PAVEMENT PUMPING CORRELATED WITH TRAFFIC LOADS

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SYNOPSIS

This paper reports one of the researches conducted by the highway research laboratories of Purdue University and the State Highway Commission of Indiana. The report supplements previous studies on pavement pumping in Indiana and the indicated correlation is developed between the increase in the amount of pavement pumping with the number and magnitude of truck loads. The report is divided into two parts, namely: (1) the presentation of data covering the extent and increase of pavement pumping for the period 1940–1947; and (2), an analysis of truck weight data obtained by the Indiana State Highway Planning Survey for the period 1936–1946. The performance-survey data indicated that the pumping problem was almost non-existent in Indiana before 1940 and that since this date, the amount of pumping has become accelerated and that more and more rigid pavements have been and are becoming affected. Approximately 6.0 percent of the rigid pavements were affected by pumping action in 1943 and in 1947 the percentage had risen to about 12.0. Even though most of the rigid pavements in Indiana are still in excellent condition, structurally, this situation cannot prevail indefinitely when, on the average for the past four years, 60 new miles of pavement pumping per year have developed and only 30 miles per year of pumping pavements were either reconstructed or repaired. The Indiana truck-weight data indicate, for the period 1936 to 1946, that the number of violations of the 18,000-pound-axle-load law has increased greatly and that the number of trucks with gross loads exceeding 40,000 lb., likewise, has increased. It was concluded that much of the pavement pumping has been caused by overloads, for the pavement designs employed, which represent a relatively small percentage of the total number of loads, and that strict enforcement of the present Indiana axle-load and gross-load laws should do much to reduce the number of future rigid pavement failures; also, that research should be initiated immediately to determine the destructive characteristics of repetitive 18,000-lb. axle loads as well as different spacing of axles carrying 18,000-lb. loads and pavement designs to withstand heavier loads. It should be noted that damage caused to non-rigid pavements and to structures by excessive loads is not included in this report since the failures take a form different from those caused by pumping action. The performance survey data indicate that the increase in the amount and the severity of pavement pumping is becoming increasingly more serious and that drastic measures will need to be taken immediately in order to protect a large portion of the present state highway system which is still in excellent condition.

For the past eight years the staff of the Joint Highway Research Project has been conducting extensive condition surveys of rigid and flexible pavements on the state system throughout Indiana (*1*, *2*, *3*, *4*, *5*, *6*).[1] The data collected from these surveys have been used to evaluate the many factors which influence the performance of a highway, including such variables as climate, soils, materials, and design.

One of the important Indiana problems revealed by these performance surveys was that of pavement pumping. This action "consists of the deflection of the slab under moving-wheel loads which results in the ejection of water carrying particles in suspension. As the action progresses, cavities develop in those areas immediately under the pumping slabs, thereby diminishing or removing the subgrade support." Pumping occurs only on rigid-type pavements, the failure of other types being of a different character. If the action continues for prolonged periods, the pavements, in heavily-traveled truck lanes, become almost

[1] Italicized figures in parentheses refer to the list of references at the end of the paper.

impassable in a matter of a few years' or, in some instances, in only a few months' time.

Since pavement pumping was almost unheard of in Indiana in the years preceding 1940, and since this action has become progressively more severe both during and after the last World War with the advent of more and heavier truck loads, it is logical that considerably research thinking should be directed to information on the number and magnitude of the heavier truck loads to be found traveling our highways. Actual truck-weight data have been collected by the Indiana State Highway Planning Survey for the years of 1936, 1942, 1943, 1944, and 1946. An analysis of some of these truck-weight data in conjunction with the information collected from the large-scale performance surveys should give some clue as to the magnitude of the axle loads, as well as the gross loads, that have been responsible for the severe damages inflicted on most of the primary roads in the state since 1940.

The purpose of this report is to determine the extent of the indicated correlation between the performance-survey data obtained on rigid pavements in Indiana and the truck-weight and truck-volume data collected by the Indiana State Highway Planning Survey. Information on the effects of heavy loads on non-rigid pavements is not included in the report.

PERFORMANCE SURVEY PROCEDURES

In the spring of 1943, a survey was made to determine the location, amount, and severity of pumping of rigid pavements throughout the State. The State Highway Commission district offices furnished maps which were marked to show the locations of all rigid pavements in distress in the respective district areas. Field inspections of each of the roads in distress were then made in company with a representative of the district office. The field data were compiled in tabular form and were plotted on a general soil and highway map of the state. The results of this first state-wide pumping survey indicated rather conclusively that certain soil areas were susceptible to pumping when crossed by roads which were used as heavy truck routes (*1*).

Several partial surveys of pumping pavements have been made since 1943, and reasonably complete progress records have been maintained on a few of the pavements, including U. S. 30, west of Valparaiso. During the war, and the year immediately following, a marked increase in the amount and severity of pumping was observed in some soil areas and on certain truck routes. In order to evaluate the factors causing the pavement damage, it was decided in the spring of 1947, to make a second complete state-wide survey of the rigid pavements in the State.

Before the survey was initiated, each district office was asked to prepare a map showing the roads which should be included in the field inspection trips. All six districts submitted this information promptly. The maps were used to plan the field trips. Whenever practicable, a representative of the district office took part in the inspection.

The procedures followed in obtaining the pavement-pumping data in 1943 and in 1947 consisted essentially of inspecting the rigid pavements in the state system and recording the severity of pumping. The early stages of pumping are usually indicated by mud stains on the pavement at joints and cracks or along the sides. Such spots are readily identifiable after periods of rainfall and as a result all pumping slabs can be logged by stationing or by speedometer reading. In these surveys, this degree of pumping was considered as "slight." As the pumping progresses the forward slab in the direction of traffic becomes displaced vertically downward in relation to the adjacent slab and the resulting "fault" produces roughness in the riding characteristics of the pavement. These faults can be measured and logged and the resulting data can be used as an index of performance. In the third stage of pumping, the amount of faulting increases, the pavement breaks and cracks, and the resulting pieces frequently become tilted or "turned on end."

During the 1947 survey, a fourth type of pavement distress was recognized, namely faulting of a rigid pavement slab at a joint or crack on a sand subgrade. The final type of distress was that of pumping through resurface materials which had been placed on a previously pumping pavement.

In 1941, some preliminary surveys were made on a number of rigid pavements in Indiana, notably on S. R. 67 (*7*). This particular project was surveyed from the Illinois-Indiana state line to the Indiana-Ohio state line and at the time of the survey no noticeable pumping was to be found.

PLANNING SURVEY TRUCK-WEIGHT DATA

The truck-weight data were obtained by the Indiana State Highway Planning Survey at 20 trucks at each station for a period of eight hours once a year. This 8-hr. period was from 6 a.m. to 2 p.m.; weighings were made for a total of four hours in each direction. Most of the surveys have been made during the month of August and approximately at the same date

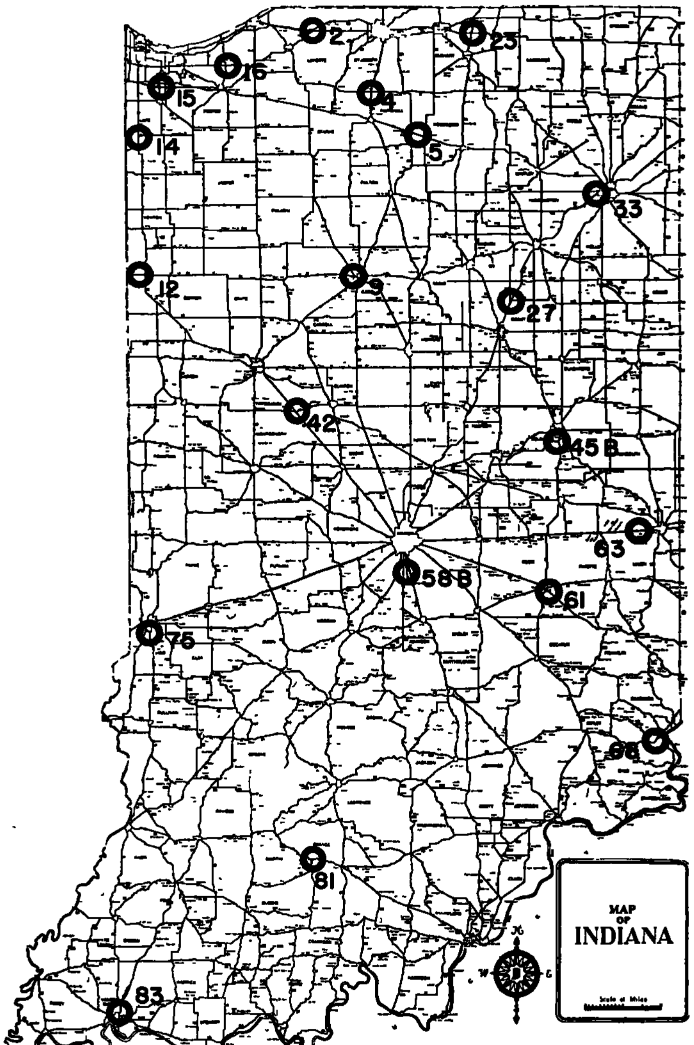

Figure 1. Location of Truck Weighing Stations

special loadometer stations located throughout the state (Fig. 1). Truck weight surveys were made at 20 stations during the years of 1936, 1942, 1943, 1944, and 1946. A survey consisted of counting all vehicles and weighing each year for each station. The number of trucks thus weighed is a very small portion of the yearly traffic. During a 24-hr. survey in November 1946, at Station 15 on U. S. 30, 1319 trucks were counted while 244 were weighed during the 8-hr. period from 6 a.m. to 2 p.m. This would indicate that about 18.5 percent of the total daily truck traffic would be weighed during a survey of a loadometer station.

