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IN THIS ISSUE

3 articles on Dual-Drum Pavers:

A Study of 34–E Dual-Drum Pavers 1

Dual-Drum Paver Productivity: A Motion Picture 10

How a Dual-Drum Paver Operates 11

Dual-Drum Paving: Cost vs. Mixing Time . 12

2 articles on Time and Fuel Consumption:

Time and Fuel Consumption for Highway-User Benefit Studies 16

Fuel and Time Consumption Rates for Trucks in Freight Service 22

New Publication: Highway Progress, 1959 . . . 32

Errata 32

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A Study of 34-E Dual-Drum Pavers

Y THE DIVISION OF PHYSICAL RESEARCH
UREAU OF PUBLIC ROADS

Reported [1] by DONALD O. WOOLF,
Highway Physical Research Engineer

This article summarizes data obtained in studies of the mixing of portland cement ıcrete in 34–E dual-drum pavers, concted by 13 State highway departments. terminations were made of the desirable ıe of mixing and the amount of overload ich could be permitted. The results inated that the highest strengths were ained at a 60-second mixing time, exclue of transfer time, and that an overload 10 or 20 percent could be tolerated. It s also found that very little loss in ength of the concrete resulted when the xing time was reduced to 40 seconds, lusive of transfer time, but when the xing time was reduced to 30 seconds a loss strength of 5 to 6 percent occurred. A xing time of more than 60 seconds, excluе of transfer time, was found to be undeıble since it involved waste of effort and ulted in loss of strength without gain in uniformity of the concrete.

N December 1957, the Bureau of Public Roads suggested that a study of the pro:tion of portland cement concrete in 34–E ıl-drum pavers be made by interested te highway departments, to determine the st desirable mixing time and the permissible rload, if any. State highway specifications wed that, exclusive of the transfer time rered to move the concrete from the first to second drum, some States permitted a mix- time of as little as 50 seconds, while other tes required mixing times of as much as up 20 seconds. Some State specifications perted no overload, but others allowed overls of from 10 to 20 percent. It was believed t factual information on the effect of ing time and of amount of overload might mit the more rapid production of concrete hout reduction in quality. Lower cost of concrete in place should then be obtained.

'he program proposed by the Bureau of ›lic Roads suggested that mixing times of 60, and 90 seconds, exclusive of transfer e, be used. Since most States used a ing time of about 60 seconds, this was ən as a standard of comparison. The 30-ınd time was suggested as part of the gram to provide concrete which might sibly be undermixed; the 90-second time intended to determine if extended mixing concrete would abrade the aggregate to ı an extent that excessive fines would be luced, causing the strength of the concrete uffer. The States were informed, however, that these times could be changed to suit their particular interests, if they so desired.

As proposed in the program, many States used an overload of 10 percent in their studies, and in some cases an overload of 20 percent was used. Where the project contractors objected to the larger overload because of possible resultant wear on their equipment and waste of material, the 20-percent overload was omitted.

The suggested program also recommended that for a given combination of mixing time and overload, samples for test be taken from each tenth batch of 90 consecutive batches of concrete. It was further recommended that three samples be taken from each batch sampled, one sample representing each third of the concrete as discharged from the bucket. Specimens for compression and flexure tests were made from certain of the batches sampled and tests for air content, unit weight, and uniformity of composition were made on certain other batches.

Conclusions

The data obtained by the States were so extensive that only a considerably condensed review can be included in this report. Based on a painstaking study of all material reported, the following conclusions have been drawn.

The results of strength tests included in this investigation showed that for 34–E dual-drum pavers, the greatest strength was obtained with a mixing time of 60 seconds, not including transfer time between drums. This mixing time could be reduced to 40 seconds, exclusive of transfer time, with but very little reduction in the strength of the concrete. Reduction of the mixing time to 30 seconds, exclusive of transfer time, caused a reduction in strength of 5 to 6 percent. Concrete mixed for 30 seconds occasionally showed segregation but generally could be placed and finished without difficulty. In some studies it was found desirable to increase the water-cement ratio slightly for concrete mixed for only 30 seconds.

A mixing time of more than 60 seconds, exclusive of transfer time, was found to be undesirable, since it involved waste of effort and resulted in loss of strength without gain in the uniformity of the concrete. Little evidence of excessive abrasion of the aggregate was noted, however, even with mixing times as long as 90 seconds.

