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Barrier-line locations for no-passing zones are compared in this issue
(U S 66 near Lebanon, Missouri)

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E. A. STROMBERG, Editor

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The Effect of Barrier-Line Location at No-Passing Zones

BY THE HIGHWAY TRANSPORT RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by CHARLES W. PRISK
Highway Engineer

In standard practice the barrier line at no-passing zones on two-lane highways is placed parallel and close to the roadway center-line marking. Missouri and Iowa, however, place the barrier line in the center of the lane from which passing is prohibited. The plan was developed in Missouri largely as an economy measure which has particular application on narrow pavement, for the painted stripe in this mid-lane location is not subject to constant wear by vehicle tires. A comparative study of the two marking types, conducted in cooperation with the Missouri State Highway Department on a 16-mile section of U S 66, is reported in this article.

No-passing zones on half the test section were marked with the Missouri standard, and on the other half the national standard was used. Two selected single-direction no-passing zones, one of each type, were studied intensively. A two-direction no-passing zone with Missouri markings was also studied. Information was collected on speeds and transverse placements of vehicles and on starting and finishing points of all passing maneuvers, approaching and within these zones.

Some of the traffic operation characteristics differed but little on the two types of markings. In critical conditions for transverse placement, however, particularly for vehicles traveling into a no-passing zone in the face of oncoming traffic, or where wide vehicles were involved, the advantage was consistently with the national standard marking. The national standard also showed favorable performance in a comparison of daylight and night driving, and in the extent to which drivers complied with the no-passing restriction. Obscurement of the mid-lane barrier line by preceding vehicles undoubtedly caused some drivers to encroach, without deliberate intention, on the no-passing zone area. Interviews with drivers leaving the test section revealed no decisive preference for either type of marking.

THE two-lane, two-way highway is the wheel horse of our transportation system. For economic reasons, it will undoubtedly persist as a popular type, despite the operating hazards inherent in its design. Warranted, therefore, are the many researches dedicated to improvements in the traffic capacity, safety, and other functional characteristics of this most common of all highway types.

Vehicle overtaking and passing actions on two-lane highways are essential to maintenance of reasonable capacities and necessary flexibility in traffic flow. Passings can normally be undertaken by the driver at any time he is assured that the left lane will be free of oncoming traffic throughout the time of his maneuver. The presence of opposing traffic that might interfere with passing is obvious when sight distances are adequate, but wherever alinement changes or other factors introduce a short sight-distance condition, the driver has no positive assurance that his passing can be completed without interference. This has led to rather general use of the no-passing-zone pavement marking which defines the limited section throughout which passing is not safe. According to reports of the President's Highway Safety Conference, 27 State highway departments are regularly marking no-passing zones, where needed, on more than 70 percent of the hard-surfaced mileage under their jurisdiction. The remaining States are similarly marking substantial portions of their mileage, and the totals are increasing each year. The value of this control measure is now well established.

Standardization of No-Passing-Zone Markings

What drivers see and understand has a profound effect on their driving actions and reactions, and what they do not fully see or understand often bears on their traffic mishaps. Much effort has been directed, therefore, toward standardizing all traffic-control devices, among them the marking design for no-passing zones. Many differences exist among the States. Since no-passing zones are locations of exposure to relatively high hazard, it is vitally important that all drivers quickly and accurately interpret the "line language" of pavement marking. Variations in color, in pattern, and in location of the barrier line with respect to the center-line marking subject motorists to possible confusion that may result in abnormal behavior or accident.

Though there is only partial agreement on certain details of the no-passing-zone marking design, practically all State and local jurisdictions place the barrier line a few inches to the side of the center-line marking to indicate that passing is prohibited from the lane on that side of the center line. This is the nationally recommended standard.[1]

Drastic exceptions to the national standard are found in Missouri and Iowa where, for a number of years, the barrier line has been positioned in the center of the driving lane from which passings are prohibited. This marking design was first adopted by Missouri to facilitate maintenance of a serviceable barrier line at a lateral position on the roadway where it would not be subject to the constant

[1] *Manual on Uniform Traffic Control Devices for Streets and Highways*, prepared by a joint committee of the American Association of State Highway Officials, the Institute of Traffic Engineers, and the National Conference on Street and Highway Safety. Published by the Bureau of Public Roads.

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grinding and abrasive action created by heavy commercial tires. On narrow pavements, especially those with a lip curb, the problem of maintaining a serviceable barrier line near the roadway center was most pronounced. Placing the barrier line at the center of the driving lane produces the economy of longer effective life—in some cases, serviceable characteristics have been retained for as long as 3 years. Also given consideration in the Missouri decision was the relatively greater hazard of painting lines where the striping equipment has to straddle the center line rather than proceed entirely within one lane.

Missouri Site Studied

To evaluate the effect of the two types of no-passing zones on driving practices, the Missouri State Highway Department and the Bureau of Public Roads cooperated in a series of special traffic studies in that State during the summer of 1949. The highway selected was U S 66, a principal cross-country route with a high proportion of out-of-State traffic.

In the 16.5-mile test section chosen for study, approximately one-half the length was marked with the national standard no-passing-zone design; the other half with the Missouri standard design. Two single-direction no-passing zones as nearly alike as possible, one with the national standard marking and one with the Missouri marking, were studied intensively. A two-direction no-passing zone with Missouri markings was also studied.

Three types of information were assembled. First, and perhaps most significant, was a vehicle speed and transverse-placement study, during which data were obtained for more than 11,500 vehicles. Second, the start and finish points were recorded for all passings (in one direction) attempted or completed within 500 feet each way from the beginning of the barrier line, at both the Missouri standard and the national standard zones. The third class of data resulted from interviewing approximately 1,000 drivers as they left the test section.

Conclusions

Based on the data collected and analyzed for this report, the following conclusions are offered:

1. Some of the traffic operation characteristics on the two marking systems did not appear to differ greatly. Speed values varied only slightly and drivers not familiar with a particular system displayed only small differences in their speed characteristics at the two zones. However, in an analysis of the more critical conditions for transverse placement, particularly those cases involving vehicles traveling into a no-passing zone in the face of oncoming traffic and those involving the wider vehicles in the commercial class, the findings show that although the differences in placement were small, the advantage was quite consistently with the national standard marking design. Drivers of the vehicles in these categories were significantly farther away laterally from potential head-on collisions and sideswipe accidents.

Figure 1.—Standard informational sign used at 3- to 5-mile intervals.

2. In the national standard zone, the average transverse placement of vehicles at night resembled rather closely the daytime condition. In the Missouri zone, the difference between day and night operation was somewhat more marked. It is of interest to note that in each of the six comparative studies on the Missouri zone, the average vehicle was closer to the center line at night than during the day. On the national standard zone, the placement at night for the average vehicle was, at four of the six points studied, farther from the center line than in daylight. At the remaining two, the difference between the day and night placement was less than at the corresponding locations on the Missouri zone.

3. Since observance of no-passing zone markings is very largely a voluntary matter, the extent to which drivers comply is a significant measure of the effectiveness of the markings. The average infringement on the no-passing zone area by drivers observed completing passings was greater at the locations where the barrier line was in the middle of the driving lane, and on this count also, the national standard showed superiority.

4. Direct interview of a representative sample of drivers who had just left the test section revealed no decisive preference for either type of marking. This was as true for Missouri drivers as for drivers from States bordering Missouri and for drivers from other States.

5. Even though some slight improvement in transverse placement occurred when the barrier line was extended forward with a dashed or solid line, driver observance of the extended zone was poor and this cannot be termed an effective means of bettering operating conditions, regardless of the type of no-passing zone.

Location of Test Section

The test section on U S 66 was 16.5 miles in length, extending easterly from Lebanon, Mo., to the Laclede–Pulaski County line. The pavement there was a 20-foot bituminous surfacing over old concrete, flanked by gravel shoulders of adequate width. For the study, approximately half the section length was marked with the national standard no-passing-zone design. The remaining mileage was marked in the Missouri fashion, with the barrier line located in the center of the driving lane.

The terrain traversed by this portion of U S 66 is moderately rolling. No-passing zones are relatively frequent. Traveling westbound through the 16.5-mile section the driver sees 39 no-passing zones; eastbound he traverses 36 zones. The aggregate length of no-passing zone for westbound travel is 6.0 miles; eastbound it is 5.5 miles. These represent restrictions on passing amounting to 36.4 percent and 33.3 percent of the total length traveled by westbound and eastbound drivers, respectively. Signs reading Do Not Cross Yellow Line When in Your Lane (fig. 1) were in place at intervals of 3 to 5 miles along the route, but none was in the vicinity of the zones selected for special study.

To obtain the uniformity desired in the condition of markings throughout the 16.5 miles, the center-line marking was repainted throughout as a dashed, reflectorized white line. Most of the previously existing reflectorized yellow barrier lines in the center of the driving lanes had been painted a year or more earlier and were not too prominent in daylight. These lines were totally obliterated with asphalt paint on the 9.2 miles in the easterly portion of the test section and new reflectorized yellow barrier lines were painted next to the center-line marking in accordance with the national standard. On the 7.3 miles in the western portion, the existing barrier lines were retraced with reflectorized yellow paint.

Two single-direction no-passing zones as nearly identical as could be found were selected for detailed study—one in the eastern, and one in the western portion of the test section. These were designated as sites N (national standard) and M (Missouri standard), respectively. Site N was 4.5 miles west of the Laclede-Pulaski County line near the middle of the length marked with national standard no-passing zones. Figure 2 is a general view of site N. The zone studied is on the grade in the background. The location of site M was 4.4 miles from the east city limits of Lebanon, approximately centered in the test length with the Missouri standard markings. The cover illustration is a photograph of that site, taken from the beginning of the barrier line. The approaches at both sites were on tangent alinement and the sight-distance restriction at the no-passing zone was caused in both cases by summit vertical curves. The standard used in Missouri for this route calls for marking no-passing zones at any point where the sight distance, measured from points 4.5 feet above the road surface, is less than 800 feet. At each of the two study sites, the sight distance from the driver's eye to the pavement surface at the beginning of the barrier line was 550 feet. The zone at site N was marked for westbound traffic and the one at site M for eastbound traffic. At site M the grade in the zone was 4.5 percent; at site N, 4.0 percent.

Figure 2.—No passing zone at site N, marked with the national standard, starts near foot of grade in background.

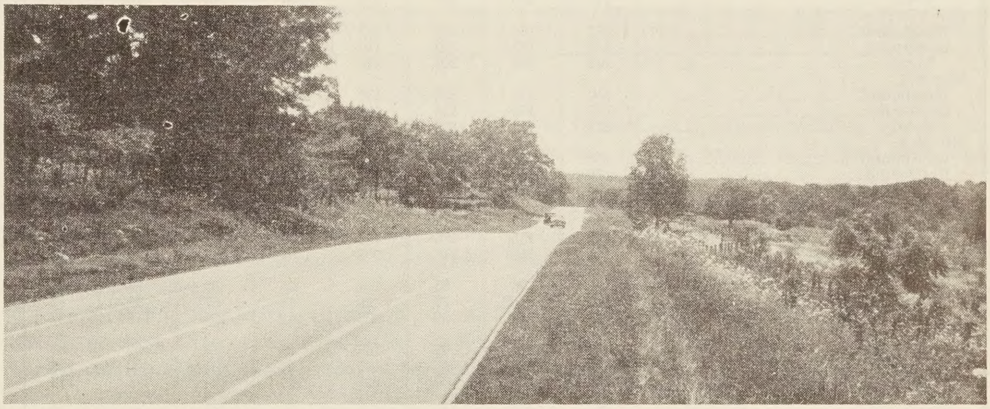

Figure 3.—Two-direction no-passing zone at site B, marked with the Missouri standard in both lanes.

Speed and Placement Studies

Speed and placement data were first recorded for three different study locations in the vicinity of each zone, as indicated below and in figure 4:

No. 1.—500 feet in advance of the start of the barrier line.

No. 2.—At the start of the barrier line.

No. 3.—300 feet beyond the start of the barrier line.

During the course of these studies it was decided to experiment with both a dashed and a solid extension of the yellow barrier line at the approach end. Following study No. 3 a 200-foot dashed extension was painted at both sites. Later the dashed extension of the barrier line was made a solid line. Under these two conditions, three additional locations were studied at sites N and M, as follows:

No. 4.—At the start of the original barrier line (same as No. 2), but with a 200-foot dashed extension of the barrier line.

No. 5.—At the approach end of a 200-foot solid extension of the barrier line.

No. 6.—At the start of the original barrier line (same as Nos. 2 and 4), but with the 200-foot solid extension of the barrier line.