No steps of any kind toward enforcement of legal weight restrictions were taken during these surveys so that, at least to a certain extent, the data obtained may be considered representative of the actual traffic. It is recognized that, even though no legal action was taken against violators of load laws, drivers of some overloaded vehicles may have avoided the weighing stations upon learning that trucks were being weighed. This factor would make the estimate of heavy gross weights and axle loads too low. However, it has been observed that the truck traffic is a higher proportion of the total traffic during the night-time hours, so that this percentage is, in all probability, low.

RESULTS

Table 1 shows the summary of the pavement pumping by State Highway Commission existed in 1943 and again in 1947. Tables 2 to 7 inclusive present the detailed information on the severity and amount of pumping by roads and by State Highway Commission districts. In considering the summary data (Table 1) it is to be noted that 243.4 miles of pumping were logged in 1943. Since that time 117.5 miles of the 1943 pumping pavements have been corrected. Despite the fact that this large mileage has been repaired there still remains in 1947, 324.9 miles of pumping, thus showing 199.0 miles net increase in total pumping since 1943. To this figure can be added that of 47.8 miles of faulted pavements on sand which occurred on heavily-traveled truck routes thus making a total of 246.8 miles of net increase, including the faulted pavements—an increase of slightly more than 100 percent over the 1943 figure.

Data on classification of pumping by roads is shown in Tables 2 to 7. It is to be noted that the Greenfield District shows the greatest increase in the number of miles of pumping (61.8 miles) followed closely by Seymour (58.4 miles). However, the Seymour District has a very low mileage of severe pumping (9.7 miles) in contrast to the LaPorte District which has 44.9 miles of severe pumping and no slight pumping. In the LaPorte District the 1943 survey shows 78.5 miles of pumping and it is this district which has corrected the greatest number of miles since that time (38.0 miles).

On S. R. No. 2 west of South Bend, on U. S. No. 41 in the Calumet Region, on U. S. No. 12 near Michigan City, and on U. S. No. 30 east of Valparaiso, 47.8 miles of pavement were logged where definite faulting had occurred at joints, or in some instances, at cracks. These pavements are all located on sand subgrades, some of which have a high-water table.

A portion of the data shown in Tables 2 to 7

TABLE 1
SUMMARY OF RIGID PAVEMENT PUMPING—STATE-WIDE RECAPITULATION

District	Est. Length Pumping Miles			Net Increase Pumping 1943–1947	1947 Est. Length Pumping Miles by Severity Class			Miles Faulting on Sand—not Pumping	Miles Pumping thru Resurface 1947
	1943	Corrected	1947		Slight	Moderate	Severe		
Crawfordsville	32.8	4.0	65.2	36.4	9.0	41.0	15.2	0	0
Ft. Wayne	49.8	27.5	40.4	18.1	1.1	6.0	33.3	0	0.3
Greenfield	25.5	9.3	78.0	61.8	16.8	15.8	45.4	0	0
La Porte	78.5	38.0	58.1	17.6	.0	13.2	44.9	47.8	1.9
Seymour	29.9	25.7	62.6	58.4	30.0	22.9	9.7	0	1.6
Vincennes	26.9	13.0	20.6	6.7	3.0	7.4	10.2	0	1.5
Totals	243.4	117.5	324.9	199.0	59.9	106.3	158.7	47.8	5.3

324.9 Pumping in 1947
117.5 Corrected pumping since 1943
———
442.4 Total 1947 pumping and 1943 pumping corrected
243.4 Pumping in 1943
———
199.0 Miles, net increase

324.9 Pumping in 1947
47.8 Faulting only, 1947
———
372.7 Total pavement in distress, 1947
117.5 Corrected
———
490.2 Total, including corrected pumping
243.4 Pumping in 1943
———
246.8 Miles, net increase, including faulting

TABLE 2
SUMMARY OF RIGID PAVEMENT PUMPING CRAWFORDSVILLE DISTRICT

Road No.	From	To	County	Year Built	Pv't Sect. in.	Soil	Exp. or Con. Jt.	Severity Pumping 1947	Est. Length Pumping, miles			Remarks
									1943	Cor-rected	1947	
U. S. 40	S. R. 340	Brazil	Clay	1939	9-7-9	Old drift	Yes	Moderate			6.8[a]	Severe pumping in cuts
U. S. 40	Brazil	Putnam Co	Clay	1941	9-7-9	Old drift	Yes	Slight			4.5[a]	
U. S. 40	Putnam Co.	Manhattan	Putnam	1941	9-7-9	Old drift	Yes	Moderate			1.2[a]	
U. S. 40	Manhattan	Putnamville	Putnam	1942	9-7-9	Old drift	Yes	Moderate			1.4[a]	
U. S. 40	Putnamville	S. R. 43	Putnam	1937	9-7-9	Old drift	Yes	Slight			2.4[a]	
U. S. 40	S. R. 43	Mt. Meridian	Putnam	1937	9-7-9	New drift	Yes	Slight			1.6[a]	
U. S. 40	Mt. Meridian	Hendricks Co	Putnam	1939	9-7-9	New drift	Yes	Slight			0.4[a]	Slight pumping with faulting
U. S. 40	Putnam Co	E. Stilesv'le	Hendricks	1939	9-7-9	New drift	Yes	Slight			0.1[a]	
U. S. 41	Farmersburg	Terre Haute	Vigo	1923	8	Old drift	No	Severe			2.4	
U. S. 41	Lyford	Mecca Road	Parke	1925	7	Shale	No	Severe			0.6	
U. S. 41	Rockville	Fountain Co	Parke	1925	7	Shale	No	Moderate			1.0	
U. S. 41	Warren Co	U. S. 52	Benton	1926	7	Moraine	No	Severe			0.2	
U. S. 41	U. S. 52	Newton Co	Benton	1926	7	New drift	No	Severe			6.4	
U. S. 52	Hendricks Co.	Lebanon	Boone	1923 & 1936	7 9-7-9	New drift	Part	Moderate	1.0		0.5[b]	
U. S. 52	N. of Lebanon	Clinton Co.	Boone	1924 & 1939	7 9-7-9	Moraine	Part	Moderate			11.3[a]	
U. S. 52	Boone Co	Tippecanoe Co	Clinton	1939	9-7-9	Moraine & New drift	Yes	Moderate	30.0		6.2[a]	
U. S. 52	Clinton Co.	Lafayette By-Pass	Tippecanoe	1925 & 1943	7 9-7-9	New drift	Part	Moderate		4.0	9.5[a]	Realigned and treated with cement slurry
U. S. 52	Lafayette	By-Pass	Tippecanoe	1935	9-7-9	Old drift	Yes	Severe	0.8		1.7	
U. S. 52	Laf'ette By-Pass	Otterbein	Tippecanoe	1927	9-7-9	New drift	No	Moderate	1.0		2.4	
U. S. 52	Otterbein	S. R. 352	Benton	1927 & 1934	9-7-9	New drift	No	Severe			0.3	
U. S. 52	S. R. 352	U. S. 41	Benton	1926	9-7-9	New drift	No	Moderate			0.7	
S. R. 67	Greene Co.	Spencer	Owen	1935	9-6-9	Shale	Yes	Severe			3.6	Severe pumping in cuts
Totals									32.8	4.0	65.2	Pumping, 1947
											4.0	Corrected pumping, since 1943
											69.2	Total 1947 and 1943 pumping
											32.8	corrected
											36.4	Miles—net increase

[a] Four-land (divided) pavement. Data include mileage in both directions.
[b] Three-lane pavement (Actual lengths multiplied by 1½.)