Overloading of 34–E dual-drum pavers above their rated capacity caused a reduction in strength of 1 to 2 percent for an overload of 20 percent, and a reduction of 2 to 4 percent for an overload of 10 percent. The greater reduction for the smaller overload may have been fallacious, or it may have been possible that the mixers used in these tests actually performed better with a greater load. Data to clarify this point were not available.

In studies of the uniformity of concrete produced by 34–E dual-drum pavers, it was found that the quality of concrete depended on the operations preceding the paver mixing operation. If a harsh mix was fed to the paver, extended mixing time still furnished a harsh concrete. If a properly sized and proportioned mix was used, most, if not all, of the mixers studied in this investigation furnished well mixed concrete after only 30 seconds of mixing.

It should be noted that some contractors objected to an overload of more than 10 percent on the grounds that their equipment would not handle it. Also, some contractors were not able to use a mixing time shorter than 50 seconds, due to their inability to supply materials to the paver.

In general, it is believed that the results of the strength tests of concrete were more indicative of the effectiveness of the mixers used than were the results of tests for uniformity of concrete. The tests made for the latter purpose were of considerable value, but if studies of this type should be conducted in the future, a marked increase in the number of tests for compressive strength would be recommended, with elimination of the flexural strength tests and a reduction in the tests for uniformity. If it could be devised, a test for cement content in the mixed concrete which could be made in entirety on the project would be recommended, with another test for water content of the concrete.

Scope of Data

The studies of the effect of mixing time and overload on the quality of portland cement concrete produced in 34–E dual-drum pavers were made by 13 State highway departments; 2 studies were made by each of 3 States, resulting in a total of 16 studies. The locations of the studies are shown in table 1. Information concerning the type of mixer used, the coarse aggregate, the nominal mixing times, and the overloads, is given in table 2.

In this article, data from the studies are presented on the effect of mixing time and overload on the compressive and flexural strengths of concrete. Also reported are determinations intended to show the uniformity (or lack of it) of single batches of concrete, as well as variations from batch to batch of concrete prepared under presumably the same

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his article was presented at the 39th Annual Meeting of Iighway Research Board, Washington, D.C., January

Table 1.—Highway construction projects in the study of 34-E dual-drum pavers

State	Project number	Date of study	Highway route number	Location
Alabama	I-65-3 (14) (15)	Oct. 1958	U.S. 31	25 miles north of Birmingham
California	III-Pla-17-A, Roc, B.	July 1959	U.S. 40	Near Roseville
Delaware	F-12(4) S-US-48(2).	July 1958	Del. 8	Dover, Division St. and Forrest Ave.
District of Columbia.	F-55(1)	June 1958		Irving St. NE.
Florida	I-4-1(2)	July 1958	U.S. 4	Near Plant City
Kansas	F-0 92	Oct. 1958	U.S. 36	Beattie Corner to Nemaha County line
Michigan	I-02-5(6)	June 1958	U.S. 12	Ypsilanti, near Willow Run Airport
Nebraska	F-250(7)	Oct. 1958	U.S. 77	Wymore to Kansas State line
New York 1	BT-57-1	Aug. 1958		Near East Chatham
New York 2	I-1119(11)	Oct. 1958		20 miles west of Albany
Ohio 1	I-196(5)	June 1958	U.S. 25	Wapakoneta bypass
Ohio 2	I-529(11)	Aug. 1958	U.S. 40	Kirkersville bypass
Virginia 1	F-FG-018-1(1)	Sept. 1958	U.S. 29	Lynchburg bypass
Virginia 2	U-101-1(3)	Oct. 1958	U.S. 29	Arlington County, Lee Highway
Washington	Cont. 5733	Oct. 1958		Olympia
West Virginia	S-2(4)	Oct. 1958	W. Va. 14	Charleston to airport

Table 2.—Type of paver, aggregate, and principal variables used in the 16 study projects

