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# Public Roads

## A JOURNAL OF HIGHWAY RESEARCH

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OF PUBLIC ROADS,
U.S. DEPARTMENT
OF COMMERCE,
WASHINGTON

Interstate Route 89 near Hopkinton, N.H.

The independent roadway design provides a high degree of safety by the elimination of headlight glare from oncoming cars. One roadway lies atop a ridge and the other is downhill across a small ravine.

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**Muriel P. Worth**, *Editor*

## IN THIS ISSUE



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# Comparison of the Splitting Tensile Strength of Concrete with Flexural and Compressive Strengths

*BY THE DIVISION OF PHYSICAL RESEARCH*
*BUREAU OF PUBLIC ROADS*

**Reported[1] by WILLIAM E. GRIEB and GEORGE WERNER, Highway Research Engineers**

***Much interest has been shown in the use of the splitting tensile test for determining the direct tensile strength properties of concrete because of the questionable results sometimes obtained from other tensile tests. The splitting tensile test was developed more than 10 years ago and has been used successfully in other countries, but its use in the United States has been limited. Although American research laboratories are familiar with the splitting tensile test, little research data has been published. Consequently, information on correlation of this test and the more familiar tests, such as the flexural and compressive strength tests, are required for evaluation of the usefulness of this test.***

***As a step toward meeting the need for evaluation of the splitting tensile test, more than 6,000 concrete specimens were tested in the laboratory of the Bureau of Public Roads to compare the splitting tensile strength test results with those obtained from flexural and compressive strength tests. The concretes used in the tests were prepared with crushed stone, gravel, and lightweight aggregates. An analysis of the results of these tests is presented in this article. Results showed a straightline relation between the splitting tensile strength and the flexural strength. The relation between the splitting tensile and compressive strengths was curvilinear. The maximum size and the type of aggregate used in the concrete mixture had an effect on the ratio of the splitting tensile strength to the flexural and compressive strengths. These tests also showed that the splitting tensile strengths are not affected as much as the flexural strengths by the moisture condition of the specimens at the time of testing.***

## *Introduction*

A RELATIVELY simple test for determining the tensile strength of concrete was devised about 15 years ago; it was developed independently in Japan by Akazawa (*1*)[2] and in Brazil by Carneiro and Barcellos (*2*). This test is known as the splitting tensile or the indirect tensile test. Because it has a number of advantages over the beam test for flexural strength or the direct tensile test on cylinders, this test has been received with favor in the United States for use in determining the tensile strength of concrete. The splitting tensile test usually is made on a 6- by 12-inch cylinder and no capping or grinding of bearings is necessary when proper molds are used, and special grips are not required. The breaks at the failure of the specimen are through the vertical diametral plane and the location of the break does not change as it does in the flexural beam test or the direct tensile test. Furthermore, the specimens are usually smaller and less susceptible to damage than the specimens used for the other two types of tension tests. Also, moisture content of the splitting tensile cylinder has less effect on the tensile strength than moisture content of a concrete beam has on flexural strength. A standard method for making the splitting tensile test has been proposed by the ASTM Committee, C–9, on Concrete and Concrete Aggregates.

Although an appreciable number of laboratories in the United States have used the splitting tensile test, most of the published data about it have been developed in Europe. Wright (*3*) and Thaulow (*4*) concluded from their studies that splitting tensile strength is affected less by the moisture content of the concrete than flexural strength, and that the splitting tensile test provides more uniform results than other types of tensile tests. Test results indicated that splitting tensile strengths are about one-and-a-half times greater than those obtained from direct tensile tests and about two-thirds of those obtained from flexural tests.

Two investigators in the United States recently published separate reports on results of the splitting tensile test. Mitchell (*5*) evaluated the splitting tensile test as a measure of the tensile strength of concrete. He also discussed the different theoretical considerations of failures of brittle materials and concluded that the Mohr theory is a satisfactory means of expressing failure conditions in this test. Hanson (*6*) suggested the use of a combination of the compressive strength and splitting tensile strength tests to determine the resistance of lightweight concrete for structures to shear and diagonal tension. He reported that the splitting tensile strength correlates with the diagonal tension or shear capacity of lightweight concrete in beams loaded to failure. He further indicated that the flexural strength test results can be erratic when moisture distribution in beams is not uniform and that, therefore, flexural strength cannot be correlated directly with the load performance of concrete in structural members. The thought was expressed that the nonuniform distribution of moisture in concrete prepared for tests does not affect the uniformity of either splitting tensile strengths or compressive strengths as much as it affects flexural strengths.

## *Tests by the Bureau of Public Roads*

Tests have been made in the laboratory of the Bureau of Public Roads during the 10-year period, 1951–1961, to determine the relation shown between the splitting tensile, flexural, and compressive strengths of many

[1] Presented at the 65th annual meeting of the American Society for Testing and Materials, New York, N.Y., June 1962.

[2] References indicated by italic numbers in parentheses are listed on page 106.

concretes. During this period, more than 2,000 tests of each type were made. The major variables in these tests were: the type and size of coarse aggregate, the cement content, the moisture content of specimens when they were tested, and the age of the concrete at time of the test.

The specimens were prepared and tested in accordance with the applicable ASTM methods and, except when so noted, were continuously moist cured until test. The splitting tensile and compressive tests were made on 6- by 12-inch cylinders, and the flexural tests were made on 6- by 6- by 21-inch beams that were loaded at the third points. All specimens were cast in metal molds.

Most of the splitting tensile tests were made in connection with other investigations; consequently, materials, mixes, and ages of concrete differed greatly. Twelve different brands of cement and four different siliceous sands that had fineness moduli ranging from 2.60 to 3.00 were used in the tests. The age of specimens at time of test ranged from 7 to 365 days, and the cement content ranged from 4.0 to 8.0 bags per cubic yard of concrete. To develop comparative data on tensile, flexural, and compressive strength test results, one specimen for each type of test was made from a single batch of concrete; these specimens were cured in the same manner and tested at the same age.

## *Conclusions*

The results of tests made in the laboratory of the Bureau of Public Roads warrant the following conclusions.

For a given coarse aggregate and method of curing, a linear relation exists between the splitting tensile strength and the flexural strength of concrete. The relation between the splitting tensile strength and the compressive strength of concrete is curvilinear.

The relation between splitting tensile strength and flexural strength differs according to the type and maximum size of the coarse aggregate used. The relation between splitting tensile strength and compressive strength also differs according to the type and maximum size of the coarse aggregate used.

For a given coarse aggregate and method of curing, the ratio of the splitting tensile strength to the flexural strength is constant, and this relation is not affected by either the cement content of the concrete or the age at test. The ratio of the splitting tensile strength to the compressive strength decreases as the compressive strength increases; therefore, this ratio is affected by both the concrete's cement content and the age at test.

For moist-cured specimens, the splitting tensile strength averaged approximately five-eighths of the flexural strength for gravel concrete, two-thirds of the flexural strength for limestone concrete, and three-fourths of the flexural strength for lightweight aggregate concrete. Similar results are not given for the splitting tensile and compressive strengths because of the nonlinear relation that existed between these strengths.

The splitting tensile strength of the concrete was affected less by drying than the flexural strength. This effect was more pronounced for concrete prepared with lightweight aggregates than for concrete made with natural aggregates. The reduction in splitting tensile strength caused by drying was greater than the reduction in compressive strength of the concrete.

No appreciable difference existed between the unit splitting tensile strength of 6- by 6-inch and 6- by 12-inch cylinders.

## *Description of Test*

A brief description of the method used by Public Roads to make the splitting tensile test follows. To avoid excessive repetition, the splitting tensile test is referred to as the "splitting" test. A 6- by 12-inch cylinder was placed horizontally between the bearing block on the platen and the upper spherically-seated bearing block of a compression testing machine so that the bearing load was applied to opposite elements of the cylinder. Strips of plywood, about one-eighth of an inch thick, three-fourths of an inch wide, and twelve inches long, were placed on the upper and lower bearing elements of the cylinder to ensure uniform bearing pressure. The cylinder was positioned so that the center of its upper bearing element coincided with the center of the upper bearing block of the testing machine. Figure 1 shows a cylinder positioned in the testing machine prior to being loaded. The load was applied at the rate of 150 p.s.i. per minute. In the proposed ASTM method, the load is to be applied at a rate in the range of 100 to 200 p.s.i. per minute or approximately 11,000 to 23,000 pounds per minute for a 6- by 12-inch cylinder. When the cylinder failed, it split through the center and little shattering occurred. A typical break is shown in figure 2.

**Table 1.—Comparison of splitting tensile strength with flexural and compressive strengths of concrete containing 1½-inch crushed stone [1]**

| Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C |
|---|---|---|---|---|
| *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 180 | 350 | 51 | 1, 390 | 12. 9 |
| 185 | 350 | 53 | 1, 350 | 13. 7 |
| 210 | 355 | 59 | 1, 470 | 14. 3 |
| 255 | 410 | 62 | 1, 960 | 13. 0 |
| 255 | 380 | 67 | 1, 710 | 14. 9 |
| 280 | 420 | 67 | 2, 330 | 12. 0 |
| 285 | 475 | 60 | 2, 500 | 11. 4 |
| 340 | 475 | 72 | 2, 730 | 12. 5 |
| 345 | 445 | 78 | 2, 720 | 12. 7 |
| 345 | 535 | 64 | 2, 860 | 12. 1 |
| 360 | 530 | 68 | 3, 250 | 11. 1 |
| 360 | 555 | 65 | 3, 160 | 11. 4 |
| 370 | 520 | 71 | 2, 980 | 12. 4 |
| 395 | 590 | 67 | 3, 710 | 10. 6 |
| 395 | 510 | 77 | 3, 250 | 12. 2 |
| 410 | 660 | 62 | 3, 780 | 10. 8 |
| 415 | 640 | 65 | 3, 540 | 11. 7 |
| 430 | 630 | 68 | 5, 070 | 8. 5 |
| 430 | 600 | 72 | 3, 810 | 11. 3 |
| 430 | 640 | 67 | 3, 700 | 11. 6 |
| 430 | 645 | 67 | 3, 520 | 12. 2 |
| 435 | 670 | 65 | 3, 860 | 11. 3 |
| 445 | 630 | 71 | 3, 670 | 12. 1 |
| 465 | 805 | 58 | 4, 570 | 10. 2 |
| 500 | 730 | 68 | 5, 320 | 9. 4 |
| 500 | 800 | 63 | 4, 610 | 10. 8 |
| 505 | 730 | 69 | 5, 620 | 9. 0 |
| 505 | 740 | 68 | 5, 400 | 9. 4 |
| 515 | 790 | 65 | 4, 460 | 11. 5 |
| 525 | ------ | ------ | 4, 990 | 10. 5 |
| 530 | 785 | 68 | 6, 050 | 8. 8 |
| 530 | 750 | 71 | 6, 050 | 8. 8 |
| 535 | 850 | 63 | 6, 940 | 7. 7 |
| 540 | ------ | ------ | 5, 210 | 10. 4 |
| 555 | ------ | ------ | 6, 010 | 9. 2 |
| 560 | 750 | 75 | 5, 790 | 9. 7 |
| 560 | 890 | 63 | 6, 200 | 9. 0 |
| 565 | 855 | 66 | 6, 730 | 8. 4 |
| 565 | 875 | 65 | 5, 580 | 10. 1 |
| 565 | 790 | 72 | 6, 720 | 8. 4 |
| 565 | 955 | 59 | 6, 270 | 9. 0 |
| 595 | 880 | 68 | 5, 940 | 10. 0 |
| 595 | 775 | 77 | 6, 150 | 9. 7 |
| 600 | 805 | 75 | 5, 660 | 10. 6 |
| 605 | ------ | ------ | 6, 090 | 9. 9 |
| 620 | 925 | 67 | 7, 370 | 8. 4 |
| 625 | 885 | 71 | 7, 250 | 8. 6 |
| 635 | 875 | 73 | 7, 210 | 8. 8 |
| Average ratios------ | | 67 | -------- | 10. 7 |

[1] Each strength was the average result for five tests. Specimens were stored in moist air until tested. Cement content ranged from 4 to 7½ bags per cubic yard and age at test ranged from 7 to 365 days.

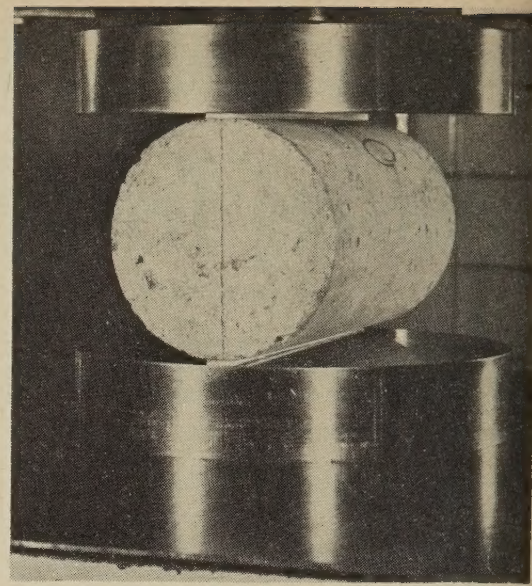

*Figure 1.—Cylinder in testing machine for splitting tensile test.*

The following formula [3] was used to calculate the splitting tensile strength of the specimen:

$$T=\frac{2P}{\pi\, ld}$$

Where,

$T$=Splitting tensile strength, p.s.i.
$P$=Maximum applied load at failure, pounds.
$l$=Length of cylinder, inches.
$d$=Diameter of cylinder, inches.

## *Effect of Type of Coarse Aggregate*

A study was made to determine the effect that the type of coarse aggregate has on the relation of splitting strength to the flexural and compressive strengths of concrete. Specimens were made from concretes prepared with a crushed limestone from a single source, a gravel from a single source, and lightweight fine and coarse aggregates from 10 different sources. When natural sand was used, it was obtained from a single source.

[3] For derivation of formula, see reference to Wright's article (3).

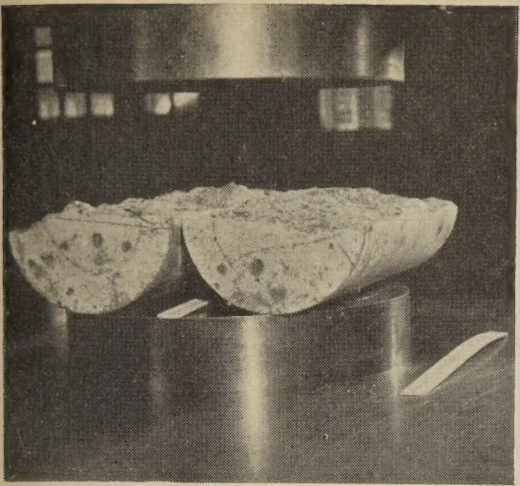

*Figure 2.—Typical break in splitting tensile test.*

**Concrete prepared with crushed limestone**

The splitting, flexural, and compressive strengths of 48 concrete mixtures prepared with a crushed limestone having a maximum size of 1½ inches are shown in table 1. The results have been tabulated in order of ascending splitting strengths. The cement content of this concrete ranged from 4 to 7½ bags per cubic yard, and the age of the specimens at time of test was from 7 to 365 days; therefore, a wide range in strengths resulted. The splitting-flexural and splitting-compressive strength ratios of identical concretes, expressed as percentages, also are given in table 1. The splitting-flexural strength ratios ranged from 51 to 78 percent and the average ratio was 67 percent; the splitting-compressive strength ratios ranged from 7.7 to 14.9 percent and the average ratio was 10.7. As can be observed from the data in table 1, splitting-compressive strength ratios tended to decrease as the compressive strength of the concrete increased. The nonlinear relation between these strengths shows that an average ratio is not applicable throughout the strength range. However, such a ratio serves as a useful index for comparison purposes.

**Table 2.—Comparison of splitting tensile strength with flexural and compressive strengths of concrete containing 1½-inch gravel [1]**

| Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C |
|---|---|---|---|---|
| *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 150 | 250 | 60 | 1,180 | 12.7 |
| 250 | 450 | 56 | 1,960 | 12.8 |
| 260 | 410 | 63 | 2,130 | 12.2 |
| 270 | 400 | 68 | 2,330 | 11.6 |
| 280 | 400 | 70 | 1,940 | 14.4 |
| 280 | 410 | 68 | 2,060 | 13.6 |
| 295 | 505 | 58 | 2,680 | 11.0 |
| 300 | 530 | 57 | 2,980 | 10.1 |
| 320 | 510 | 63 | 6,860 | 11.2 |
| 335 | 525 | 64 | 2,600 | 12.9 |
| 340 | 580 | 59 | 3,110 | 10.9 |
| 345 | 555 | 62 | 3,130 | 11.0 |
| 355 | 540 | 66 | 3,440 | 10.3 |
| 355 | 670 | 53 | 3,960 | 9.0 |
| 360 | 625 | 58 | 3,240 | 11.1 |
| 360 | 670 | 54 | 3,670 | 9.8 |
| 365 | 690 | 53 | 3,980 | 9.2 |
| 365 | 630 | 58 | 3,800 | 9.6 |
| 370 | 740 | 50 | 4,100 | 9.0 |
| 375 | 670 | 56 | 3,720 | 10.1 |
| 390 | 640 | 61 | 3,900 | 10.0 |
| 390 | 570 | 68 | 3,360 | 11.6 |
| 405 | 505 | 80 | 3,100 | 13.1 |
| 415 | 760 | 55 | 4,340 | 9.6 |
| 435 | 635 | 69 | 5,300 | 8.2 |
| 435 | 780 | 56 | 4,610 | 9.4 |
| 440 | 695 | 63 | 4,440 | 9.9 |
| 445 | 780 | 57 | 4,600 | 9.7 |
| 465 | ------ | ------ | 4,120 | 11.3 |
| 540 | 790 | 68 | 5,660 | 9.5 |
| 570 | 790 | 72 | 6,660 | 8.6 |
| Average ratios------ | | 62 | -------- | 10.8 |

[1] Each strength is the average result for two to five tests. Specimens were stored in moist air until tested. Cement content ranged from 4½ to 7½ bags per cubic yard and age at test ranged from 7 to 365 days.

**Concrete prepared with gravel**

Splitting, flexural, and compressive strengths and the strength ratios of 31 concrete mixtures prepared with a siliceous gravel of 1½-inch maximum size are shown in table 2. The cement contents were from 4½ to 7½ bags per cubic yard and the age of specimens at time of test ranged from 7 to 365 days. The ratios of the splitting strengths to the flexural strengths ranged from 50 to 80 percent and the average ratio was 62 percent. The splitting-compressive strength ratios ranged from 8.2 to 14.4 percent and the average ratio was 10.8.

**Concrete prepared with lightweight aggregate**

The splitting, flexural, and compressive strengths and the strength ratios of 61 concrete mixtures prepared with lightweight aggregates are shown in table 3. The different fine and coarse lightweight aggregates, including expanded clays, slags, and shales, were used in these tests. Each aggregate was obtained from a different source and the maximum size of the coarse aggregates differed within a range of three-eighths to three-fourths of an inch. The cement contents of the concrete were 6½ and 8 bags per cubic yard, and the ages of the specimens at time of test ranged from 7 to 365 days. The splitting-flexural strength ratios of the lightweight aggregate concrete ranged from 57 to 88 percent and the average ratio was 76 percent; the splitting-compressive strength ratios ranged from 5.3 to 11.2 percent and the average ratio was 8.0 percent.

**Relationships for types of coarse aggregate**

The relations between the splitting and flexural strengths of concretes prepared with the three types of coarse aggregate—crushed limestone, gravel, and lightweight—are shown in figure 3. The relations were linear, but the slopes differed according to the type of aggregate used. In summary, the average ratio of the splitting strength to the flexural strength was: 67 percent for the concrete made with the crushed limestone, 62 percent for the concrete made with gravel, and 76 percent for the concrete made with the lightweight aggregate.

The relations between the splitting and compressive strengths of the concretes prepared with the three types of coarse aggregate are shown in figure 4. These relations also differed according to the type of aggregate used; but, unlike the splitting-flexural relations, they were nonlinear. The average ratio of the splitting strength to the compressive strength for the concrete made with crushed stone was 10.7 percent, for the concrete made with gravel it was 10.8 percent, and for the concrete made with the lightweight aggregate it was 8.0 percent.