TABLE 3
SUMMARY OF RIGID PAVEMENT PUMPING, FORT WAYNE DISTRICT

Road No.	From	To	County	Year Built	Pv't Sect. in.	Soil	Exp. or Con. Jt.	Severity Pumping 1947	Est. Length Pumping, miles 1943	Cor-rected	1947	Remarks
U. S. 6	Marshall Co.	S. R. 15	Elkhart	1932	9-7-9	Moraine	No	Severe			0 8	
U. S. 6 .	S. R. 15	Noble Co.	Elkhart	1932	9-7-9	Moraine	No	Severe	0 3		0 5	
U. S. 6 ..	S. R. 9	Kend'ville	Noble	1930	9-7-9	Moraine	No	Moderate	0 5		0 4	
U. S. 6.....	Kend'ville	DeKalb Co.	Noble	1929	9-7-9	Moraine	No	Severe	0.3		0.1	
U. S. 20 ...	Angola	Ohio S. Line	Steuben	1927	7	Moraine	No	Severe			5 8	Pv't badly broken.Being repd.
U. S. 24 . .	Miami Co.	Wabash	Wabash	1929	9-7-9	New drift	No	Slight			0 2	
U. S. 24 ..	Wabash	Hunt Co.	Wabash	1929	9-7-9	Moraine	No	Severe			0 9[a]	Mod. pumping in cuts.
U. S. 24 .	Whitley Co.	Ft. Wayne	Allen	1939	9-7-9	Moraine	Yes	Moderate	5 0		5 1	
U. S. 24	N. Haven	Ohio S. Line	Allen	1930	9-7-9	Lacust.	No	Severe			2 1	
U. S. 27 ...	Jay Co.	S. R. 118	Adams	1930	9-7-9	Moraine	No	Severe			4 1	
U. S. 27 .	U. S. 6	Steuben Co.	DeKalb	1935	9-6-9	Moraine	Yes	Slight	6.0		0 9	Surveyed in 1947, but not in 1943
U. S. 27	DeKalb Co.	Angola	Steuben	1935	9-6-9	Moraine	Yes	Moderate			0 5	
U. S. 30	Warsaw	Whitley Co.	Kosciusko	1924	7	Moraine	No	Severe			4 9	
U. S. 30	Kosciusko Co.	Col. City	Whitley	1924 & 1937	7 9-7-9	Moraine	No	Severe	10.2		10 4	
U. S. 30	Col. City	Ft. Wayne	Allen & Whitley	1924	7	Moraine	No		16.0	16 0		0.3 mi. pumping thru resurfacing U. S. 24 and U. S. 30 combined traffic
U. S 30	Ft. Wayne	N. Haven	Allen	1930	9-7-9	Lacust.	No	Severe			1 7[b]	
U. S 30	N. Haven	Ohio S. Line	Allen	1923	8	Lacust.	No	Severe			2.0	
U. S. 6	Noble Co.	U. S. 27	DeKalb	1930	9-7-9	Moraine	No		9 3	9.3		Bituminous resurface since 1943
U. S. 20	LaGrange Co.	S. R. 27	Steuben	1924	8	Moraine	No		0 7	0 7		Patched by contract
U. S. 20	S. R. 9	Steuben Co.	LaGrange	1928	9-7-9	Moraine	No		0 5	0 5		Patched by contract
U. S. 20	Elkhart Co.	S. R. 9	LaGrange	1924	7	Moraine	No		1.0	1 0		Patched by contract
Totals..	....							....	49.8	27.5	40 4	Pumping, 1947
											27.5	Corrected Pumping, since 1943
											67 9	Total 1947 pumping & 1943
											49.8	pump. cor.
											18.1	Miles—net increase

[a] East-bound two lanes of a four-lane divided pavement.
[b] Three-land pavement, mileages based upon two lanes (Actual mileage multiplied by 1½).

TABLE 4
SUMMARY OF RIGID PAVEMENT PUMPING, GREENFIELD DISTRICT

Road No.	From	To	County	Year Built	Pv't Sect in.	Soil	Exp. or Con. Jts.	Severity Pumping 1947	Est. Length Pumping, miles			Remarks
									1943	Corrected	1947	
S. R. 9	S. R. 37	Marion	Grant	1926	7	New drift	No	Slight			2.0	
U. S. 27	Portland	Bryant	Jay	1933	9-7-9	Moraine & Shale drift	No	Severe	0 5 (U. S. 27, both sections)		4.1	
U. S. 27	Bryant	Adams Co.	Jay	1930	9-7-9	Shale	No	Severe			0.7	
U. S. 31	Marion Co.	Greenwood	Johnson	1941	9-7-9	Moraine	Yes	Slight			0.7	In so.-bound lanes or 4-lane div. pvt.
S. R. 37	Strawtown	S. R 13	Hamilton	1939	9-7-9	New drift	Yes	Slight			2 0	
S. R. 37	S. R 13	S. R. 28	Madison	1939	9-7-9	New drift	Yes	Slight			0 3	
S R. 37	S R. 28	Rigdon	Madison	1940	9-7-9	New drift	Yes	Slight			6.2	
S. R. 37	Rigdon	Marion By-Pass	Grant	1940	9-7-9	New drift	Yes	Slight			3.4	
U. S. 40	Indianapolis	Cumberland	Marion	1937	9-7-9	New drift	Yes	Slight			0.2[a]	Slight pumping, scattered
U. S. 40	Cumberland	Greenfield	Hancock	1934	9-7-9	New drift	No	Slight			1 0	Slight pumping in light cuts
U. S. 52	Royalton	Indianapolis	Marion	1922 & 1935	8 9-7-9	Moraine	Part	Severe	0.5		16.9[b]	
S. R. 67	S. R. 44	Hendricks Co.	Morgan	1940	9-6-9	Shale	Yes	Moderate	0.5		5 8	
S. R. 67	Hendricks Co.	Indianapolis	Marion	1934 & 1939	9-7-9	New drift	Part	Slight			0 6	
S. R. 67	Indianapolis	Post Road	Marion	1935	9-7-9	New drift	Yes	Slight			0.4[b]	
S. R. 67	Post Road	Hancock Co.	Marion	1935	9-7-9	New drift	Yes	Moderate	2 0		4 9[b]	
S. R. 67	Marion Co	Madison Co.	Hancock	1936	9-7-9	New drift	Yes	Severe	3.0		6 7[b]	
S. R. 67	Hancock Co.	S. R 9	Madison	1936	9-7-9	New drift	Yes	Moderate			5.1[b]	
S. R. 67	S. R. 3	Jay Co.	Delaware	1928	9-7-9	New drift	No	Severe	15 0		2 8	
S. R 67	Delaware Co.	Portland	Jay	1929	9-7-9	Moraine & Shale Drift	No	Severe			12.7	
S. R. 67	Bryant	Ohio S. L.	Jay	1928	9-7-9	Shale drift	No	Severe			1.5	
S. R. 52	S. R. 121	S. R. 1	Franklin	1930 & 1933	9-7-9	Shale	No	Resurf.	4.0	4.0		Bituminous resurfacing since 1943
Totals.									25 5	9.3	78.0	Pumping, 1947
											9.3	Corrected pumping since 1943
											87.3	Total 1947 and 1943 pumping
											25.5	corrected
											61.8	Miles—net increase

[a] Four-lane pavement. (Actual lengths multiplied by 2.)
[b] Three-lane and four-lane pavement. Mileage based upon two lanes.

TABLE 5

SUMMARY OF RIGID PAVEMENT PUMPING, LA PORTE DISTRICT

Road No.	From	To	County	Year Built	Pv't Sect. in.	Soil	Exp. or Con. Jt.	Severity Pumping 1947	Est. Length Pumping, miles			Remarks
									1943	Corrected	1947	
S. R. 2	U. S. 20	South Bend	St. Joe	1942	9–7–9	Org. Sand	Yes	Faulted				Faulted, but not pump., 19.0 miles.
U. S. 6	Lake Co.	S. R. 49	Porter	1929	9–7–9	Lacust.	No	Resurf.	3.5	3.5		Bit. resurf., 0.1 miles pump.
U. S. 6	U. S. 31	Elk Co.	Marshall	1932	9–7–9	Moraine	No	Severe	6.0	6.0	0.1	Short locations of severe pump. E. of U. S. 31. Bit. Resurf.—Walkerton to U. S. 31, since 1943.
S. R. 8	U. S. 41	Cr. Point	Lake	1933	9–7–9	Sh. Moraine	No	Moderate			0.1	
U. S. 20	Gary	S. R. 49	Porter	1943	Conc. Resurf.	Lacust.	Yes	Resurf.	10.0	10.0		Conc. Resurf., 1.8 miles pump.
U. S 20	S. R. 49	S. R. 43	Port. & LaPort.	1940	9–8–9	Sh. Moraine	No	Moderate			5.8[a]	Faulted, but not pump., 13 2 miles
U. S. 20	S. R. 43	U. S. 35 (E)	LaPorte	1940	9–7–9	Lacust. & Sh. Moraine	Yes	Moderate			3.8[a]	Faulted but not pumping, 4.6 miles
U. S. 20	U. S. 35 (E)	S. R. 2	LaPorte	1941	9–7–9	Sh. Moraine	Yes	Severe			3.0[a]	
S. R. 25	Cass Co.	Rochester	Fulton	1928	9–7–9	Moraine	No	Severe			0.2	Short locations of inferior pv't.
U. S. 30	U. S. 41	S. R. 2	Lake & Port.	1940	9–7–9	Sh. Moraine	Yes	Severe	38.0		39.0[b]	Contains subgrade treat. test sects.
U. S. 30	S. R. 2	S. R. 43	Port & LaPort.	1940	9–7–9	Sand	Yes	Faulted				Faulted but not pump., 1.8 miles. Sand used as subgrade treatment
U. S. 41	Kentland	Morocco	Newton	1926	7	Moraine	No	Severe	20.0	17.5	2.5	Patched and rebuilt.
U S. 41	U S. 30	U. S. 6	Lake	1935	9–7–9	Org. Sand	Yes	Faulted				Faulted, but not pumping 9.2 miles.
S R 43	Chalmers	Reynolds	White	1929	9–7–9	New drift	No	Severe			0.1	Short locations in drift under sand in cuts.
S. R. 53	S. R. 8	U. S. 30	Lake	1940	9–7–9	Sh. Moraine	Yes	Moderate			3.5	Long sects of continuous pumping.
U. S. 12	Lake Co.	S. R 49	Porter	1923–33	7–8–7 / 9–7–9	Lacust.	No	Resurf.	1.0	1.0		Bit. Resurf. since 1943
Totals					..			. . .	78.5	38.0	58.1	
											38.0	Corrected pumping since 1943
											96.1	Tot. 1947 pump. & 1943 pump
											78.5	corrected
											17.6	Miles, net increase
											58.1	Pumping, 1947
											47.8	Faulting only, 1947
											105.9	Total pavement in distress, 1947
											38.0	
											143.6	Total, including cor. pumping
											98.5	
											65.4	Miles, net increase

[a] Four-lane pavement. (Actual length multiplied by 2.)
[b] Four-lane (divided) pavement. Data include mileage in both directions.

