alternatives.

Mitigating Changes in Pavement Response

From a pavement response standpoint, some of the noted increases in slab deflection and stress are significant. However, these increases can be mitigated via small increases in slab thickness and/or strength.

Increases in bearing stress should also be considered rationally. Before taking measures to compensate for any increases that may occur, the factor of safety already inherent in the design should be determined first. If this factor is above a reasonable threshold, then alternate dowel spacings may be adequate without further modifications to the design. However, if the factor of safety is believed to be marginal or too low, several options exist.

First, an increase in the concrete strength can be specified that, in turn, will increase the bearing strength and thus the factor of safety. An increase in slab thickness will also offset increases in the slab response. A reduction in the bearing stress can also be sought by increasing the dowel diameter, or by considering an elliptical dowel. From this analysis, it was found that while the elliptical bar alternatives for each of the three pavement thicknesses showed nearly identical slab responses (stresses and deflections), there was a significant decrease in dowel bearing stress when compared to the round dowels – a decrease ranging from 17 to 29%.

Summary

The analyses described herein have been conducted using proven and accepted engineering techniques and principles. Comparisons are made of various pavement responses resulting from various dowel configurations compared to conventional dowel spacings in use today.

The following observations have been made:

1. Corner dowel spacing – while no significant changes in slab stresses or deflections are calculated, there is a notable increase in the bearing stress at the dowel-concrete interface.
2. Removing centerline dowels – some changes in slab edge stress and deflection are noted, along with increases in the bearing stress at the dowel-concrete interface.
3. Alternative dowel spacings – for each of the alternatives evaluated herein, only small changes in slab edge stress and deflection are noted. The bearing stresses at the dowel-concrete interface are virtually unchanged, and are actually noted to decrease in some instances.

In each case, rational measures should be taken to first check the factor of safety, and then to mitigate and changes in slab response only when necessary.

Table 1. Results of Dowel Corner Spacing Analysis.

Thickness and Dowel Design	Corner Dowel Spacing (in.)	Peak Edge Stress		Peak Corner Deflection		Peak Edge Deflection		Peak Dowel Bearing Stress	
		(psi)	(% chg.)	(in.)	(% chg.)	(in.)	(% chg.)	(psi)	(% chg.)
❶ 7 in. Slab, 1-in. Round Dowel	6**	271	**	0.032	**	0.013	**	4410	**
	8	271	0%	0.032	0%	0.013	0%	4770	8%
	10	271	0%	0.032	1%	0.013	0%	5130	16%
	12	271	0%	0.033	2%	0.013	0%	5487	24%
❷ 9 in. Slab, 1¼-in. Round Dowel	6**	170	**	0.024	**	0.011	**	2717	**
	8	170	0%	0.024	0%	0.011	0%	2962	9%
	10	170	0%	0.024	0%	0.011	0%	3210	18%
	12	170	0%	0.024	0%	0.011	0%	3453	27%
❸ 14 in. Slab, 1½-in. Round Dowel	6**	77	**	0.015	**	0.008	**	1542	**
	8	77	1%	0.015	1%	0.008	0%	1695	10%
	10	77	1%	0.015	1%	0.008	0%	1862	21%
	12	77	0%	0.015	0%	0.008	0%	2025	31%
❹ 7 in. Slab, Small Elliptical Dowel	6**	264	**	0.032	**	0.013	**	3641	**
	8	264	0%	0.032	0%	0.013	0%	3924	8%
	10	264	0%	0.032	1%	0.013	0%	4212	16%
	12	265	0%	0.032	1%	0.013	0%	4495	23%
❺ 9 in. Slab, Medium Elliptical Dowel	6**	172	**	0.024	**	0.011	**	1943	**
	8	171	0%	0.024	0%	0.011	0%	2122	9%
	10	172	0%	0.024	0%	0.011	0%	2300	18%
	12	172	0%	0.024	0%	0.011	0%	2478	28%
❻ 14 in. Slab, Large Elliptical Dowel	6**	77	**	0.015	**	0.008	**	1098	**
	8	78	0%	0.015	0%	0.008	0%	1209	10%
	10	78	0%	0.015	0%	0.008	0%	1329	21%
	12	78	0%	0.015	0%	0.008	0%	1445	32%