**Table 3.—Comparison of splitting tensile strength with flexural and compressive strengths of concrete containing lightweight aggregate [1]**

| Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C |
|---|---|---|---|---|
| *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 300 | 445 | 67 | 3,190 | 9.4 |
| 310 | 430 | 72 | 3,430 | 9.0 |
| 315 | 520 | 61 | 3,290 | 9.6 |
| 335 | 460 | 73 | 2,980 | 11.2 |
| 340 | 435 | 78 | 3,040 | 11.2 |
| 340 | 505 | 67 | 4,200 | 8.1 |
| 345 | 445 | 78 | 3,570 | 9.7 |
| 350 | 510 | 69 | 4,130 | 8.5 |
| 360 | 485 | 74 | 4,110 | 8.8 |
| 360 | 540 | 67 | 4,290 | 8.4 |
| 360 | 500 | 72 | 4,290 | 8.4 |
| 365 | 480 | 76 | 3,690 | 9.9 |
| 385 | 575 | 67 | 6,800 | 5.7 |
| 385 | 520 | 74 | 4,060 | 9.5 |
| 385 | 460 | 84 | 3,740 | 10.3 |
| 390 | 535 | 73 | 4,330 | 9.0 |
| 390 | 500 | 78 | 3,900 | 10.0 |
| 405 | 485 | 84 | 4,080 | 9.9 |
| 420 | 565 | 74 | 4,800 | 8.8 |
| 420 | 565 | 74 | 5,290 | 7.9 |
| 420 | 560 | 75 | 6,060 | 6.9 |
| 425 | 580 | 73 | 6,060 | 7.0 |
| 425 | 570 | 75 | 4,480 | 9.5 |
| 425 | 610 | 70 | 5,300 | 8.0 |
| 425 | 610 | 70 | 4,870 | 8.7 |
| 425 | 750 | 57 | 6,300 | 6.7 |
| 440 | 710 | 62 | 8,030 | 5.5 |
| 440 | 570 | 77 | 7,830 | 5.6 |
| 445 | 555 | 80 | 4,440 | 10.0 |
| 445 | 635 | 70 | 6,600 | 6.7 |
| 450 | 550 | 82 | 5,100 | 8.8 |
| 450 | 575 | 78 | 5,920 | 7.6 |
| 460 | 610 | 75 | 5,120 | 9.0 |
| 460 | 530 | 87 | 7,020 | 6.6 |
| 470 | 635 | 74 | 7,460 | 6.3 |
| 470 | 570 | 82 | 5,000 | 9.4 |
| 470 | 635 | 74 | 7,850 | 6.0 |
| 470 | 680 | 69 | 7,800 | 6.0 |
| 480 | 645 | 74 | 6,980 | 6.9 |
| 480 | 610 | 79 | 4,880 | 9.8 |
| 485 | 605 | 80 | 5,080 | 9.5 |
| 490 | 560 | 88 | 5,740 | 8.5 |
| 490 | 630 | 78 | 6,930 | 7.1 |
| 490 | 635 | 77 | 7,490 | 6.5 |
| 490 | 740 | 66 | 6,800 | 7.2 |
| 495 | 670 | 74 | 5,740 | 8.6 |
| 495 | 735 | 67 | 7,590 | 6.5 |
| 495 | 690 | 72 | 6,340 | 7.8 |
| 500 | 635 | 79 | 8,610 | 5.8 |
| 515 | 640 | 80 | 7,760 | 6.6 |
| 520 | 620 | 84 | 6,660 | 7.8 |
| 520 | 645 | 81 | 5,790 | 9.0 |
| 525 | 680 | 77 | 9,870 | 5.3 |
| 530 | 640 | 83 | 8,790 | 6.0 |
| 530 | 685 | 77 | 7,630 | 6.9 |
| 530 | 650 | 82 | 6,760 | 7.8 |
| 540 | 630 | 86 | 6,350 | 8.5 |
| 540 | 660 | 82 | 9,060 | 6.0 |
| 555 | 710 | 78 | 8,790 | 6.3 |
| 565 | 650 | 87 | 7,730 | 7.3 |
| 605 | 705 | 86 | 6,840 | 8.8 |
| Average ratios------ | | 76 | -------- | 8.0 |

[1] Each strength is the average result of three tests. Specimens were stored in moist air until tested. Cement content was 6½ or 8 bags per cubic yard and age at test ranged from 7 to 365 days.

## *Effect of Size of Coarse Aggregate*

Splitting, flexural, and compressive strength data obtained from tests on concrete made with crushed limestone of 1-inch maximum size were compared with the data given in

**Table 4.—Comparison of splitting tensile strength with flexural and compressive strengths of concrete containing 1-inch crushed stone [1]**

| Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C |
|---|---|---|---|---|
| *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 450 | 640 | 70 | 4,120 | 10.9 |
| 475 | 690 | 69 | 5,230 | 9.1 |
| 475 | 640 | 74 | 5,330 | 8.9 |
| 490 | 675 | 73 | 4,350 | 11.3 |
| 495 | 650 | 76 | 4,680 | 10.6 |
| 495 | 695 | 71 | 5,150 | 9.6 |
| 500 | 720 | 69 | -------- | ------ |
| 505 | 775 | 65 | 5,280 | 9.6 |
| 505 | 740 | 68 | 5,640 | 9.0 |
| 505 | 760 | 66 | 5,380 | 9.4 |
| 510 | 695 | 73 | 5,020 | 10.2 |
| 515 | 755 | 68 | 5,500 | 9.4 |
| 515 | 690 | 75 | 5,650 | 9.1 |
| 520 | 750 | 69 | 5,320 | 9.8 |
| 520 | 755 | 69 | 6,010 | 8.7 |
| 520 | 695 | 75 | 4,900 | 10.6 |
| 525 | 765 | 69 | 5,600 | 9.4 |
| 525 | 705 | 74 | 5,010 | 10.5 |
| 525 | 710 | 74 | 5,560 | 9.4 |
| 530 | 735 | 72 | 5,100 | 10.4 |
| 535 | 720 | 74 | 5,110 | 10.5 |
| 535 | 730 | 73 | 5,530 | 9.7 |
| 540 | 690 | 78 | 5,410 | 10.0 |
| 540 | 730 | 74 | 5,620 | 9.6 |
| 545 | 740 | 74 | 5,770 | 9.4 |
| 545 | 715 | 76 | 5,890 | 9.3 |
| 545 | 675 | 81 | 5,610 | 9.7 |
| 545 | 740 | 74 | 5,350 | 10.2 |
| 550 | 780 | 71 | 6,760 | 8.1 |
| 550 | 735 | 75 | 5,770 | 9.5 |
| 555 | 740 | 75 | 5,320 | 10.4 |
| 555 | 745 | 74 | 5,730 | 9.7 |
| 555 | 740 | 75 | 5,330 | 10.4 |
| 555 | 800 | 69 | 5,810 | 9.6 |
| 560 | 755 | 74 | 5,500 | 10.2 |
| 560 | 795 | 70 | 5,980 | 9.4 |
| 565 | 790 | 72 | 5,940 | 9.5 |
| 565 | 735 | 77 | 5,100 | 11.1 |
| 565 | 705 | 80 | 5,540 | 10.2 |
| 565 | 790 | 72 | 6,110 | 9.2 |
| 565 | 840 | 67 | 5,980 | 9.4 |
| 570 | 800 | 71 | 5,760 | 9.9 |
| 575 | 830 | 69 | 6,160 | 9.3 |
| 575 | 820 | 70 | 5,830 | 9.9 |
| 580 | 740 | 78 | 6,200 | 9.4 |
| 585 | 765 | 76 | 6,010 | 9.7 |
| 595 | 755 | 79 | 5,910 | 10.1 |
| 595 | 785 | 76 | 5,640 | 10.5 |
| 605 | 800 | 76 | 5,940 | 10.2 |
| 615 | 775 | 79 | 6,450 | 9.5 |
| 620 | 700 | 89 | 6,140 | 10.1 |
| 625 | 810 | 77 | 6,050 | 10.3 |
| Average ratios------ | | 73 | -------- | 9.8 |

[1] Each strength is the average result of three to five tests. Specimens were stored in moist air until tested. Cement content ranged from 5¼ to 6 bags per cubic yard and age at test was 28 days.

table 1 for concrete prepared with the same type of coarse aggregate but having a maximum size of 1½ inches. The results of strength tests made at 28 days on concrete specimens prepared with the crushed stone having a 1-inch maximum size and the calculated strength ratios are shown in table 4. These tests were made on specimens from 52 mixes that had been prepared with 26 different admixtures and with cement contents that ranged from 5¼ to 6 bags per cubic yard. The single age of the specimens and the limited range in their cement content caused smaller differences in strengths than were obtained for specimens prepared with limestone having a maximum size of 1½ inches.

The splitting-flexural strength ratios of the concrete containing the 1-inch crushed stone ranged from 65 to 89 percent and the

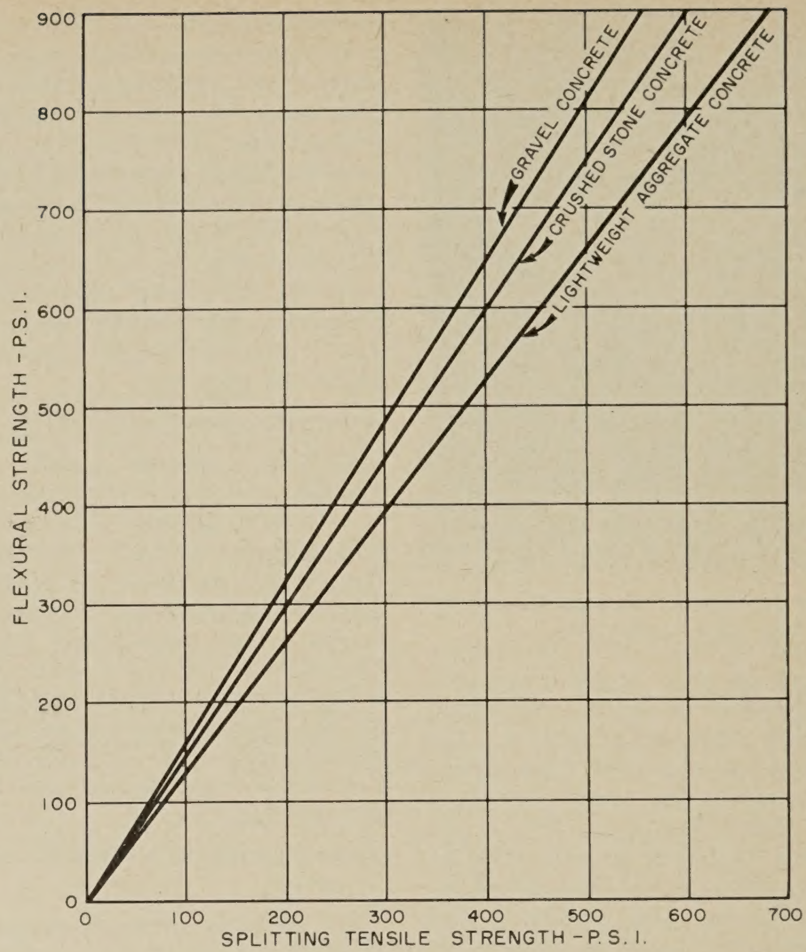


*Figure 3.—Relation between flexural and splitting tensile strengths for concrete made with three types of aggregate.*

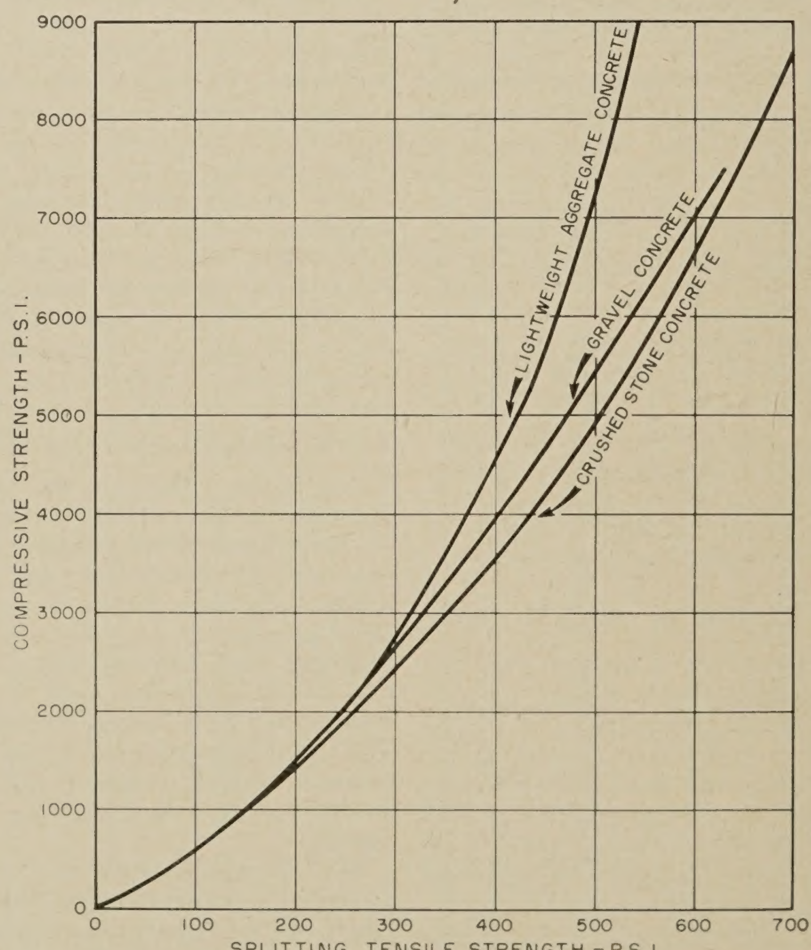


*Figure 4.—Relation between compressive and splitting tensile strengths for concrete made with three types of aggregate.*

average ratio was 73 percent. The splitting-compressive strength ratios ranged from 8.1 to 11.3 percent and the average ratio was 9.8 percent. The corresponding average strength ratios of the concrete containing the 1½-inch crushed limestone were 67 and 10.7 percent, respectively. The splitting-flexural and splitting-compressive strength relations for the concrete containing 1-inch and 1½-inch crushed limestone aggregate are shown in figure 5. It is evident that the maximum size of the coarse aggregate only had a slight effect on these strength relations.

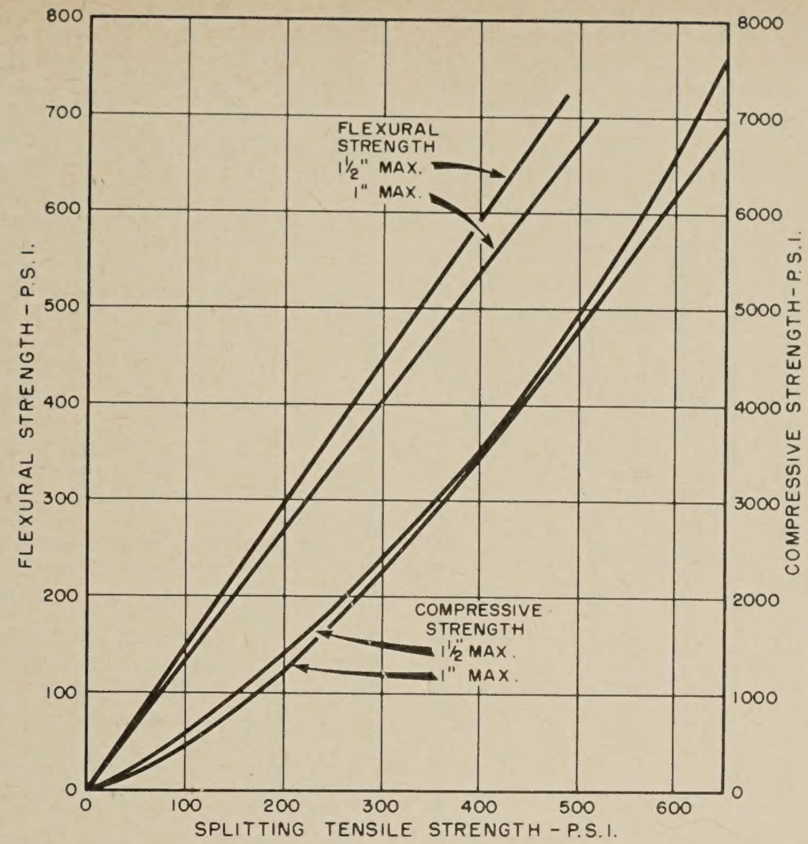


*Figure 5.—Effect of size of aggregate on relation of splitting tensile to flexural and compressive strengths.*

**Table 5.—Effect of drying on splitting tensile, flexural, and compressive strengths of concrete containing lightweight aggregate and tested at 28 days [1]**

| Curing [2] | Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C | Ratio of strength of dry specimens to strength of moist cured specimens [3] | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Splitting | Flexural | Compressive |
| | *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* | *Percent* | *Percent* | *Percent* |
| Moist | 345 | 445 | 78 | 3, 570 | 9. 7 | ------ | ------ | -------- |
| Dry | 245 | 210 | 117 | 3, 350 | 7. 3 | 71 | 47 | 94 |
| Moist | 360 | 485 | 74 | 4, 110 | 8. 8 | ------ | ------ | -------- |
| Dry | 280 | 220 | 127 | 3, 770 | 7. 4 | 78 | 45 | 92 |
| Moist | 420 | 565 | 74 | 5, 290 | 7. 9 | ------ | ------ | -------- |
| Dry | 295 | 210 | 140 | 5, 120 | 5. 8 | 70 | 37 | 97 |
| Moist | 425 | 750 | 57 | 6, 300 | 6. 7 | ------ | ------ | -------- |
| Dry | 320 | 210 | 152 | 5, 680 | 5. 6 | 75 | 28 | 90 |
| Moist | 425 | 585 | 73 | 6, 060 | 7. 0 | ------ | ------ | -------- |
| Dry | 285 | 180 | 158 | 5, 740 | 5. 0 | 67 | 31 | 95 |
| Moist | 425 | 610 | 70 | 4, 870 | 8. 7 | ------ | ------ | -------- |
| Dry | 350 | 265 | 132 | 4, 730 | 7. 4 | 82 | 43 | 97 |
| Moist | 450 | 550 | 82 | 5, 100 | 8. 8 | ------ | ------ | -------- |
| Dry | 300 | 220 | 136 | 4, 550 | 6. 6 | 67 | 40 | 89 |
| Moist | 460 | 610 | 75 | 5, 120 | 9. 0 | ------ | ------ | -------- |
| Dry | 290 | 245 | 118 | 5, 550 | 5. 3 | 63 | 40 | 107 |
| Moist | 490 | 560 | 88 | 5, 740 | 8. 5 | ------ | ------ | -------- |
| Dry | 330 | 205 | 161 | 5, 480 | 6. 0 | 67 | 37 | 95 |
| Moist | 495 | 670 | 74 | 5, 740 | 8. 6 | ------ | ------ | -------- |
| Dry | 330 | 190 | 174 | 5, 530 | 6. 0 | 67 | 28 | 96 |
| Moist | 495 | 690 | 72 | 6, 340 | 7. 8 | ------ | ------ | -------- |
| Dry | 345 | 265 | 130 | 6, 510 | 5. 3 | 70 | 38 | 103 |
| Moist | 520 | 645 | 81 | 5, 790 | 9. 0 | ------ | ------ | -------- |
| Dry | 375 | 295 | 127 | 5, 820 | 6. 4 | 72 | 46 | 101 |
| Moist | 530 | 685 | 77 | 7, 620 | 7. 0 | ------ | ------ | -------- |
| Dry | 325 | 260 | 125 | 7, 080 | 4. 6 | 61 | 38 | 93 |
| Moist | 540 | 630 | 86 | 6, 350 | 8. 5 | ------ | ------ | -------- |
| Dry | 310 | 220 | 141 | 5, 740 | 5. 4 | 57 | 35 | 90 |
| Average: | | | | | | | | |
| Moist | 455 | 605 | 76 | 5, 570 | 8. 3 | ------ | ------ | -------- |
| Dry | 315 | 230 | 138 | 5, 330 | 6. 0 | 69 | 38 | 96 |

[1] Each strength is the average result of three tests. Cement content was 6½ or 8 bags per cubic yard.
[2] Moist specimens were stored in moist air at 73° F. continuously for 28 days. Dry specimens were stored in moist air for 7 days, followed by 21 days in laboratory air at 73° F. and 50 percent relative humidity.
[3] Ratio of the strength of dry specimens to the strength of the corresponding moist cured specimens.

## *Effect of Drying on Lightweight Aggregate Concrete*

Tests were made at 28 and 365 days to determine the effect of drying on the splitting, flexural, and compressive strengths of concrete prepared with lightweight aggregates. One-half of the specimens tested at 28 days was given 7 days of moist curing at 73° F., which was followed by 21 days of storage in laboratory air at 73° F. and 50 percent relative humidity; the other half of the specimens was moist cured continuously. One-half of the specimens tested at 365 days was given 7 days of moist curing, which was followed by 358 days of storage in laboratory air; the other half was moist cured continuously. Differences in the aggregates used and cement contents—6½ and 8 bags per cubic yard of concrete—caused a wide range in strengths. The strength results of the tests at 28 days and the ratios of splitting-flexural and splitting-compressive strengths are shown in table 5. The last three columns of the table contain data showing the splitting, flexural, and compressive strength ratios of the dry specimens (7 days moist cured and then dried in laboratory air) to the wet specimens (continuously moist cured). Similar data obtained from the tests at 365 days are shown in table 6.