The zones at sites N and M were both single-direction zones. To measure the effect of having a no-passing zone marked for both directions of travel, in which case there is a barrier line at the center of both lanes and a line at the roadway center as well, a site B (for both directions) was also chosen for study. This was located in the section marked with the Missouri standard, 6.1 miles east from the east city limits of Lebanon. The general conditions at site B are portrayed in figure 3.

At each of the three study sites, observations were made in daylight, between 3 and 6 p. m., and at night, between 8 and 11 p. m. Speed, transverse placement, and classification of vehicle types were obtained with the automatic-recording speed-placement equipment. This is the equipment described in the April 1940 issue of PUBLIC ROADS,[2] except that adding machines were substituted for the graphic recorders to produce a coded record on adding-machine tape. For vehicles entering the no-passing zone, special notation was

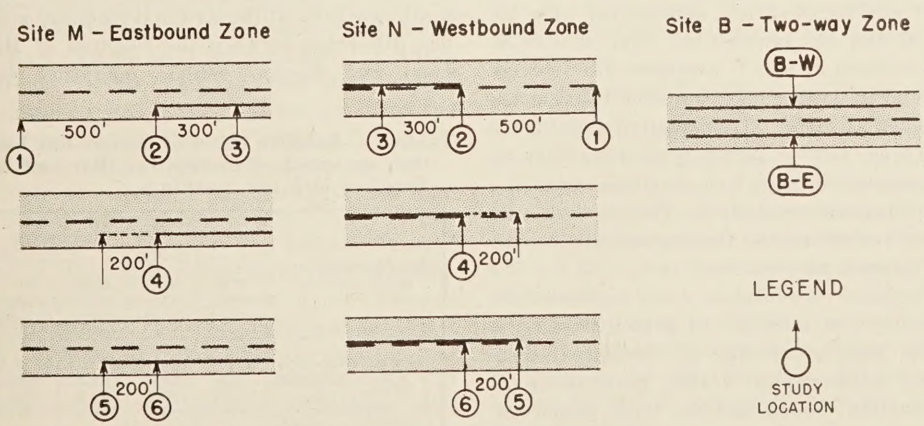

Figure 4.—Positions of study locations at the three no-passing sites: Site M marked with the Missouri standard, site N marked with the national standard, and site B marked with the Missouri standard in a two-way zone.

[2] *New techniques in traffic behavior studies*, by E. H. Holmes and S. E. Reymer. PUBLIC ROADS, vol. 21, No. 2, April 1940.

Table 1.—Hourly traffic volumes at study sites

Site and direction of travel	Daylight traffic				Night traffic			
	3–4 p. m.	4–5 p. m.	5–6 p. m.	Average	8–9 p. m.	9–10 p. m.	10–11 p. m.	Average
Site M–1:								
Westbound	115	128	101	115	82	54	45	60
Eastbound	182	186	143	170	64	102	92	86
Total	297	314	244	285	146	156	137	146
Site M–2:								
Westbound	125	132	157	138	67	31	66	54
Eastbound	123	133	102	119	72	72	50	65
Total	248	265	259	257	139	103	116	119
Site M–3:								
Westbound	116	101	109	109	71	55	55	60
Eastbound	110	133	110	118	87	66	50	68
Total	226	234	219	227	158	121	105	128
Site M–4:								
Westbound	125	121	92	113	58	62	73	64
Eastbound	119	103	129	117	75	60	48	61
Total	244	224	221	230	133	122	121	125
Site M–5:								
Westbound	125	117	121	121	92	65	83	80
Eastbound	111	130	128	123	51	79	49	60
Total	236	247	249	244	143	144	132	140
Site M–6:								
Westbound	128	126	147	134	60	61	78	67
Eastbound	117	154	119	130	50	79	37	55
Total	245	280	266	264	110	140	115	122
Site N–1:								
Westbound	132	100	106	113	87	56	69	71
Eastbound	106	103	120	110	69	53	51	57
Total	238	203	226	223	156	109	120	128
Site N–2:								
Westbound	130	131	150	137	123	148	156	142
Eastbound	122	130	115	122	77	97	84	86
Total	252	261	265	259	200	245	240	228
Site N–3:								
Westbound	160	183	170	171	119	80	72	90
Eastbound	126	159	172	152	83	58	68	70
Total	286	342	342	323	202	138	140	160
Site N–4:								
Westbound	120	121	112	118	82	86	84	84
Eastbound	131	135	136	134	52	57	55	55
Total	251	256	248	252	134	143	139	139
Site N–5:								
Westbound	132	96	83	104	95	52	83	77
Eastbound	106	115	77	99	47	57	62	55
Total	238	211	160	203	142	109	145	132
Site N–6:								
Westbound	122	105	97	108	58	73	52	61
Eastbound	120	127	103	117	42	51	62	52
Total	242	232	200	225	100	124	114	113
Site B:								
Westbound	139	200	148	162	91	75	72	79
Eastbound	131	122	99	117	65	60	72	66
Total	270	322	247	279	156	135	144	145

made on the tape if opposing traffic was within 300 feet of the observed vehicle at the time its placement was recorded. In addition, an observer maintained a record of the start and finish of all passings attempted or completed by traffic traveling toward the zone within a distance of 500 feet in each direction from the approach end of the barrier line. A series of posts set at 100-foot intervals, with reflectorized stripes indicating distance from the beginning of the barrier line, facilitated these observations, particularly at night. Hourly traffic volumes by direction were read from traffic counters throughout the period of study.

Table 2.—Traffic classification

Vehicle type	Proportion of total traffic	
	Daylight (3–6 p. m.)	Night (8–11 p. m.)
	Percent	*Percent*
Missouri passenger cars	34. 5	34. 0
Foreign passenger cars	45. 5	23. 3
Single-unit trucks [1]	11. 1	8. 3
Truck combinations	7. 8	32. 6
Busses	1. 1	1. 8
Total	100. 0	100. 0

[1] Includes panels and pick-ups.

Many Out-of-State Drivers

The test section carried a daily traffic volume averaging between 3,500 and 4,000 vehicles during the period of the study, June 30 to July 15, 1949. July 4 fell on a Monday, making a long holiday week end, but the traffic flow nevertheless was remarkably uniform throughout the observations. The average traffic for all daylight hours of study on the Missouri standard, site M, was 251 vehicles per hour; at site N it was 247 vehicles per hour. Corresponding volumes during the night studies were 130 vehicles per hour at site M and 150 vehicles per hour at site N. The volumes at site B averaged 279 vehicles per hour in the daylight hours and 145 vehicles per hour at night. This relative stability in the traffic volume factor lends reliability to the comparison of driver practices under the several conditions studied. Table 1 shows the hourly variations and the day and night average volumes at each site.

A detailed classification count made on July 5 is shown in table 2. Of principal interest is the high percentage of foreign (out-of-State) passenger-car traffic, particularly in the daylight hours, and the large proportion of truck combinations at night. The proximity of the holiday undoubtedly accounted in some measure for both conditions, but other observations on this route have consistently shown relatively large percentages of foreign passenger-car and nighttime commercial traffic.

Driving Speeds

The information obtained on traffic speeds indicates also that operating conditions at the two principal test sites were substantially similar. The daytime speed at site M averaged 52.5 miles per hour for vehicles approaching the no-passing zone, and at site N the average speed was 52.3 miles per hour. Within the no-passing zones, vehicles averaged 50.1 miles per hour at site M and 50.4 miles per hour at site N. The slight decrease in speed is accounted for, at least in part, by the grade of approximately 4 percent that vehicles ascended in passing through the zone. Nighttime speeds were slightly lower but followed the same general pattern of decreasing slightly upon entering the no-passing zone.

At site B, where only a single study within the two-direction zone was made, speeds were found to be a little lower than at sites M and N. The daytime average was 48.4 miles per hour for eastbound and 47.6 miles per hour for westbound traffic during daylight hours. Corresponding night speeds were 45.3 and 49.4 miles per hour.

The difference in the effect of the two barrier-line locations on the driving speeds of Missouri and foreign vehicles is of some importance in appraising the no-passing-zone designs. Table 3 shows that foreign passenger-car drivers traveled at a slightly higher average speed than Missouri drivers on the approach to both types of no-passing zones, but tended generally to reduce their speed more than Missouri drivers as they traveled through the zone. The one exception was the case of foreign drivers in the national standard zone at night, where the average speed actually increased 0.9 mile per hour.

Perhaps of most significance is the fact that in every instance the speed decrease occurring as vehicles traveled into the no-passing zone was greater both day and night for Missouri drivers at the national standard zone than it was for the same drivers at the Missouri zone. Similarly, the speed of foreign drivers consistently showed greater change at the Missouri zone than at the national standard zone. The difference between the reaction of Missouri and foreign vehicle operators was

Table 3.—Relative effect of barrier-line location on speed of drivers familiar and unfamiliar with the markings

Zone marking and study location	Daylight speed		Night speed	
	Missouri drivers	Foreign drivers	Missouri drivers	Foreign drivers
Missouri standard:	*M. p. h.*	*M. p. h.*	*M. p. h.*	*M. p. h.*
Approaching zone	52. 8	53. 8	49. 1	50. 2
Within zone	51. 6	50. 1	48. 9	47. 8
Difference	−1. 2	−3. 7	−. 2	−2. 4
National standard:				
Approaching zone	52. 8	52. 9	48. 5	49. 2
Within zone	50. 0	49. 6	47. 2	50. 1
Difference	−2. 8	−3. 3	−1. 3	+. 9

greater on the Missouri standard than on the national standard. This finding seems logical because Missouri drivers in general would be more familiar with the widely used national standard than other drivers are with the Missouri type of marking.

Transverse Placement

The lateral position of vehicles on the roadway is one of the most sensitive indications of the differences in traffic operation caused by varying the barrier-line location. Extensive study of the placement data has been made to isolate significant driver-behavior characteristics associated with the two types of marking. The dimension used to identify vehicle placement is the distance in feet from the center line of the roadway to the center line of the vehicle.

A compilation of the average placements of vehicles traveling in and through the zones, segregated by day and night and by vehicle type for each study site, is given in table 4. As previously indicated, sites M and B had the barrier line in the center of the driving lane, and site N had the barrier line next to the center-line marking. Site B was the two-direction zone, but site M was marked only for eastbound traffic and site N only for westbound traffic. Since sites M and N were almost identical in physical conditions, traffic volume, and normal speed, the placement of vehicles traveling in the single direction controlled by the respective zones has been selected for analysis.

The values shown in table 4, therefore, pertain to vehicles traveling eastbound at site M, westbound at site N, and for each direction separately at site B. The few vehicles using the left lane for passing in violation of the markings at the several study sites have been omitted from the placement summaries and are treated separately in the section of the report dealing with driver obedience to the no-passing zones.

Table 4.—Average transverse placement (distance from center line of vehicle to center line of roadway) at the several study sites

Study location and barrier-line type	Transverse placement in daylight					Transverse placement at night				
	Missouri passenger cars	Foreign passenger cars	Single-unit trucks	Truck combinations	All vehicles	Missouri passenger cars	Foreign passenger cars	Single-unit trucks	Truck combinations	All vehicles
Site 1:	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
Missouri standard	5.08	5.10	5.33	5.15	5.10	4.61	4.67	4.90	4.90	4.70
National standard	4.16	4.04	4.50	4.60	4.22	3.89	3.82	3.90	4.57	4.09
Site 2:										
Missouri standard	4.34	4.19	4.52	4.92	4.34	4.37	3.90	4.20	4.45	4.21
National standard	4.23	4.07	4.43	4.71	4.21	4.18	4.22	4.56	4.76	4.29
Site 3:										
Missouri standard	4.73	4.61	4.99	4.80	4.71	4.28	4.71	4.20	4.70	4.57
National standard	4.73	4.61	5.29	5.29	4.73	4.60	4.50	4.50	5.04	4.62
Site 4:										
Missouri standard	4.37	4.13	4.68	4.78	4.33	4.20	4.09	4.60	4.57	4.28
National standard	4.16	4.01	4.62	5.03	4.30	4.18	4.04	4.74	4.97	4.45
Site 5:										
Missouri standard	4.29	4.08	4.55	4.71	4.25	3.89	4.08	4.10	4.31	4.10
National standard	4.19	3.69	4.35	4.57	4.03	4.07	3.88	4.40	4.56	4.20
Site 6:										
Missouri standard	4.52	4.29	4.84	4.73	4.48	4.22	4.21	4.60	4.40	4.30
National standard	4.49	4.20	5.05	4.96	4.50	4.57	4.05	4.80	4.86	4.54
Site B (Mo. standard):										
Eastbound	4.70	4.70	4.65	4.90	4.73	4.66	4.68	4.90	4.80	4.68
Westbound	4.42	4.23	4.62	4.60	4.32	4.28	4.27	4.45	4.54	4.28

Close Agreement of Average Placements

The relatively close agreement between the average placement values at locations 2, 3, 4, and 6 on the Missouri and national standard zones is a noteworthy feature of table 4. These four locations were either within the no-passing zone or at the approach end of the normal barrier line, as indicated earlier. Location 5 was at the approach end of the extended barrier line and location 1 was 500 feet in advance of the no-passing zone.