** Baseline case   1 psi = 6.9 kPa; 1 in. = 25.4 mm

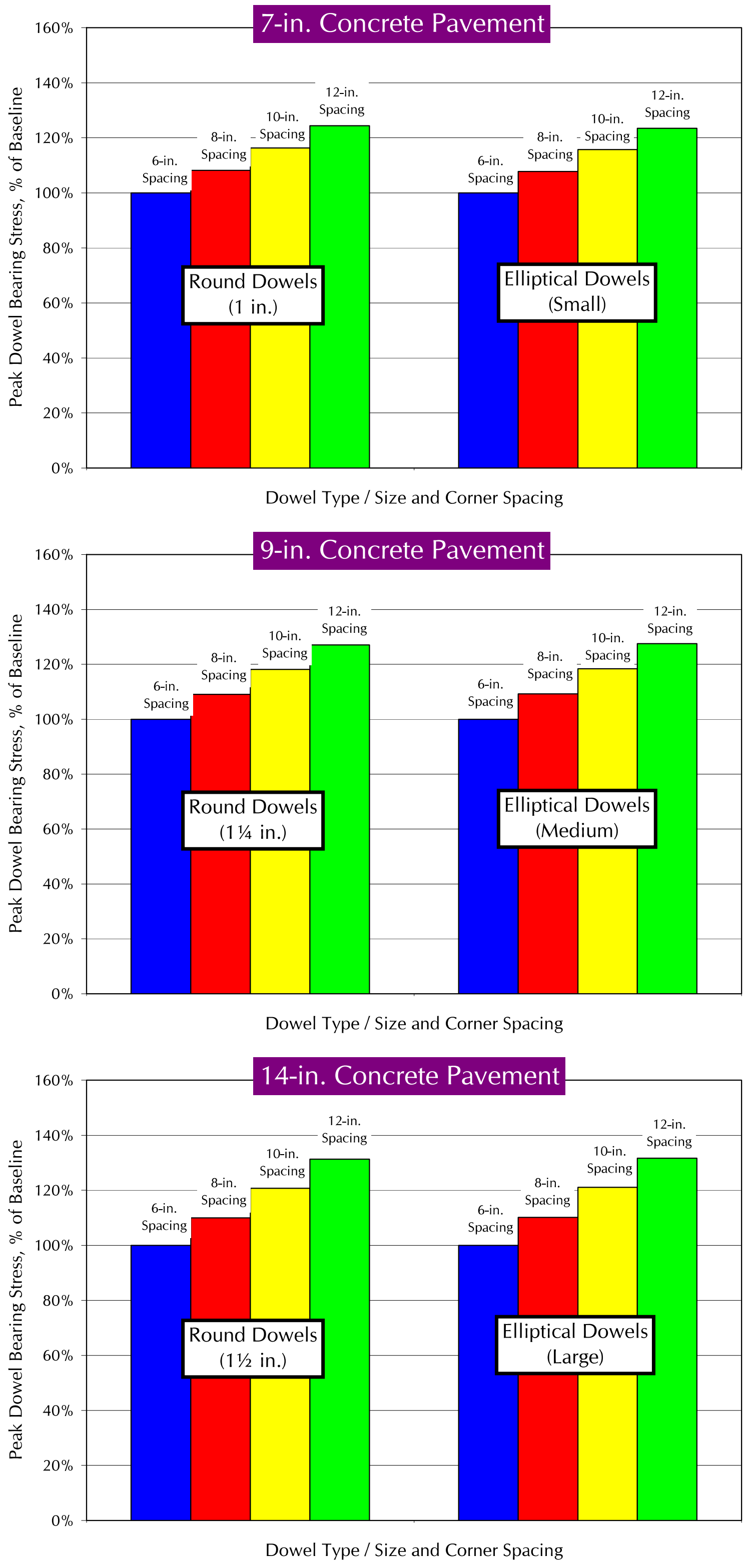


Figure 9. Slab Responses for varied Corner Dowel Spacing.

Table 2. Results of Centerline Dowel Leave-Out Analysis.