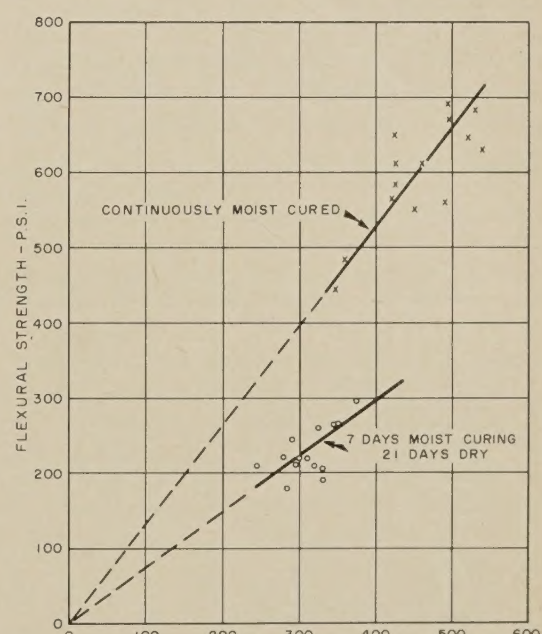


*Figure 6.—Effect of drying on relation of flexural and splitting tensile strengths of concrete containing lightweight aggregate, at 28 days.*

**Table 6.—Effect of drying on splitting tensile, flexural, and compressive strengths of concrete containing lightweight aggregate and tested at 365 days** [1]

| Curing [2] | Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C | Ratio of strength of dry specimens to strength of moist cured specimens [3] | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Splitting | Flexural | Compressive |
| | *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* | *Percent* | *Percent* | *Percent* |
| Moist | 340 | 505 | 67 | 4,200 | 8.1 | ------ | ------ | -------- |
| Dry | 335 | 330 | 102 | 3,580 | 9.4 | 99 | 65 | 85 |
| Moist | 360 | 540 | 67 | 4,290 | 8.4 | ------ | ------ | -------- |
| Dry | 290 | 270 | 107 | 3,950 | 7.3 | 81 | 50 | 92 |
| Moist | 440 | 570 | 77 | 7,830 | 5.6 | ------ | ------ | -------- |
| Dry | 430 | 535 | 80 | 5,390 | 8.0 | 98 | 94 | 69 |
| Moist | 440 | 710 | 62 | 8,030 | 5.5 | ------ | ------ | -------- |
| Dry | 380 | 330 | 115 | 7,140 | 5.3 | 86 | 46 | 89 |
| Moist | 470 | 635 | 74 | 7,850 | 6.0 | ------ | ------ | -------- |
| Dry | 395 | 295 | 134 | 6,740 | 5.9 | 84 | 46 | 86 |
| Moist | 470 | 635 | 74 | 7,460 | 6.3 | ------ | ------ | -------- |
| Dry | 495 | 205 | 241 | 5,330 | 9.3 | 105 | 32 | 71 |
| Moist | 500 | 635 | 79 | 8,610 | 5.8 | ------ | ------ | -------- |
| Dry | 490 | 470 | 104 | 6,360 | 7.7 | 98 | 74 | 74 |
| Moist | 515 | 640 | 80 | 7,760 | 6.6 | ------ | ------ | -------- |
| Dry | 480 | 420 | 114 | 6,090 | 7.9 | 93 | 66 | 78 |
| Moist | 525 | 680 | 77 | 9,870 | 5.3 | ------ | ------ | -------- |
| Dry | 495 | 400 | 124 | 9,060 | 5.5 | 94 | 59 | 92 |
| Moist | 530 | 640 | 83 | 8,790 | 6.0 | ------ | ------ | -------- |
| Dry | 420 | 380 | 111 | 7,530 | 5.6 | 79 | 59 | 86 |
| Moist | 540 | 660 | 82 | 9,060 | 6.0 | ------ | ------ | -------- |
| Dry | 415 | 205 | 202 | 7,380 | 5.6 | 77 | 31 | 81 |
| Averages: | | | | | | | | |
| Moist | 465 | 625 | 75 | 7,610 | 6.3 | ------ | ------ | -------- |
| Dry | 420 | 350 | 130 | 6,230 | 7.0 | 90 | 57 | 82 |

[1] Each strength is the average result of three tests. Cement content was 6½ or 8 bags per cubic yard.
[2] Moist specimens were continuously stored in moist air at 73° F. Dry specimens were stored in moist air for 7 days, followed by 358 days in laboratory air at 73° F. and 50 percent relative humidity.
[3] Ratio of the strength of dry specimens to the strength of the corresponding moist cured specimens.

**Table 8.—Effect of cement content on splitting tensile, flexural, and compressive strengths of concrete prepared with different aggregates** [1]

| Cement content | Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C |
|---|---|---|---|---|---|
| LIMESTONE (three-fourths inch maximum size) [2] | | | | | |
| *Bags/cu. yd.* | *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 6.5 | 550 | 760 | 72 | 5,820 | 9.5 |
| 8.0 | 580 | 805 | 72 | 6,360 | 9.1 |
| LIMESTONE (1½ inches maximum size) [3] | | | | | |
| 4.1 | 400 | 595 | 67 | 3,480 | 11.5 |
| 6.0 | 530 | 760 | 70 | 5,550 | 9.5 |
| 7.5 | 580 | 870 | 67 | 6,630 | 8.7 |
| GRAVEL (1½ inches maximum size) [4] | | | | | |
| 4.5 | 280 | 450 | 62 | 2,960 | 9.5 |
| 7.0 | 400 | 610 | 66 | 4,960 | 8.1 |
| LIGHTWEIGHT AGGREGATE [5] | | | | | |
| 6.5 | 430 | 580 | 74 | 5,590 | 7.7 |
| 8.0 | 465 | 605 | 77 | 6,220 | 7.5 |

[1] Specimens were stored in moist air at 73° F. until tested.
[2] Each strength is the average result of 12 tests. Age at test ranged from 7 to 365 days.
[3] Each strength is the average result of 100 tests. Age at test was 28 days.
[4] Each strength is the average result of 20 tests. Age at test was 28 days.
[5] Each strength is the average result of 75 tests. Age at test ranged from 7 to 365 days.

From the tests at 28 days, the average ratio of splitting-flexural strengths was 76 percent for the wet specimens and 138 percent for the dry specimens. Corresponding ratios for the tests made at 365 days were 75 and 130 percent. Likewise, the average ratio of splitting-compressive strengths for the tests at 28 days was 8.3 percent for the wet specimens and 6.0 percent for the dry specimens. Similar ratios for the tests at 365 days were 6.3 and 7.0 percent. The effect of the moisture content of concrete containing lightweight aggregate on the splitting-flexural and splitting-compressive relations is shown in figures 6–9. The comparative ratios and relations determined in this study emphasize the importance of the effect of moisture content of lightweight aggregate concrete on the splitting-flexural strength relations. The influence of the moisture content on the splitting-compressive strength relations was very pronounced in the results of the tests at 28 days, but no significant influence was indicated in the results of the tests at 365 days.

As stated previously, the last three columns of tables 5 and 6 show the ratios of the strengths of dry specimens to the strengths of the corresponding wet specimens for each of the three types of strength tests. For the tests at 28 days, the average ratios were 69, 38, and 96 percent for the splitting, flexural, and compressive strength tests, respectively. Similar ratios for the tests at 365 days were 90, 57, and 82 percent. Based on individual test ratios at 28 and 365 days, the reduction in splitting strength from 22 of the 25 tests was less than 33 percent; but the reduction in flexural strength from 19 of the 25 tests was 50 percent or more.

In tests at both 28 and 365 days, dry storage of concrete containing lightweight aggregate had an appreciably greater deleterious effect on flexural strength than on splitting strength. This might have been caused by the fine cracks that developed on the surface of the concrete as the flexural test specimens dried. Because the exteriors of the test cylinders were under compression, the splitting strength was not affected as much by the surface condition of the test specimens. Conversely, in tests at 28 days, the compressive strength was affected less by dry storage than the splitting strength, the average reduction being 31 percent for splitting strength and 4 percent for compressive strength. But in tests at 365 days drying caused little difference in the reduction of splitting and compressive strengths of concretes prepared with lightweight aggregates.

**Table 7.—Effect of drying on splitting tensile, flexural, and compressive strengths of concrete containing crushed stone**

| Aggregate and curing [1] | Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C | Ratio of strength of dry specimens to strength of moist cured specimens [2] | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Splitting | Flexural | Compressive |
| Crushed limestone, maximum size three-fourths inch: [3] | | | | | | | | |
| | *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* | *Percent* | *Percent* | *Percent* |
| 28 days moist | 575 | 800 | 72 | 5,700 | 10.1 | ------ | ------ | -------- |
| 7 days moist and 21 days dry | 485 | 480 | 101 | 5,720 | 8.5 | 84 | 60 | 100 |
| Crushed limestone, maximum size 1½ inches: [4] | | | | | | | | |
| 28 days moist | 565 | 795 | 71 | 5,410 | 10.4 | ------ | ------ | -------- |
| 1 day moist and 27 days dry | 360 | 410 | 88 | 3,530 | 10.2 | 64 | 52 | 65 |
| 7 days moist and 21 days dry | 495 | 480 | 103 | 5,430 | 9.1 | 88 | 60 | 100 |
| 7 days moist, 20 days dry, and 1 day wet | 590 | 515 | 115 | 5,120 | 11.5 | 104 | 65 | 95 |

[1] Moist cured specimens were stored in moist air at 73° F. Dry specimens were stored in laboratory air at 73° F. and 50 percent relative humidity.
[2] Ratio of the strength of partially moist cured specimens to the strength of the corresponding moist cured specimens.
[3] Each strength is the average result of six tests. Cement content was 6½ or 8 bags per cubic yard.
[4] Each strength is the average result of five tests. Cement content was 6 bags per cubic yard.

## *Effect of Drying on Crushed Limestone Concrete*

The results of two series of tests made to study the effect of drying on the splitting

**Table 9.—Effect of age at test on splitting tensile, flexural, and compressive strengths of concrete** [1]

| Age at test | Splitting strength (S) | Flexural strength (F) | Ratio S to F | Compressive strength (C) | Ratio S to C |
|---|---|---|---|---|---|
| Gravel (1½ inches maximum size) [2] | | | | | |
| *Days* | *P.s.i.* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 7 | 270 | 450 | 60 | 2,360 | 11.4 |
| 14 | 350 | 590 | 59 | 3,410 | 10.3 |
| 28 | 375 | 610 | 61 | 3,370 | 11.1 |
| Lightweight Aggregate [3] | | | | | |
| 7 | 385 | 510 | 75 | 4,030 | 9.6 |
| 28 | 455 | 610 | 75 | 5,610 | 8.1 |
| 90 | 470 | 630 | 75 | 6,760 | 7.0 |
| 365 | 460 | 610 | 75 | 7,450 | 6.2 |
| Limestone (three-fourths inch maximum size) [4] | | | | | |
| 7 | 510 | 740 | 69 | 4,740 | 10.8 |
| 28 | 575 | 800 | 72 | 5,700 | 10.1 |
| 90 | 540 | 805 | 67 | 6,700 | 8.1 |

[1] Specimens were stored in moist air at 73° F. until tested.
[2] Each strength is the average result of 15 tests. Cement content ranged from 4½ to 7½ bags per cubic yard.
[3] Each strength is the average result of 40 tests. Cement content was 6½ or 8 bags per cubic yard.
[4] Each strength is the average result of 6 tests. Cement content was 6½ or 8 bags per cubic yard.

**Table 10.—Effect of length of cylinder on splitting tensile strength of concrete** [1]

| Splitting tensile strength [2] | |
|---|---|
| 6- by 6-in. cylinders | 6- by 12-in. cylinders |
| *P.s.i.* | *P.s.i.* |
| 270 | 275 |
| 300 | 300 |
| 385 | 430 |
| 430 | 360 |
| 355 | 390 |

[1] Specimens were stored in moist air at 73° F. until tested. Each strength is the average result of two tests.
[2] Average splitting tensile strength for both sizes of cylinders was 350 p.s.i.

**Table 11.—Effect of bearing surface on splitting tensile strength of concrete** [1]

| Splitting tensile strength | |
|---|---|
| Plywood bearings [2] | Lumnite cement bearings [3] |
| *P.s.i.* | *P.s.i.* |
| 535 | 515 |
| 540 | 535 |
| 575 | 640 |
| 540 | 570 |
| 440 | 430 |
| 445 | 445 |
| 440 | 440 |
| 430 | 440 |

[1] Specimens were stored in moist air at 73° F. until tested. Each strength is the average of three tests.
[2] Average splitting strength was 495 p.s.i.
[3] Average splitting strength was 500 p.s.i.

**Table 12.—Comparison of uniformity of splitting strength with flexural and compressive strengths of concrete prepared with crushed limestone of 1-inch maximum size** [1]

| Batch number | Splitting strength | | Flexural strength | | Compressive strength | |
|---|---|---|---|---|---|---|
| | | Variation from average | | Variation from average | | Variation from average |
| | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 1 | 555 | 1.3 | 760 | −3.1 | 5,690 | 2.9 |
| | 555 | 1.3 | 720 | −8.2 | 5,540 | 0.2 |
| 2 | 550 | 0.4 | 775 | −1.1 | 5,570 | 0.7 |
| | 515 | −6.0 | 845 | 7.8 | 5,620 | 1.6 |
| 3 | 545 | −0.5 | 795 | 1.4 | 5,500 | −0.5 |
| | 515 | −6.0 | 705 | −10.1 | 5,440 | −1.6 |
| 4 | 530 | −3.3 | 850 | 8.4 | 5,570 | 0.7 |
| | 560 | 2.2 | 805 | 2.7 | 5,640 | 2.0 |
| 5 | 545 | −0.5 | 685 | −12.6 | 5,420 | −2.0 |
| | 540 | −1.5 | 750 | −4.3 | 5,390 | −2.5 |
| 6 | 565 | 3.1 | 840 | 7.1 | 5,610 | 1.4 |
| | 515 | −6.0 | 770 | −1.8 | 5,560 | 0.5 |
| 7 | 560 | 2.2 | 795 | 1.4 | 5,330 | −3.6 |
| | 545 | −0.5 | 685 | −12.6 | 5,480 | −0.9 |
| 8 | 545 | −0.5 | 780 | −0.5 | 5,510 | −0.4 |
| | 535 | −2.4 | 760 | −3.1 | 5,420 | −2.0 |
| 9 | 535 | −2.4 | 765 | −2.4 | 5,330 | −3.6 |
| | 530 | −3.3 | 860 | 9.7 | 5,550 | 0.4 |
| 10 | 605 | 10.4 | 835 | 6.5 | 5,230 | −5.4 |
| | 510 | −6.9 | 820 | 4.6 | 5,210 | −5.8 |
| 11 | 560 | 2.2 | 740 | −5.6 | 5,310 | −4.0 |
| | 560 | 2.2 | 735 | −6.2 | 5,300 | −4.2 |
| 12 | 550 | 0.4 | 805 | 2.7 | 5,630 | 1.8 |
| | 550 | 0.4 | 805 | 2.7 | 5,660 | 2.4 |
| 13 | 530 | −3.3 | 810 | 3.3 | 5,650 | 2.2 |
| | 540 | −1.5 | 820 | 4.6 | 5,620 | 1.6 |
| 14 | 495 | −9.7 | 900 | 14.8 | 6,010 | 8.7 |
| | 580 | 5.8 | 785 | 0.1 | 5,720 | 3.4 |
| 15 | 630 | 15.0 | 760 | −3.1 | 5,700 | 3.1 |
| | 575 | 4.9 | 770 | −1.8 | 5,710 | 3.3 |
| Average | 548 | 3.5 | 784 | 5.1 | 5.530 | 2.4 |
| Coefficient of variation, percent | ---------- | 5.0 | ---------- | 7.2 | ---------- | 3.1 |

[1] Specimens were stored in moist air at 73° F. until tested. Age at test was 28 days and cement content was 6 bags per cubic yard.

flexural, and compressive strengths of concrete prepared with a crushed limestone coarse aggregate are shown in table 7. The first series of tests produced results similar to those obtained in tests at 28 days on the lightweight aggregate concrete. The second series of tests was made at 28 days on four different groups of specimens; for each group, the specimens were cured by a different combination of alternating moist and dry storage.

**First series**

In the first series of tests, the maximum size of the crushed stone was three-fourths of an inch, which was the same maximum size as some of the lightweight aggregates used. The results showed that drying caused average strength losses of 16, 40, and 0 percent for the splitting, flexural, and compressive tests, respectively. The corresponding strength losses for the lightweight aggregate concrete, shown in table 5, were 31, 62, and 4 percent. In general, the comparison of the data from tests at 28 days indicates that drying caused greater strength losses in concrete prepared with lightweight aggregate than in the concrete prepared with the limestone coarse aggregate. The difference in strength loss was greater for the flexural than the splitting test and was insignificant for the compressive test.

**Second series**

In the second series of tests, the maximum size of the crushed stone used was 1½ inches. For each type of strength test, 20 specimens were made: (1) Five control specimens were moist cured continuously; (2) five specimens were moist cured for 1 day, then were stored in laboratory air for 27 days; (3) five specimens were moist cured for 7 days, then were stored in laboratory air for 21 days; and (4) five specimens were moist cured for 7 days, were stored in laboratory air for 20 days, and then were immersed in water for 1 day. The data, given in table 7, show that the flexural strength was affected more by drying than the splitting or compressive strengths. The losses in splitting and compressive strengths caused by drying were approximately the same. Comparisons between similarly cured concretes prepared with crushed stone aggregate having maximum sizes of ¾ and 1½ inches are also shown in table 7. Of particular note is the fact that in each of the three strength tests, the strength losses caused by the same drying conditions were nearly identical for concretes prepared with the two sizes of coarse aggregate.

## COLLATERAL STUDIES

In conjunction with the research program that has been described, additional data of interest and value are discussed in the paragraphs that follow.

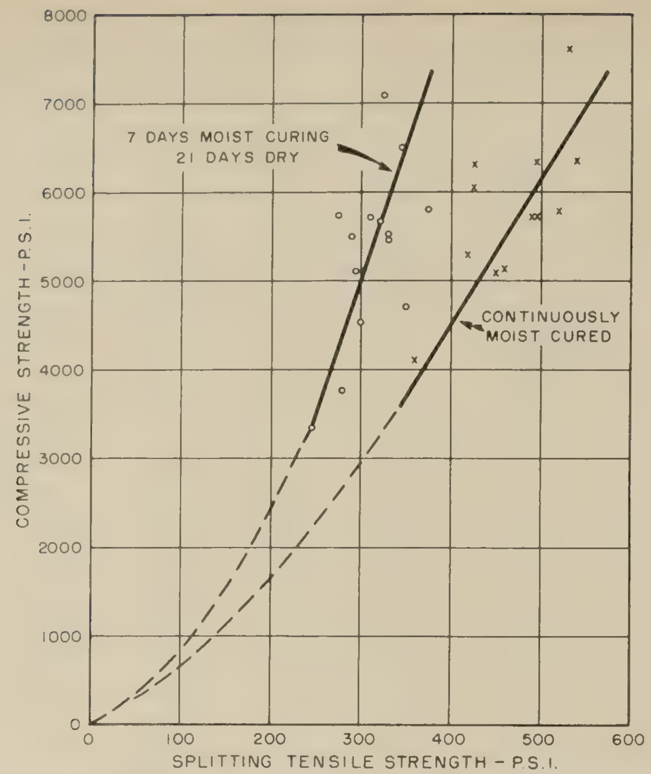


*Figure 7.—Effect of drying on relation of compressive and splitting tensile strengths of concrete containing lightweight aggregate, at 28 days.*

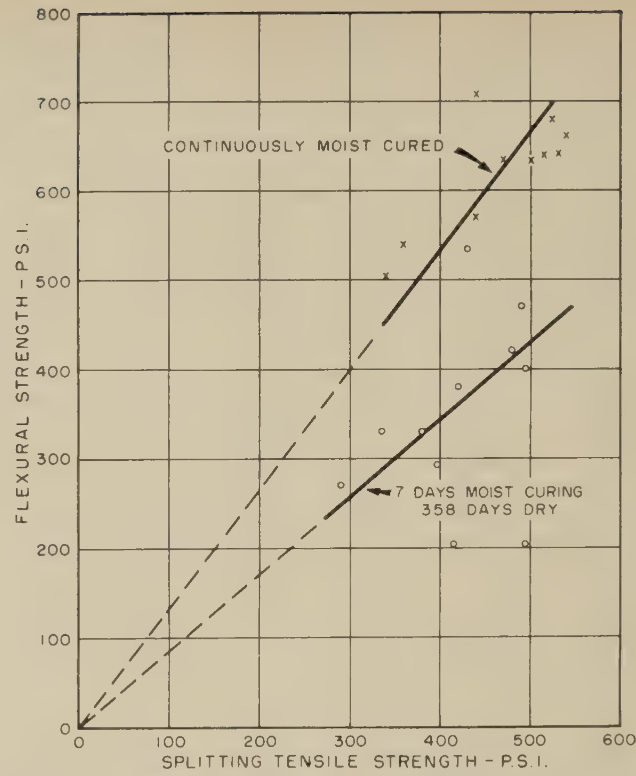


*Figure 8.—Effect of drying on relation of flexural and splitting tensile strengths of concrete containing lightweight aggregate, at 365 days.*

## *Cement Content*

At a number of places in the article mention has been made that the cement content of the concrete was different in the test specimens. The effect of cement content on splitting-flexural and splitting-compressive strength relations is shown by the data in table 8. They indicate that the range in cement content used in this investigation had little influence on the splitting-flexural ratios of concrete prepared with the same type and maximum size of coarse aggregate. However, the splitting-compressive ratios decreased as the cement content of the concrete was increased for each group of comparative specimens.