TABLE 6
SUMMARY OF RIGID PAVEMENT PUMPING, SEYMOUR DISTRICT

Road No.	From	To	County	Year Built	Pv't Sect. in.	Soil	Exp. or Con. Jt.	Severity Pumping 1947	Est. Length Pumping, miles			Remarks
									1943	Cor-rected	1947	
S. R. 3	N. Vernon	Decatur Co.	Jennings	1937	9–7–9	Old drift	Yes	Slight			1.2	Confined to cuts
S R. 3	Jennings Co	Westport	Decatur	1937	9–7–9	Moraine	Yes	Moderate			1.0	
S. R. 29	Greensburg	Shelby Co.	Decatur	1929	9–7–9	Moraine	No	Slight			0.4	
U. S. 31	Jeffersonville	Speed	Clark	1926	9–7–9	Old drift	No	Resur-faced	3.0	3.0		Bit. resurfacing, 0 8 miles pump-ing.
U. S. 31	Speed	Scott Co.	Clark	1941	9–7–9	Old drift	Yes	Resur-faced	2.0	2.0		Bit. resurfacing
U. S. 31	Clark Co	Jackson Co	Scott	1941	9–7–9	Old drift	Yes	Moderate			0.8	Confined to cuts.
U. S. 31	Scott Co.	U. S. 50	Jackson	1940	9–7–9	Old drift	Yes	Moderate	0.7	.7	2.8	Joints treated with cement slurry
U. S. 31	U. S. 50	Bartholomew Co.	Jackson	1937	9–7–9	Old drift	Yes	Moderate			6.8	
U. S. 31	Jackson Co.	S R. 7	Bartholo-mew	1937	9–7–9	Old drift & Moraine	Yes	Slight			7.0	
U. S 31	S. R. 7	U. S. 31A	Bartholo-mew	1941	9–7–9	Moraine	Yes	Severe	1.0		8.9	
U. S. 31	Bartholomew Co	Edinburg	Johnson	1943	9–8–9	New drift	Yes	Moderate			1.4	
U. S. 31.	Edinburg	Franklin	Johnson	1926	9–7–9	New drift	No	Moderate			0.2	
S. R. 37	Bedford	Near Oolitic	Lawrence	1935	9–6–9	Resid. L. S.	Yes	Slight			0.2	
S. R. 37	Near Oolitic	Monroe Co.	Lawrence	1929	9–7–9	Resid. L. S.	No	Moderate			0.7	
S. R. 37	Lawrence Co	Bloomington	Monroe	1929	9–7–9	Resid. L. S.	No	Slight			0.5	
S. R. 45	Stanford	Bloomington	Monroe	1929	9–7–9	Resid.L. S.	No	Slight			0.6	
S. R. 46	Nr. New Point	Franklin Co	Decatur	1942	9–6–9	Old drift	Yes	Slight			0.4	
S. R. 46	Decatur Co.	Batesville	Franklin	1938	9–7–9	Old drift	Yes	Slight			1.1	
S. R. 46	Batesville	Dearborn	Ripley	1938	9–7–9	Old drift	Yes	Slight }	2.0		5.2	
S. R. 46	Ripley	U. S. 52	Dearborn	1938	9–6–9	Old drift & shale	Yes	Slight }				
U. S. 50	Bedford	Jackson Co.	Lawrence	1933	9–7–9	Resid. L. S.	No	Moderate			0.1	
U. S. 50	Lawrence Co.	Brownstown	Jackson	1934	9–7–9	Shale	No	Moderate			1.7	
U. S. 50	Brownstown	Seymour	Jackson	1932	9–7–9	Alluvial	No	Moderate	12.0	12.0	0.1	Bit. resur 0 2 miles pumping
U S 50	U. S. 31	North Vernon	Jackson & Jennings	1929	9–7–9	Old drift	No	Resur-faced				
U S. 50	No Vernon	Ripley Co	Jennings	1929	9–7–9	Old drift	No	Slight	2.0	2.0	3.1	1943 pumping on west end now bit. resurf. 1947 pumping on east end.
U. S. 50	Jennings Co.	Versailles	Ripley	1929	9–7–9	Old drift	No	Moderate	0.2		0.4	
U. S. 50	Versailles	Near Elrod	Ripley	1931	9–7–9	Old drift	No	Moderate			2.2	
U. S. 50	Near Aurora	Aurora	Dearborn	1939	9–7–9	Shale	Yes	Severe	1.0		0.8	In cuts near Aurora
U. S. 50	Lawrenceburg	Ohio S. L	Dearborn	1940	9–7–9	Shale	Yes	Slight			0.8[a]	
U. S. 52	Dearborn Co	Brookville	Franklin	1928	9–7–9	Shale	No	Resur-faced	6.0	6.0		Bit. resurf. 0.2 miles pumping
S. R. 56	S R 3	Near Madison	Jefferson	1932	9–7–9	Old drift	No	Moderate			2.1	
S. R. 56	Nr Madison	Madison	Jefferson	1932	9–7–9	Shale	No	Resur-faced				Bit resurf. 0 4 miles pumping

TABLE 6, *Continued*

Road No.	From	To	County	Year Built	Pv't Sect. in.	Soil	Emp. or Con. Jt.	Severity Pumping 1947	Est. Length Pumping, miles			Remarks
									1943	Cor-rected	1947	
S. R. 62 .	S. R.3	Scott Co.	Clark	1937	9–6–9	Old drift & shale	Yes	Moderate			1.3	
S. R. 67 ..	S. R. 43	Morgan Co.	Owen	1938	9–6–9	Old drift	Yes	Slight			1.8	
S. R 67 ..	Owen Co.	S. R. 39	Morgan	1939	9–6–9	Old drift	Yes	Slight			0.5	
U. S. 150...	Greenville	Floyd Knobs	Floyd	1932	9–7–9	Shale	No	Moderate			1.3	In cuts and "borrow" fills
Totals ..									29.9	25.7	62.6	Pumping 1947
											25 7	Corrected pumping since 1943
											88 3	Total 1947 and 1943 pumping corrected
											29.9	
											58.4	Miles—net increase

[a] Four-lane (divided) pavement. Data includes mileage in both directions.

TABLE 7
SUMMARY OF RIGID PAVEMENT PUMPING, VINCENNES DISTRICT

Road No.	From	To	County	Year Built	Pv't Sect. in.	Soil	Exp. or Con. Jt.	Severity Pumping 1947	Est. Length Pumping, miles 1943	Est. Length Pumping, miles Corrected	Est. Length Pumping, miles 1947	Remarks
S. R. 37. ..	Paoli	Lawrence Co.	Orange	1929	9-7-9	Resid.-L. S.	No	Slight			0.2	
U. S. 41 ...	Evansville	S. R. 57	Vanderburg	1924 1936	8 9-7-9	Lacust.	Part	Severe			0 9	In South-bound lanes of 4-lane pvt.
U. S. 41 ..	S. R. 57	Gibson Co.	Vanderburg	1924 1940	7-8-7 9-7-9	Lacust.	Part	Severe	5.0	1.7	3.3	
U. S. 41 .	Vanderburg Co.	Princeton	Gibson	1924 1940	7 9-7-9	Lacust.	Part	Moderate	12.0[a]	4.9	1.3[a]	Pvt. repaired or resurfaced.
U. S. 41 .	Princeton	Hazelton	Gibson	1924	7 & 8	Old Drift	No	Severe	0.5		0.1	
U. S. 41 ...	Hazelton	Vincennes	Knox	1926	7	Alluvial	No	Moderate			0.6	
U. S. 41 . .	Shelburn	Farmersburg	Sullivan	1923	8	Old Drift	No	Severe			0.8	
S. R. 45 .	Jasper	Hayesville	Dubois	1928	9-7-9	Resid. (Sand-stone & Sh.)	No	Moderate			0.2	In cuts.
U. S. 50. ..	Washington	Loogootee	Daviess	1930	9-7-9	Old Drift	No	Severe	1.5		4.1	Being repaired at time of survey.
U. S. 50 ...	Shoals	Lawrence Co.	Martin	1933	9-7-9	Shale	No	Severe	1 0		1.0	Pumping in shale cuts.
U. S. 50....	Martin Co.	S. R. 37	Lawrence	1933	9-7-9	Resid. (L. S.)	No	Slight	0.5		1.0	
S. R. 56 .	Hayesbille	Orange Co.	Dubois	1922	7		No	Resur-faced				Bit. resurf., 0.1 miles pumping.
S. R. 56 ...	Dubois Co.	Near Fr. Lick	Orange	1928	9-7-9	Shale	No	Resur-faced				Bit. resurf., 0.1 miles pumping.
S. R. 56	Near Fr. Lick	U. S. 150	Orange	1928	9-7-9	Alluvial	No	Moderate			0.2	
S. R. 57 .	U. S. 41	Gibson Co.	Vanderburg	1941	9-7-9	Lacust.	Yes	Slight			0.5	Contains test sects. on compaction.
S. R. 57	Vanderburg	Oak City	Gibson & Warrick	1939	9-6-9	Lacust.	Yes	Moderate			2.5	Extensive pumping on borrow fills.
S. R. 62 ...	Warrick Co.	Gentryville	Spencer	1924	6	Lacust.	No	Resur-faced				Bit. resurf., 1.3 miles pumping.
S. R. 62 ...	Gentryville	Dale	Warrick & Spencer	1928	9-7-9	Shale	No	Slight			0.2	
S. R. 64 .	Princeton	Oak. City	Gibson	1929	9-7-9		No	Slight			0.1	
S. R. 67 . .	Vincennes	Bicknell	Knox	1928	9-7-9	Shale	No	Moderate			0.9	
S. R. 67 .	Sandborn	Switz. City	Knox & Green	1930	9-7-9	Shale	No	Moderate			0.9	
S. R. 67....	Switz. City	Worthington	Greene	1930	9-7-9	O. Drift	No	Moderate			0.8	
S. R. 67 .	Worthington	Owen Co.	Greene	1935	9-6-9	Shale	Yes	Slight			1.0	Extensive in cuts.