Thickness and Dowel Design	Dowels Remaining	Peak Edge Stress		Peak Corner Deflection		Peak Edge Deflection		Peak Dowel Bearing Stress		Critical Dowel Position
		(psi)	(% chg.)	(in.)	(% chg.)	(in.)	(% chg.)	(psi)	(% chg.)	
❶ 7 in. Slab, 1-in. Round Dowel	12**	271	**	0.032	**	0.013	**	4410	**	Corner
	10	281	4%	0.032	0%	0.014	2%	4439	1%	Corner
	8	297	9%	0.032	0%	0.014	5%	4482	2%	Corner
	6	315	16%	0.032	0%	0.015	10%	4648	5%	Edge
❷ 9 in. Slab, 1¼-in. Round Dowel	12**	170	**	0.024	**	0.011	**	2717	**	Corner
	10	175	3%	0.024	0%	0.011	1%	2752	1%	Corner
	8	184	8%	0.024	0%	0.011	3%	2747	1%	Corner
	6	195	15%	0.024	1%	0.011	6%	2972	9%	Edge
❸ 14 in. Slab, 1½-in. Round Dowel	12**	77	**	0.015	**	0.008	**	1542	**	Corner
	10	78	2%	0.015	1%	0.008	1%	1531	-1%	Corner
	8	81	5%	0.015	1%	0.008	2%	1570	2%	Edge
	6	83	9%	0.015	2%	0.008	3%	1769	15%	Edge
❹ 7 in. Slab, Small Elliptical Dowel	12**	264	**	0.032	**	0.013	**	3641	**	Corner
	10	274	4%	0.031	0%	0.013	1%	3665	1%	Corner
	8	289	9%	0.031	0%	0.014	4%	3695	2%	Corner
	6	307	16%	0.032	0%	0.014	9%	3839	5%	Edge
❺ 9 in. Slab, Medium Elliptical Dowel	12**	172	**	0.024	**	0.011	**	1943	**	Corner
	10	177	3%	0.024	0%	0.011	1%	1969	1%	Corner
	8	186	8%	0.024	0%	0.011	3%	1965	1%	Corner
	6	197	15%	0.024	1%	0.012	6%	2129	10%	Edge
❻ 14 in. Slab, Large Elliptical Dowel	12**	77	**	0.015	**	0.008	**	1098	**	Corner
	10	79	2%	0.015	1%	0.008	1%	1089	-1%	Corner
	8	81	5%	0.015	1%	0.008	2%	1125	2%	Edge
	6	84	8%	0.015	2%	0.008	4%	1272	16%	Edge