## *Age of Concrete at Test*

The effect of age of the concrete at test on the splitting-flexural and splitting-compressive strength relations is shown by data in table 9. They were obtained from several groups of specimens for which the cement content of the concrete was different in each group. To minimize the influence of the cement content, the same number of specimens for each cement content was tested at each of the indicated ages. The data in table 9 show that no appreciable difference in splitting-flexural strength ratios occurred for concrete prepared with the same type and maximum size of coarse aggregate; but, for each group of specimens, the splitting compressive strength ratios decreased as the age at test increased.

## *Length of Test Cylinder*

In the main research program, tests were made only on 6- by 12-inch cylinders. To determine whether the length of the cylinder

**Table 13.—Comparison of uniformity of splitting strength with flexural and compressive strengths of concrete made with lightweight aggregate and moist cured [1]**

| Batch number | Splitting strength | Splitting strength: Variation from average | Flexural strength | Flexural strength: Variation from average | Compressive strength | Compressive strength: Variation from average |
|---|---|---|---|---|---|---|
| | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 1 | 355 | − 1.9 | 480 | 1.3 | 2,940 | −7.8 |
| | 340 | − 6.1 | 465 | − 1.9 | 3,240 | 1.6 |
| 2 | 290 | −19.9 | 490 | 3.4 | 3,460 | 8.5 |
| | 350 | − 3.3 | 555 | 17.1 | 3,320 | 4.1 |
| 3 | 400 | 10.5 | 510 | 7.6 | 3,270 | 2.6 |
| | 415 | 14.6 | 480 | 1.3 | 3,220 | 1.0 |
| 4 | 340 | − 6.1 | 500 | 5.5 | 2,980 | −6.5 |
| | 390 | 7.7 | 480 | 1.3 | 3,060 | −4.0 |
| 5 | 365 | 0.8 | 445 | − 6.1 | 3,120 | −2.1 |
| | 410 | 13.3 | 445 | − 6.1 | 3,110 | −2.4 |
| 6 | 390 | 7.7 | 455 | − 4.0 | 3,190 | 0.1 |
| | 360 | − 0.6 | 480 | 1.3 | 3,340 | 4.8 |
| 7 | 360 | − 0.6 | 490 | 3.4 | 3,260 | 2.3 |
| | 415 | 14.6 | 460 | − 3.0 | 3,420 | 7.3 |
| 8 | 375 | 3.6 | 465 | − 1.9 | 3,270 | 2.6 |
| | 335 | − 7.5 | 500 | 5.5 | 3,220 | 1.0 |
| 9 | 295 | −18.5 | 475 | 0.2 | 3,290 | 3.2 |
| | 335 | − 7.5 | 480 | 1.3 | 3,260 | 2.3 |
| 10 | 380 | 5.0 | 410 | −13.5 | 3,150 | −1.2 |
| | 390 | 7.7 | 455 | − 4.0 | 3,110 | −2.4 |
| 11 | 375 | 3.6 | 470 | − 0.8 | 3,200 | 0.4 |
| | 350 | − 3.3 | 475 | 0.2 | 3,120 | −2.1 |
| 12 | 335 | − 7.5 | 480 | 1.3 | 3,260 | 2.3 |
| | 365 | 0.8 | 430 | − 9.3 | 3,190 | 0.1 |
| 13 | 370 | 2.2 | 455 | − 4.0 | 3,160 | −0.9 |
| | 350 | − 3.3 | 510 | 7.6 | 3,030 | −5.0 |
| 14 | 380 | 5.0 | 485 | 2.3 | 3,060 | −4.0 |
| | 310 | −14.4 | 475 | 0.2 | 3,130 | −1.8 |
| 15 | 375 | 3.6 | 465 | − 1.9 | 3,120 | −2.1 |
| | 350 | − 3.3 | 445 | − 6.1 | 3,130 | −1.8 |
| Average | 362 | 6.8 | 474 | 4.1 | 3,188 | −2.9 |
| Coefficient of variation, percent | -------- | 8.8 | -------- | 5.7 | -------- | 4.3 |

[1] Specimens were stored in moist air at 73° F. until tests. Age at test was 28 days and cement content was 6 bags pe[r] cubic yard.

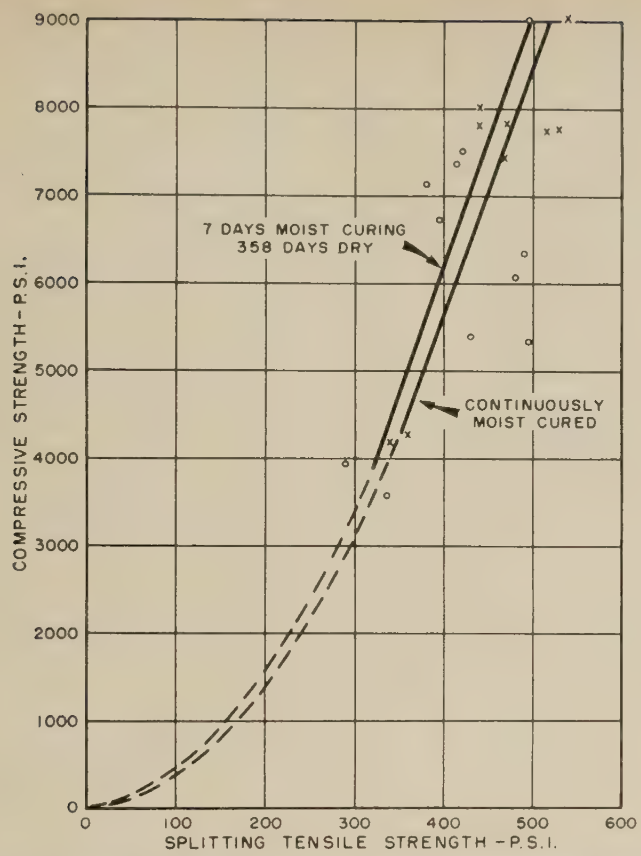


***Figure 9.—Effect of drying on relation of compressive and splitting tensile strengths of concrete containing lightweight aggregate, at 365 days.***

**Table 14.—Comparison of uniformity of splitting strength with flexural and compressive strengths of concrete made with lightweight aggregate and given intermittent curing [1]**

| Batch number | Splitting strength | | Flexural strength | | Compressive strength | |
|---|---|---|---|---|---|---|
| | | Variation from average | | Variation from average | | Variation from average |
| | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* | *P.s.i.* | *Percent* |
| 1 | 295 | 7.7 | 240 | −2.0 | 2,720 | −0.9 |
| | 270 | −1.5 | 260 | 6.1 | 2,910 | 6.0 |
| 2 | 260 | −5.1 | 270 | 10.2 | 2,770 | 0.9 |
| | 295 | 7.7 | 230 | −6.1 | 2,810 | 2.4 |
| 3 | 275 | 0.4 | 220 | −10.2 | 2,860 | 4.2 |
| | 310 | 13.1 | 225 | −8.2 | 2,710 | −1.3 |
| 4 | 260 | −5.1 | 250 | 2.0 | 2,700 | −1.6 |
| | 280 | 2.2 | 230 | −6.1 | 2,680 | −2.4 |
| 5 | 250 | −8.8 | 220 | −10.2 | 2,670 | −2.7 |
| | 265 | −3.3 | 295 | 20.4 | 2,720 | −0.9 |
| 6 | 290 | 5.8 | 235 | −4.1 | 2,980 | 8.6 |
| | 280 | 2.2 | 225 | −8.2 | 2,820 | 2.7 |
| 7 | 270 | −1.5 | 265 | 8.2 | 2,830 | 3.1 |
| | 245 | −10.6 | 225 | −8.2 | 2,840 | 3.5 |
| 8 | 260 | −5.1 | 225 | −8.2 | 2,420 | −11.8 |
| | 230 | −16.1 | 235 | −4.1 | 2,510 | −8.6 |
| 9 | 275 | 0.4 | 245 | 0.0 | 2,700 | −1.6 |
| | 290 | 5.8 | 255 | 4.1 | 2,770 | 0.9 |
| 10 | 305 | 11.3 | 265 | 8.2 | 2,700 | −1.6 |
| | 300 | 9.5 | 260 | 6.1 | 2,580 | −6.0 |
| 11 | 310 | 13.1 | 270 | 10.2 | 2,770 | 0.9 |
| | 285 | 4.0 | 230 | −6.1 | 2,890 | 5.3 |
| 12 | 250 | −8.8 | 255 | 4.1 | 2,730 | −0.5 |
| | 255 | −6.9 | 245 | 0.0 | 2,740 | −0.2 |
| 13 | 300 | 9.5 | 245 | 0.0 | 2,830 | 3.1 |
| | 270 | −1.5 | 260 | 6.1 | 2,570 | −6.4 |
| 14 | 245 | −10.6 | 245 | 0.0 | 2,820 | 2.7 |
| | 270 | −1.5 | 215 | −12.2 | 2,820 | 2.7 |
| 15 | 260 | −5.1 | 250 | 2.0 | 2,720 | −0.9 |
| | 270 | −1.5 | 260 | 6.1 | 2,770 | 0.9 |
| Average | 274 | 6.2 | 245 | 6.3 | 2,745 | 3.2 |
| Coefficient of variation, percent | -------- | 7.6 | -------- | 7.7 | -------- | 4.3 |

[1] Specimens were stored in moist air at 73° F. for 7 days, followed by 21 days of storage in laboratory air at 73° F. and 50 percent relative humidity. Cement content was 6 bags per cubic yard.

affects the results of splitting tests, 6- by 6-inch and 6- by 12-inch cylinders were made from the same batch of concrete and tested at the same age. No appreciable difference was noted between the strengths obtained in tests of the two different lengths of cylinders. The results of these tests are given in table 10.

### *Type of Bearing Surface*

A limited series of tests was made to determine the effect of the type of bearing material on splitting-tensile strength. Tests were made on similar specimens of concrete; in these tests plywood bearing strips and neat Lumnite cement bearings were used. A metal jig was used so that strips of the neat Lumnite cement, one-half inch wide and one-eighth inch thick, were cast on diametrically opposite elements of the cylinder. The strips were cast against plane plate glass and all specimens were kept moist until tested. As shown in table 11, the two types of bearing surfaces caused no appreciable differences in the strengths obtained in these tests.

### *Uniformity Tests*

Tests were made to determine the uniformity of the splitting strength as compared with the uniformity of the compressive and flexural strengths of similar concrete. For these tests, 15 batches of concrete were made on each of three days, and two specimens for each type of test were prepared from each batch. All batches of concrete were prepared to be as nearly alike as possible. The specimens were tested at an age of 28 days.

On the first mixing day, specimens were made with crushed limestone having a maximum size of 1 inch and were continuously moist cured until tested. The splitting, flexural, and compressive strengths and the variations from the average strengths are given in table 12. The average variation and the coefficient of variation for each type of test are also given in this table. The coefficient of variation for the splitting strength tests was 5.0 percent, for the flexural strength tests it was 7.2 percent, and for the compressive strength tests it was only 3.1 percent.

On the second mixing day, specimens were made with lightweight aggregate having a maximum size of three-fourths of an inch and were continuously moist cured until tested. The results of these tests are shown in table 13. The coefficient of variation for the splitting strength tests was 8.8 percent, for the flexural strength tests it was 5.7 percent, and for the compressive strength tests it was 4.3 percent.

On the third mixing day, specimens were made with lightweight aggregate and were similar to those made on the second day, but these specimens were given 7 days moist curing followed by 21 days of storage in laboratory air. The results of the strength tests on these specimens are given in table 14. The coefficient of variation for the splitting strength tests was 7.6 percent, for the flexural strength tests it was 7.7 percent, and for the compressive strength tests it was 4.3 percent.


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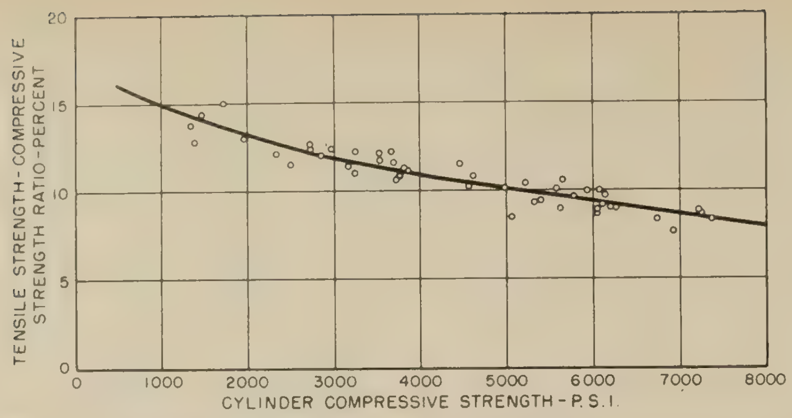


*Figure 10.—Relation between ratio of splitting tensile to compressive strength and compressive strength for concrete made with crushed stone of 1½ inches maximum size.*

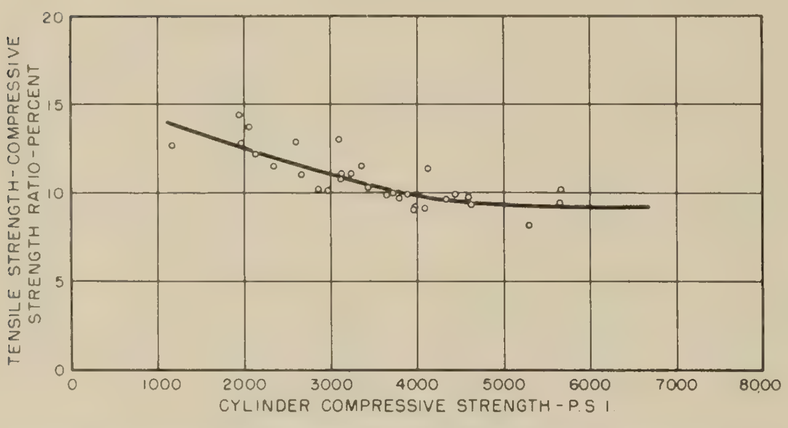


*Figure 11.—Relation between ratio of splitting tensile to compressive strength and compressive strength for concrete made with gravel of 1½ inches maximum size.*

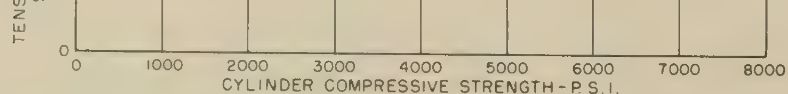


*Figure 12.—Comparison of relation between ratios of splitting tensile to compressive strengths and compressive strengths. Test results of four laboratories.*

### *Comparison of Results*

The previously mentioned report by Thaulow (*4*) contains a graph, included there as figure 3, that shows a comparison of splitting tensile tests performed in Japan by Akazawa (*1*), in Brazil by Carneiro and Barcellos (*2*), and in Denmark by Efsen and Glarbo (*7*). The data obtained by these investigators were plotted as the relation between the splitting-compressive strength ratio in percentage, and the compressive strength in p.s.i. The data given in tables 1 and 2 of this article have been plotted in a similar manner in figures 10 and 11, respectively; and the relations established are compared in figure 12 with those shown in the Thaulow report. It is apparent that the relations developed by the Bureau of Public Roads are similar to those developed by other investigators. The Bureau's data show that the relation between the splitting-compressive strength ratio and the compressive strength is related to the type of coarse aggregate used in the concrete. It is not known what materials were used by the other investigators.

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# The Effect of Expressway Design on Driver Tension Responses

*BY THE TRAFFIC OPERATIONS RESEARCH DIVISION*
*BUREAU OF PUBLIC ROADS*

**Reported[1] by RICHARD M. MICHAELS,**
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***The relationship of highway design to driving stress has been the subject of considerable discussion. The study reported in this article was aimed at measuring driver tension by use of the galvanic skin reflex. Four expressways of differing design were driven. It was found that a freeway with complete control of access and good geometric design generates significantly less driver tension than less rigorous designs. Also, tension is dependent on traffic volume, rising sharply as volume approaches practical capacity. The results do raise the question of whether tension rises because capacity is reached or whether the capacity limitation occurs because at higher volumes tension rises sharply, hence causing the driver to make compensatory responses.***

***Comparisons of freeways with urban arterials and primaries indicated the latter generated up to four and one-half times as much tension as the freeway. The real benefit comes from the almost total elimination of marginal conflicts for the freeway driver. The results of this study indicate that there may be two factors involved in the concept of comfort and convenience. Comfort may reflect the unpredictable interferences in driving; convenience may reflect the predictable interferences such as traffic control devices. If comfort and convenience can be separated, the GSR may be a direct measure of route comfort.***

## *Introduction*

A PREVIOUS study conducted by the Bureau of Public Roads (*1*)[2] indicated that driver tension responses, as measured by galvanic skin reflex (GSR), could be used to differentiate between different types of city streets. In the study reported here, the same technique was used in an attempt to determine whether driver tension responses could be used similarly to differentiate between types of design of expressways, and also to determine whether such responses could be used to indicate differences in other types of highways.

With the basic aim of differentiating between expressway designs by using driver tension as the distinguishing measure, two types of tension-inducing events were of prime interest: (1) events of traffic interferences similar to those encountered on urban streets, and (2) events associated with the interferences caused by geometric design features of the highways. Considerable evidence supports the superiority of expressway design over the older highway designs or highways with less control of access. However, it is still a rather moot point as to whether any differences exist among the various philosophies of design that are being proposed for controlled-access highways.

### Expressways studied

In the Washington, D.C., metropolitan area, it was possible to find expressway designs of considerably different types, which were distinguishable on the basis of their age, as well as their design features and design speed. For this study, four expressways of different designs were selected; although these four routes represent considerably different designs, none may be considered extreme in any sense.

- The first expressway, built specifically to standards for highways in the National System of Interstate and Defense Highways, is an Interstate route with a design speed of 70 miles per hour.
- The second expressway, a 15-year old parkway with a design speed of 50 miles per hour, was designed to standards that were considerably less rigorous in terms of both curvature and grade than presently are acceptable for Interstate highways in flat or rolling terrain.
- The third expressway, an intermediate highway in terms of both age and design criteria, is a 10-year old urban freeway having relatively modern curvature and grade characteristics and a design speed of 70 miles per hour. Its weakness lies in the substandard design of the acceleration and deceleration lanes.
- The fourth expressway, a highway having a geometric design comparable to that for the Interstate expressway with the exception of a higher magnitude of grade and curvature, had only partial control of access in the section used for this study; it had crossovers in the median and several at-grade intersections. In addition, substandard connections provided commercial establishments on the expressway with numerous points of access to a frontage road that followed the same route for most of the section under study.

In general, accomplishment of the basic aim of the study involved attempts to differentiate among these four different types of expressway designs; to examine the tension responses generated on these four expressways as functions of design characteristics and traffic interference; to determine the relation of tension responses to traffic volume; and to relate the results of the first two efforts to the design of other types of highways.

## *Procedure*

Sections of the four test routes, each approximately 8½ miles long and generally close to the Washington, D. C., area, were chosen for this study. On two of the routes, the volume of traffic was relatively low, and they had no appreciable peak hours of traffic—less than 500 vehicles per hour in two lanes during daylight hours. Consequently, studies were made only during offpeak hours, from 10 a.m. to 3 p.m. On the other two routes, which are important expressways used for work trips into Washington, definite peak periods of traffic occurred. Test runs, timed to cover the periods of maximum traffic, were made on these two routes during morning and evening peak hours and also during the time corresponding to the offpeak hours on the other two routes. Prior to the beginning of this study, traffic volume counts were made on the routes with peak-hour traffic, during both the offpeak and peak hours, so that the GSR data collected could be related to traffic volume.

[1] Presented at the 41st annual meeting of the Highway Research Board, Washington, D.C., January 1962.

[2] References indicated by italic numbers in parentheses are listed on page 112.

Six test drivers were used; all were males and their ages ranged from 17 to 22 years. Two of the six had had previous experience in using the GSR equipment and were fairly familiar with the plan of the study and the operation of the instrument. Two teams of three drivers and a standard passenger car that had automatic transmission were used. Three people were in the test car during each run; and each member of this three-man team served on successive individual runs as a driver, an observer, and a data recorder.

The observer sat in the front seat with the driver and defined the cause of any change made in the position or speed of the test vehicle—interferences from traffic or from design characteristics of the highway—for the data recorder who entered the information on the GSR record. Factors considered as possible causes for changes in vehicle speed or position had been coded into eight categories, four were traffic related and four were design related. A list of these interferences is shown in table 1: numbers 4 through 7 apply to those attributed to highway characteristics, and the rest of the numbers apply to those attributed to traffic.

For each run, electrodes were fixed to the first and third fingers of the driver's left hand, and the sensitivity level of the GSR equipment was adjusted to a point at which a shock stimulus presented by the observer would cause a full-scale deflection of the recorder pen. Once adjusted, the sensitivity level was not changed while the particular driver was making his runs. Each driver covered the test route in one direction, took a short break, and returned. The travel times for the 8½-mile test sections varied from 8 to 21 minutes. Each of the six test drivers covered each of the four routes, as follows: 12 times each for offpeak and peak traffic hours on each of two routes, and 12 times each for each of the two routes that had no peak-hour traffic.