At this latter point, the average lateral position of all vehicles differed 0.88 foot on the two systems in the day study and 0.61 foot at night and, in both cases, the distance from the roadway center line was greater at the Missouri standard zone. The observations at study site M–1 were made July 4 when the weather was partly cloudy, with light showers, and the traffic volume was higher than normal. Site M–1 was also slightly beyond the crest of a vertical curve for eastbound drivers who had just left another no-passing zone about 150 feet before their vehicle placement was recorded. Location N–1, by contrast, was on a nearly flat section and the nearest no-passing zone for westbound drivers in advance of this study site was approximately one-fourth mile to the east. This range in conditions is the suspected cause of the differences between the M–1 and N–1 values.

At site B, the horizontal alinement on the two approaches to the observation point varied slightly. Eastbound traffic entered the zone on tangent alinement, while westbound traffic entered on a curve to the left, which condition is believed to account for westbound average placements being consistently closer to the center line at site B–W than at B–E. No physical or other differences that might influence vehicle paths were evident at any of the other study locations at sites M and N.

As will be seen from table 4, the difference in the average placement values for the two no-passing-zone designs is least at study sites M–3 and N–3. In the daytime, the average placement of all vehicles within the Missouri zone was 4.71 feet, measured from center of vehicle to center of roadway, and on the national standard it was 4.73 feet. The corresponding night values were 4.57 and 4.62 feet. These data were recorded at a point 300 feet within each of the test zones, which is certainly one of the more critical locations.

Effect of Traffic Conditions

The data in table 4 include vehicles moving through the test zones singly and in groups, and with and without traffic in the opposing lane. To study these several movement categories independently, the total traffic through the test zones was classified into three groups as follows:

1. Free moving.—Vehicles that were at least 6 seconds behind any other vehicle traveling in the same direction, and were not within 300 feet of any vehicle traveling in the opposite direction.

2. With opposing traffic.—Vehicles that were within 300 feet of a vehicle traveling in the opposite direction.

3. Others.—All other vehicles not in the first two classes, except those that were making a passing maneuver.

Because of the marked similarity in average placements, all passenger-car data from the daytime studies were segregated into these three categories and standard deviations computed for each of the comparative studies. Table 5 shows that, with a single exception (passenger cars with opposing traffic in the national standard zone, study site N–3), the dispersion of placements is greater on the national standard marking than it is on the Missouri marking.

It might be expected that the placement distribution of those vehicles with opposing traffic would always show less dispersion than the distribution for vehicles in the other two movement classifications, because of the imminent danger of colliding head-on with vehicles in the left lane. At all but one of the studies on the national standard this was true, but at three of the six studies on the Missouri standard zone the dispersion was

Table 5.—Standard deviations of transverse placement of Missouri and foreign passenger cars in daylight

Study location and barrier-line type	Standard deviation of transverse placement			
	Free moving	With opposing traffic	Other	All movements
Site 1:				
Missouri standard	0.9063	0.7989	0.8443	0.8511
National standard	1.1385	1.1261	1.6160	1.3260
Site 2:				
Missouri standard	.7611	.7376	.7366	.7521
National standard	1.2147	.8481	1.0524	1.0571
Site 3:				
Missouri standard	.7994	.9290	.6962	.8085
National standard	.8943	.7715	.8777	.8921
Site 4:				
Missouri standard	.7150	.7461	.6997	.7367
National standard	.9442	.7998	1.0899	1.0318
Site 5:				
Missouri standard	.7516	.6782	.7658	.7754
National standard	1.1995	.8727	1.0444	1.0253
Site 6:				
Missouri standard	.9203	.6349	.7815	.7796
National standard	.9834	.9101	.8770	.9128

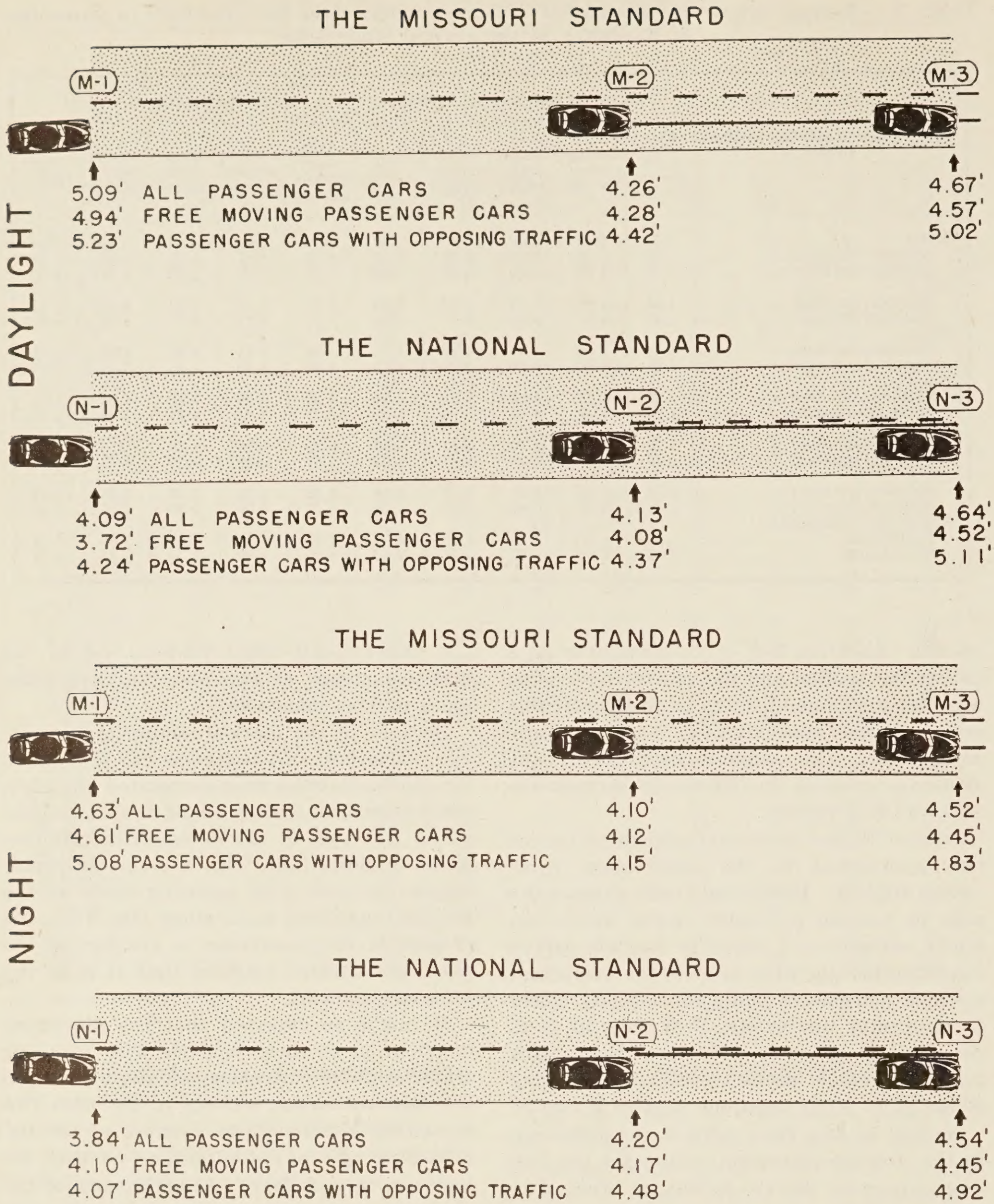

Figure 5.—Transverse placement: Distance from center line of vehicle to center line of roadway for passenger cars in no-passing zones, in daylight and at night.

greater than for one of the other movement classifications. In general, passenger-car drivers using the national standard zone showed somewhat less precision in following a central path than they did when traversing the Missouri standard zone. However, it will be seen that the presence of opposing traffic increased the tendency of drivers on the national standard marking to follow a central path more than it did on the Missouri design. Furthermore, the precision with which the central path was followed on the national standard was slightly superior to that found on the Missouri marking when passenger cars were 300 feet into the zone and faced with traffic in the opposite lane.

Effect of Light Conditions

Figure 5 shows additional comparative data on passenger-car driver practices at the two test zones, under day and night conditions. As previously explained, the placements at site M–1 appear to have been influenced by local factors and probably should not be compared with those for site N–1 for that reason. However, as vehicles reached the beginning of the barrier line and traveled 300 feet into either type of zone, a definite shift to the right occurred in the vehicle path. This shift ranged from about 0.3 foot to 0.75 foot over the 300-foot section. In the daytime, the amount of the shift was greater on the national standard zone; at night, it was greater on the Missouri zone. The net difference between the average placement within the two zones, however, was less than 0.05 foot, either day or night. It will be seen that under all conditions the maximum lateral shift between locations 2 and 3 occurred when oncoming traffic was in the left lane.

Figures 6 and 7 permit more detailed examination of the placement distributions of this important class of traffic at these two points. Passenger cars at the beginning of the national standard barrier line tended to have a more sprawling distribution pattern than at the Missouri standard. This was true both day and night. Within the zones, the distribution of placements was more compact. For both day and night operation within the zone and on either type of marking, about three-fourths of all passenger cars were driven with their centers in the range of 3.6 to 5.5 feet from the roadway center line.

A measure of the relative effectiveness of the two barrier-line locations in inducing vehicle drivers to stay a proper distance from the center line while traversing a no-passing section appears in table 6. Regardless of light conditions, vehicle type, or class of vehicle movement, the proportion of vehicles with placements less than 4.5 feet from the roadway center in the national standard zone was, with several minor exceptions, smaller than in the Missouri type zone. Taken as a whole, the proportion within 3.5 feet of the center line was slightly smaller on the Missouri standard, but in the significant class of vehicles with opposing traffic, the national standard showed marked superiority in the daytime results and was substantially the same as the Missouri standard at night. A lower percentage of commercial vehicles, in every case, was found within 3.5 or 4.5 feet of the center line on the national standard, and their average placement, both day and night in that zone, averaged approximately 0.3 foot farther from the pavement center.

Nighttime is known to be the critical period for many traffic-control devices. Consequently, special attention has been devoted to day and night comparisons at the two barrier-line locations. Data for study of the differences between average placements of all vehicles day and night are presented in table 7. Where the barrier line was located in the center of the driving lane, the average placement at night was consistently nearer the roadway center than the daytime average, as will be seen from the predominance of minus signs in the first column. This is not as generally true where the barrier line was located next to the center line.

Previous studies have indicated that on a typical roadway section removed from a no-passing zone, drivers follow a path closer to the center line at night. That finding is verified by the data obtained in this study at sites M–1 and N–1. From table 7 it is evident that the Missouri standard no-passing-zone marking offers no effective deterrent to this practice. By comparison, the studies on the national standard zone show that the average placement at night closely approximated the daytime position. In some instances, the average night driver was even slightly farther away from the center line than the average daytime driver. At all six study sites compared, the difference between day and night placement averages on the national standard marking was either less than on the Missouri standard or was such as to provide greater clearance from the center line at night than

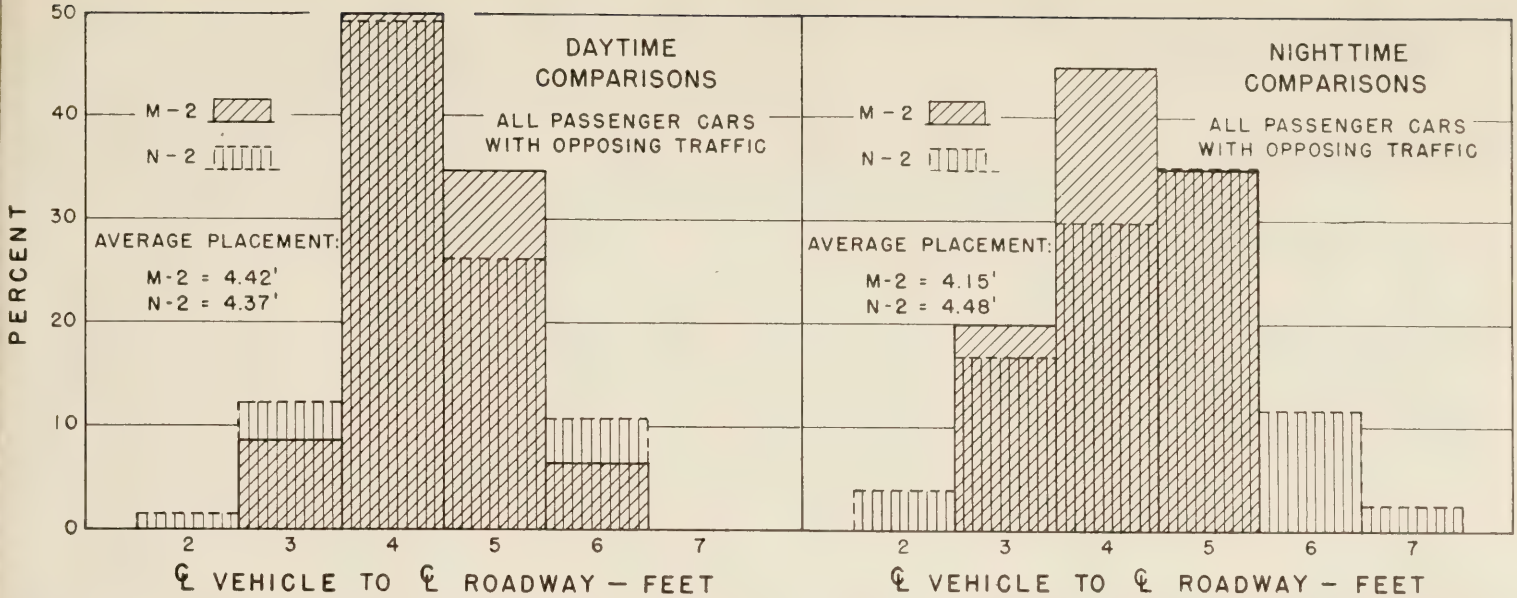

Figure 6.—Distribution of transverse placement of passenger cars at the start of the no-passing barrier line, with opposing traffic, in daylight and at night.