** Baseline case   1 psi = 6.9 kPa; 1 in. = 25.4 mm

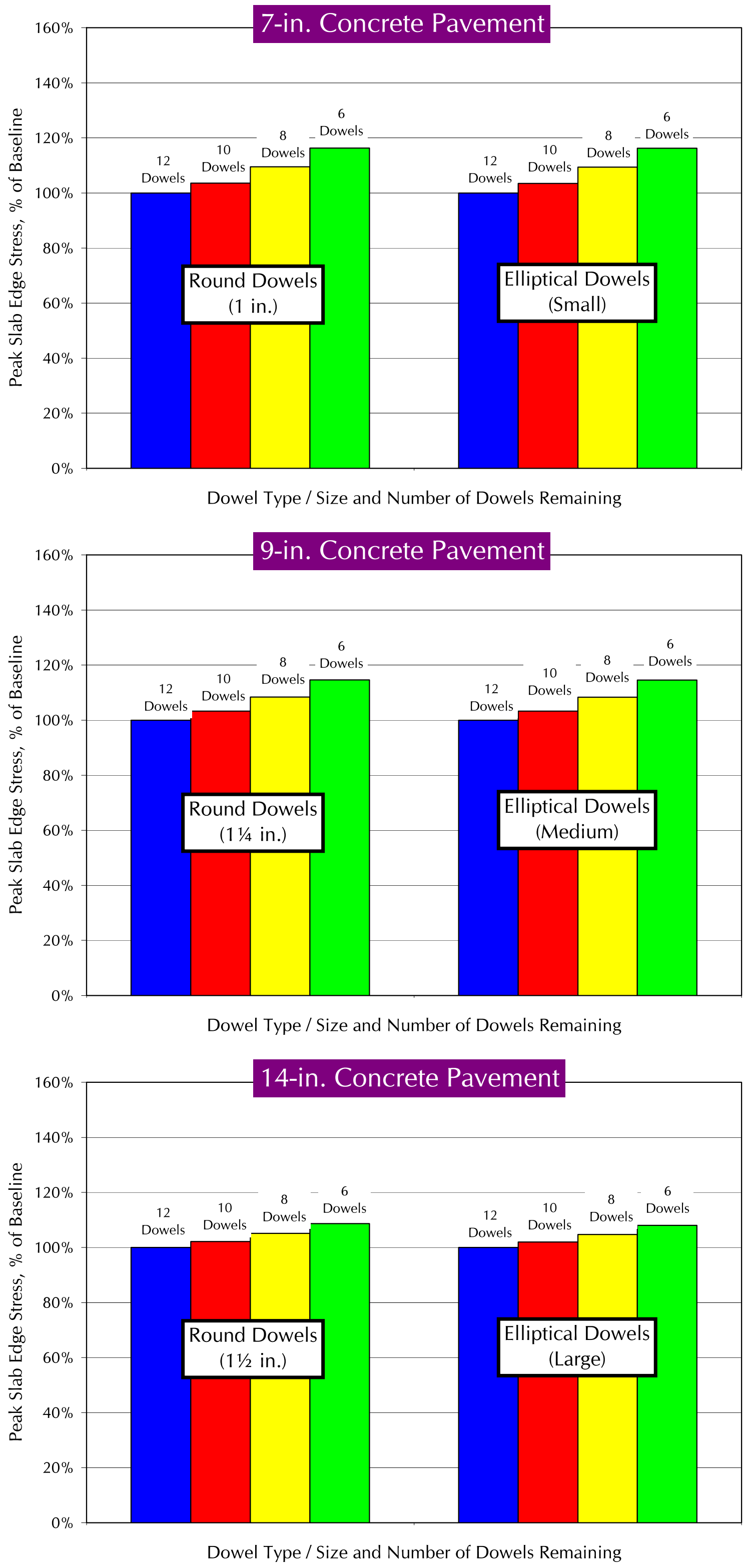


Figure 10. Slab Responses for varied Centerline Dowel Leave-out.

Table 3. Results of Alternative Dowel Spacing Analysis.

Thickness and Dowel Design	Dowel Design (No. Dowels)	Peak Edge Stress		Peak Corner Deflection		Peak Edge Deflection		Peak Dowel Bearing Stress	
		(psi)	(% chg.)	(in.)	(% chg.)	(in.)	(% chg.)	(psi)	(% chg.)
❶ 7 in. Slab, 1-in. Round Dowel	Conv. (12)**	271	**	0.032	**	0.013	**	4410	**
	Alt. A (11)	275	1%	0.032	0%	0.013	1%	4126	-6%
	Alt. B (9)	282	4%	0.032	1%	0.014	2%	4331	-2%
	Alt. C (8)	289	7%	0.032	1%	0.014	3%	4341	-2%
❷ 9 in. Slab, 1¼-in. Round Dowel	Conv. (12)**	170	**	0.024	**	0.011	**	2717	**
	Alt. A (11)	172	1%	0.024	0%	0.011	0%	2528	-7%
	Alt. B (9)	177	4%	0.024	1%	0.011	1%	2647	-3%
	Alt. C (8)	180	6%	0.024	1%	0.011	2%	2657	-2%
❸ 14 in. Slab, 1½-in. Round Dowel	Conv. (12)**	77	**	0.015	**	0.008	**	1542	**
	Alt. A (11)	77	1%	0.015	0%	0.008	0%	1416	-8%
	Alt. B (9)	79	3%	0.015	1%	0.008	1%	1469	-5%
	Alt. C (8)	80	4%	0.015	2%	0.008	2%	1460	-5%
❹ 7 in. Slab, Small Elliptical Dowel	Conv. (12)**	264	**	0.032	**	0.013	**	3641	**
	Alt. A (11)	268	1%	0.032	0%	0.013	0%	3409	-6%
	Alt. B (9)	275	4%	0.032	1%	0.013	2%	3581	-2%
	Alt. C (8)	282	7%	0.032	1%	0.014	3%	3588	-1%
❺ 9 in. Slab, Medium Elliptical Dowel	Conv. (12)**	172	**	0.024	**	0.011	**	1943	**
	Alt. A (11)	174	1%	0.024	0%	0.011	0%	1807	-7%
	Alt. B (9)	178	4%	0.024	1%	0.011	1%	1892	-3%
	Alt. C (8)	182	6%	0.024	1%	0.011	2%	1898	-2%
❻ 14 in. Slab, Large Elliptical Dowel	Conv. (12)**	77	**	0.015	**	0.008	**	1098	**
	Alt. A (11)	78	1%	0.015	0%	0.008	0%	1007	-8%
	Alt. B (9)	79	3%	0.015	1%	0.008	1%	1046	-5%
	Alt. C (8)	80	4%	0.015	2%	0.008	2%	1041	-5%