All data were recorded on chart paper; they included pertinent information about the route and driver as well as the GSR data. Because only the galvanic skin responses aroused by the specific, observable interferences were considered in this study, only the GSR data that were associated with the interferences listed in table 1 were analyzed. The basic measure of tension was defined as the magnitude of GSR per unit of time; this measure equalized the data for differences either in length of routes or in running times and tended to make the distribution of the GSR data more symmetrical than would have been obtained with GSR magnitude as the measure.

### *Tension Responses and Traffic Volumes*

The relationship between tension responses and volume of traffic, which varied on the four routes from approximately 300 to 3,500 vehicles per hour in the two lanes, was of fundamental interest. The data collected for all routes were combined according to volume, and the curve of tension responses versus the traffic volume is shown in figure 1. Because this curve shows only the effect of traffic interferences on tension, it illustrates the direct relationship between driver tension and volume of traffic. The relationship seemed to be quite linear up to about 2,400 vehicles per hour in two lanes, and then the rise in tension appeared to increase exponentially. Tension-traffic volume data also were analyzed for the individual drivers and the same general form of the curve was found for all.

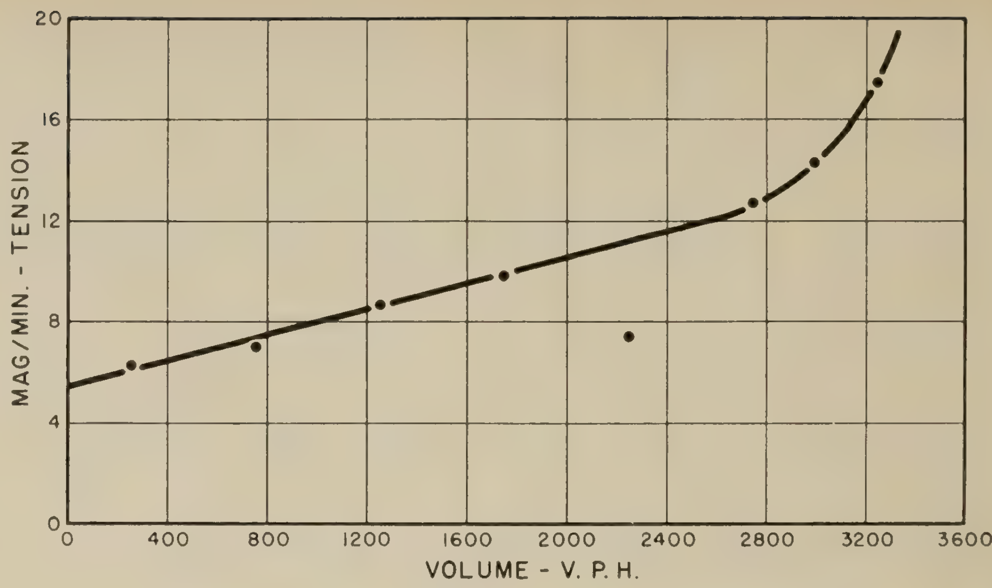


*Figure 1.—Effect of traffic volume on tension responses.*

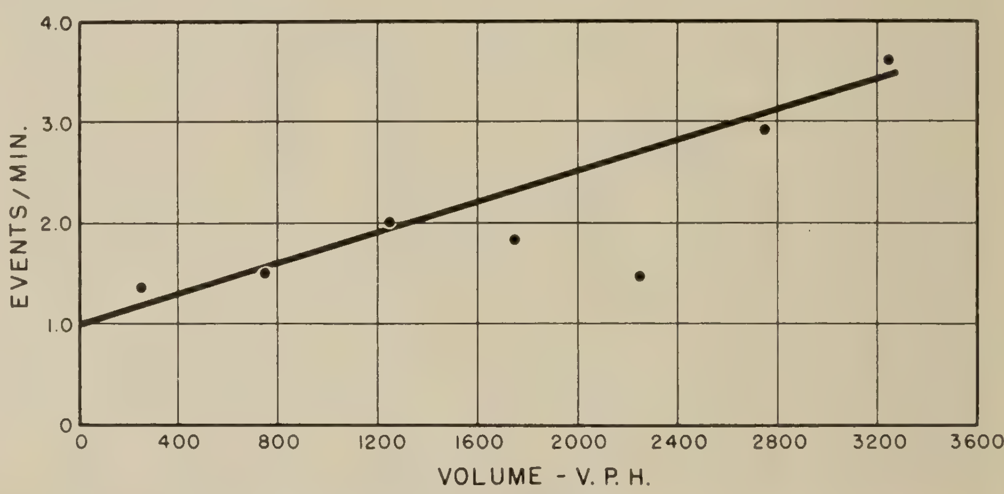


*Figure 2.—Effect of traffic volume on rate of occurrence of interferences.*

A two-way analysis of variance was performed on the data collected for driver tension responses to traffic volume, and an analysis was made of the trend of tension in relation to volume. The summary for these analyses is shown in table 2. The interaction term was found to be insignificant and was pooled with the residual. The results indicated a significant difference both among drivers and traffic volumes at better than the 0.01 level. In addition, the quadratic as well as the linear component of trend was significant at the 0.01 level. Thus, the form of the curve shown in figure 1 appears to be reliable.

A basic question in the use of the GSR concerned whether it was measuring something more than simply the frequency of occurrenc of the interferences. If the same function de fined the relation between interference pe unit of time and the traffic volume as it di for driver tension and traffic volume, then th same results could be obtained simply b counting the number changes in the speed o position of the vehicle. To examine this possi bility, the number of traffic interferences pe unit of time as a function of traffic volume wa calculated, and the resultant data are plotte in figure 2. The same type of analysis of var ance performed for the tension-traffic volum data was carried out on the interferences-pe minute data. The summary of this analysis i shown in table 3. In this analysis, as in th previous one, differences among the two maj variables were significant. The linear tren among the volumes also was significant at th 0.01 level, but the quadratic component di not reach significance at this level. Thus th straight line relation shown in figure 2 was th best fit to the data.

From the two analyses of variance, it seen reasonable to conclude that the traffic inte ferences do induce a greater behavioral r

**Table 1.—Driving interferences**

| Interferences— | | |
|---|---|---|
| Identification Number | Name | Description |
| 1 | Instream vehicles | Conflicts caused by vehicles traveling in same direction. |
| 2 | Merging or crossing vehicles | Position or speed change caused by vehicles converging on test car. |
| 3 | Exiting vehicles | Position or speed change caused by vehicles diverging from traffic stream. |
| 4 | Gradient | Change in speed or position caused by grade. |
| 5 | Curvature | Change in speed or position caused by curvature. |
| 6 | Pavement changes | Position or speed change caused by variations in highway surface. |
| 7 | Shoulder objects | Position or speed change caused by shoulder objects such as cars or abutments. |
| 8 | Pedestrians | Changes caused by conflicts with pedestrians or animals. |

**Table 2.—Summary of analysis of variance on tension caused by traffic volume**

| Source of variance | Sum of squares | $df$ | Mean square | F, ratio |
|---|---|---|---|---|
| Between subjects | 2,034.38 | 5 | 406.88 | [1] 25.70 |
| Between volume | 2,865.04 | 5 | 573.01 | [1] 36.20 |
| Error | 1,535.76 | 97 | 15.83 | -------- |
| TOTAL | 6,435.18 | 107 | -------- | -------- |
| Linear trend | 1,705.45 | 1 | -------- | [1] 107.73 |
| Quadratic trend | 117.72 | 1 | -------- | [1] 7.44 |

[1] Significant at the 0.01 level.

**Table 3.—Summary of analysis of variance on frequency of interferences caused by volume**

| Source of variance | Sum of squares | $df$ | Mean square | F, ratio |
|---|---|---|---|---|
| Between subjects | 15.99 | 5 | 3.20 | [1] 4.77 |
| Between volume | 79.87 | 5 | 15.97 | [1] 19.72 |
| Error | 78.16 | 97 | 0.81 | -------- |
| TOTAL | 174.02 | 107 | -------- | -------- |
| Linear trend | 70.15 | 1 | 70.15 | [1] 86.60 |
| Quadratic trend | 4.47 | 1 | 4.47 | 5.52 |

[1] Significant at the 0.01 level.

**Table 4.—Summary of analysis of variance of tension responses caused by traffic interferences**

| Source of variation | Sum of squares | $df$ | Mean square | F, ratio |
|---|---|---|---|---|
| Subjects | 1,122.6 | 5 | 224.52 | [1] 11.79 |
| Routes | 468.0 | 3 | 156.0 | [1] 8.19 |
| Direction | 32.5 | 1 | 32.50 | 1.71 |
| Routes and subjects | 300.6 | 15 | 20.04 | 1.05 |
| Direction and routes | 118.5 | 3 | 39.50 | 2.07 |
| Direction and subjects | 64.7 | 5 | 12.94 | -------- |
| Error | 4,858.8 | 255 | 19.05 | -------- |
| TOTAL | 6,965.7 | 287 | -------- | -------- |

[1] Significant at the 0.01 level.

**Table 5.—Summary of analysis of variance of highway characteristics (4–7)**

| Source of variation | Sum of squares | $df$ | Mean square | F, ratio |
|---|---|---|---|---|
| Subjects | 2,416.4 | 5 | 483.3 | [1] 26.6 |
| Routes | 1,592.5 | 3 | 530.8 | [1] 29.2 |
| Direction | 95.4 | 1 | 95.4 | 5.2 |
| Routes and subjects | 1,564.6 | 15 | 104.3 | [1] 5.7 |
| Direction and routes | 19.1 | 3 | 6.4 | -------- |
| Direction and subjects | 243.1 | 5 | 48.6 | 2.7 |
| Error | 4,633.2 | 255 | 18.2 | -------- |
| TOTAL | 10,564.3 | 287 | -------- | -------- |

[1] Significant at the 0.01 level.

sponse than is indicated simply by the frequency of their occurrences. Thus, the use of the GSR may be a behavioral measure of the operational efficiency of a highway, and also it may be a measure of the practical capacity of a highway.

## *Differentiating Among the Highways*

The average magnitude of response per minute was determined for each test driver, for each route, and for the four traffic interferences during the offpeak hours. These data were subjected to an analysis of variance for which the summary is shown in table 4. No significant differences were noted between the data for directions, inbound vs. outbound, but significant differences were noted between data for the drivers and the data for the four routes.

Ordering the tension data according to highway, the highway built to Interstate standards generated less tension for each of the six drivers than the other three highways. Because this ranking included differences in tension caused by traffic volume, a correction was applied to the data shown in figure 1 to eliminate the effect of differences in volume – even during the offpeak hours, the urban freeway always carried three to four times more traffic than the other routes. All tension responses were corrected by multiplying them by a weight, which was the ratio of tension at a volume of 500 vehicles per hour to the tension at 1,250 vehicles per hour. An analysis of variance was performed with the corrected data and, as before, a significant difference among the routes was found. Now, the ranking of the four routes was still reliable, but the lowest level of tension was for the urban freeway, and the next higher levels of tensions were successively for the Interstate route, the parkway, and the freeway having only partial control of access.

The data for average magnitude of response per minute for offpeak traffic hours also were analyzed to determine the effects of interferences caused by highway design characteristics. Analysis of variance was performed in the same manner as for the traffic interferences. The results, which showed significant effects among the drivers and the routes, are given in table 5. Significant rank order among the highways also was determined; this order, from the lowest to highest tension induction was: the urban freeway, the parkway, the freeway having partial control of access, and the Interstate route.

## *GSR Magnitude Related to Interferences*

An analysis for the average magnitude of GSR among the eight driving interferences was made. A rank test was employed rather than an analysis of the average magnitudes of the GSR themselves. Although a rank test is weak, its use avoids the necessity for meeting the distributional assumptions that would be required for stronger normal tests. The ranks for each route were compared; the test drivers were considered as replicates. A summary for the four routes, with the significance of the rank order, is shown in table 6. This data shows the Interstate route had a ranking among the events that was significant at the 0.01 level. A comparison was made on the combined rankings of the four routes and the ranking of events was significant at better than the 0.01 level.

The ordering among the eight different interferences indicates very clearly that the traffic interferences consistently generated the highest magnitude of GSR. The highest average magnitude was generated by merging vehicles and the second highest by both instream conflicts and exiting vehicles. Among the highway characteristics, the highest magnitude of driver tension was induced by changes in pavement characteristics; this was followed very closely by that induced during negotiation of curves.

**Table 6.—Rank order of average magnitude of GSR generated by interferences for each route [1]**

| Rank [2] | Interstate highway | Urban freeway | Parkway | Expressway with partial control of access | All |
|---|---|---|---|---|---|
| 1 | 2 | 2 | 2 | 3 | 2, merging vehicles |
| 2 | 1 | 3 | 3 | 1 | 1, instream vehicles |
| 3 | 7 | 1 | 1 | 2 | 3, exiting vehicles |
| 4 | 6 | 5 | 6 | 8 | 6, pavement |
| 5 | 5 | 6 | 7 | 6 | 7, shoulder objects |
| 6 | 3 | 8 | 5 | 5 | 5, curvature |
| 7 | 4 | 4 | 4 | 4 | 4, grade |
| 8 | 8 | 7 | 8 | 7 | 8, pedestrians |
| | Reliability of rank $P<0.01$ | Reliability of rank $P<0.15$ | Reliability of rank $P<0.07$ | Reliability of rank $P<0.11$ | Reliability of rank $P<0.01$ |

[1] For definition of events see table 1.
[2] Ordering is from highest GSR average to lowest.

**Table 7.—Percentage distribution of interference—offpeak data**

| Route | Interferences | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| Interstate highway: | | | | | | | | |
| In | 21.0 | 0.8 | 0.5 | 23.9 | 37.4 | 11.9 | 2.3 | 0.2 |
| Out | 24.0 | 0.7 | 0.3 | 26.8 | 39.1 | 3.9 | 1.8 | 0.2 |
| Urban freeway: | | | | | | | | |
| In | 48.4 | 2.4 | 0.4 | 11.2 | 26.3 | 5.5 | 0.2 | 0.1 |
| Out | 51.9 | 1.2 | 0.9 | 12.9 | 22.3 | 5.2 | 0.8 | 0.4 |
| Parkway: | | | | | | | | |
| In | 29.4 | 1.7 | 0.8 | 8.0 | 43.7 | 6.2 | 0.5 | 0.8 |
| Out | 28.3 | 1.1 | 1.4 | 11.3 | 41.9 | 6.2 | 0.7 | 0.5 |
| Expressway with partial control of access: | | | | | | | | |
| In | 30.7 | 2.6 | 0.9 | 17.2 | 37.2 | 9.0 | 1.0 | 0.6 |
| Out | 31.3 | 2.2 | 1.0 | 18.0 | 38.8 | 5.5 | 0.8 | 0.2 |

### *Frequency of Interferences*

The importance of the rankings of the average magnitude of the GSR is meaningful, in part, according to the frequency with which the interferences actually occurred. Futher analysis of the distribution of the occurrence of the interferences was carried out on the data for all test drivers combined; the distributions for each of the highways are shown in table 7. Two interferences accounted for approximately 70 percent of them on all the routes: Interference No. 1, instream traffic interferences; and interference No. 5, negotiation of curves. The differences shown in table 7 indicate that on the urban freeway, instream interferences were considerably greater than the interferences of changes in curvature; this was expected because of the relatively high volume of traffic on this expressway even during the offpeak traffic hours. On the parkway, however, this pattern was reversed, which indicated the greater frequency and higher degree of curvature of this type of highway design. It is interesting to note that this reversal occurred even though the traffic volume was greater on the parkway than on the Interstate route. This reversal, therefore, indicated that the differences in GSR were caused by design characteristics.

**Two groups of interferences**

The eight interferences were divided into two groups for analysis; one for those caused by traffic and one for those caused by highway design characteristics. The frequency of occurrence for these interferences is given in table 8. Inspection showed considerable similarity of interferences among the four routes, the major difference being noted for those occurring on the parkway. This difference was indicated by the sharp increase in the number of interferences caused by highway curvature as opposed to the number of interferences from this source for the other three routes.

The data on the distribution of traffic interferences, also shown in table 8, indicate that instream conflicts are the dominant type of interference for drivers on freeways. These data were consistent for all routes for offpeak traffic hours—between 90 and 95 percent of all interferences were instream conflicts. Information in table 8 also shows that on the high-volume urban freeway more than half of all the observed interferences were caused by traffic, but only approximately one-fourth of the interferences noted for the Interstate highway were caused by traffic.

### *Tension Induction on Freeway and Urban Arterial*

Data also were available for two of the six test drivers for the same urban arterial studied previously (*1*), a four-lane rural primary highway with no control of access, and a freeway. These data, however, were restricted to traffic interferences and did not reflect tension caused by highway design characteristics. A comparison of data from these two highways and the high-type expressway is presented in table 9. The ratios of driver tension are shown in the last column of the table. The results of the comparison indicate the superiority of controlled-access design in reducing traffic interferences.

### *Discussion*

The results of this study indicate that the GSR can be used as a measure to differentiate among types of expressway design. Although actual differences in the designs of the four expressways, all in good condition, were relatively small, significant differences among them were noted in terms of tension responses. The differences attributed to each of the tw types of interferences studied demonstrate the effect of the different highway designs.

For traffic interferences, the urban freewa and the Interstate route were significant less tension inducing than the other two hig ways. Actually, for the through driver, bo of these roads were nearly comparable terms of tension induction because the urba freeway has geometric design characteristi that meet Interstate standards over most the study section. Marginal characteristi related to shoulders and ramps represent t deficiencies of the urban freeway, but wh equated for traffic volumes, the two routes a very similar.

This study showed that, as far as t frequency and magnitude of traffic conflic are concerned, highways designed to mode freeway standards are clearly superior those more loosely designed. Control access on expressways eliminates much of t marginal conflict for the through driver; th was demonstrated in the contrast between t Interstate route and the design having on partial control of access. The latter w consistently the most tension inducing rou the major difference was in an increase in t frequency of the occurrence of conflicts w merging and exiting vehicles, that is, margi interferences. This difference was furth shown in the comparisons of the GSR da for the primary and urban arterial. Th routes generated around 30 percent of th conflicts from marginal interferences, the high-type expressway generated less th 10 percent from such interferences.

Table 8.—Percentage distribution of highway and traffic interferences—offpeak hours

| Route | Highway interferences | | | | Traffic interferences | | | | Percentage of total interferences from traffic |
|---|---|---|---|---|---|---|---|---|---|
| | 4 | 5 | 6 | 7 | 1 | 2 | 3 | 8 | |
| Interstate highway: | | | | | | | | | |
| In | 31.7 | 49.5 | 15.8 | 3.0 | 93.0 | 3.8 | 2.3 | 0.9 | 23.0 |
| Out | 37.4 | 54.5 | 5.5 | 2.6 | 95.5 | 2.7 | 1.1 | 0.7 | 26.0 |
| Urban freeway: | | | | | | | | | |
| In | 25.9 | 60.9 | 12.7 | 0.5 | 94.3 | 4.7 | 0.9 | 0.1 | 54.4 |
| Out | 31.2 | 54.2 | 12.6 | 1.9 | 95.4 | 2.2 | 1.7 | 0.7 | 56.9 |
| Parkway: | | | | | | | | | |
| In | 13.8 | 74.9 | 10.5 | 0.8 | 89.8 | 5.2 | 2.4 | 2.6 | 35.9 |
| Out | 18.8 | 69.7 | 10.3 | 1.1 | 90.5 | 3.6 | 4.5 | 1.4 | 34.2 |
| Expressway with partial control of access: | | | | | | | | | |
| In | 26.7 | 57.7 | 14.0 | 1.6 | 88.4 | 7.4 | 2.5 | 1.7 | 35.1 |
| Out | 28.5 | 61.5 | 8.7 | 1.2 | 90.2 | 6.3 | 2.9 | 0.7 | 35.5 |

**Table 9.—Tension generated on three types of highways**

| Type of highway | Tension, magnitude/minute | | | Ratio of tension on three routes to tension on expressway | | |
|---|---|---|---|---|---|---|
| | Driver A | Driver B | Average | Driver A | Driver B | Average |
| Controlled access | 5.7 | 5.5 | 5.6 | 1.00 | 1.00 | 1.00 |
| Primary with uncontrolled access | 10.8 | 8.8 | 9.8 | 1.89 | 1.60 | 1.75 |
| Urban arterial | 13.9 | 23.5 | 18.7 | 2.44 | 4.27 | 3.34 |

A similar but more subtle interaction was noted for the parkway; the tolerance of high curvature and gradient interacted with the traffic interferences to increase the level of tension for the drivers. The driver had increased difficulties in handling the conflicts in traffic when he also had to cope with rather large changes in the geometrics of the highway itself.

The tension-producing relationships among the highways lend support to the hypothesis, proposed in the previous study with GSR (*1*), that one of the basic determinants of driver tension is the degree of predictability that exists in the driving environment. It was obvious from this study that, under high-volume traffic conditions, the driver is interacting with vehicles around him and must condition his performance to his expectation of what other vehicles are doing and will do. In general, he does not have enough information to develop stable or reliable predictions about the activities of these other vehicles. On a highway having only partial control of access, his problem is confounded by the increase in marginal activity, especially when both entering and exiting interferences involve large, angular closing rates. Thus, increasing traffic volume, increasing marginal activity, and increasing variations in the highway itself all contribute to the complexity of the driving and in turn make it more difficult for the driver to develop stable predictions about his driving environment.