TABLE 7, *Continued*

Road No.	From	To	County	Year Built	Pv's Sect. in	Soil	Exp. or Con Jt	Severty Pumping 1347	Est. Length Pumping, miles			Remarks
									1943	Cor rected	1947	
U. S. 50	U. S. 41	Daviess Co	Knox	1929–31	9–7–9		No		1.5	1.5		Bit. resurface.
U. S. 50	Knox Co.	S. R. 57	Daviess	1931	9–7–9	O. Drift	No		0 2	0.2		Bit. resurface
U. S. 50	S. R. 45	U. S. 150	Martin	1931	9–7–9	Shale	No		4.0	4.0		Bit. resurface.
U. S. 150	U. S. 50	Lawrence Co.	Martin	1933	9–7–9	Shale	No		0 3	0.3		Bit. resurface.
U. S. 150	Martin Co.	S. R. 37	Orange	1929	8	Shale	No		0 4	0.4		Bit. resurface.
				1936	9–7–9							
Totals	. . .	.					.		26.9	13 0	20.6	Pumping, 1947
											13.0	Corrected pumping since 1943
											33.6	Total 1947 pumping and 1943 pump corrected.
											26.9	
											6.7	Miles, net increase

[a] Four-lane pavement. (Actual length multiplied by 2.)

have been plotted on state-highway maps (Figs. 2–3) in order that the intensity of the problem can be evaluated readily. The results of the 1943 survey (*1*) have been replotted with symbols comparable with those used in pumping pavements which have been reconstructed or which have been otherwise corrected are also indicated by an appropriate symbol. Likewise, the 47.8 miles of pavements on sand which are faulted are indicated.

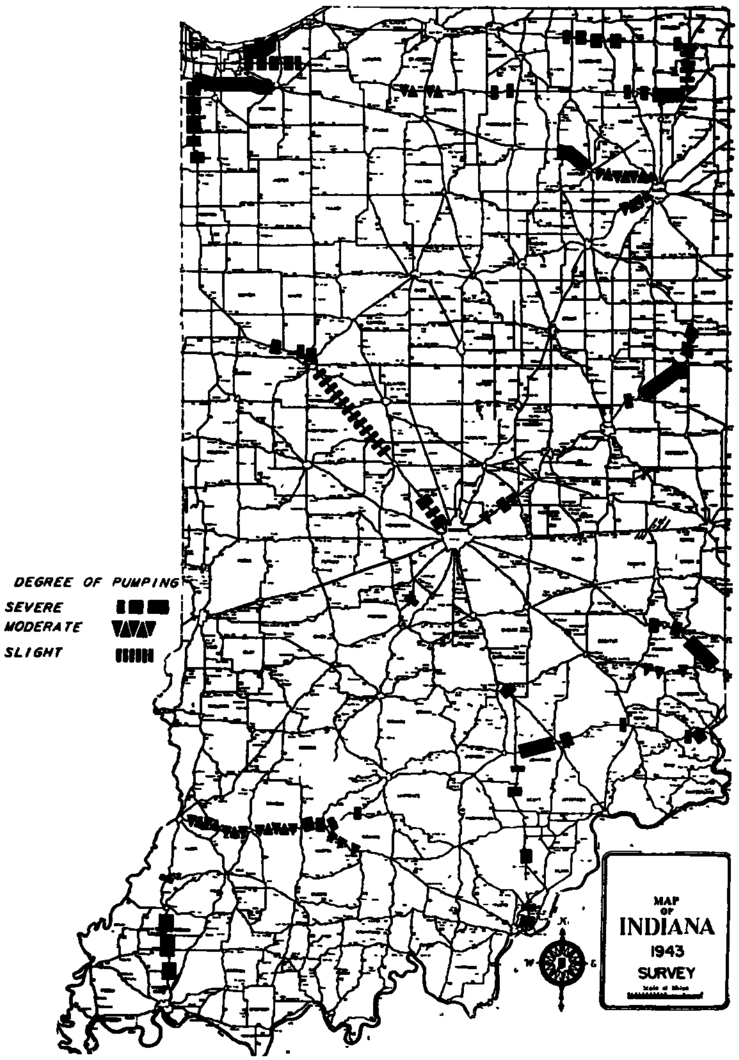

Figure 2. Pumping of Rigid Pavements

the 1947 survey. Figure 2 shows the plot of the 1943 pumping pavements. Some of the results of the 1947 survey are shown in Figure 3.

In addition to showing the degree of pumping, i.e., slight, moderate, and severe, the

The Indiana State Highway Planning Survey traffic data have been summarized in graphical form in Figures 4 to 9. In general, the number of trucks in different weight groups are presented as a percentage of the total vehicular traffic. Figure 4 shows the annual-average 24-hr. traffic at the 20 loadometer stations for each of four years. Also shown are the actual number of vehicles recorded during the weighing period, the total commercial vehicles with different maximum axle loads are presented graphically in Figure 6. The number of trucks in each axle-load group is shown in Figure 7, and the number of trucks violating the gross-weight limit is shown in Figure 8.

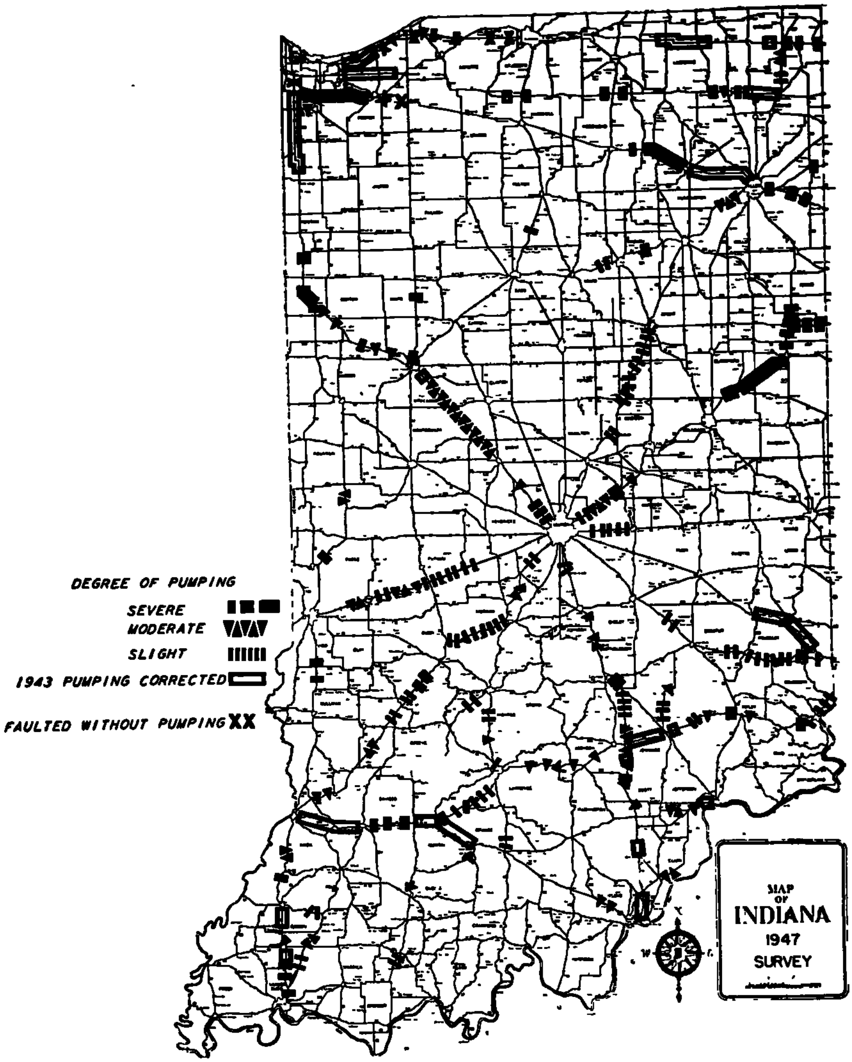

Figure 3. Pumping of Rigid Pavements

hicles counted, and the total number of trucks weighed. Trucks in different weight groups are plotted in Figure 5 as a percentage of the total number of vehicles counted during the weighing period. The percentage of the total

For purposes of comparing the pumping performance of different pavements with the frequency of loads, the percentages of vehicles at the indicated stations with axle loads greater than 18,000 lb. are presented in Figure 9.