** Baseline case   1 psi = 6.9 kPa; 1 in. = 25.4 mm

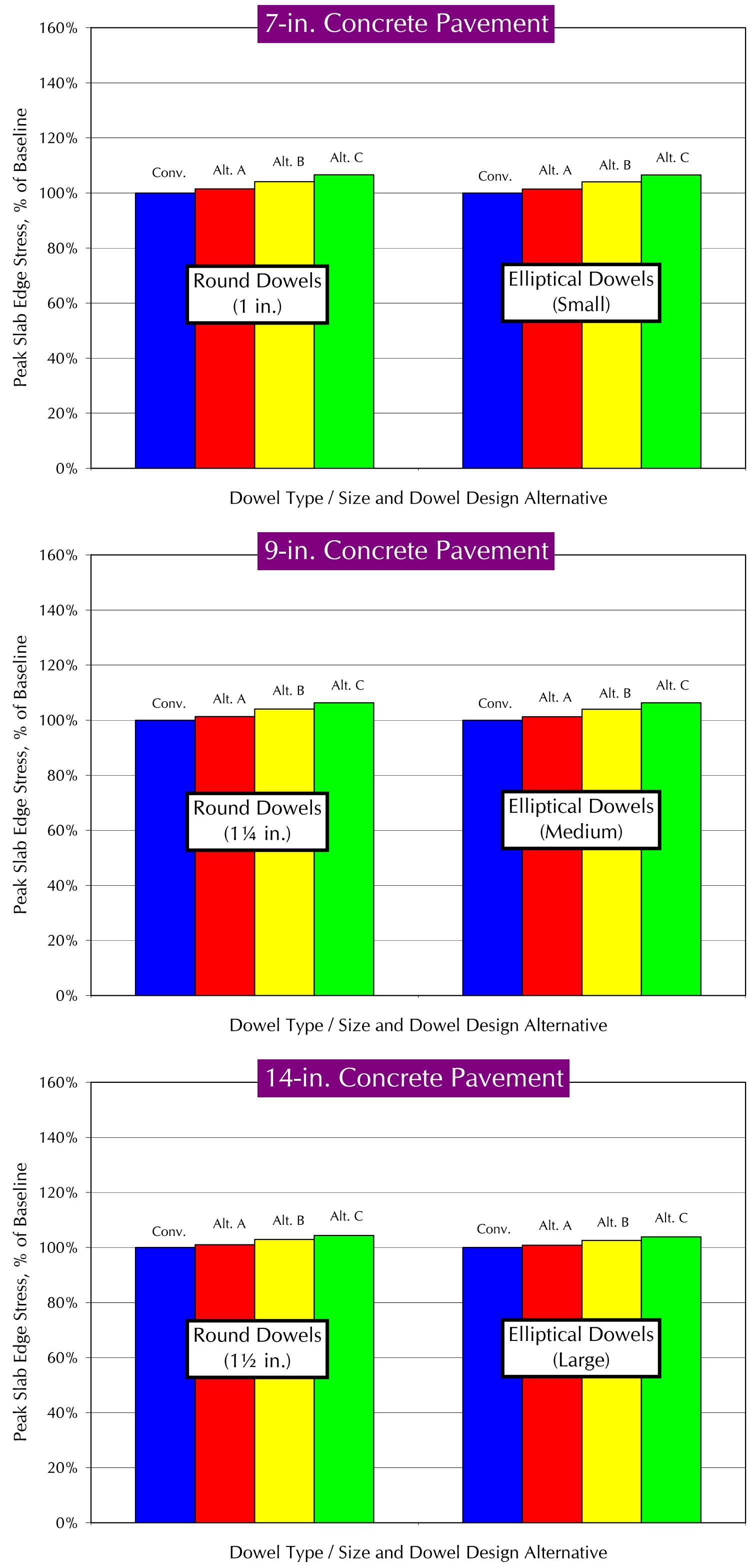


Figure 11. Slab Responses for Alternative Dowel Spacings.