### Highway rankings

The results of the rankings of the routes for the highway characteristics are rather anomalous. The Interstate route, which operated well relative to traffic interferences, generated the highest tension from highway interferences. The resolution of this paradox may well be the differences in travel speed on these highways. A systematic difference among the four expressways occurred in terms of the speed adopted by the drivers—an average of: between 60 and 65 miles per hour on the Interstate route, nearly 50 miles per hour on the urban freeway, and nearly 40 miles per hour on the parkway.

The increasing speeds indicated that drivers compensate for infrequent traffic interferences—either from low volume of traffic or good highway design—by traveling faster. In other words, drivers tend to make their speeds contingent upon the perceived complexity of the driving situation. In effect, the design of the Interstate route permitted a driver to increase his speed to the point at which the highway characteristics of curvature, grade, and pavement condition began to affect his operation of the vehicle. Such a conclusion would suggest that drivers adopt some kind of a critical level of driving tension.

In these terms, tension induced in driving may well represent one mechanism by which the driver can stabilize the system. That is, by driving at or near the speed at which tension responses increase sharply, the driver will be able to determine qualitatively an upper limit to his control over the driving situation. Obviously, this kind of criterion will be applicable to interferences caused by either traffic or highway conditions, or both. When traffic conditions are such that the driver is subject to considerable stress, he will reduce his speed and thereby decrease the frequency of tension-inducing stimuli. When traffic is not a factor, he will utilize the highway characteristics and drive sufficiently fast to get information from the road itself to give him a measure of performance.

### Comfort and convenience

The results of this study also bear on the problem of comfort and convenience. For many years, it has been known that driver choices among alternative routes could not be accounted for either on the basis of economy of operation or of time. It has been necessary, therefore, to postulate the additional factor of comfort and convenience. The basic problem with such a construct is to develop an operational definition that will make it measurable. Differences in tension responses on different highways may represent one avenue for resolving this problem.

Data in this study indicate that a rural primary highway as an alternate route for a freeway generates twice as much tension as the freeway itself. Furthermore, on the highways such as this that have no control of access, nearly 30 percent of the traffic interferences arose from marginal conflicts, but on the freeway less than 10 percent of the traffic interferences arose from these sources. However, little difference was noted in tension generated by instream conflicts, except that fewer of these conflicts occurred on the freeway. Thus, two major factors appear to account for the differences in tension generated by the freeway and the primary having uncontrolled access: (1) proportion of marginal interferences, and (2) frequency of instream conflict. Such a breakdown suggests a logical distinction between comfort and convenience. Thus, the comfort of a route may be defined as the tension caused by unpredictable conflicts. Considered in terms of the predictability of the interferences, route comfort appears to be measurable by use of the GSR.

Convenience may be defined as the degree of freedom that a driver has in setting the level of performance of his own system. Elements in the route that restrict the driver or force conformity to external controls would make that route inconvenient. For example, a wide variety of traffic control devices generally are predictable, but they force the driver to make control changes that may conflict both with the operation of his system and his driving objectives. Similarly, interaction with other vehicles in the traffic stream frequently is predictable, at least at moderate volumes of traffic, yet it restricts the driver's freedom of action. In this respect, it is interesting to note that the relation between tension and traffic volume, shown by data in figure 1, breaks sharply around 2,800 vehicles per hour or an average of 1,400 vehicles per lane per hour. This may represent the point at which the traffic situation becomes highly unpredictable; in terms of this discussion, the point at which driving would change from being inconvenient to being uncomfortable. Because the data of this study show only small differences in the average GSR from instream interferences, it is entirely possible that their frequency of occurrence alone may be an adequate measure of convenience. Claffey (*2*) used such a measure in his studies of comfort and convenience, but he made no distinction between the two factors.

It is difficult to determine the weighting of the two factors of marginal and instream conflicts to fit some route choice equation. However, by using the GSR as an overall measure of both factors, the data given in table 9 show that the freeway generated the least tension; the primary route having uncontrolled access generated 1.75 times more tension and the arterial highway generated 3.34 times more tension than the freeway. By subjective responses, the drivers evaluated the three routes in a direct but non-linear relation with tension; that is, their dislike of a route increased more rapidly than tension increased. Considerable research will be required to verify this relation and factors related to the choice among alternative routes.

Comparison of the data from this study clearly shows the superiority of modern expressway design over other types of highway design. Nearly all traffic interfererces were minimized by these modern designs, except for certain of those occurring within the traffic stream. Thus, even under high-volume traffic conditions, modern freeway design will help to restrict the type of conflicts with which a driver must deal to those that are the easiest for him to resolve efficiently. However, this study also indicated that modifications in highway design alone may not necessarily increase overall system stability.

## REFERENCES

(1) *Tension Responses of Drivers Generated on Urban Streets,* by R. M. Michaels, Highway Research Board Bulletin 271, 1960, pp. 29–44.

(2) *Characteristics of Passenger-Car Travel on Toll Roads and Comparable Free Roads for Highway User Benefit Studies,* by P. J. Claffey, Public Roads, vol. 31, No. 8, June 1961, pp. 167–176.

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# PAVEMENT RESEARCH

**(Second AASHO Road Test Film)**

The second film produced in connection with the AASHO Road Test, *Pavement Research,* has been released by the Bureau of Public Roads. This 16-mm. color film has a running time of 37 minutes; it shows the tests made on rigid and flexible-type pavements, the rationale for analysis of the data, and the principal test results. As a companion film to *Materials and Construction,* which recorded the Test for the 1956–1958 period, *Pavement Research* summarizes the program for the 1958–1961 period. A short description of the AASHO Road Test and production of these two films appears in Public Roads, vol. 32, No. 3, August 1962, p. 63.

Prints of *Pavement Research,* and of the first film *Materials and Construction,* are available on a loan basis from the Bureau of Public Roads, Photographic Section, 1717 H Street NW., Washington 25, D.C. These prints may be borrowed by any responsible organization. There is no charge other than for express or postage fees. Requests should be submitted well in advance of the desired showing date, and alternate dates should be indicated, if possible. Immediate return is required. Inquiries about purchase of the film or films should be addressed to the Public Roads Photographic Section.

# Passenger Car Fuel-Consumption Rates

*BY THE ECONOMIC RESEARCH DIVISION*
*BUREAU OF PUBLIC ROADS*

**By NATHAN LIEDER,**
**Statistician**

***Information on fuel-consumption rates of passenger cars presented in this article was collected primarily to provide data for the report submitted to Congress as part of the Bureau of Public Roads Highway Cost Allocation Study. The analysis in the article is more detailed than could be prepared for that report.***

***Fuel-consumption rates have many uses, the paramount one being in the forecasting of tax revenues that will be available for highway programs. Fuel-consumption rates also are helpful tools for measuring the use made of highways and for determining the fairness of the tax burdens imposed on different types of vehicles.***

***The findings on passenger-car fuel-consumption rates are expected to be useful to highway administrators and planners and to others requiring information on fuel-consumption rates. These findings reflect the actual, normal daily use of many privately-owned passenger cars rather than reports for test vehicles or for those employed for a few specialized purposes.***

### *Introduction*

FUEL-CONSUMPTION rates enter into estimates for fuel tax contributions of the different classes of motor-vehicles. Estimates of the tax yield have many uses; two may be noted: (1) determination of highway-user tax schedules that rest equitably on the classes of vehicles, and (2) calculation of benefit-cost analyses for highway system segments for which the traffic composition can be postulated. To obtain the best possible measures, past bases for estimating rates of fuel-consumption must be examined, and they must be revised, if need be, to reflect more accurately the changes in vehicles and their use.

The Bureau of Public Roads estimated average motor-vehicle payments to the Highway Trust Fund as part of the Highway Cost Allocation Study required by Section 210 of the Highway Revenue Act of 1956 (*1*).[1] Estimated fuel-consumption rates served as one basis for calculating the average vehicle payments. The rate for passenger cars was based, in part, upon data on the use of privately-owned passenger cars that had been submitted for specified periods between October 1959 and March 1961 by groups of employees of nine State highway departments and the corresponding Division, and some Regional, offices of the Bureau of Public Roads. Because all reports were not available in time to permit a detailed analysis for use in the report to Congress, this article presents an analysis of all the data collected. The findings should be of use to administrators and planners because they reflect the actual, daily use of many privately-owned passengers cars rather than reports for test vehicles or for those employed for a few specialized uses.

### *Summary*

The major findings of this investigation of the rates of motor-fuel consumption reported for a number of privately-owned passenger cars in normal daily use are, as follows.

- Cars in class 0, those having six cylinders including compacts, consumed less gasoline in daily operation than the standard American cars used in the study.
- For any specified vehicle-transmission class, a change of ten percent in mileage driven at speeds of 35 miles per hours or less caused a corresponding change of 0.002 gallon per mile in the fuel-consumption rate—either increase or decrease.
- Year model of the vehicle did not affect the average fuel-consumption rates sufficiently to serve as an efficient factor for use in forecasting gas consumption.

### *Procedure*

As shown in table 1, the nine States participating in this study began the collection of data at different times during the period October 1959 to March 1960, and each State collected reports for four seasons. Most of the States used data from a different group of employees each season; but, Connecticut and Illinois used the data from one slate of employees for all four seasons; and New Mexico used data from two groups, one for the first two seasons and the other for the remaining two seasons.

Each participating employee was given a form on which to record information concerning the vehicle, the mileage driven, and the amount of fuel consumed. Acceptable forms had to contain a record of four or more purchases of gasoline and the first and last purchases had to show a full gas tank. An early edition of the model form distributed for this study contained neither space requiring the reporting of the number of engine cylinders for each car nor the date of each gas purchase. Consequently, California and Arizona did not collect information on the number of cylinders, and most of the States did not ask participants to record the date of each fuel purchase. Any follow-up study should require the reporting of information for these two items.

With the exception of Utah, the States that selected more than one group of employees for the study experienced less seasonal variation in the number of reports received than Connecticut and Illinois, where only one group of employees had been used. The fact that employee participation was completely voluntary, coupled with the possibility that the enthusiasm of the employees waned with time, may have been a factor in the seasonal variation in the number of responses. Change in employment of some employees is thought to have been another factor contributing to the differences in the number of responses from season to season. It may be hypothesized that the first factor was a very influential cause of the variation in seasonal participation in the States that used a single employee group. But, even a one-hundred-percent participation in all States would not guarantee that the reports so faithfully mirrored the vehicle population of a State or the Nation as to permit the use of unweighted data in the estimation of average fuel-consumption rates for all motor-vehicles. Therefore, this article reports unweighted averages and users may supply appropriate weights to suit different situations. However, a set of national averages obtained by special weighting of the reported data is presented in table 10.

### *Factors Studied*

The relationship of fuel-consumption rates to factors of vehicle weight, engine size (horsepower), and transmission type of vehicle, and to season of the year and to stop-and-go driving have been analyzed in earlier studies. The analysis presented here was based upon these factors or related factors, plus vehicle year model. Planners and administrators can find State or national data for such factors in the records of highway

[1] References indicated by italic numbers in parentheses are listed on page 120.

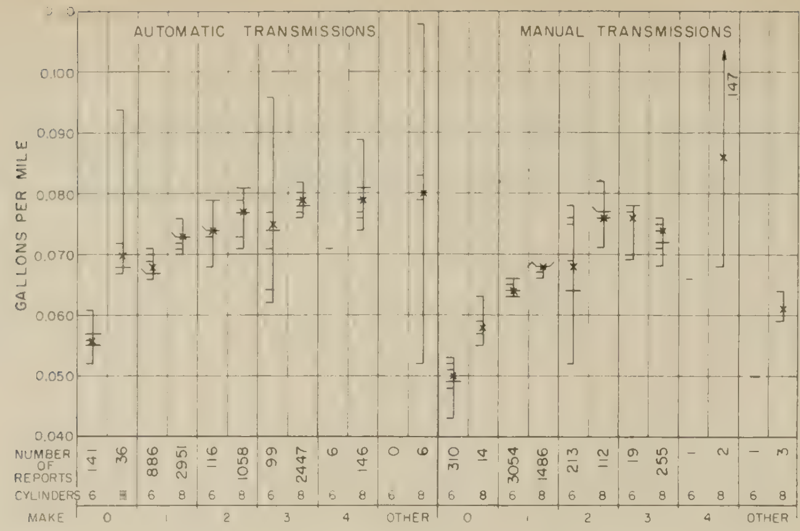


*Figure 1.—Average fuel-consumption rates for vehicles for each reporting State and total number of reports by vehicle make class, transmission type, and number of cylinders: 1960.*

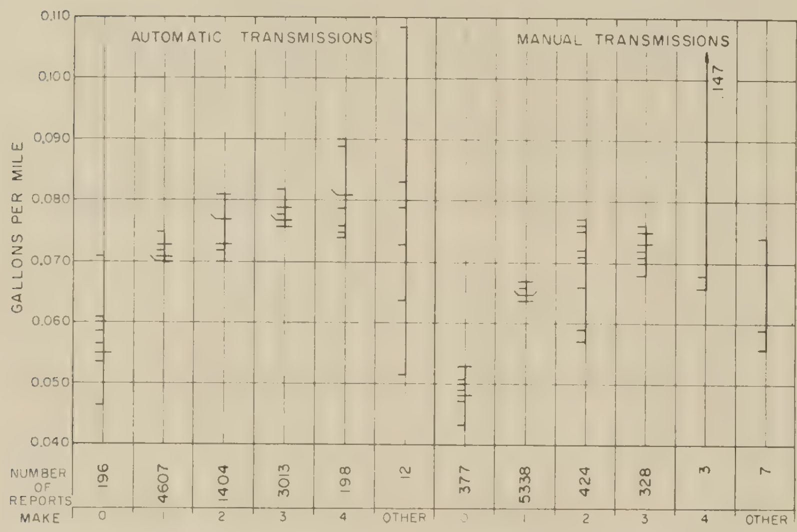


*Figure 2.—Average fuel-consumption rates for vehicles for each reporting State and total number of reports by vehicle make class and transmission type: 1960.*

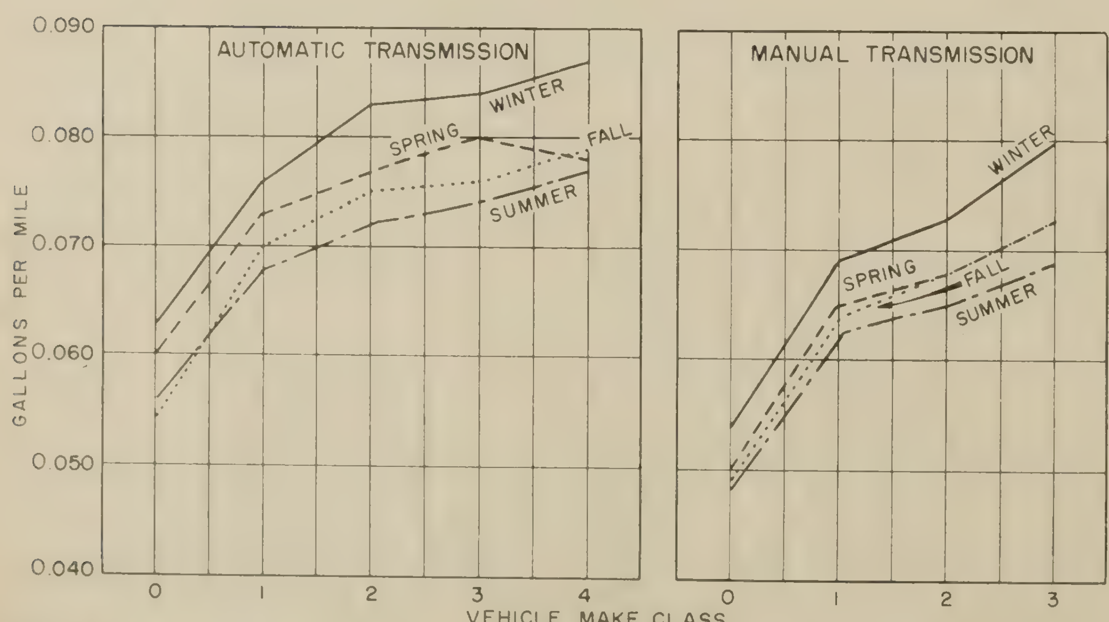


*Figure 3.—Average fuel-consumption rates by season for vehicles in each make class by transmission type: 1960.*

departments, motor-vehicle administrators, automobile manufacturers, and similar sources. Because other analysts concerned with the tax yield from fuel consumption have not found it feasible to collect data for driver habits, quality of vehicle maintenance, and octane rating of gasoline used, no attempt was made to include such factors in this study.

Because it was impracticable to weigh the vehicles for which reports were received, no quantitative relationship between weight and fuel-consumption rates could be established in this investigation. To take weight into account in the analysis, standard American cars were grouped by make into five classes roughly indicative of weight. Some cars that could not be included in any of the other five classes have been grouped in one category, "other." Two considerations were used in making car assignments to a particular class: the number of vehicles registered for each year model of the make, and the estimated empty weight of the four-door sedan judged to be the most popular for each year model. The assignments of the makes of cars to each class are shown in table 2. It is recognized that wide differences in weight may exist within a single make. However, a relatively inexact measure based upon obtainable data should prove acceptable for broad-scale planning, provided it does not mask significant differences in fuel-consumption rates. In this investigation, the rough measures of weight by vehicle class did not seem to obscure marked differences in fuel consumption rates. Few vehicles of foreign make were included in the study; four States did not report the make of foreign vehicles and; therefore, those included were not classified by make.

The number of cylinders for each car was used as a rough measure of its engine size (horsepower). The strength of the relationship was not studied, but it is believed to have been sufficient for the purposes to be served by the analysis. Moreover, the number of cylinders could be reported objectively by all participants, whereas engine size could not.

Data for the factor of stop-and-go driving were based on the memory and judgment of the participants. At the time of each fuel purchase, when the number of gallons of gas purchased and the odometer reading were being recorded, each participant was asked also to record his estimates of either the percentage of mileage or the number of miles that had been driven at speeds of 35 miles per hour or less since the previous gas purchase. A weighted total of this mileage was calculated from each participant's report. Although speeds of 35 miles per hour or less are not always associated with the stop-and-go driving experienced on urban streets, they should be indicative of such driving. Provided that any bias caused by failure in memory or poor judgment of the respondents was small, differences in fuel-consumption rates should be correlated with the differences in the proportions of stop-and-go urban driving.

## ANALYSIS

The States sent either a set of duplicate cards or a listing of coded responses to the Washington, D.C., office of the Bureau of Public Roads. Because a few cards and coded listings were rejected, the totals shown in tables and figures have minor differences from the information transmitted. The following analysis was based upon the resultant deck.

### *Make Class, Transmission Type, and Cylinders*

Average fuel-consumption rates for American cars listed by States submitting reports as to: make class, transmission type, and number of cylinders are shown in tables 3, 4, and 5 and in figures 1 and 2. California and Arizona are not represented in figure 1 because responses from these States did not list the number of cylinders for the cars. The number of observations is the total of all acceptable seasonal reports. For some States, these observations represent the same vehicles for all four seasons; for other States, the observations represent different sets of vehicles and probably a different set of drivers each season. The vertical lines in figures 1 and 2 depict the range of fuel-consumption rates averaged for each State. Each short, horizontal line perpendicular to a vertical line represents the average fuel-consumption rate for the vehicle class for a State. Two States having the same average are represented by short horizontals on either side of the vertical. Each additional State having the same average as two other States is represented by a short appendage to the horizontal. The "x" on each vertical represents the average fuel-consumption rate found in the study for all vehicles of a given classification. The study averages are not necessarily national averages.

Because Illinois collected almost half of the observations, its reports weight the study averages more than those of any other State. Parenthetically, it may be noted that, with one exception, the average fuel-consumption rates found in the Illinois Study are not at either extreme of any of the distributions of State averages. The one exception is in the class of other American cars having eight cylinders and automatic transmissions. The Illinois average for this class is based on two observations.

#### Make class of cars

Several deductions may be drawn from the data shown in tables 3 and 4, and figure 1. Probably the most significant one concerns vehicles in class 0, which contained American compact cars. The average fuel-consumption rates for the cars in class 0 were smaller than the average rates for the other classes of American cars except for the eight-cylinder cars in class 0 that had automatic transmissions. The contrast was more definitely established for the six-cylinder cars than for the eight-cylinder cars in class 0. The low average rate of fuel-consumption for the eight-cylinder cars in class 0 is probably an

**Table 1.—Participating States in each Region, starting period, and number of records tabulated**

| Public Roads Region, and State | Starting period | Number of records tabulated [1] | | | | |
|---|---|---|---|---|---|---|
| | | Spring | Summer | Autumn | Winter | Total |
| Region 1: | | | | | | |
| Connecticut | January 1960 | 85 | 93 | 76 | 149 | 403 |
| Region 3: [1] | | | | | | |
| North Carolina | January 1960 | 190 | 178 | 182 | 207 | 757 |
| Region 4: | | | | | | |
| Illinois | January 1960 | 2,079 | 1,909 | 1,688 | 2,265 | 7,941 |
| Region 5: | | | | | | |
| Kansas | October 1959 | 196 | 182 | 205 | 204 | 787 |
| Region 7: | | | | | | |
| Arizona | January 1960 | 184 | 184 | 208 | 204 | 780 |
| California | January 1960 | 523 | 502 | 481 | 470 | 1,976 |
| Region 8: | | | | | | |
| Oregon | March 1960 | 251 | 219 | 208 | 208 | 886 |
| Region 9: [1] | | | | | | |
| New Mexico | January 1960 | 447 | 409 | 450 | 412 | 1,718 |
| Utah | February 1960 | 341 | 304 | 265 | 277 | 1,187 |
| Total | | 4,296 | 3,980 | 3,763 | 4,396 | 16,435 |

[1] Includes reports submitted by employees of the Regional office of the Bureau of Public Roads, which were not tabulated by the States.