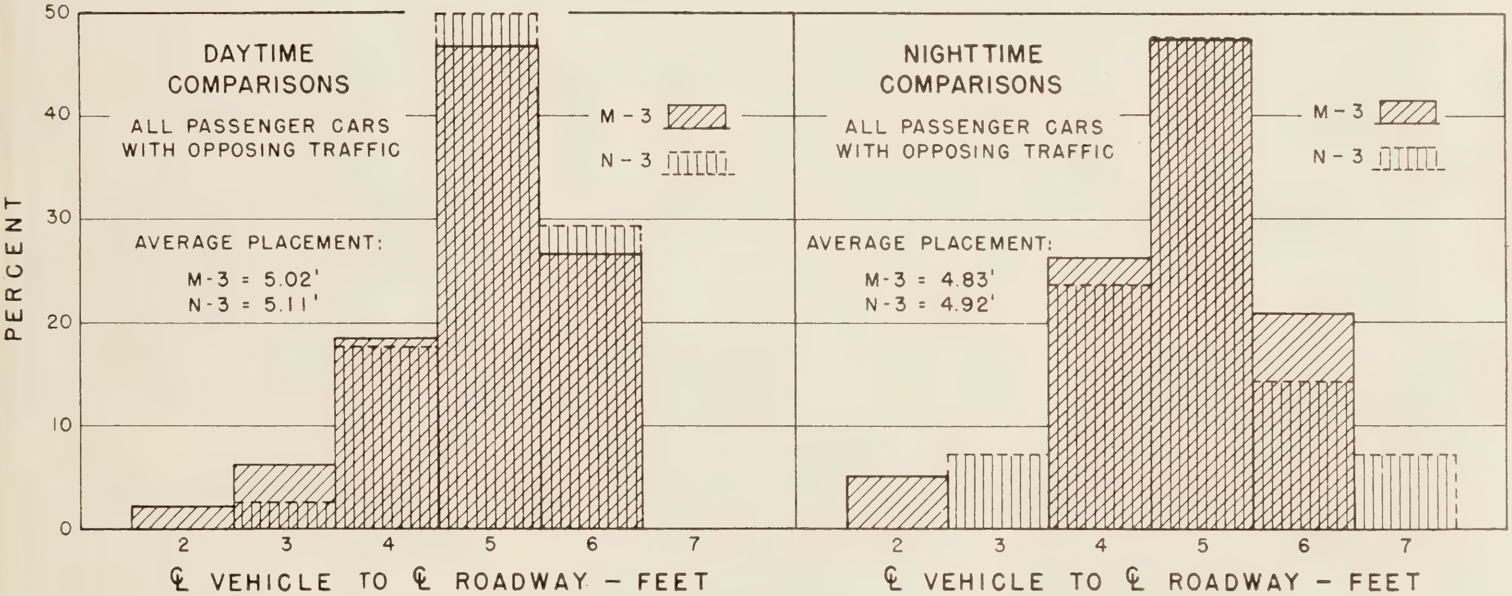

Figure 7.—Distribution of transverse placement of passenger cars 300 feet beyond the start of the no-passing barrier line, with opposing traffic, in daylight and at night.

in the daytime. With the ever-present hazard of sideswipe collisions on narrow pavements, where center-of-the-lane barrier-line marking has been thought to be most applicable, this finding is worthy of attention.

Driver Obedience to Markings

The information recorded on driver compliance with the various types of no-passing-zone markings shows that passings were frequently completed after the barrier line was reached. This may reflect an attitude that the completion of passings is permissible beyond the beginning of the barrier line and not that the maneuver must be completed before reaching it. Whatever the typical driver's reasoning, the average return point of pass completions observed in the vicinity of both the Missouri standard and the national standard zones in this study was beyond the start of the barrier line.

Table 8 is a compilation of the comparative obedience data. The average point of completion was calculated from the beginning of the normal-length barrier line and, in the case of the extended zones, from the start of the extended barrier line.

In general, the completion point was considerably farther into the no-passing zone when the barrier line was located in the center of the driving lane. For the normal zone, the average was 228 feet in the day study and 202 feet at night, as compared with 86 feet and 172 feet, respectively, on the national standard design. No great difference was evident between Missouri and foreign drivers in the daytime results, but at night the latter did not observe either barrier line as well as the local drivers.

On the extended zones, roughly the same pattern of compliance existed. The additional 200 feet of length on the advance end of the barrier lines apparently served only to increase the infringement on the no-passing zones by approximately the same amount.

The data in table 8 indicate that the number of passings recorded was somewhat greater during the studies on the national standard zone. Aside from the effects of alinement and traffic volume which, as previously stated, were quite similar, the sight-

Table 6.—Effect of barrier-line location on average transverse placement, and percentage of vehicles with placement less than 3.5 and 4.5 feet from roadway center while in no-passing zone (sites M–3 and N–3)

Light condition and movement classification	Average transverse placement		Percentage [1] with placement less than—			
			3.5 feet		4.5 feet	
	Missouri standard	National standard	Missouri standard	National standard	Missouri standard	National standard
Passenger Cars						
Daylight:	*Feet*	*Feet*	*Percent*	*Percent*	*Percent*	*Percent*
Free moving	4.57	4.52	10.5	13.1	48.7	49.2
With opposing traffic	5.02	5.11	8.2	*2.9	26.6	*20.6
Other	4.57	4.56	5.0	12.2	49.4	*45.4
All movements	4.67	4.64	7.6	10.9	44.2	*42.3
Night:						
Free moving	4.45	4.45	13.8	*11.9	62.1	*56.6
With opposing traffic	4.83	4.92	5.2	7.2	31.6	*30.9
Other	4.43	4.43	11.9	19.1	57.1	*52.4
All movements	4.52	4.54	11.1	13.8	53 4	*49.4
Commercial Vehicles						
Daylight:						
Free moving	4.85	5.09	11.8	*3.7	35.3	*11.1
With opposing traffic	4.85	5.71	0	*0	28.6	*0
Other	5.06	5.37	0	*0	18.8	*7.4
All movements	4.92	5.29	4.3	*1.6	27.7	*9.7
Night:						
Free moving	4.51	5.02	7.1	*0	50.0	*9.1
With opposing traffic	4.90	5.02	4.7	*0	33.3	*8.3
Other	4.48	4.81	17.4	*12.0	52.2	*40.0
All movements	4.64	4.91	10.3	*6.3	44.8	*25.0
All Vehicles						
Daylight:						
Free moving	4.62	4.62	10.8	11.4	46.3	*42.9
With opposing traffic	4.98	5.18	6.4	*2.6	27.0	*18.4
Other	4.64	4.65	4.3	10.8	45.2	*41.0
All movements	4.71	4.73	7.0	9.7	41.3	*37.9
Night:						
Free moving	4.46	4.53	11.6	*10.4	58.1	*50.6
With opposing traffic	4.86	4.94	5.0	5.6	32.5	*25.9
Other	4.45	4.52	13.8	17.5	55.3	*49.5
All movements	4.57	4.62	10.7	12.3	49.9	*44.7

[1] Asterisks indicate cases where the percentage for the national standard is lower than (or equal to) the comparable percentage for the Missouri standard.

restriction of sight distance available for passing on the mileage approaching site N from the east may account for the somewhat greater number of passings recorded at that location. The difference between the average position of the passing completion points on the two types of barrier-line marking, however, seems more likely to be related to the difference in barrier-line location than to the factor just mentioned.

Table 7.—Difference between average transverse placement of vehicles (all types) in daylight and at night

Study location and movement classification	Difference between placement in daylight and at night [1]	
	On Missouri standard	On national standard
Site 1:	*Feet*	*Feet*
Free moving	−0.34	+0.30
With opposing traffic	−.13	−.06
Other	−.54	−.50
All movements	−.40	−.13
Site 2:		
Free moving	−.16	+.14
With opposing traffic	−.05	+.13
Other	−.16	−.01
All movements	−.13	+.08
Site 3:		
Free moving	−.16	−.09
With opposing traffic	−.12	−.24
Other	−.19	−.13
All movements	−.14	−.11
Site 4:		
Free moving	−.08	+.13
With opposing traffic	−.03	+.23
Other	+.02	+.10
All movements	−.05	+.15
Site 5:		
Free moving	−.17	+.35
With opposing traffic	−.06	+.25
Other	−.35	+.01
All movements	−.15	+.17
Site 6:		
Free moving	−.23	+.14
With opposing traffic	+.18	+.29
Other	−.27	−.13
All movements	−.18	+.04

[1] Minus sign indicates that placement at night was closer to roadway center line than placement in daylight; plus sign indicates placement at night farther away than in daylight.

distance conditions leading to the test sites may have had a relation to the actual frequency of passings recorded. The mile immediately west of site M had 0.3 mile of eastbound no-passing zones while the mile east of site N, by comparison, had 0.45 mile of westbound no-passing zones. This more severe

Obscurement of Barrier Line

When the barrier line is located in the center of the driving lane, it is frequently obscured in part or totally by vehicles on the road ahead. Figure 8 has been constructed to show the comparative conditions of view from the driver's seat when trailing the vehicle ahead at various distances. It assumes that the vehicle ahead is in normal position on a 20-foot pavement and that the approach to the no-passing zone is on tangent alinement. The driver sees the Missouri-type barrier line only by looking under or through the vehicle ahead and, for all practical purposes, his maximum notice of the beginning of the barrier line is the distance between him and the rear of the vehicle ahead. Overtaking and passing studies conducted on rural highways by the Bureau of Public Roads [3] indicate that the average passing vehicle is approximately 55 feet behind the car ahead when it starts into the left lane to pass.

With the barrier line next to the center line, the driver can see to a varying extent around the side of the vehicle ahead and his advance view of the barrier line is considerably longer. If he moves laterally toward the center of the roadway from his normal position, preparatory to passing, his view of the barrier line next to the center line increases rapidly, as indicated by figure 8.

[3] *Passing practices on rural highways*, by C. W. Prisk. Proceedings of the Highway Research Board, vol. 21, 1941.

Table 8.—Effect of barrier-line location on driver observance of no-passing zones

Light condition and barrier-line type	Passings completed in vicinity of no-passing zones by—					
	Missouri drivers		Foreign drivers		All drivers	
	Number of passings	Average completion point [1]	Number of passings	Average completion point [1]	Number of passings	Average completion point [1]
Normal Length Zones						
Daylight:		*Feet*		*Feet*		*Feet*
Missouri standard	20	230	37	227	57	228
National standard	28	66	86	93	114	86
Night:						
Missouri standard	14	160	7	286	21	202
National standard	31	87	33	252	64	172
Extended Zones						
Daylight:						
Missouri standard	23	404	46	406	69	405
National standard	33	280	58	342	91	320
Night:						
Missouri standard	11	413	9	528	20	465
National standard	7	307	16	341	23	330

[1] Average completion point is the distance traveled into the no-passing zone before returning to the right lane.