DISCUSSION OF RESULTS

The pavement-performance-survey data and the truck-weight data submitted in this paper, combined with impressions obtained by riding on pavements throughout the state system, indicate that many rigid pavements in Indiana are failing structurally and at an accelerated rate. In addition, there is evidence to indicate that this problem is widespread and that it is not confined to Indiana (*5*). While more than 3,500 miles of the 4,000 miles of rigid pavements in the State are not now pumping, the

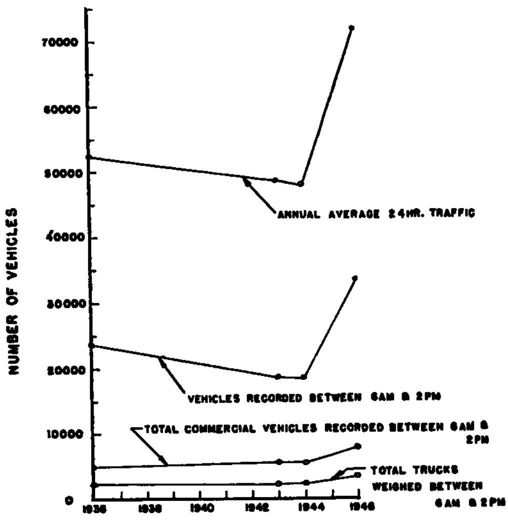

Figure 4. Traffic Trends Between 1936 and 1946 at 20 Loadometer Stations.

rate of increase of pavement pumping in Indiana since 1943 (60 new miles of pumping pavement per year) furnishes grounds for apprehension. Since pavement pumping, faulting, and the resulting structural failures are confined almost entirely to the primary roads of the State, such as U. S. 6, 12, 20, 30, 40, 50, 52, 31, 41, and S. R. 67 and since pavement pumping on dual-lane pavements is predominantly on the outside, heavily-traveled lanes, it is indicated that the frequent application of heavy loads is the major contributing cause of this problem. Analysis of the mechanics of pavement pumping would lead, of course, to the same conclusion. However, Indiana is topographically flat; soils susceptible to pavement pumping predominate throughout the State; and most of the existing pavements have not been designed to carry some of the loads to which they are now being subjected. It follows that it is reasonable to anticipate an increasing amount of pavement pumping unless rigid restrictions are placed on the amount of loads to be carried on pavements through the State.

Pavement Design, Pavement Age, and Soils.

The performance surveys of both 1943 and and 1947 show that pumping has occurred on the primary, heavily traveled roads, regardless of geometric sections and other features of design. It has occurred on pavements with thickened edges without joints, on pavements with thickened edges with both contraction and expansion joints and on pavements without contraction joints but with expansion joints. Some short sections of non-reinforced, non-jointed pavements with thickened middle have pumped. However, it has been observed on some sections of pavements that design features, such as expansion joints, accentuated the pumping problem.

In regard to pavement age, a study of the records of pavement damage due to pumping shows no positive correlation between pavement age and the development of pumping. In many instances pavements have been constructed and have given good service for many years without signs of distress, and then start to deteriorate rapidly under traffic loads. In contrast, some new pavements have begun to fail within a year or two after construction. For these reasons, it is indicated that the age of a pavement is not a factor in the problem of pavement pumping.

In the 1943 survey report (*1*) the importance of soils as a variable in pavement pumping was developed. It was shown in this study that heavily traveled roads crossing plastic clay-like soils were particularly vulnerable to this action but that other stretches of the same roads constructed on sand or gravel subgrades showed no signs of pumping. It was concluded in this work that the soil factor is an important variable in evaluating the pumping problem. The large number of miles of faulted pavements located on sand subgrades indicates that both the physical characteristics and the degree of compaction of granular base courses, which are used to eliminate pumping on new constructions, must be given careful consideration.

Truck Weights

One of the first steps taken after receipt of the State Highway Planning Survey truck weight data was that of statistical analysis in order to determine whether the trends observed were significant or should be attributed to chance variations due to sampling errors. For each weight classification in Figures 5 and 6 the average percentage was calculated, grouping all stations for all years. This average percentage value was plotted on the graph as a dot-dash line. Control limits are also shown on the graph. These limits were calculated from the following formula:[2]

$$p = \bar{p} \pm 3\sqrt{\frac{\bar{p}(100 - \bar{p})}{N}}$$

where p is the average percentage under consideration and N is the total number of vehicles counted in the year in question.

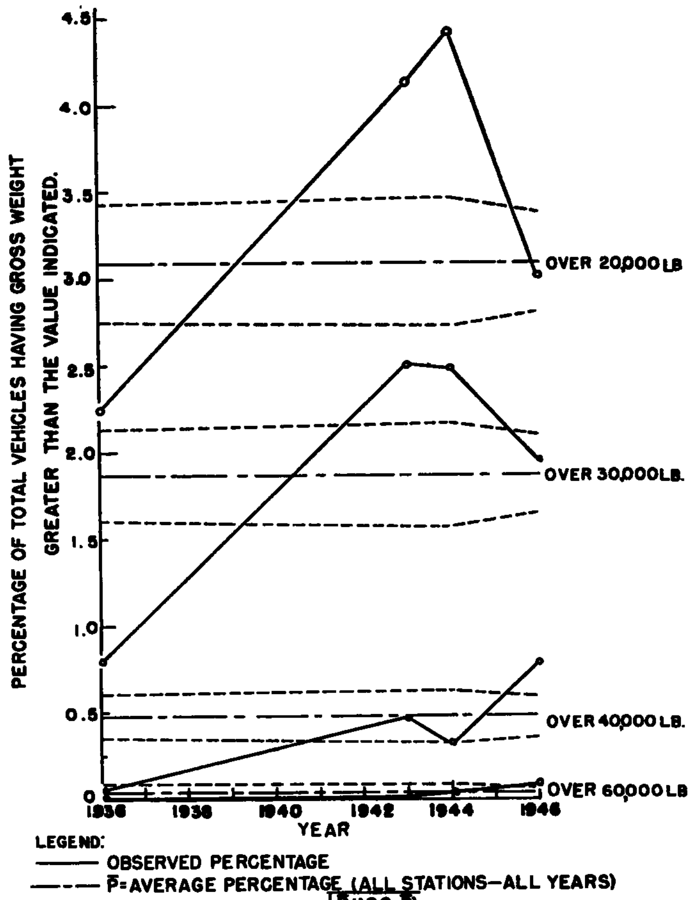

Figure 5. Percentage of Vehicles with Gross Weight Greater than the Value Indicated on the Basis of Total Number of Vehicles Counted during Weighing Period.

The area on the graph between the average percentage and the control limits may be considered as that range of values within which a

[2] *A.S.T.M.*—"Manual on Presentation of Data," August, 1940.

given percentage may be expected to vary due to chance or normal variation in sampling. If a value falls outside the control limits a very high degree of probability is indicated (99.7 percent) that the value is significantly different from the average. It will be observed from the formula that the spread of the control limits is affected by the average percentage concluded that the percentage of vehicles heavier than 40,000 lb. was significantly lower, in 1936, than the average for the four years considered, and that the percentage in 1946 was significantly higher than the average; this trend can not be attributed to chance.

The trends in axle loadings (Fig. 6) conform very closely to the trends in gross weights;

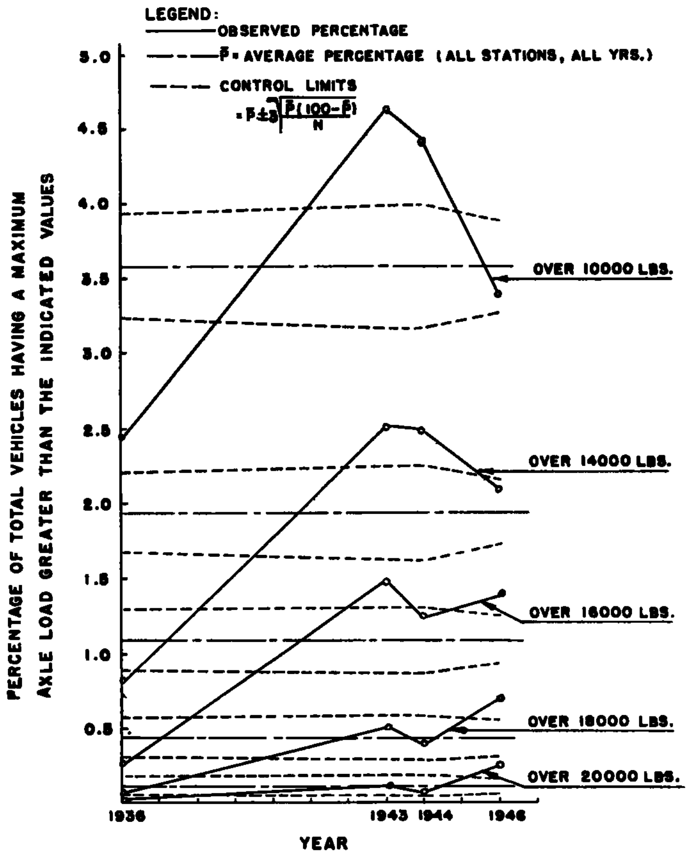

Figure 6. Percentage of Vehicles with Different Maximum Axle Loads Based on Total Number of Vehicles Counted during Weighing Period

considered and by the sample size, N. If N, in this case number of vehicles counted in any particular year, is small, the spread between control limits will be large.