**Table 2.—American-make cars grouped in classes, roughly indicative of weight**

| Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other |
|---|---|---|---|---|---|
| Corvair<br>Crosley<br>Falcon<br>Henry J<br>Lark<br>Rambler<br>Valiant<br>Willys | Chevrolet<br>Ford<br>Plymouth<br>Studebaker | Dodge<br>Hudson<br>Kaiser-Frazer<br>Nash<br>Pontiac | Buick<br>Chrysler<br>DeSoto<br>Edsel<br>Mercury<br>Oldsmobile<br>Packard<br>LaSalle | Cadillac<br>Continental<br>Imperial<br>Lincoln | Corvette<br>Hawk<br>Jeep<br>Thunderbird |

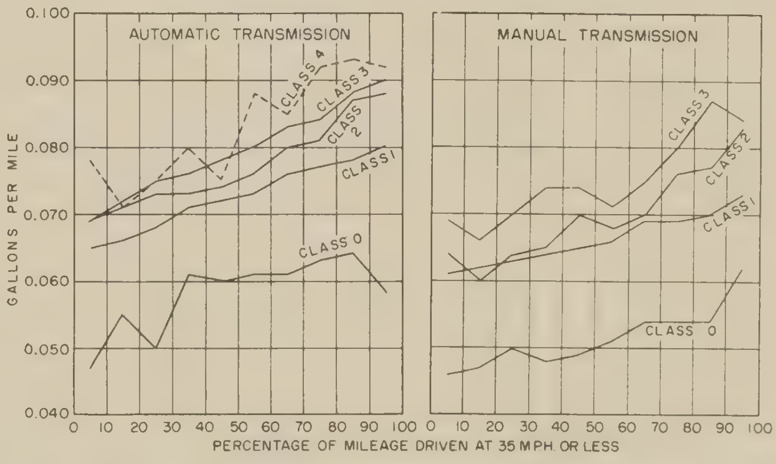


*Figure 4.—Average fuel-consumption rates of American cars by percentage of miles driven at 35 m.p.h. or less for vehicles in each make and transmission class: 1960.*

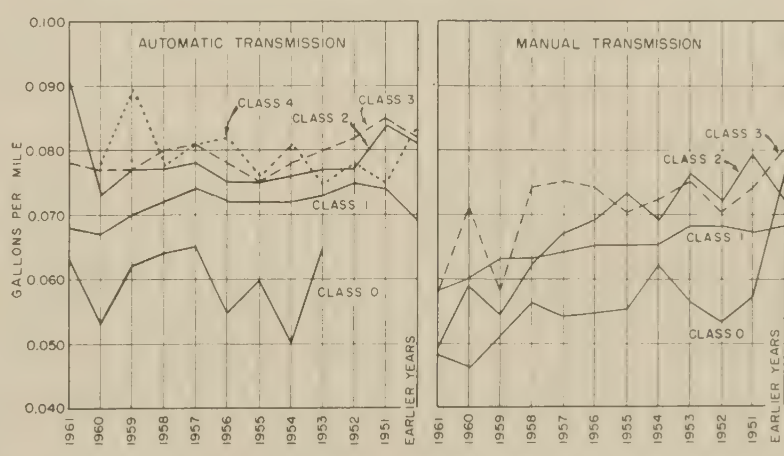


*Figure 5.—Average fuel-consumption rates by year model for vehicles in each make and transmission class: 1960.*

**Table 3.—Data on miles of travel and fuel-consumption rates, gallons per mile, for American cars with automatic transmissions, taken from 1960 reports that listed number of cylinders [1]**

| Location and vehicle make class | Automatic transmission | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6 cylinders | | | 8 cylinders | | | Total | | |
| | Reports | Travel | Fuel | Reports | Travel | Fuel | Reports | Travel | Fuel |
| | *Number* | *Veh.-mi.* | *Gal./miles* | *Number* | *Veh.-mi.* | *Gal./miles* | *Number* | *Veh.-mi.* | *Gal./miles* |
| Connecticut: [2] | | | | | | | | | |
| Class 0 | 2 | 2, 937 | 0. 055 | 0 | 0 | ---- | 2 | 2, 937 | 0. 055 |
| Class 1 | 29 | 34, 076 | . 067 | 86 | 109, 989 | 0. 071 | 115 | 144, 065 | . 070 |
| Class 2 | 3 | 3, 572 | . 068 | 22 | 29, 060 | . 071 | 25 | 32, 632 | . 070 |
| Class 3 | 11 | 11, 789 | . 074 | 65 | 76, 970 | . 080 | 76 | 88, 759 | . 079 |
| Class 4 | 0 | 0 | ---- | 4 | 3, 882 | . 089 | 4 | 3, 882 | . 089 |
| Other | 0 | 0 | ---- | 0 | 0 | ---- | 0 | 0 | ---- |
| All | 45 | 52, 374 | . 068 | 177 | 219, 901 | . 074 | 222 | 272, 275 | . 073 |
| North Carolina: [3] | | | | | | | | | |
| Class 0 | 7 | 12, 609 | . 055 | 0 | 0 | ---- | 7 | 12, 609 | . 055 |
| Class 1 | 50 | 53, 189 | . 067 | 196 | 245, 164 | . 070 | 246 | 298, 353 | . 070 |
| Class 2 | 8 | 6, 631 | . 074 | 59 | 62, 855 | . 073 | 67 | 69, 486 | . 073 |
| Class 3 | 2 | 2, 128 | . 062 | 115 | 131, 953 | . 076 | 117 | 134, 081 | . 076 |
| Class 4 | 0 | 0 | ---- | 8 | 10, 828 | . 076 | 8 | 10, 828 | . 076 |
| Other | 0 | 0 | ---- | 0 | 0 | ---- | 0 | 0 | ---- |
| All | 67 | 74, 557 | . 065 | 378 | 450, 800 | . 072 | 445 | 525, 357 | . 071 |
| Illinois: [3] | | | | | | | | | |
| Class 0 | 88 | 123, 852 | . 056 | 15 | 18, 511 | . 068 | 103 | 142, 363 | . 057 |
| Class 1 | 613 | 697, 568 | . 067 | 1, 672 | 1, 817, 931 | . 073 | 2, 285 | 2, 515, 499 | . 072 |
| Class 2 | 66 | 62, 839 | . 074 | 597 | 658, 998 | . 077 | 663 | 721, 837 | . 077 |
| Class 3 | 58 | 50, 062 | . 077 | 1, 530 | 1, 665, 695 | . 079 | 1, 588 | 1, 715, 757 | . 079 |
| Class 4 | 0 | 0 | ---- | 59 | 70, 628 | . 079 | 59 | 70, 628 | . 079 |
| Other | 0 | 0 | ---- | 2 | 1, 331 | . 108 | 2 | 1, 331 | . 108 |
| All | 825 | 934, 321 | . 067 | 3, 875 | 4, 233, 094 | . 076 | 4, 700 | 5, 167, 415 | . 075 |
| Kansas: [3] | | | | | | | | | |
| Class 0 | 5 | 5, 829 | . 061 | 3 | 2, 474 | . 094 | 8 | 8, 303 | . 071 |
| Class 1 | 55 | 58, 998 | . 069 | 221 | 234, 155 | . 076 | 276 | 293, 153 | . 075 |
| Class 2 | 4 | 4, 388 | . 079 | 62 | 64, 156 | . 081 | 66 | 68, 544 | . 081 |
| Class 3 | 2 | 1, 853 | . 064 | 144 | 153, 834 | . 082 | 146 | 155, 687 | . 082 |
| Class 4 | 0 | 0 | ---- | 10 | 12, 914 | . 074 | 10 | 12, 914 | . 074 |
| Other | 0 | 0 | ---- | 1 | 1, 026 | . 083 | 1 | 1, 026 | . 083 |
| All | 66 | 71, 068 | . 069 | 441 | 468, 559 | . 079 | 507 | 539, 627 | . 078 |
| Oregon: [2] | | | | | | | | | |
| Class 0 | 18 | 25, 894 | . 057 | 3 | 4, 235 | . 072 | 21 | 30, 129 | . 059 |
| Class 1 | 45 | 50, 762 | . 066 | 178 | 206, 248 | . 072 | 223 | 257, 010 | . 071 |
| Class 2 | 19 | 21, 126 | . 073 | 91 | 98, 016 | . 077 | 110 | 119, 142 | . 077 |
| Class 3 | 6 | 6, 041 | . 074 | 118 | 138, 998 | . 078 | 124 | 145, 039 | . 077 |
| Class 4 | 6 | 6, 820 | . 071 | 18 | 20, 494 | . 077 | 24 | 27, 314 | . 075 |
| Other | 0 | 0 | ---- | 0 | 0 | ---- | 0 | 0 | ---- |
| All | 94 | 110, 643 | . 066 | 408 | 467, 991 | . 075 | 502 | 578, 634 | . 073 |
| New Mexico: [2] | | | | | | | | | |
| Class 0 | 12 | 15, 248 | . 057 | 9 | 11, 095 | . 067 | 21 | 26, 343 | . 061 |
| Class 1 | 56 | 61, 274 | . 070 | 331 | 394, 332 | . 073 | 387 | 455, 606 | . 073 |
| Class 2 | 7 | 7, 221 | . 079 | 116 | 120, 583 | . 081 | 123 | 127, 804 | . 081 |
| Class 3 | 6 | 3, 945 | . 096 | 223 | 253, 389 | . 078 | 229 | 257, 334 | . 078 |
| Class 4 | 0 | 0 | ---- | 30 | 35, 741 | . 081 | 30 | 35, 741 | . 081 |
| Other | 0 | 0 | ---- | 2 | 2, 372 | . 079 | 2 | 2, 372 | . 079 |
| All | 81 | 87, 688 | . 070 | 711 | 817, 512 | . 076 | 792 | 905, 200 | . 075 |
| Utah: [3] | | | | | | | | | |
| Class 0 | 8 | 10, 782 | . 052 | 6 | 10, 532 | . 068 | 14 | 21, 314 | . 060 |
| Class 1 | 38 | 40, 613 | . 071 | 267 | 334, 856 | . 073 | 305 | 375, 469 | . 073 |
| Class 2 | 9 | 10, 715 | . 074 | 111 | 124, 805 | . 079 | 120 | 135, 520 | . 077 |
| Class 3 | 14 | 15, 087 | . 071 | 252 | 309, 402 | . 077 | 266 | 324, 489 | . 077 |
| Class 4 | 0 | 0 | ---- | 17 | 18, 915 | . 081 | 17 | 18, 915 | . 081 |
| Other | 0 | 0 | ---- | 1 | 1, 452 | . 052 | 1 | 1, 452 | . 052 |
| All | 69 | 77, 197 | . 069 | 654 | 799, 962 | . 075 | 723 | 877, 159 | . 075 |
| All agencies: | | | | | | | | | |
| Class 0 | 140 | 197, 151 | . 056 | 36 | 46, 847 | . 070 | 176 | 243, 998 | . 059 |
| Class 1 | 886 | 996, 480 | . 068 | 2, 951 | 3, 342, 675 | . 073 | 3, 837 | 4, 339, 155 | . 072 |
| Class 2 | 116 | 116, 492 | . 074 | 1, 058 | 1, 158, 473 | . 077 | 1, 174 | 1, 274, 965 | . 077 |
| Class 3 | 99 | 90, 905 | . 075 | 2, 447 | 2, 730, 241 | . 079 | 2, 546 | 2, 821, 146 | . 079 |
| Class 4 | 6 | 6, 820 | 071 | 146 | 173, 402 | . 079 | 152 | 180, 222 | . 079 |
| Other | 0 | 0 | ---- | 6 | 6, 181 | . 080 | 6 | 6, 181 | . 080 |
| All | 1, 247 | 1, 407, 848 | . 067 | 6, 644 | 7, 457, 819 | . 076 | 7, 891 | 8, 865, 667 | . 075 |

[1] Nineteen observations for 4-cylinder Willys are excluded from the tabulations.
[2] Includes reports from employees of Division Office of Bureau of Public Roads and State highway employees.
[3] Includes reports from employees of both the Division and Regional Offices of the Bureau of Public Roads and State highway employees.

unreliable estimate based upon too small a sample of the vehicles in this category. However, the differential in fuel-consumption rates points up the advantage of considering vehicle distributions by various characteristics that influence fuel-consumption before making estimates of the gallons of fuel to be consumed in highway use.

**Transmission type**

For all classes of cars, this study confirmed that the type of transmission and engine size as measured by number of cylinders have an effect on fuel-consumption rates. With the exception of class 0 vehicles, the effect of the type of transmission for cars in every day use seems to have been more marked than the effect of the number of cylinders. Therefore, computation of fuel-consumption rates in which the number of cylinders is not considered should yield estimates acceptable for many purposes. Furthermore, by ignoring the effect of the number of cylinders, the data received from California and Arizona could be included in the computations for a unified analysis. In figure 2, State averages are shown but no differentiation by transmission type has been made, as in figure 1.

**Differences in rates among States**

Differences in average fuel-consumption rates among States for any given class of car were related to the number of observations and decreased with a large number of observations. This was demonstrated most markedly by the data received for class 1 vehicles. The decrease in the differences of average fuel-consumption rates among the States studied indicated that the average rate of fuel-consumption in a vehicle weight class for any State approaches that of the other States without regard to their geographical location. It is possible that this similarity of fuel-consumption rates would not be maintained in mountainous areas or at high altitudes as fuel-consumption rates have been directly related to changes in altitude. Although this study was not designed to provide information on the relative importance of this factor reports of several other studies have shown that altitude does affect the rate of fuel-consumption (*2*).

## *Miles Per Gallon*

Because the data in this article are expected to be used for purposes requiring fuel-consumption rates to be weighted by miles of travel, the data have been expressed as gallons per mile. However, many readers of this article and perhaps many of the prospective users of the data are more familiar with rates expressed as miles per gallon. Table 6 therefore, contains fuel-consumption rates expressed as miles per gallon that correspond to the gallon-per-mile rates calculated from the reports received from all participants for each of the six classes of American cars, as shown in table 5.

## *Seasonal Variation*

Data shown in table 7 and figure 3 confirmed that fuel-consumption rates vary in relation to the season of the year. Rates at either extreme were reported for summer and winter. The smallest rates were reported for summer and the largest rates were reported for the winter season. Spring and fall reports indicated intermediate rates of fuel-consumption which generally were near the annual average. The rates given in table 7 may be used with forecasts of seasonal travel to produce somewhat more refined forecasts of total fuel to be consumed than can be produced without a consideration of the seasonal differences in consumption.

## *Stop-and-Go Driving*

For each transmission type within each make class, the rate of fuel consumption tended to vary directly as the proportion of stop-and-go driving changed, as measured by the percentage of driving speeds reported as not exceeding 35 m.p.h. Data in table 8 and figure 4 illustrate this relationship. The jagged progression of data for class 0 and

**Table 4.—Data on miles of travel and fuel-consumption rates, gallons per mile, for American cars with manual transmissions, taken from 1960 reports that listed number of cylinders [1]**

| Location and vehicle make class | Manual transmission | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 6 cylinders | | | 8 cylinders | | | Total | | |
| | Reports | Travel | Fuel | Reports | Travel | Fuel | Reports | Travel | Fuel |
| | *Number* | *Veh.-mi.* | *Gal./miles* | *Number* | *Veh.-mi.* | *Gal./miles* | *Number* | *Veh.-mi.* | *Gal./miles* |
| Connecticut: [2] | | | | | | | | | |
| Class 0 | 6 | 11,211 | 0.048 | 0 | 0 | ------ | 6 | 11,211 | 0.048 |
| Class 1 | 88 | 112,325 | .063 | 25 | 31,221 | 0.067 | 113 | 143,546 | .064 |
| Class 2 | 12 | 19,976 | .052 | 4 | 4,329 | .077 | 16 | 24,305 | .057 |
| Class 3 | 0 | 0 | ------ | 10 | 13,136 | .068 | 10 | 13,136 | .068 |
| Class 4 | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| Other | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| All | 106 | 143,512 | .060 | 39 | 48,686 | .068 | 145 | 192,198 | .062 |
| North Carolina: [3] | | | | | | | | | |
| Class 0 | 13 | 19,479 | .043 | 0 | 0 | ------ | 13 | 19,479 | .043 |
| Class 1 | 181 | 215,585 | .064 | 116 | 131,667 | .068 | 297 | 347,252 | .065 |
| Class 2 | 13 | 8,032 | .076 | 6 | 6,790 | .077 | 19 | 14,822 | .076 |
| Class 3 | 2 | 1,530 | .069 | 28 | 31,644 | .072 | 30 | 33,174 | .072 |
| Class 4 | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| Other | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| All | 209 | 244,626 | .063 | 150 | 170,101 | .069 | 359 | 414,727 | .065 |
| Illinois: [3] | | | | | | | | | |
| Class 0 | 159 | 232,473 | .049 | 4 | 5,151 | .063 | 163 | 237,624 | .050 |
| Class 1 | 1,819 | 2,030,607 | .064 | 774 | 864,000 | .068 | 2,593 | 2,894,607 | .065 |
| Class 2 | 124 | 126,410 | .069 | 60 | 68,005 | .076 | 184 | 194,415 | .072 |
| Class 3 | 7 | 4,838 | .077 | 128 | 135,654 | .076 | 135 | 140,492 | .076 |
| Class 4 | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| Other | 1 | 1,767 | .050 | 1 | 1,273 | .064 | 2 | 3,040 | .056 |
| All | 2,110 | 2,396,095 | .063 | 967 | 1,074,083 | .069 | 3,077 | 3,470,178 | .065 |
| Kansas: [3] | | | | | | | | | |
| Class 0 | 14 | 16,007 | .053 | 1 | 1,481 | .059 | 15 | 17,488 | .053 |
| Class 1 | 148 | 157,402 | .066 | 77 | 86,648 | .068 | 225 | 244,050 | .067 |
| Class 2 | 8 | 8,894 | .064 | 6 | 5,149 | .082 | 14 | 14,043 | .070 |
| Class 3 | 1 | 1,010 | .078 | 7 | 9,111 | .071 | 8 | 10,121 | .071 |
| Class 4 | 0 | 0 | ------ | 1 | 1,474 | .068 | 1 | 1,474 | .068 |
| Other | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| All | 171 | 183,313 | .065 | 92 | 103,863 | .069 | 263 | 287,176 | .066 |
| Oregon: [2] | | | | | | | | | |
| Class 0 | 35 | 58,625 | .049 | 0 | 0 | ------ | 35 | 58,625 | .049 |
| Class 1 | 186 | 226,029 | .063 | 81 | 100,601 | .066 | 267 | 326,630 | .064 |
| Class 2 | 10 | 10,209 | .078 | 6 | 5,812 | .077 | 16 | 16,021 | .077 |
| Class 3 | 2 | 2,483 | .070 | 17 | 18,304 | .074 | 19 | 20,787 | .073 |
| Class 4 | 1 | 1,132 | .066 | 0 | 0 | ------ | 1 | 1,132 | .066 |
| Other | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| All | 234 | 298,478 | .061 | 104 | 124,717 | .067 | 338 | 423,195 | .063 |
| New Mexico: [2] | | | | | | | | | |
| Class 0 | 48 | 64,579 | .052 | 5 | 6,625 | .057 | 53 | 71,204 | .053 |
| Class 1 | 442 | 477,937 | .066 | 278 | 323,252 | .068 | 720 | 801,189 | .067 |
| Class 2 | 24 | 20,600 | .075 | 19 | 22,960 | .076 | 43 | 43,560 | .075 |
| Class 3 | 7 | 5,418 | .078 | 41 | 48,411 | .072 | 48 | 53,829 | .073 |
| Class 4 | 0 | 0 | ------ | 1 | 433 | .147 | 1 | 433 | .147 |
| Other | 0 | 0 | ------ | 2 | 2,099 | .059 | 2 | 2,099 | .059 |
| All | 521 | 568,534 | .065 | 346 | 403,780 | .069 | 867 | 972,314 | .067 |
| Utah: [3] | | | | | | | | | |
| Class 0 | 35 | 52,172 | .051 | 4 | 9,880 | .055 | 39 | 62,052 | .051 |
| Class 1 | 189 | 229,214 | .065 | 134 | 160,690 | .068 | 323 | 389,904 | .066 |
| Class 2 | 22 | 28,434 | .064 | 11 | 13,382 | .071 | 33 | 41,816 | .066 |
| Class 3 | 0 | 0 | ------ | 24 | 27,092 | .075 | 24 | 27,092 | .075 |
| Class 4 | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| Other | 0 | 0 | ------ | 0 | 0 | ------ | 0 | 0 | ----- |
| All | 246 | 309,820 | .062 | 173 | 211,044 | .068 | 419 | 520,864 | .065 |
| All agencies: | | | | | | | | | |
| Class 0 | 310 | 454,546 | .050 | 14 | 23,137 | .058 | 324 | 477,683 | .050 |
| Class 1 | 3,053 | 3,449,099 | .064 | 1,485 | 1,698,079 | .068 | 4,538 | 5,147,178 | .065 |
| Class 2 | 213 | 222,555 | .068 | 112 | 126,427 | .076 | 325 | 348,982 | .071 |
| Class 3 | 19 | 15,279 | .076 | 255 | 283,352 | .074 | 274 | 298,631 | .074 |
| Class 4 | 1 | 1,132 | .066 | 2 | 1,907 | .086 | 3 | 3,039 | .079 |
| Other | 1 | 1,767 | .050 | 3 | 3,372 | .061 | 4 | 5,139 | .057 |
| All | 3,597 | 4,144,378 | .063 | 1,871 | 2,136,274 | .069 | 5,468 | 6,280,652 | .065 |

[1] Nineteen observations for 4-cylinder Willys are excluded from the tabulation.
[2] Includes reports from employees of Division Office of Bureau of Public Roads and State highway employees.
[3] Includes reports from employees of both the Division and Regional Offices of the Bureau of Public Roads and State highway employees.

class 4 cars having automatic transmissions are probably the result of an insufficient number of sample cases.