Under other conditions of alinement, the comparative distances at which barrier lines at the two locations could be seen will differ, of course, but there is little doubt that the advantage in driver viewing distance will remain with the national standard in the majority of instances. The lack of advance view is believed to be a prominent factor in the relatively poorer observance found at the Missouri-type zone.

Effect of Extended Barrier Lines

As noted previously, the barrier lines were extended to see if this disadvantage of short advance view of the no-passing zone could be overcome. The 200-foot dashed and solid extensions of the barrier lines did not materially change the average location on the road where passings were completed, but they did influence the average placement of vehicles entering the zones. Table 9 presents the average placements obtained at each zone for three conditions, viz, the normal-length zone, the zone extended at the advance end with a 200-foot dashed line, and the zone extended with a 200-foot solid line. All three studies were made at the beginning of the normal-length barrier line in the two test zones.

The dashed extension on the Missouri standard zone made no appreciable difference in the average day or night placement. On the national standard with the dashed extension, however, the average position of vehicles with opposing traffic was 0.33 foot farther away from the roadway center in the day study and 0.43 foot farther away at night.

With the solid extension, the vehicles with opposing traffic again were affected the most. No great difference was found on the Missouri zone in the daytime, but at night this class of vehicles averaged 0.36 foot farther away from the center line. On the national standard the difference was still greater. The placement results with the solid line extension show that vehicles used a path appreciably farther to the right than they did with no extension or with only a dashed line extension, and that a greater effect generally was caused on the national standard than on the Missouri type zone.

Opinions of Drivers

The Missouri State Highway Department, using the post card questionnaire survey technique, has solicited driver reaction to their no-passing-zone markings on several occasions. One of these surveys made a few years ago, in which almost 12,000 cards were passed out to motorists and 3,063 were returned, indicated a 2½ to 1 preference for locating the barrier line in the center of the driving lane.

As a check on this finding and to eliminate any possibility of bias being caused by having motorists who are intrigued by novel traffic controls responding in greater numbers than those not so interested, a 100-percent sample of driver reaction was obtained as a phase of the study. Interviewers stationed at the extremities of the 16.5-mile test section stopped all outbound traffic and asked drivers these questions:

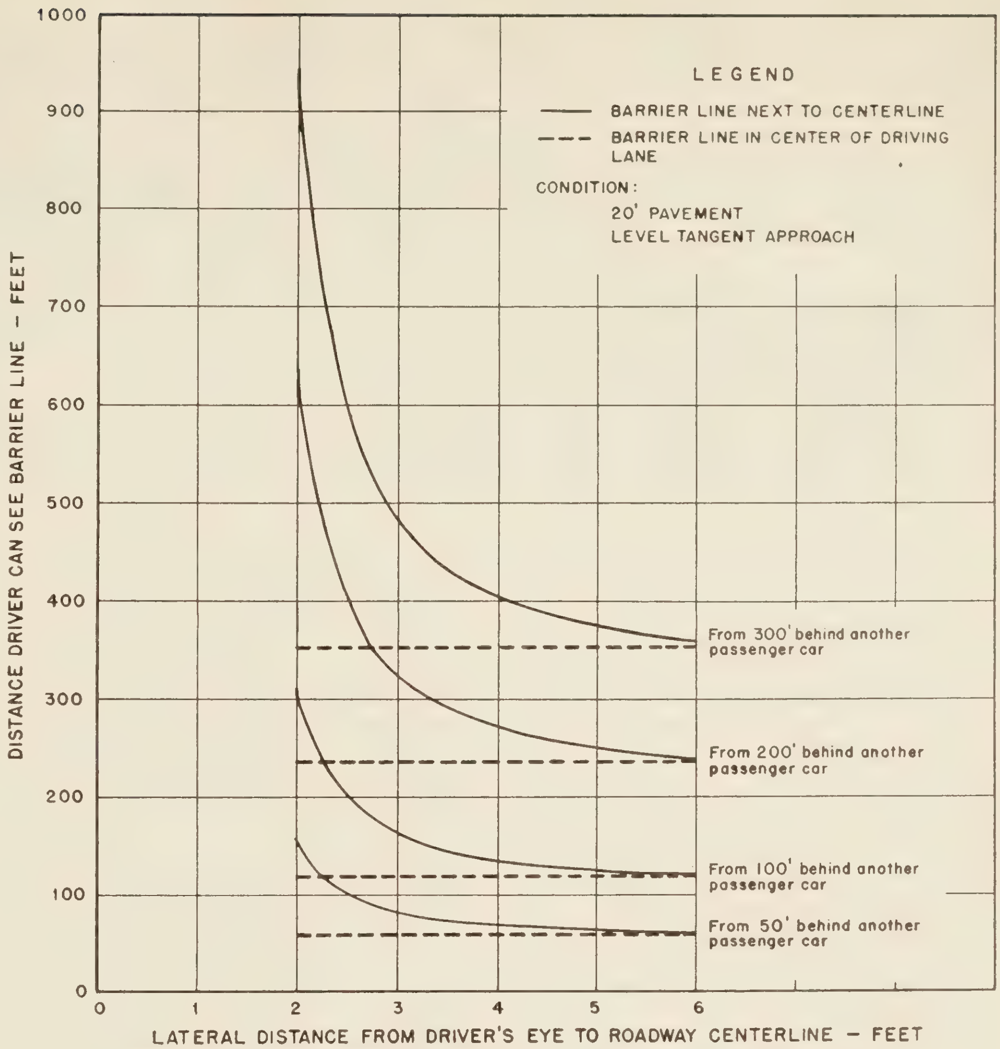

Figure 8.—Obscurement of barrier line by vehicles on the road ahead.

1. Did you notice the two different systems of marking no-passing zones?
2. Do you have a preference for either system?
3. Which system does your State use?

The State of registration of the vehicle was also noted on the interview form. Station NQ adjoined the national standard, and station MQ the Missouri standard.

A summary of the returns from the 1,005 drivers interviewed appears in table 10. Replies were segregated by drivers of vehicles registered in Missouri, States bordering Missouri, and all other States, to isolate the factor of familiarity. More than 93 percent of all drivers who had traveled over the test section stated that they had noticed the two types of markings. As shown by the reply to the third

Table 9.—Effect on average transverse placement of extending no-passing zone with 200-foot dashed and solid barrier lines

Light condition and movement classification	Placement on Missouri standard					Placement on national standard				
	Normal zone, site M-2	Dashed extension, site M-4		Solid extension, site M-6		Normal zone, site N-2	Dashed extension, site N-4		Solid extension, site N-6	
		Average placement	Change from normal [1]	Average placement	Change from normal [1]		Average placement	Change from normal [1]	Average placement	Change from normal [1]
	Feet	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*	*Feet*
Daylight movement:										
All vehicles	4.34	4.33	−0.01	4.48	+0.14	4.21	4.30	+0.09	4.50	+0.29
Free moving	4.36	4.28	−.08	4.43	+.07	4.14	3.92	−.22	4.29	+.15
With opposing traffic	4.53	4.58	+.05	4.66	+.13	4.42	4.75	+.33	4.81	+.39
Night movement:										
All vehicles	4.21	4.28	+.07	4.30	+.09	4.29	4.45	+.16	4.54	+.25
Free moving	4.20	4.20	0	4.20	0	4.28	4.35	+.07	4.43	+.15
With opposing traffic	4.48	4.55	+.07	4.84	+.36	4.55	4.98	+.43	5.10	+.55

[1] Minus sign indicates placement with dashed or solid extension of barrier line was closer to roadway center line than with normal length of barrier line; plus sign indicates placement farther from center line.

Table 10.—Summary of driver interviews at ends of test section [1]

	Drivers from Missouri			Drivers from Illinois, Kansas, Oklahoma, and Arkansas			Drivers from other States			All drivers		
	Station NQ	Station MQ	Total	Station NQ	Station MQ	Total	Station NQ	Station MQ	Total	Station NQ	Station MQ	Total
Different systems noticed:												
Yes	126	135	261	158	101	259	192	227	419	476	463	939
No	5	9	14	10	5	15	17	20	37	32	34	66
Preference:												
Missouri standard	56	68	124	85	62	147	76	132	208	217	262	479
National standard	67	63	130	73	42	115	122	105	227	262	210	472
No choice	8	13	21	10	2	12	11	10	21	29	25	54
System used in own State:												
Missouri standard	---	---	---	2	3	5	2	9	11	---	---	---
National standard	---	---	---	159	100	259	202	225	427	---	---	---
Other	---	---	---	3	0	3	2	3	5	---	---	---
Not known	---	---	---	4	3	7	3	10	13	---	---	---

[1] Eastbound drivers were interviewed at the east end of the test section, at station NQ, adjoining the mileage marked with the national standard; westbound drivers at the west end, at station MQ, adjoining the mileage marked with the Missouri standard.

question, practically every out-of-State driver knew also that his State placed the barrier line next to the center line.

When asked for an expression of preference, Missouri drivers, border-State drivers, and other drivers were all quite evenly divided between the two systems. Neither interview station was within sight of a no-passing-zone marking, but drivers tended to favor the marking standard they had more recently seen. Missouri drivers at station NQ, for example, who had just seen about 9 miles of the national standard marking, showed a 67 to 56 preference for having the barrier line next to the center line, while Missouri drivers at station MQ, having just passed about 7½ miles of the Missouri standard, voted 68 to 63 for the barrier line at the center of the driving lane.

Summary of Findings

The findings of this special study of no-passing-zone marking designs are of necessity based on observation and analysis of traffic performance in a State where only one marking design generally prevails. That one design, which prescribes the position of the barrier line at the center of the driving lane, rather than next to the center line, is the exception rather than the rule among the States. The operating experience from which this report has been prepared may not, therefore, be precisely representative of the performance that would be found if the situation were reversed and the Missouri design were in widespread use. To the extent possible, the effects of familiarity have been explored and discussed so that this factor and the principal data will appear in their proper relation.

The major results derived from comparative study of vehicles traversing the two types of no-passing-zone marking are as follows:

1. Average operating speeds 500 feet in advance of the no-passing zones compared were almost identical, and were slightly over 52 miles per hour for vehicles proceeding toward the zone. At a point 300 feet within each of the zones the general average speed level was lower by 2 to 3 miles per hour, and the greater decreases occurred with foreign drivers on the Missouri type marking and with Missouri drivers on the national standard marking. The difference between the Missouri and the foreign drivers' reaction to the zone, measured in terms of that speed change, was larger at the Missouri zone, probably because Missouri drivers were better acquainted with the conventional barrier-line location than foreign drivers were with the center-of-the-lane position used throughout Missouri.

2. A remarkable similarity exists between the average placement values obtained in comparable studies at the two sites for all locations at or beyond the start of the barrier line. The least difference between average placements at comparable locations in the two zones was observed at a point 300 feet beyond the beginning of the barrier line. Here, on the Missouri marking, the average placement of all vehicles, expressed in terms of the distance from vehicle center to roadway center, was 4.71 feet in the day study and 4.57 feet at night. Corresponding values for the national standard zone were 4.73 feet and 4.62 feet.

At the two-direction no-passing zone marked with the Missouri design, the average placement for the direction with a tangent approach was 4.73 feet in the daytime and 4.68 feet at night. For the opposite direction, the respective values were 4.32 feet and 4.28 feet, indicating only a small difference between average placements on the one-direction and the two-direction zones.

3. The average placement of vehicles at a point 300 feet within both types of no-passing zones was from 0.3 to 0.75 foot farther from the center line than it was for vehicles at the beginning of the barrier line. The maximum differences occurred when opposing traffic was in the left lane. At both types of zones, about three-fourths of all passenger cars traveled with their centers in the range of 3.6 to 5.5 feet of the center line when they were actually within the zone.

4. Detailed analysis of the placement distribution pattern shows interesting differences between the results obtained at the two test zones. On the national standard, vehicle paths were somewhat more widely dispersed than on the Missouri zone. Statistical measures of dispersion for the placement data show that passenger cars, for example, did not generally follow a central path as precisely on the national standard as they did on the Missouri zone. However, it is significant that less dispersion in vehicle placements occurred within the national standard zone than in the Missouri zone when oncoming traffic was in the opposing lane.

5. Regardless of light condition, vehicle type, or class of vehicle movement, the percentage of vehicles with their centers within 4.5 feet of the center line of the pavement was, with a few minor exceptions, less at a point 300 feet within the national standard zone than it was at the corresponding location marked with the Missouri design. The percentage of vehicles that had placements of 3.5 feet or less was a little lower in the Missouri zone when all classes of vehicle movement were considered together. However, a much smaller percentage of the vehicles with opposing traffic on the national standard had placements in this range than on the Missouri standard during the day. At night the corresponding percentages were approximately equal. Without exception, fewer commercial vehicles were centered within 3.5 or 4.5 feet of the roadway center in the national standard zone. Their average placement was also farther from the center line, 5.29 feet on the national standard as compared with 4.92 feet on the Missouri zone in the daytime, and 4.91 feet as compared with 4.64 feet at night.