On the curve (Fig. 5) for percentage of vehicles with gross weight exceeding 40,000 lb., the point representing this percentage in 1936 fell below the lower control limit; the point for 1946 fell above the upper limit. It may be the curve of percentage of vehicles with a maximum axle load over 18,000 lb. corresponds to the curve of percentage of vehicles over 40,000 lb. in gross weight. The average percentage for all years for these two truck categories were 0.44 and 0.48, respectively. In 1946, 0.70 percent of all vehicles had a maximum axle load greater than 18,000 lb.; 0.79 percent were over 40,000 lb. gross weight. It is to be noted that the percentage of vehicles with axle loads over 10,000 lb. increased approximately one and one-third times from 1936 to 1946, while in contrast, the percentage with axle loads over 18,000 lb. increased about eleven times during this same period.

The most significant factor to be noticed in examining the truck-weight data is that there has been a large upward trend in volume and

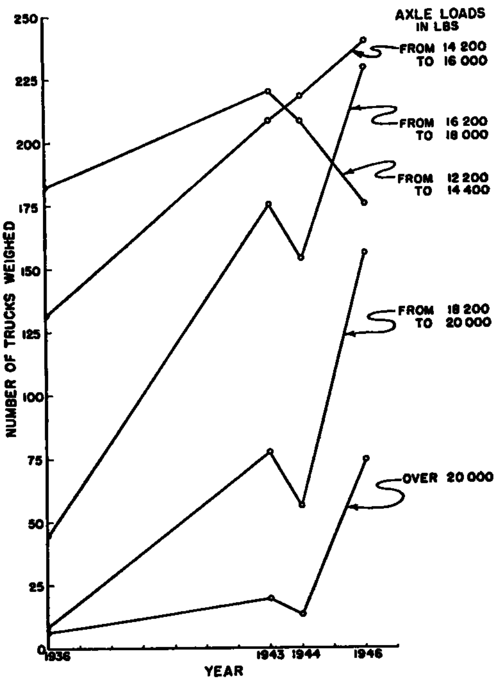

Figure 7. Number of Trucks with Different Axle Loads (at 20 Loadometer Stations During One 8-Hour Period Each Year).

weight of trucks between 1936 and 1946. The data for 1942, 1943, and 1944 show the truck traffic to be fairly constant, with minor fluctuations in various weight increments. The 1946 truck traffic is greatest, in both volume and weight, for any of the years, and is much greater than for the year 1936.

The number of trucks with a gross load of over 30,000 lb. recorded in 1936 during the 8-hr. survey at 20 stations was 185, while in 1946 it had increased to 658. In the same period the trucks over 40,000 lb. gross weight increased from 13 to 263 and those over 50,000 lb. gross weight increased from 4 to 105. At the same time the total number of trucks counted increased from 4,887 to only 7,330 which demonstrates that the number of heavy trucks increased greatly in relation to the total truck traffic.

Trucks are classified at a station as light trucks, medium trucks, heavy trucks, tractor trucks (semi-trailer), and trucks with trailers. From 60 to 65 percent of the trucks fall into the light and medium truck category. The data show that the number of trucks in

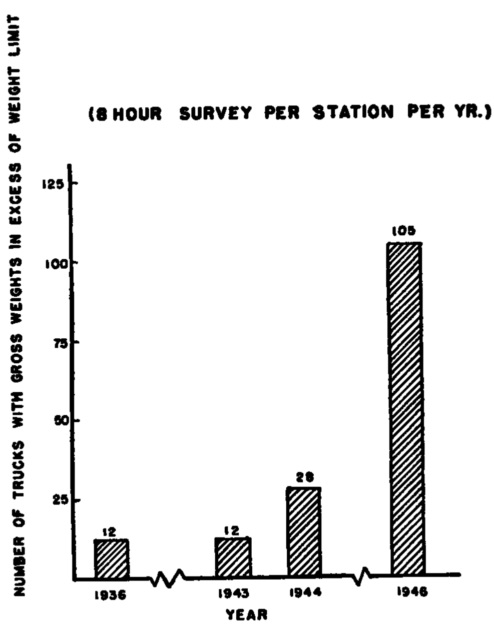

Figure 8. Trucks with Gross Weights in excess of Gross Weight Limit at 20 Special Indiana Loadometer Stations.

relation to the total traffic varied from 21.5 percent in 1936 to 31.1 percent in 1943. The large percentages for 1942 and 1943 are probably due to the large decrease in the number of passenger cars due to the inability to obtain tires and gasoline. Considering that trucks are about 20 percent of the total traffic and that about 60 percent of the trucks fall into the light and medium categories, this leaves only a small percentage of the total traffic in the heavier classifications.

Violations of Truck Weight Laws.

The following provisions of the Indiana traffic laws (*10*) are pertinent to a consideration of the truck weight data:

"(a) The total gross weight, with load, in pounds of any vehicle or combination of vehicles shall not exceed the weight computed by multiplying the distance in feet between the first and last axles of such vehicles or combination of vehicles plus 40 by 700.

"(b) The total weight concentrated on the roadway surface from any tandem axle group shall not exceed twenty-four thousand pounds plus an additional seven hundred pounds computed for each lineal foot between the centers of the first and last axles of said group.

"(c) No vehicle shall have a maximum wheel weight unladen or with load in excess of nine thousand pounds, nor in excess of eight hundred pounds per inch width of tire, measured between flanges of rim, nor an axle weight in excess of eighteen thousand pounds.

"(d) Axle weight as used in this section shall be considered the total weight concentrated on one or more axles spaced less than forty inches from center to center.

"(e) For the purposes of this act an axle shall be constructed to be the common axis of rotation of one or more wheels or rollers whether power driven or freely rotating, and whether in one or more segments and regardless of the number of wheels carried thereon.

"(f) Tandem axle group as used in this section shall be considered to be two or more axles spaced more than forty inches from center to center having at least one common point of weight suspension."

These provisions do not differ in essential respects from the limitations imposed by other States in the region, particularly in respect to axle loads.

In considering the number of trucks that exceeded the gross-weight limit, it should be noted that there was a change in the law after 1936. In 1936 the gross-weight limit was a constant value of 40,000 lb. In the other years considered in this report it was $(L + 40) \times 700$ lb. where L = distance in feet between first and last axles. This allows considerably heavier loads without exceeding the gross weight limit. Loads above 50,000 lb. now may easily be carried without violation. In spite of this change in the law to permit heavier gross loads, of the trucks weighed, 3.2 percent (0.3 percent of the total traffic) were found in violation of the gross weight limit in 1946 while only 0.5 percent (0.05 percent of the total traffic) were in violation in 1936..

In addition to violating the gross-weight limit, many trucks violated the axle-load limit of 18,000 lb. In 1936, 0.6 percent of the trucks weighed were in violation of this limitation, while in 1946 it had increased to 7.1 percent.

In considering the violations of both limitations, it should be noted that they cannot be added to obtain the total number of violations, for there is duplication. In addition, trucks might violate the allowable tandem axle loading and not violate either the gross-weight or single-axle limit. However, considering those

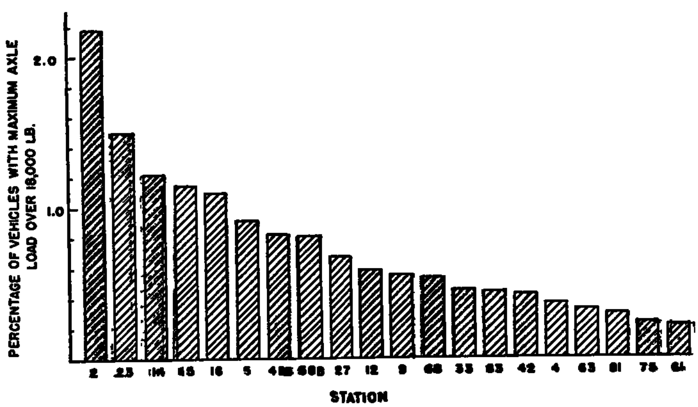

Figure 9. Variation between Different Stations in Percentage of Total Traffic Having Heavy Axle Loads—1946

that violated the 18,000-lb. axle-load limit, and adding a small percentage for violations of other limitations, an increase of from 1 percent of the trucks violating the law in 1936 to 8 percent in 1946 is a conservative estimate of the total violations.

These data are confirmed, in part, by Lynch (9) whose nationwide report on truck loads was issued in 1942. He states that "Since the original loadometer operations in the 1936–1940 period, the frequency of heavy gross weights has increased materially in all regions. The same is true of the frequency of heavy axle loads."