### Hypothesis

A hypothesis may be put forth that, if transmission type and vehicle class are held constant, a linear relationship exists between fuel-consumption rates and the percentage of driving at speeds not exceeding 35 miles per hour, and that these lines are parallel within a transmission type. However, instead of fitting a straight line for each vehicle class, the data for classes 1, 2, and 3 were averaged. Under the hypothesis, these averages for the combined classes represent points on a line that is parallel to the lines for the separate classes. A straight line was fitted by the method of least squares to the combined class averages. The slope for automatic transmissions was 0.00020; the slope for manual transmissions was 0.00017. Both slopes differed from zero by a significant amount, as determined by the "t" test. The slope indicated that for every increase of 10 percent in mileage of stop-and-go driving, the rate of fuel consumption increased approximately 0.002 of a gallon per mile when transmission and vehicle class were held constant. The lowest rate of fuel consumption per mile of travel should be realized when stop-and-go driving is reduced to zero. However, the absence of stop-and-go driving is often accompanied by an increase in speed that tends to negate the benefit of uninterrupted driving, and some indications (*3*) have been noted that fuel-consumption rates increase when vehicle speeds pass a critical point. This factor may be very important in an analysis of fuel-consumption requirements for travel on some sections of highway.

## *Year Model*

The age of vehicles as indicated by the year of the model also was considered as a factor that affects fuel-consumption rates. Annual data are available on the registered number of passenger cars classified by year model and on the number of vehicles manufactured and sold. Such data can be obtained from manufacturers, trade associations, and official registration records. It had been hoped that the age of the vehicles could provide another factor for use in estimating fuel-consumption, but a sufficiently pronounced relationship was not established in this study. Table 9 and figure 5 contain information that shows the year model of vehicles to have little noticeable effect on fuel-consumption rates when large numbers of vehicles in normal operation are considered.

## *Foreign Cars*

Reports received for foreign cars totaled 522. Of these, 162 reports did not include the number of cylinders; 341 reports represented 4-cylinder cars; 17 reports represented 6-cylinder cars; 2 reports represented 8-cylinder cars. The fuel consumption rate of foreign cars classified as "cylinder unknown" was calculated at 0.037 gallon per mile; the same rate determined for foreign cars having 4 cylinders. Therefore, most of the cars in the cylinders unknown class reasonably may be assumed to have been 4-cylinder vehicles. The average fuel-consumption rate for the 6-cylinder foreign cars was 0.058 gallon per mile; and for the 8-cylinder cars, it was 0.079 gallon per mile. Because only two reports represented foreign cars having automatic transmissions, that factor was not related to fuel-consumption rates for this group of vehicles.

## *Application of Study Data*

One possible application of the fuel-consumption rates determined from this study is illustrated in table 10. All the entries for vehicles and mileage in this table are estimates that had been prepared by the Highway Cost Allocation Study staff of the Bureau of Public Roads.

Table 5.—Data on miles of travel and fuel-consumption rates, gallons per mile, for American cars taken from 1960 reports that did not list number of cylinders

| Location and vehicle make class | Automatic transmissions | | | Manual transmissions | | |
|---|---|---|---|---|---|---|
| | Reports | Travel | Fuel | Reports | Travel | Fuel |
| | *Number* | *Veh.-mi.* | *Gal./mi.* | *Number* | *Veh.-mi.* | *Gal./mi.* |
| Arizona: [1] | | | | | | |
| Class 0 | 9 | 9, 550 | 0. 054 | 25 | 34, 659 | 0. 047 |
| Class 1 | 200 | 216, 656 | . 070 | 242 | 274, 135 | . 065 |
| Class 2 | 57 | 66, 681 | . 072 | 22 | 21, 355 | . 071 |
| Class 3 | 141 | 157, 937 | . 076 | 18 | 20, 623 | . 070 |
| Class 4 | 10 | 12, 117 | . 090 | 0 | 0 | ------ |
| Other | 1 | 2, 228 | . 064 | 0 | 0 | ------ |
| All | 418 | 465, 169 | . 073 | 307 | 350, 772 | . 064 |
| California: [1] | | | | | | |
| Class 0 | 11 | 14, 578 | . 047 | 28 | 34, 319 | . 048 |
| Class 1 | 570 | 683, 978 | . 071 | 558 | 677, 128 | . 065 |
| Class 2 | 173 | 220, 816 | . 073 | 77 | 104, 046 | . 059 |
| Class 3 | 326 | 403, 316 | . 077 | 36 | 41, 660 | . 075 |
| Class 4 | 36 | 46, 188 | . 081 | 0 | 0 | ------ |
| Other | 5 | 5, 139 | . 073 | 3 | 4, 510 | . 074 |
| All | 1, 121 | 1, 374, 015 | . 073 | 702 | 861, 663 | . 064 |
| All agencies: [2] | | | | | | |
| Class 0 | 196 | 268, 126 | . 058 | 377 | 546, 661 | . 050 |
| Class 1 | 4, 607 | 5, 239, 789 | . 072 | 5, 338 | 6, 098, 441 | . 065 |
| Class 2 | 1, 404 | 1, 562, 462 | . 076 | 424 | 474, 383 | . 068 |
| Class 3 | 3, 013 | 3, 382, 399 | . 079 | 328 | 360, 914 | . 074 |
| Class 4 | 198 | 238, 527 | . 080 | 3 | 3, 039 | . 079 |
| Other | 12 | 13, 548 | . 075 | 7 | 9, 649 | . 065 |
| All | 9, 430 | 10, 704, 851 | . 074 | 6, 477 | 7, 493, 087 | . 065 |

[1] Includes reports from employees of the Division Office of the Bureau of Public Roads and State highway employees.
[2] The totals shown here for all agencies include the totals from tables 3 and 4.

Table 6.—Fuel-consumption rates in gallons per mile computed as miles per gallon, from 1960 reports for American cars

| Vehicle make class | Automatic transmission | | Manual transmission | |
|---|---|---|---|---|
| | *Gallons* [1] *per mile* | *Miles per gallon* | *Gallons* [1] *per mile* | *Miles per gallon* |
| 0 | 0. 058 | 17. 3 | 0. 050 | 20. 1 |
| 1 | . 072 | 14. 0 | . 065 | 15. 3 |
| 2 | . 076 | 13. 1 | . 068 | 14. 7 |
| 3 | . 079 | 12. 7 | . 074 | 13. 5 |
| 4 | . 080 | 12. 5 | . 079 | 12. 7 |
| Other | . 075 | 13. 4 | . 065 | 15. 4 |
| All | . 074 | 13. 5 | . 065 | 15. 5 |

[1] Data are the same shown in table 5 for all agencies.

Table 7.—Fuel-consumption rates for American cars, classified by make and transmission class, related to number [1] of reports received and the season of the year: 1960

| Season | Fuel-consumption rates | | | | | | Number of reports | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other |
| AUTOMATIC TRANSMISSION | | | | | | | | | | | | |
| | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | | | | | | |
| Spring | 0. 060 | 0. 073 | 0. 077 | 0. 080 | 0. 078 | 0. 076 | 42 | 1, 183 | 383 | 789 | 58 | 3 |
| Summer | . 056 | . 068 | . 072 | . 074 | . 077 | . 072 | 59 | 1, 135 | 339 | 733 | 55 | 5 |
| Fall | . 054 | . 070 | . 075 | . 076 | . 079 | ------ | 53 | 1, 076 | 325 | 671 | 38 | 0 |
| Winter | . 063 | . 076 | . 083 | . 084 | . 087 | . 077 | 42 | 1, 213 | 357 | 820 | 47 | 4 |
| All | . 058 | . 072 | . 076 | . 079 | . 080 | . 075 | 196 | 4, 607 | 1, 404 | 3, 013 | 198 | 12 |
| MANUAL TRANSMISSION | | | | | | | | | | | | |
| Spring | 0. 050 | 0. 065 | 0. 068 | 0. 073 | ------ | ------ | 95 | 1, 422 | 114 | 104 | 0 | 0 |
| Summer | . 048 | . 062 | . 065 | . 069 | . 068 | . 067 | 95 | 1, 222 | 100 | 72 | 1 | 3 |
| Fall | . 049 | . 064 | . 068 | . 073 | ------ | . 079 | 108 | 1, 192 | 109 | 62 | 0 | 1 |
| Winter | . 054 | . 069 | . 073 | . 080 | . 088 | . 060 | 79 | 1, 502 | 101 | 90 | 2 | 3 |
| All | . 050 | . 065 | . 068 | . 074 | . 079 | . 065 | 377 | 5, 338 | 424 | 328 | 3 | 7 |

[1] Nineteen observations for 4-cylinder Willys are excluded from the tabulations.

**Table 8.—Number[1] of reports and fuel-consumption rates for American cars related to percentage of mileage driven at speeds of 35 m.p.h. or less: 1960**

| Mileage driven at speeds of 35 m.p.h. or less | Fuel-consumption rates | | | | | | Number of reports | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other |
| AUTOMATIC TRANSMISSION | | | | | | | | | | | | |
| *Percent* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | | | | | | |
| 0.0–9.9 | 0.047 | 0.065 | 0.069 | 0.069 | 0.078 | 0.066 | 9 | 250 | 76 | 184 | 17 | 2 |
| 10.0–19.9 | .055 | .066 | .071 | .072 | .071 | ---- | 28 | 679 | 174 | 401 | 36 | ---- |
| 20.0–29.9 | .050 | .068 | .073 | .075 | .075 | .052 | 21 | 642 | 194 | 391 | 36 | 1 |
| 30.0–39.9 | .061 | .071 | .073 | .076 | .080 | .078 | 20 | 551 | 167 | 361 | 26 | 2 |
| 40.0–49.9 | .060 | .072 | .074 | .078 | .075 | .080 | 25 | 516 | 135 | 328 | 15 | 2 |
| 50.0–59.9 | .061 | .073 | .076 | .080 | .088 | ---- | 38 | 553 | 163 | 332 | 16 | ---- |
| 60.0–69.9 | .061 | .076 | .080 | .083 | .085 | ---- | 16 | 336 | 99 | 270 | 18 | ---- |
| 70.0–79.9 | .063 | .077 | .081 | .084 | .092 | .076 | 10 | 298 | 122 | 197 | 10 | 2 |
| 80.0–89.9 | .064 | .078 | .087 | .088 | .093 | .114 | 11 | 283 | 91 | 193 | 9 | 1 |
| 90.0–100.0 | .058 | .080 | .088 | .090 | .092 | .074 | 18 | 499 | 183 | 356 | 15 | 2 |
| All | .058 | .072 | .076 | .079 | .080 | .075 | 196 | 4,607 | 1,404 | 3,013 | 198 | 12 |
| MANUAL TRANSMISSION | | | | | | | | | | | | |
| 0.0–9.9 | 0.046 | 0.061 | 0.064 | 0.069 | ---- | ---- | 38 | 374 | 18 | 23 | ---- | ---- |
| 10.0–19.9 | .047 | .062 | .060 | .066 | .066 | ---- | 70 | 962 | 60 | 34 | 1 | ---- |
| 20.0–29.9 | .049 | .063 | .064 | .070 | .067 | 0.067 | 56 | 701 | 63 | 36 | 1 | 1 |
| 30.0–39.9 | .048 | .064 | .065 | .074 | ---- | .048 | 31 | 647 | 40 | 39 | ---- | 1 |
| 40.0–49.9 | .049 | .065 | .070 | .074 | ---- | .050 | 25 | 484 | 55 | 31 | ---- | 1 |
| 50.0–59.9 | .051 | .066 | .068 | .071 | ---- | ---- | 50 | 599 | 41 | 42 | ---- | 1 |
| 60.0–69.9 | .053 | .069 | .070 | .075 | ---- | ---- | 30 | 353 | 37 | 28 | ---- | ---- |
| 70.0–79.9 | .054 | .069 | .076 | .080 | ---- | .068 | 26 | 336 | 30 | 16 | ---- | 1 |
| 80.0–89.9 | .054 | .070 | .077 | .087 | ---- | .070 | 19 | 297 | 20 | 17 | ---- | 2 |
| 90.0–100.0 | .059 | .073 | .083 | .084 | .147 | .088 | 32 | 585 | 60 | 62 | 1 | 1 |
| All | .050 | .065 | .068 | .074 | .079 | .065 | 377 | 5,338 | 424 | 328 | 3 | 7 |

[1] Nineteen observations for 4-cylinder Willys are excluded from the tabulations.

**Table 9.—Number[1] of reports and average fuel-consumption rates for American cars, classified by vehicle make, transmission class, and year model: 1960**

| Year model | Fuel-consumption rates | | | | | | Number of reports | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other | Class 0 | Class 1 | Class 2 | Class 3 | Class 4 | Other |
| AUTOMATIC TRANSMISSION | | | | | | | | | | | | |
| | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | *Gal./mi.* | | | | | | |
| 1961 | 0.063 | 0.068 | 0.091 | 0.078 | ---- | ---- | 4 | 4 | 2 | 3 | ---- | ---- |
| 1960 | .053 | .067 | .073 | .077 | 0.078 | ---- | 95 | 278 | 104 | 138 | 6 | ---- |
| 1959 | .062 | .070 | .077 | .077 | .090 | 0.069 | 43 | 723 | 161 | 309 | 12 | 4 |
| 1958 | .064 | .072 | .077 | .080 | .078 | .082 | 11 | 744 | 115 | 256 | 8 | 3 |
| 1957 | .065 | .074 | .078 | .081 | .081 | .059 | 22 | 956 | 201 | 419 | 25 | 2 |
| 1956 | .055 | .072 | .075 | .078 | .082 | .064 | 6 | 687 | 162 | 446 | 37 | 1 |
| 1955 | .060 | .072 | .075 | .075 | .076 | .108 | 9 | 579 | 259 | 569 | 20 | 2 |
| 1954 | .050 | .072 | .076 | .078 | .081 | ---- | 1 | 277 | 101 | 262 | 9 | ---- |
| 1953 | .065 | .073 | .077 | .080 | .075 | ---- | 5 | 210 | 141 | 218 | 29 | ---- |
| 1952 | ---- | .075 | .077 | .082 | .078 | ---- | ---- | 69 | 50 | 136 | 16 | ---- |
| 1951 | ---- | .074 | .084 | .085 | .075 | ---- | ---- | 63 | 37 | 96 | 12 | ---- |
| Older than 1951 | ---- | .069 | .081 | .082 | .084 | ---- | ---- | 17 | 71 | 161 | 24 | ---- |
| All | .058 | .072 | .076 | .079 | .080 | .075 | 196 | 4,607 | 1,404 | 3,013 | 198 | 12 |
| MANUAL TRANSMISSION | | | | | | | | | | | | |
| 1961 | 0.048 | 0.058 | 0.049 | 0.057 | ---- | ---- | 1 | 7 | 2 | 3 | ---- | ---- |
| 1960 | .046 | .060 | .059 | .071 | ---- | 0.068 | 196 | 234 | 30 | 10 | ---- | 1 |
| 1959 | .051 | .063 | .054 | .058 | ---- | .061 | 89 | 464 | 42 | 6 | ---- | 3 |
| 1958 | .056 | .063 | .062 | .074 | ---- | ---- | 32 | 396 | 10 | 7 | ---- | ---- |
| 1957 | .054 | .064 | .067 | .075 | ---- | .068 | 20 | 584 | 11 | 9 | ---- | 1 |
| 1956 | ---- | .065 | .069 | .074 | ---- | ---- | ---- | 594 | 22 | 24 | ---- | ---- |
| 1955 | .055 | .065 | .073 | .070 | ---- | ---- | 8 | 742 | 49 | 36 | ---- | ---- |
| 1954 | .062 | .065 | .069 | .072 | ---- | ---- | 6 | 509 | 48 | 38 | ---- | ---- |
| 1953 | .056 | .068 | .076 | .075 | .068 | ---- | 9 | 630 | 78 | 65 | 1 | ---- |
| 1952 | .053 | .068 | .072 | .070 | ---- | ---- | 4 | 306 | 27 | 19 | ---- | ---- |
| 1951 | .058 | .067 | .079 | .074 | .066 | .066 | 7 | 240 | 29 | 26 | 1 | 2 |
| Older than 1951 | .078 | .068 | .072 | .080 | .147 | ---- | 5 | 632 | 76 | 85 | 1 | ---- |
| All | .050 | .065 | .068 | .074 | .079 | .065 | 377 | 5,338 | 424 | 328 | 3 | 7 |

[1] Nineteen observations for 4-cylinder Willys are excluded from the tabulations.

Table 10.—Estimated fuel-consumption data and fuel-tax yield for passenger cars in United States for calendar 1960

| Make class [1] | Number of vehicles | Vehicle-miles (at 9,600 miles per vehicle) | Gallons per mile | Gallons of gasoline | Fuel-tax yield at four cents a gallon (dollars) |
|---|---|---|---|---|---|
| AUTOMATIC TRANSMISSION | | | | | |
| Class 0 | 1,417,710 | 13,610,016,000 | 0.058 | 789,380,900 | 31,575,236 |
| Classes 1 and 5 | 19,199,630 | 184,316,448,000 | .072 | 13,270,784,300 | 530,831,372 |
| Class 2 | 7,323,744 | 70,307,942,400 | .076 | 5,343,403,600 | 213,736,144 |
| Class 3 | 11,634,682 | 111,692,947,200 | .079 | 8,823,742,800 | 352,949,712 |
| Class 4 | 1,474,140 | 14,151,744,000 | .080 | 1,132,139,500 | 45,285,580 |
| Foreign | ---------- | ---------------- | ------ | ---------------- | ---------------- |
| Total | 41,049,906 | 394,079,097,600 | .075 | 29,359,451,100 | 1,174,378,044 |
| MANUAL TRANSMISSION | | | | | |
| Class 0 | 2,126,565 | 20,415,024,000 | 0.050 | 1,020,751,200 | 40,830,048 |
| Classes 1 and 5 | 12,799,754 | 122,877,638,400 | .065 | 7,987,046,500 | 319,481,860 |
| Class 2 | 1,830,936 | 17,576,985,600 | .068 | 1,195,235,000 | 47,809,400 |
| Class 3 | 1,292,742 | 12,410,323,200 | .074 | 918,363,900 | 36,734,556 |
| Class 4 | 163,793 | 1,572,412,800 | .079 | 124,220,600 | 4,968,824 |
| Foreign | 2,166,898 | 20,802,220,800 | .037 | 769,682,200 | 30,787,288 |
| Total | 20,380,688 | 195,654,604,800 | .061 | 12,015,299,400 | 480,611,976 |
| AUTOMATIC AND MANUAL TRANSMISSIONS | | | | | |
| Class 0 | 3,544,275 | 34,025,040,000 | 0.053 | 1,810,132,100 | 72,405,284 |
| Classes 1 and 5 | 31,999,384 | 307,194,086,400 | .069 | 21,257,830,800 | 850,313,232 |
| Class 2 | 9,154,680 | 87,884,928,000 | .074 | 6,538,638,600 | 261,545,544 |
| Class 3 | 12,927,424 | 124,103,270,400 | 078 | 9,742,106,700 | 389,684,268 |
| Class 4 | 1,637,933 | 15,724,156,800 | .080 | 1,256,360,100 | 50,254,404 |
| Foreign | 2,166,898 | 20,802,220,800 | .037 | 769,682,200 | 30,787,288 |
| Total | 61,430,594 | 589,733,702,400 | .070 | 41,374,750,500 | 1,654,990,020 |

[1] Other class American cars have been included in class 5 figures.

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