6. Study of the difference between day and night placement data at all comparable sites reveals that the night averages were generally closer to the daytime averages where the barrier line was next to the center line. At a number of the studies on the national standard marking, the night placements actually averaged slightly farther to the right at night than in the daytime. This did not occur at any of the studies on the Missouri zone.

7. The average driver completing a passing maneuver in the vicinity of the test zones overran the Missouri type no-passing marking by 228 feet in the daytime as compared with 86 feet on the national standard zone. At night the difference was not as great but the national standard zone was still shown more respect. Extension of the barrier line at the advance end with dashed or solid lines resulted in lengthening the average violations roughly by the amount of the extension, but the extended barrier lines seemed to encourage drivers to drive somewhat farther from the center line as they approached the zone. This effect was more pronounced where the barrier line was next to the center line. The driver's advance view of the beginning of a barrier line that is located in the center of the lane is definitely hampered by the geometric limitations involved as vehicles trail one another on the approach to the zone. This factor could easily be responsible for the relatively poorer observance recorded at the Missouri type zone.

8. A 100-percent sample of drivers interviewed immediately after traveling some dis-

(Continued on page 36)

Age-Strength Relations for Air-Entrained Concrete

BY THE PHYSICAL RESEARCH BRANCH
BUREAU OF PUBLIC ROADS

Reported by FRANK H. JACKSON
Supervising Highway Physical
Research Engineer

Although it is generally recognized that entrained air in concrete has an adverse effect upon strength, exact information as to the amount of reduction to be anticipated at the later ages has been lacking. Data which are presented in this article indicate that for the usual class A structural concrete (6 sacks per cubic yard and 3 inch slump) a reduction in compressive and flexural strength of approximately 10 percent can be anticipated for ages up to and including 5 years. This is on the basis of approximately equal cement content and slump for both types of concrete, and with the sand content of the air-entrained concrete reduced by an amount approximately equal to the volume of entrained air. The tests also reveal the influence of the chemical composition of cement upon the rate of strength development. They show that the strength of concrete containing type II cement, although comparatively low at early ages, may exceed the strength of concrete containing typical type I cement (high in tricalcium aluminate) at later ages by a substantial amount.

THE tests herein reported were made primarily to obtain data on the rate of strength development of air-entrained concrete for ages up to 5 years as compared with the strength of similar concrete without air entrainment.

As the result of over 10 years practical experience in the use of air-entrained concrete, most engineers have become convinced of the value of air entrainment to improve the durability or weather resistance of concrete. It has been demonstrated both by laboratory research and by experience that the resistance of concrete to frost action can be increased many fold by the introduction of entrained air within the range of 3 to 6 percent. Unfortunately, however, this improvement in durability is almost always accompanied by a reduction in strength which, at the conventional testing periods of 7 and 28 days and for concrete containing approximately 6 sacks of cement per cubic yard, usually averages around 10 percent. This tendency to lower strength has worried many structural designers ever since air entrainment was introduced, not so much because of the early strength loss as the fear that still further reduction in strength might occur with increased age.

In the original program prepared in 1944, it was planned to make freezing and thawing tests as well as strength tests. However, the necessity for using the laboratory's refrigeration equipment for work connected with the war forced the abandonment of the freezing and thawing tests, with the result that only that portion of the program involving the strength tests was carried through to completion.

Conclusions

This report presents a limited amount of data which indicate that the loss in compressive and flexural strength, at least insofar as one class of concrete is concerned, when the specimens are stored continuously moist, remains reasonably constant at about 10 percent up to an age of 5 years. The test results indicate that:

(1) For a typical class A structural concrete (6 sacks per cubic yard and 3-inch slump), the reduction in strength due to air entrainment will average approximately 10 percent for all ages up to 5 years.

(2) Concrete containing cements relatively low in tricalcium aluminate (4 to 7 percent), although lower in strength at 7 and 28 days than similar concrete containing cements relatively high in tricalcium aluminate (11 or 12 percent), will develop substantially higher strengths at ages of 1 year or more.

Materials and Proportions

Eight portland cements, representing four brands, were used in these tests. The chemical and physical properties of the cements are given in table 1. In this table cement brand No. 1 is represented by cements A and B, brand No. 2 by cements C and D, brand No. 3 by cements E and F, and brand No. 4 by cements G and H. Cements A, C, E, and G were submitted as type I and cements B, D, F, and H as type II cements. However, as will be seen from the analyses, only two of the nominally type II cements (B and H) complied with the requirements of type II with respect to the computed tricalcium silicate (C_3S not to exceed 50 percent). Cement D was just over the limit on C_3S with 51 percent, and cement F was further over the limit with 53 percent C_3S. Likewise cement C, although classified as type I, was relatively low in C_3A. It was, however, high in C_3S with 54 percent. Cements A, E, and G were typical type I cements relatively high in C_3A. All in all, the eight cements cover fairly well the range in physical and chemical properties of the types of portland cement most frequently used in highway work.

The values for C_3A as reported in table 1 are lower than those usually reported from these sources. This is partially explained by the method of making the iron oxide and alumina determinations. At the time these analyses were made (in 1944) the Bureau was still using the Jones Reductor for reducing the iron and titrating with potassium permanganate solution. When titanium dioxide is present in a cement it is also reduced by the zinc of the Jones Reductor and is titrated along with the iron. This results in a high value of iron oxide. Since alumina is calculated by subtracting the iron oxide from the total of the ammonium hydroxide group, it is correspondingly low. In the standard procedure of the American Society for Testing Materials, iron oxide is determined by reduction with stannous chloride which does not reduce titanium. However, in the absence of an actual correction for titanium dioxide, the alumina value (as determined by A.S.T.M. procedure) will include this constituent and will therefore be somewhat higher than the true value.

For cement relatively high in C_3A, the difference obtained by the two methods is of little or no significance. However, in calculating the C_3A content the differences are

Table 1.—Properties of the cements

	Brand 1		Brand 2		Brand 3		Brand 4	
	Cement A	Cement B	Cement C	Cement D	Cement E	Cement F	Cement G	Cement H
Physical properties:								
Apparent specific gravity	3.14	3.19	3.14	3.16	3.17	3.16	3.13	3.17
Specific surface cm.²/gm.	1,640	1,610	1,690	1,580	1,810	1,670	1,690	1,720
Autoclave expansion percent	0.15	0.04	0.10	0.08	0.06	0.01	0.42	0.02
Normal consistency percent	26.0	25.0	25.0	24.0	25.0	25.0	26.0	25.0
Time of set:								
Initial hours	4.0	4.0	5.0	4.0	5.2	5.2	5.0	5.0
Final hours	7.2	6.5	7.8	6.0	7.5	7.5	8.0	8.0
Tensile strength (1:3 mortar):								
At 3 days lb. per sq. in.	310	275	240	195	325	275	325	290
At 7 days lb. per sq. in.	385	360	355	275	370	370	410	370
At 28 days lb. per sq. in.	465	470	430	380	465	445	465	450
Air entrained [1] percent	3.5	6.6	5.0	4.4	3.9	4.1	5.0	5.2
Chemical analysis (percent):								
Silicon dioxide	21.30	21.85	21.35	21.55	21.05	22.85	20.40	22.70
Aluminum oxide [2]	6.49	4.42	4.66	4.29	6.44	4.09	6.16	4.66
Ferric oxide [2]	2.96	4.48	3.44	4.56	2.56	3.76	3.44	3.44
Calcium oxide	63.10	62.90	63.50	62.55	63.65	64.65	62.70	64.30
Magnesium oxide	2.64	2.73	2.84	2.97	2.43	1.16	3.00	1.25
Sulfur trioxide	1.81	1.64	1.68	1.51	1.70	1.22	1.88	1.48
Sodium oxide	.27	.23	.21	.23	.19	.17	.27	.20
Potassium oxide	.68	.44	.59	.55	.48	.47	.52	.54
Loss on ignition	1.04	1.36	1.97	2.14	1.50	1.78	1.62	1.42
Chloroform soluble	.006	.004	.006	.007	.003	.005	.006	.008
Computed compound composition (percent):								
Tricalcium silicate	42	50	54	51	48	53	48	48
Dicalcium silicate	30	25	20	24	24	26	22	29
Tricalcium aluminate [2]	12	4	7	4	12	4	11	7
Tetracalcium aluminoferrite	9	14	10	14	8	11	10	10
Calcium sulfate	3	3	3	3	3	2	3	3

[1] A.S.T.M. standard method C 185–44.
[2] Ferric oxide determined by use of Jones Reductor. See text, page 31, third column.

reflected fourfold. This fact, and the practice of rounding compound composition to the nearest whole percentage, means that a difference of only 0.2 to 0.3 percentage points in the value for alumina can mean as high as 2 percentage points difference in calculated C_3A. In the case of low C_3A cements, this may easily affect the classification of the cement as to type.

In order to avoid misunderstanding and to promote uniformity, the Bureau discontinued the use of the Jones Reductor shortly after the analyses reported in this article were made, and the standard A.S.T.M. procedure is now used for all work. Unfortunately, samples of the particular cements used in this study were not available for a repetition of the iron oxide determinations.

Aggregates for the concrete were sand and gravel from the Potomac River. The sand was well graded, with a fineness modulus of 2.62. The gravel was uniformly graded from No. 4 up to 1½-inch size. Both aggregates met the conventional physical test requirements for quality. However, attention should be called to the fact that Potomac River gravel consists essentially of siliceous particles, principally quartz and sandstone. Aggregates of this type frequently produce concrete of relatively low flexural strength as compared with aggregates which are predominately calcareous in nature. This accounts for the relatively low values for modulus of rupture which were obtained in this study.

Test Series

Two series of tests were made, one without the addition of an air-entraining agent and the other in which sufficient neutralized Vinsol resin was added to produce an air content of approximately 4 percent.[1] For each type of concrete the same weight proportions were used with all eight cements with the result that the individual cement contents varied slightly from the nominal value of 6.0 sacks per cubic yard due to variations in the water demand of the various cements. However, in no case did the actual cement content vary more than 0.08 sack per cubic yard from the nominal value. In order to maintain the same yield for the air-entrained concrete, the absolute volume of sand was reduced by an amount approximately equal to the volume of added air, the absolute volume of coarse aggregate remaining the same. The water content was also reduced, as needed, in order to obtain approximately the same slump. Complete mix data, including air contents, are given in table 2.

[1] Calculated in accordance with the procedure described in the American Society for Testing Materials standard method C 138–44.

At the time these tests were started, in 1944, air entrainment was almost universally obtained by the use of a neutralized solution of Vinsol resin, the product of a particular manufacturer. Since that time numerous proprietary air-entraining admixtures have appeared on the market. Many of these are neutralized Vinsol resins marketed under individual trade names. Tests which have been made to date by the Bureau of Public Roads indicate that any admixture which will meet the requirements of the American Society for Testing Materials specification C 260–50T, "Specifications for air-entraining admixtures for concrete—tentative," will be satisfactory for use in the manufacture of air-entrained concrete.

Two types of specimens were made for the tests: standard 6- by 12-inch cylinders for compressive strength tests and 6- by 6- by 20-inch beams for flexural strength tests. On both types of specimens, strength determinations were made after 7 days, 28 days, 1 year, and 5 years moist storage. Values reported are the averages of tests on three specimens, making a total of 384 test specimens for the entire study. Mixing, molding, curing, and testing operations were all conducted strictly in accordance with standard procedures.

Compressive strength data for each cement for both non-air-entrained and air-entrained concrete are given in table 3 with the corresponding data for flexural strength in table 4. The effect of air entrainment on compressive and flexural strength is shown in figure 1 while in figure 2 the same data have been plotted to show the effect of cement composition.