Correlation of Pumping with Truck Weights

The five stations which have the highest percentage of vehicles with maximum axle loads over 18,000 lb. (Fig. 9) are located on pavements which, without exception, show long stretches of severe pumping on plastic soils or severe faulting if the subgrade consists of sand. The stations with lowest percentages of heavy axle loads show no pumping or faulting on granular soils and no serious pumping on clay soils. The stations intermediate with respect to heavy loads are also intermediate with respect to pumping.

Station 20, on U. S. No. 20 east of Rolling Prairie (See Fig. 1) has the highest percentage of total traffic with axle loads greater than 18,000 lb. of any station. The weight data for this station may be considered representative of the traffic between South Bend and Michigan City, a distance of 34 miles. A large percentage of this mileage is faulted on a deep sand subgrade.

Station 23, on U. S. 20 east of the Junction of U. S. 20 and S. R. 5, is next to station No. 2 in percentage of high axle loads. This represents traffic from Elkhart eastward toward Toledo. The performance of the pavements in this region indicates the importance of the soil variable. The area is composed largely of granular outwash and the serious pumping, already repaired, is confined to deep cuts in which some clay-like materials are encountered.

Station 14 is on U. S. 41 south of the Junction of U. S. 41 and S. R. 2. This is one of the most seriously pumping pavements in the State and it has become necessary to rebuild almost the entire portion which is located on clay-like soils. There are also several miles of faulting on sands on a section of U. S. 41 located north of the intersection with U. S. 30. The traffic data at Station 14 probably represents a conservative estimate of the loads on this latter stretch of road.

Station 15 is located on U. S. 30 east of the Junction with S. R. 55. Almost 100 percent of that portion of this dual-lane pavement, which is located on plastic soils, is pumping severely, while 1.8 miles of pavement located on sand is faulted.

On U. S. 6 at Station 16 east of the Junction with S. R. 49, there were 3.5 miles of severe pumping, all of which have been repaired. The remainder of the road, represented by this station, is located on sand.

The next three stations, Nos. 5, 58B and 45B in order of the percentage of axle loads are all above the average for the State. Two of these, Stations 5 and 58B, are on roads which are located predominantly on granular and semi-granular material, but where plastic soils are encountered there is moderate to severe pumping. At Station 45B, the road is located primarily on exceptionally plastic soils and 15.5 miles have pumped severely and are being rebuilt.

In following the progress of pavement pumping it has been observed that the problem was confined originally to areas of extremely plastic soils. However, in more recent years pumping in Indiana has extended to areas of soils with less and less plasticity. In comparing Figure 2 with Figure 3, it will be noted that there are many new roads and new sections of roads pumping in 1947 which were not in distress in 1943. A typical example is many miles of pumping in 1947 of U. S. No. 40 between Indianapolis and Terre Haute and S. R. 67 between Indianapolis and Vincennes. The only logical explanation of this change in performance between 1943 and 1947 is the state-wide trend showing large increases in the number of heavy axle loads—particularly those in excess of 18,000-lb., together with the large increase in the number and magnitude of heavy gross loads.

There are many spot locations in the State which can be used to evaluate in part, the effect of heavy loads on pavement pumping. In 1941, U. S. 20 in Porter County was pumping so badly that it became necessary to reroute truck traffic around one particularly bad section. The detour route was, in part, on

U. S. Highway No. 12. Certain sections of this pavement started pumping immediately after the re-routing of the heavy traffic.

Another interesting case is that at the intersection of U. S. 41 with U. S. 52 in northwest Indiana. For several miles the traffic for both U. S. 41 and U. S. 52 is routed over the same road and this section of road is in considerable distress. This distress continues on U S. 52 southeast toward Lafayette, Indiana but to a lesser extent than is true on the combined U. S. 41-U. S. 52 section. In contrast, U. S. 41 is in very little distress from the junction with U. S. 52 south for many miles. The truck-weight data obtained at Stations 14 (on U. S. No. 41 south of the junction with S. R. No. 2) and 75 (located on U. S. 41, south of Terre Haute) show a striking drop in the number of heavy loads and in the number and magnitude of axle loads over 18,000 lb. at Station 75, thus indicating that most of the heavy loads found on the north section of U. S. No. 41 are diverted toward Indianapolis and Cincinnati on U. S. No. 52.

The importance of repeated heavy loads as a major variable contributing to pumping (Fig. 10) has been recognized by many observers. The comments pertaining to this factor as a result of the 1943 survey are equally applicable to the 1947 survey. In the report covering the 1943 survey it was stated (*1*, p. 311–312) that "the importance of weight is emphasized by repeated observations that passenger cars cause slight to imperceptible slab deflections while at the same joint a heavily-loaded truck will cause muddy water to squirt 4 to 5 ft. into the air. Further, on 4-lane pumping pavements in Indiana, pumping is almost entirely confined to the outside lanes—those which carry most of the heavy traffic . . . at one pumping joint, deflections of 0.002 to 0.004 in. were measured under light passenger cars, as compared to 0.14 to 0.15 in. under heavy trucks. By passing a truck over the joint at varying speeds, it was found that the slower the speed the greater was the deflection. This would account for the increased pumping that is often observed on grades where the speed of heavy trucks is reduced. . . . Successive repetitions of loads also aggravate pumping. For example, in observing the passage of 12 tanks over a joint, the first two or three produced very little movement whereas the joint was pumping severely under the last two or three."

RESULTS AND CONCLUSIONS

In this paper consideration has been given only to the influence of heavy loads on the pumping action of rigid pavements; data are not included on damage to other types of pavement or to structures.

The results of the 1943 and 1947 pavement pumping surveys in Indiana, combined with an analysis of truck-weight and traffic data obtained from the State Highway Planning Survey, together with observations made throughout Indiana and adjacent states warrant the following conclusions:

Pavement Pumping

1. Performance survey data show that the damage done to pavements due to pumping, cracking and faulting is increasing at an alarming rate. In the year of 1940 pavement pumping was practically non-existent in Indiana, while in 1943 approximately 6.0 percent of the miles of rigid pavement in the state were affected. By the spring of 1947, when the next state-wide performance survey was made, pumping had progressed to the point where approximately 12.0 percent of the entire mileage was or had been affected.

2. It is apparent that, although the programs of resurfacing or reconstructing of pumping pavements have been extensive, the rate of progressive disintegration of otherwise serviceable pavements has exceeded the rate of reconstruction or repair. Since 1943 the number of new miles of pumping pavement per year averages about 60 while the number of miles of pumping pavement reconstructed or repaired totals about 30 per year.

3. It is apparent from a study of the performance survey data covering both the 1943 and the 1947 surveys that pavement pumping in Indiana is spreading into soil areas in which there were few signs of pumping at the time of the 1943 survey. Information on the engineering characteristics of these new soil areas indicates that pumping is now occurring on soils of lower plasticity than those affected at the time of the 1943 survey.

4. The occurrence of faulting in almost 50 miles of heavily-traveled pavements located on sand subgrades is in effect a danger signal in connection with the large-scale use of granu-

lar material as subgrade treatment on new construction. However, most of the faulting observed has occurred on pavements containing expansion joints. Since this type of joint is being eliminated for new construction in Indiana, the amount of faulting on granular materials in the future may be minimized. This condition also emphasizes the need for careful design and adequate compaction of granular bases.

Traffic and Loads

5. From the standpoint of violations of the 18,000-lb. axle load law the data show, in comparing 1936 with 1946, that the number of violations increased by some 1300 percent. Since rigid pavement pumping became a problem in Indiana at about the same time that the number of violations of the 18,000-lb. axle-load as well as gross-load limit became large, it may be concluded that trucks which violate the Indiana, state-weight law are an important contributing factor to the increase in pavement pumping in the State.

6. Statistical analysis of the data indicates that the increase in percentage of vehicles over 40,000 lb. in gross weight and over 18,000 lb. in maximum axle load is significant and can not be attributed to chance variations in sampling. The curve showing the percentage of vehicles with a maximum axle load greater than 18,000 lb. in Indiana conforms very closely to the curve showing percentage greater than 40,000 lb. in gross weight, there being in 1946, 0.70 percent of all vehicles with a maximum axle load greater than 18,000 lb. and 0.79 percent with a gross weight over 40,000 lb.

7. Since vehicles with axle loads above 18,000 lb. comprise 0.7 percent of the total traffic in Indiana, the data strongly indicate that less than one percent of the traffic of the State is causing much of the pavement pumping damage.

Pavement Design vs. Increase in Loads

8. It is possible for the highway engineer to design pavements, road beds, and bridges which will be adequate for any given truck axle load or combination of axle loads. A road which will accommodate extremely heavy trucks will undoubtedly cost considerably more than highways which are adequate for trucks conforming to the present weight laws. The question at issue is whether the increased revenue obtainable by the use of heavier trucks (at the present time less than one percent of the total traffic in Indiana) will offset the necessary increase in highway use charges. This should be decided jointly by all interested parties including tax payers, highway economists, legislators, truck manufacturers and truckers, and highway designers.

A mutually agreed upon ceiling for maximum loads should be established for use by highway engineers in developing standard design criteria. Under existing conditions, both the number and magnitude of loads for each succeeding year are greater than for the last one, and many of the primary roads continue to receive loads in excess of those for which they were designed. The resulting structural failures require an increasingly larger portion of the highway budget to maintain, repair, and reconstruct roads and bridges that under a more logical condition of loadings, would give service for many additional years.

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