Effect of Air Entrainment

It will be observed that, in the case of all eight cements and for both types of test, the introduction of entrained air caused a reduc-

Table 2.—Mix data for strength specimens [1]

Cement	Vinsol resin [2]	Cement content [3]	Net water content	Slump	Weight of fresh concrete	Air content [3]
	Percent	*Sacks/cu. yd.*	*Gal./sack*	*Inches*	*Lb./cu. ft.*	*Percent*
Non-air-entrained concrete:						
A		6.0	5.4	2.5	148.6	1.0
B		6.1	5.3	2.7	149.0	.8
C		6.0	5.4	2.3	148.3	1.3
D		6.1	5.3	2.6	148.7	1.2
E		6.0	5.6	2.4	148.3	.8
F		6.0	5.5	3.0	148.7	.8
G		6.0	5.5	2.7	148.4	.8
H		6.0	5.5	2.6	147.7	1.4
Air-entrained concrete:						
A	0.0065	6.1	5.1	2.7	144.6	4.0
B	.0075	6.1	5.0	2.6	144.6	4.1
C	.0090	6.1	5.1	2.7	143.9	4.4
D	.0080	6.1	5.0	2.9	144.5	4.2
E	.0105	6.1	5.2	2.7	144.3	3.9
F	.0080	6.1	5.1	2.9	144.7	3.8
G	.0075	6.1	5.2	2.8	144.7	3.7
H	.0100	6.0	5.0	2.6	143.1	5.0

[1] Proportions by oven-dry weight (in pounds), using No. 4 to 1½-inch gravel: Non-air-entrained concrete, 94:164:355; air-entrained concrete, 94:145:355.
[2] Percentage by weight of cement. Neutralized with sodium hydroxide and added in solution form.
[3] Tests made in accordance with A.S.T.M. standard method C 138–44.

tion in strength at all ages. In compressive strength the percentage reduction varied from a low of 5 (cement G at 7 days, cement E at 1 year, and cements B and E at 5 years) to a high of 19 (cement H at 7 and 28 days). In flexural strength the corresponding range was from a low of 3 (cement G at 28 days) to a high of 21 (cement B at 7 days). In compressive strength, the average percentage reductions for all cements were 10 at 7 days, 11 at 28 days, 12 at 1 year, and 11 at 5 years. In flexural strength, the corresponding reductions were 11 at 7 days, 7 at 28 days, 9 at 1 year, and 8 at 5 years. It will be seen from these data that the reduction of strength in both compression and in flexure averaged approximately 10 percent for periods up to and including 5 years, with tests in flexure tending to show somewhat smaller reductions than those in compression.

Table 3.—Compressive strength tests [1]

Cement	Compressive strength of non-air-entrained concrete				Compressive strength of air-entrained concrete				Reduction in strength due to air entrainment			
	7 days	28 days	1 year	5 years	7 days	28 days	1 year	5 years	7 days	28 days	1 year	5 years
	P.s.i.	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*Percent*	*Percent*	*Percent*	*Percent*
A	4, 190	5, 510	6, 790	7, 100	3, 760	4, 950	6, 240	6, 390	10	10	8	10
B	3, 340	5, 010	7, 300	7, 470	2, 990	4, 590	6, 260	7, 090	10	8	14	5
C	3, 100	4, 850	6, 200	7, 090	2, 890	4, 290	5, 380	6, 230	7	12	13	12
D	2, 900	4, 500	6, 470	7, 130	2, 480	4, 100	5, 430	6, 130	14	9	16	14
E	3, 880	5, 890	6, 810	7, 010	3, 650	5, 260	6, 500	6, 630	6	11	5	5
F	3, 180	4, 890	7, 130	7, 880	2, 970	4, 520	6, 330	6, 740	7	8	11	14
G	3, 870	5, 630	6, 830	6, 970	3, 670	4, 950	5, 840	6, 340	5	12	14	9
H	3, 240	5, 150	7, 270	7, 770	2, 630	4, 180	6, 290	6, 470	19	19	13	17
Average	3, 460	5, 180	6, 850	7, 300	3, 130	4, 600	6, 030	6, 500	10	11	12	11

[1] Each value is the average of three tests of 6- by 12-inch cylinders.

Table 4.—Flexural strength tests [1]

Cement	Modulus of rupture for non-air-entrained concrete				Modulus of rupture for air-entrained concrete				Reduction in strength due to air entrainment			
	7 days	28 days	1 year	5 years	7 days	28 days	1 year	5 years	7 days	28 days	1 year	5 years
	P.s.i.	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*P.s.i.*	*Percent*	*Percent*	*Percent*	*Percent*
A	575	635	630	670	505	605	600	640	12	5	5	4
B	515	645	750	775	405	590	655	700	21	9	13	10
C	485	565	660	730	450	545	570	675	7	4	14	8
D	460	595	635	785	385	540	595	715	16	9	6	9
E	545	620	670	690	495	580	590	630	9	6	12	9
F	485	615	700	720	450	560	645	670	7	9	8	7
G	515	610	625	665	490	590	595	620	5	3	5	7
H	470	595	685	735	425	535	640	680	10	10	7	7
Average	505	610	670	720	450	570	610	665	11	7	9	8

[1] Each value is the average of three tests of 6- by 6- by 20-inch beams.

These data indicate that under certain conditions a strength reduction due to air entrainment as high as 20 percent might be obtained without exceeding an air content of 5 percent. At first sight this might seem to be quite serious. However, if we examine the strength values themselves we note that even in the case of cement H, which, with 5 percent air in the concrete, showed the largest reduction in compressive strength, the strength of the air-entrained concrete at 28 days was 4,180 pounds per square inch, which is roughly 40 percent higher than the 3,000 usually assumed for design purposes in the case of class A structural concrete. Thus it will be seen that even on the basis of a 19-percent reduction in compressive strength—the largest reduction in compressive strength found in these tests—there still remains a fairly high factor of safety in the use of air-entrained concrete in cases where compressive strength is used as the basis of design.

In flexure the lowest strength obtained with any cement at 28 days was 535 pounds per square inch. This was air-entrained concrete containing cement H with 5 percent air. As previously stated, the Potomac River gravel which was used in these tests, due to its predominately siliceous composition, produces concrete having low flexural strength as compared with concretes containing other types of aggregates, particularly those which are predominately calcareous in composition. Under these conditions it is difficult to meet the usual strength design requirement of 550 pounds per square inch modulus of rupture at 14 days without using a cement content substantially in excess of the 6.0 sacks per cubic yard used in these tests. It is recommended, in all cases where aggregate of this type is to be used in pavement concrete, that the required cement content be determined by laboratory test. This applies to both non-air-entrained and air-entrained concrete but is particularly important in the case of the latter due to the lower strength which is usually obtained.

Even in cases where the aggregates are of such a nature as to develop high flexural strength (say 700 to 750 pounds per square inch at 14 days) it is good engineering to design the mix by laboratory test in order to realize the saving in cement which the use of high-strength materials may make possible. The cement content which will develop the required flexural strength should be used as the basis of mix design and this can only be determined by test.

Significance of Strength Reductions

It should be noted that the reductions in strength herein reported are based on laboratory tests of carefully controlled concrete mixtures and that they therefore do not take into consideration the improvement in uniformity of field mixtures of air-entrained concrete which may reasonably be anticipated. It is well known that air-entrained concrete is much more workable and therefore can be placed with much less danger of segregation, water gain, etc., than concrete which does not contain entrained air. This is particularly true where the concrete is to be placed in heavily reinforced structural members where workability is of prime importance. Under these conditions, especially, it is felt that the improvement in uniformity of the concrete in the member as a whole will more than compensate for the theoretical loss in strength due to the entrained air as indicated by tests of 6- by 12-inch cylinders. These benefits are hard to measure quantitatively, but they are none the less real as will be attested by construction men generally who have used air-entrained concrete in their work.

There is another point which should be emphasized when studying the significance of strength losses due to entrained air. This is the relatively rapid deterioration of non-air-entrained concrete exposed to severe weathering as compared to concrete containing entrained air. The loss in strength which invariably accompanies deterioration due to the effect of alternate freezing and thawing may very quickly neutralize any initial strength advantage the non-air-entrained concrete may have enjoyed.

Effect of Cement Composition

The rather wide variations in chemical composition of the eight cements used in this study make it possible to study to a limited degree the age-strength relations as they are affected by variations in the three major compounds in cement—tricalcium silicate (C_3S), dicalcium silicate (C_2S), and tricalcium aluminate (C_3A). As previously stated, it was the original intent to obtain a typical type I and a typical type II cement from each of the four companies supplying cement for this investigation. In figure 2 the concrete strengths obtained with the four pairs of cements that were actually supplied have been plotted in such a way as to reveal the effect of variations in composition of each pair separately. The computed percentage of C_3A, C_3S, and C_2S for each cement is also shown at the top of figure 2.

The effect of composition on rate of strength development is immediately apparent. For example, concrete containing cement B with 4 percent C_3A, although with one exception lower in both compressive and flexural strength than concrete containing cement A at 7 and 28 days, is considerably higher in strength at the later ages of 1 and 5 years. The same is generally true of concrete containing cements E and F and cements G and

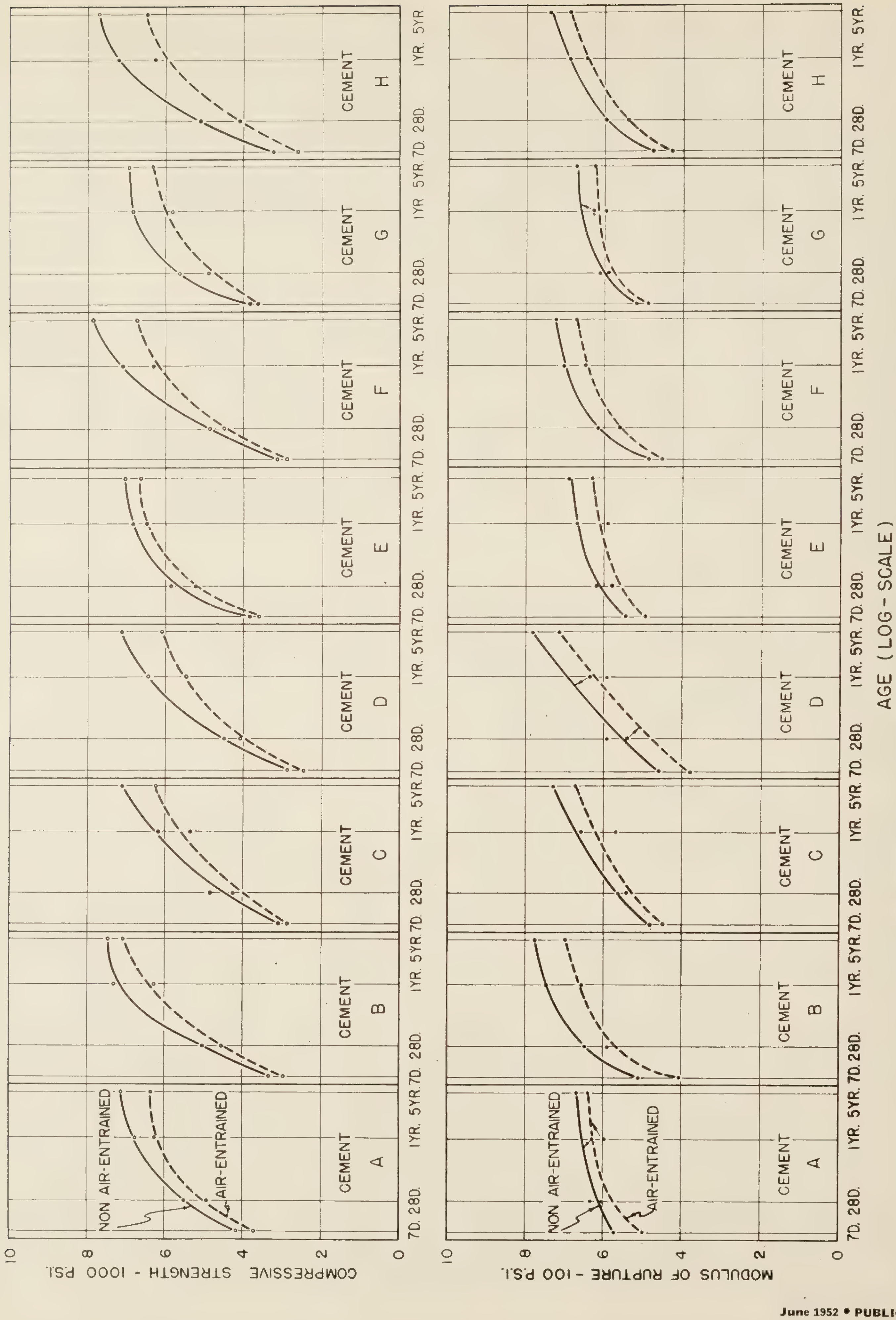

Figure 1.—Effect of air entrainment on the compressive strength (upper chart) and flexural strength (lower chart) of concrete.

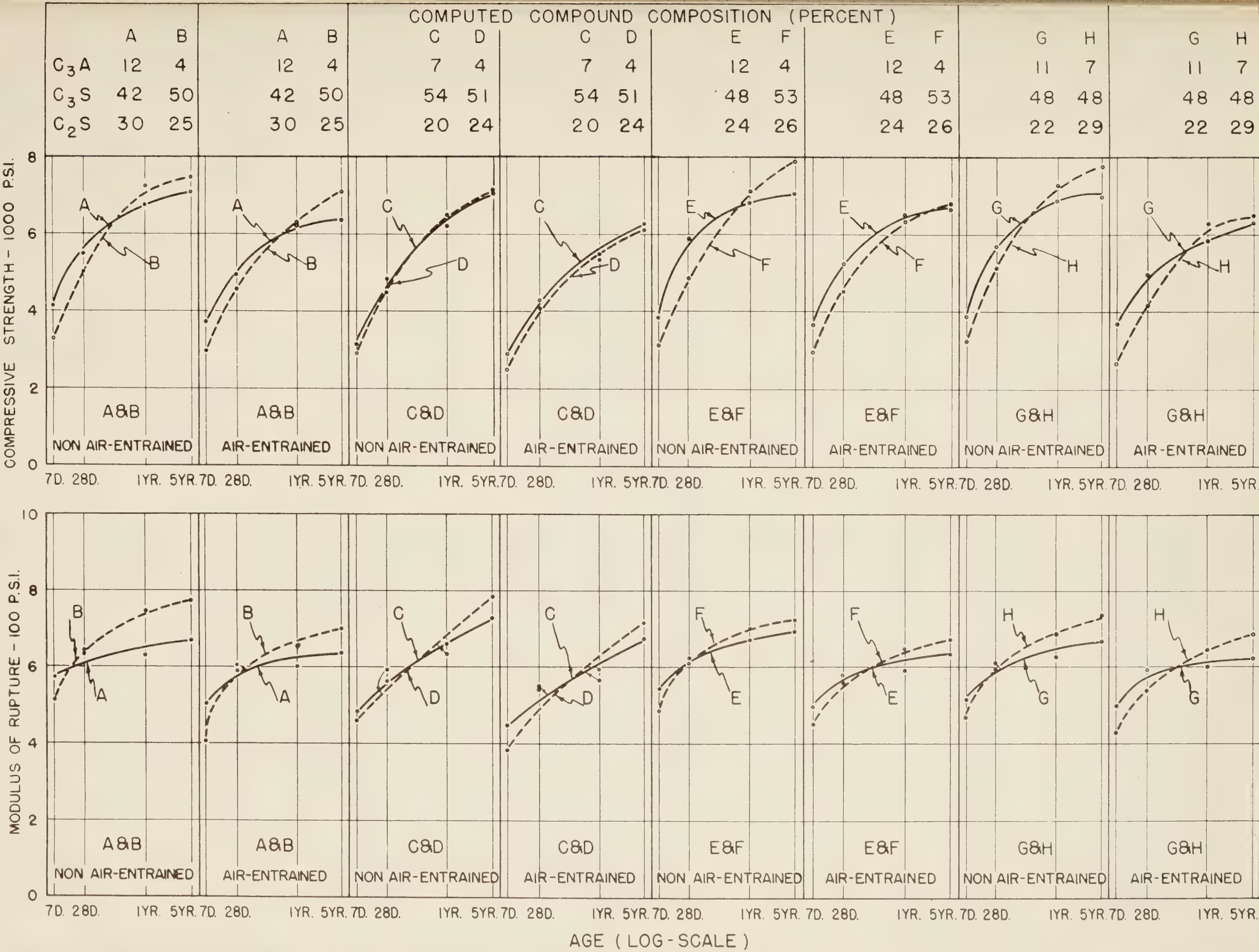

Figure 2.—Effect of cement composition on the compressive strength (upper chart) and flexural strength (lower chart) of concrete. The computed percentages of tricalcium aluminate, tricalcium silicate, and dicalcium silicate in each of the cements are shown at the top of the upper chart.

II where similar variations in C_3A are indicated. Only in the case of cements C and D are the rates of strength development about the same. In this case, both cements are sufficiently low in C_3A to be classified as type II cements although neither would qualify insofar as C_3S is concerned. It may also be noted that the two cements giving the highest compressive strengths at 5 years (F and H) in non-air-entrained concrete are also highest in combined C_3S and C_2S (79 and 77 percent, respectively) while cement G, which shows the lowest combined C_3S and C_2S (70 percent), developed the lowest compressive strength in non-air-entrained concrete at 5 years. In the case of flexural strength, cements B and D (with 4 percent C_3A and 75 percent combined C_3S and C_2S) developed the highest strength at 5 years with cement G having the lowest strength.

The above trends with respect to cement composition, although not startling, are of interest largely because they verify by actual test the generally accepted theories regarding the effect of cement composition on rate of strength development. They show in general that concrete containing type II cement, although low in early strength, is apt to exceed the strength of concrete containing type I cement by substantial amounts at later ages.

The Effect of Barrier-Line Location at No-Passing Zones

(Continued from page 30)

tance over both types of marking indicated that their preference was far from being one-sided. Of the 1,005 drivers questioned, 479 preferred the Missouri design, 472 preferred the national standard, and 54 had no choice. The expression of Missouri drivers alone was 130 to 124 for placing the barrier line next to the center line, while 21 stated they had no preference. The survey revealed too that over 93 percent of the drivers had noticed the two types of marking, and that most foreign drivers were aware that their State placed the barrier line adjacent to the center line, which is the location recommended as the national standard.

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AS OF APRIL 30, 1952

(Thousand Dollars)

STATE	UNPROGRAMMED BALANCES	ACTIVE PROGRAM: PROGRAMMED ONLY			PLANS APPROVED, CONSTRUCTION NOT STARTED			CONSTRUCTION UNDER WAY			TOTAL		
		Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles	Total Cost	Federal Funds	Miles
Alabama	$9,843	$30,684	$15,394	477.3	$8,210	$4,571	123.9	$22,335	$11,261	439.1	$61,229	$31,226	1,040.3
Arizona	804	5,747	4,146	133.0	2,210	1,583	36.8	8,881	6,171	140.7	16,838	11,900	310.5
Arkansas	7,722	6,824	3,760	246.5	4,025	2,011	153.7	16,168	8,233	450.0	27,017	14,004	850.2
California	4,258	38,400	13,759	179.9	18,985	8,366	78.8	78,258	37,784	236.7	135,643	59,909	495.4
Colorado	6,225	4,808	2,271	114.4	3,507	1,946	83.3	11,601	6,299	255.5	19,916	10,516	453.2
Connecticut	6,477	3,500	1,800	13.2	1,709	822	2.0	10,516	5,571	19.2	15,725	8,193	34.4
Delaware	2,610	1,600	800	8.0	2,767	1,032	12.1	3,281	1,630	37.7	7,648	3,462	57.8
Florida	4,964	15,034	7,782	319.8	10,922	5,527	183.9	13,974	6,766	290.6	39,930	20,075	794.3
Georgia	8,156	17,286	8,784	501.0	9,324	4,356	134.0	33,816	16,612	509.1	60,426	29,752	1,144.1
Idaho	5,630	11,600	7,305	283.0	1,221	766	39.5	5,395	3,497	127.3	18,216	11,568	449.8
Illinois	14,120	51,635	28,437	427.0	24,986	12,501	263.7	73,735	37,257	591.4	150,356	78,195	1,282.1
Indiana	12,106	36,119	18,773	206.0	11,441	6,142	226.5	24,316	12,637	252.4	71,876	37,552	684.9
Iowa	2,433	17,712	9,355	583.9	11,111	5,580	507.2	16,870	8,398	687.3	45,693	23,333	1,778.4
Kansas	8,856	11,270	5,482	1,288.4	8,187	4,078	371.8	16,744	8,750	629.2	36,201	18,310	2,289.4
Kentucky	5,213	19,497	10,200	283.4	7,388	3,990	133.6	13,587	6,868	248.8	40,472	21,058	665.8
Louisiana	3,142	18,047	8,676	127.6	13,256	6,136	79.5	17,115	8,553	172.8	48,418	23,365	379.9
Maine	3,039	7,973	4,360	45.7	2,019	1,011	10.1	7,168	3,620	63.0	17,160	8,991	118.8
Maryland	8,230	4,079	1,953	56.1	544	275	11.1	11,163	5,833	24.9	15,786	8,061	92.1
Massachusetts	7,362	7,693	3,849	11.1	2,073	836		50,159	24,360	46.6	59,925	29,045	57.7
Michigan	5,915	32,076	15,972	524.2	9,854	4,975	181.8	56,246	24,731	324.1	98,176	45,678	1,030.1
Minnesota	5,468	11,569	6,086	1,167.3	14,711	7,458	811.2	20,056	11,089	664.7	46,336	24,633	2,643.2
Mississippi	4,702	17,744	9,124	626.0	7,010	3,476	215.1	17,866	9,310	466.5	42,620	21,910	1,307.6
Missouri	11,596	30,615	15,451	890.7	12,226	6,113	301.6	43,362	22,760	648.1	86,203	44,324	1,840.4
Montana	9,919	10,234	6,163	332.0	3,954	2,273	104.3	18,844	11,310	300.0	33,032	19,746	736.3
Nebraska	12,183	12,017	6,294	527.1	8,337	4,160	182.8	17,144	8,510	557.6	37,498	18,964	1,267.5
Nevada	2,494	7,727	6,157	314.3	1,278	1,069	46.9	4,498	3,739	162.5	13,503	10,965	523.7
New Hampshire	2,612	3,661	1,974	24.1	629	314	2.2	6,461	3,219	45.0	10,751	5,507	71.3
New Jersey	2,909	13,212	6,486	34.5	5,354	2,665	9.3	31,948	15,634	21.8	50,514	24,785	65.6
New Mexico	2,130	6,776	4,339	262.9	2,469	1,584	60.7	13,399	8,570	303.8	22,644	14,493	627.4
New York	44,554	78,229	40,881	145.2	13,512	6,262	63.3	103,551	47,271	368.2	195,292	94,414	576.7
North Carolina	6,902	22,815	11,110	418.7	6,007	2,631	169.5	22,658	11,363	405.0	51,480	25,104	993.2
North Dakota	2,394	13,249	6,785	1,429.5	5,554	2,789	510.8	8,713	4,397	762.5	27,516	13,971	2,702.8
Ohio	14,906	36,531	17,944	157.0	13,139	6,485	73.6	74,269	37,777	251.6	123,939	62,206	482.2
Oklahoma	4,448	16,029	8,872	257.3	8,088	4,217	167.5	19,813	10,552	201.6	43,930	23,641	626.4
Oregon	1,836	3,789	2,240	61.4	3,629	2,141	73.3	16,849	9,567	225.2	24,267	13,948	359.9
Pennsylvania	5,098	54,807	27,396	161.7	10,127	5,051	15.6	73,765	36,625	192.8	138,699	69,072	370.1
Rhode Island	1,283	5,850	2,925	45.6	581	290	1.2	18,340	9,104	23.3	24,771	12,319	70.1
South Carolina	3,884	11,487	6,204	381.3	3,610	1,775	156.6	14,865	7,600	342.4	29,962	15,579	880.3
South Dakota	1,737	9,330	5,353	743.8	5,081	3,028	317.3	12,440	7,227	681.1	26,851	15,608	1,742.2
Tennessee	6,294	12,677	6,023	436.9	13,189	6,273	227.8	27,089	12,938	356.3	52,955	25,234	1,021.0
Texas	17,782	11,412	6,230	227.4	12,370	6,349	469.5	57,175	29,538	954.8	80,957	42,117	1,651.7
Utah	2,780	3,648	2,801	70.6	3,418	2,672	65.3	6,386	4,699	93.4	13,452	10,172	229.3
Vermont	1,483	4,600	2,484	48.8	1,699	884	21.2	5,497	2,734	35.9	11,796	6,102	105.9
Virginia	7,946	19,985	9,972	377.7	6,227	3,102	139.5	24,285	12,140	387.6	50,497	25,214	904.8
Washington	2,672	15,423	7,500	265.0	2,770	1,439	58.1	22,470	11,404	133.5	40,663	20,343	456.6
West Virginia	6,914	9,125	4,633	82.5	2,798	1,404	42.4	12,308	6,132	110.7	24,231	12,169	235.6
Wisconsin	5,145	28,370	14,883	593.5	17,255	8,290	215.1	18,927	9,693	407.8	64,552	32,866	1,216.4
Wyoming	1,979	2,072	1,360	22.4	1,856	1,311	46.7	8,051	5,208	162.0	11,979	7,879	231.1
Hawaii	1,782	7,270	3,482	13.0	439	220	5.2	10,648	4,267	24.0	18,357	7,969	42.2
District of Columbia	7,801	84	42	.2				3,252	1,819	.9	3,336	1,861	1.1
Puerto Rico	5,583	8,126	3,848	50.5	3,988	1,940	9.2	8,829	4,021	31.5	20,943	9,809	91.2
TOTAL	336,321	830,047	427,900	15,998.4	345,044	174,169	7,216.1	1,235,086	625,048	14,868.5	2,410,177	1,227,117	38,083.0

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