State	Paver	Coarse aggregate		Principal variables	
		Type	Maximum size	Nominal mixing times used	Overload
			Inches	*Seconds*	*Percent*
Alabama	A	Stone	1½	30-50-90	0-10-20
California	B	Gravel	1½	30-50-70	0-10-20
Delaware	A	Stone	2	40-70-90	0-10-20
District of Columbia.	A	Gravel	2	30-50-70	0-10-20
Florida	B	Stone	2	30-60-90	0-10-20
Kansas	A	Sand-gravel	1	50-60-70-90	0-10-20
Michigan	A	Slag	2	30-50-70	0-10-20
Nebraska	C	Stone	1	30-50-60-90	0-10-20
New York 1	B	Stone	2	40-50-60-90-120	0-10-12-20
New York 2	B	Crushed gravel.	2	60-90-120	10-20
Ohio 1	B	Stone	1½	40-50-75	0-10-20
Ohio 2	A	Gravel	--------	50-75	0-10-20
Virginia 1	B	Stone	2½	30-60-90	0-10-20
Virginia 2	D	Gravel	2½	30-60-90	0-10
Washington	B	Gravel	--------	45-60	10-20
West Virginia	C	Gravel	2	30-40-50-60	0-10

mixing conditions. The types of tests made by the several States are indicated in table 3.

Some of the States prepared formal reports at the conclusion of their individual studies, while others supplied test results in an informal manner. The data obtained by all States were so extensive that only a review of them can be included in this report. Of particular interest, among data excluded here, were those that would permit comparing the air content of concrete as determined by the Chace air meter and standard pressure or volumetric meters, and comparisons between the results of slump cone and Kelly ball tests. It is expected that these data will be summarized and reported at a future time, but their inclusion in this report was not considered necessary.

The study was unusual in that it involved considerable effort and cooperation on the part of a number of State highway departments and highway contractors. The skillful handling of difficult field testing operations by the personnel involved, often under unfavorable conditions, contributed greatly to the success and value of the study.

Procedure Problems

In determinations of the mixing time, in this article, the transfer time between drums was not included. It has been stated by some that the concrete is mixed during this transfer process. However, in their reports different States reported different lengths of transfer time, even for the same make of paver, and it was believed that it would simplify the presentation of the material if only the mixing time in the drums was considered. The values reported by the States for mixing times are shown in table 4.

The original program proposal recommended sampling of every 10th batch for testing. Some States believed that sampling of every 10th batch might be too frequent, and sampled every 20th batch instead. Where the testing staff was limited, this allowed ample time for the test procedures. Some States questioned some of the methods of test proposed, and modified or eliminated them in accordance with their experience or needs. One State cast only a few specimens for strength tests, and drilled cores from the pavement for the strength tests of record. Other differences were found among the individual studies. In general, however, the recommended program was followed sufficiently to permit use of most of the data obtained.

One of the most controversial items in the suggested program was the method of obtaining the three samples of concrete representing a single batch or bucket load. It was recom-

Table 3.—Various tests on concrete performed by the States [1]

State	Tests for compressive strength on cylinders [2]			Tests for flexural strength [3]			Tests for uniformity of plastic concrete							
							Washout		Unit Weight	Air content [4]		Slump	Kelly ball	Willis-Hime
	7 days	14 days	28 days	7 days	14 days	28 days	Fine	Coarse		Pressure	Chace			
Alabama	X	----	X	X	----	X	X	----	X	X	X	X	X	----
California	----	X	----	----	----	----	X	X	----	X	----	----	X	----
Delaware	X	X	X	----	X	----	X	X	X	X	X	X	X	----
District of Columbia	X	X	X	----	X	----	X	X	X	X	X	X	X	X
Florida	X	X	X	X	X	X	----	----	X	X	X	X	X	----
Michigan	----	----	X	----	----	X	X	X	X	----	X	X	X	----
Nebraska	X	----	X	X	----	X	----	X	X	X	X	X	X	----
New York	----	----	----	--	----	----	----	X	X	X	X	X	----	X
Ohio 1	----	----	X	X	X	----	----	X	X	X	X	X	X	----
Ohio 2	----	----	X	X	X	----	----	X	X	X	X	X	X	----
Virginia 1	----	----	X	----	X	----	X	X	X	X	X	X	X	X
Virginia 2	X	X	X	X	----	X	X	X	X	X	X	X	X	X
Washington	----	----	X	----	----	X	----	----	X	----	----	X	X	----
West Virginia	X	X	X	X	X	----	X	X	X	X	X	X	X	----

[1] No information was received from Kansas. [2] Michigan and New York used cores to test compressive strength. [3] The District of Columbia conducted a 3-day test for flexural strength. [4] Alabama and Michigan used the rollermeter method for testing air content.

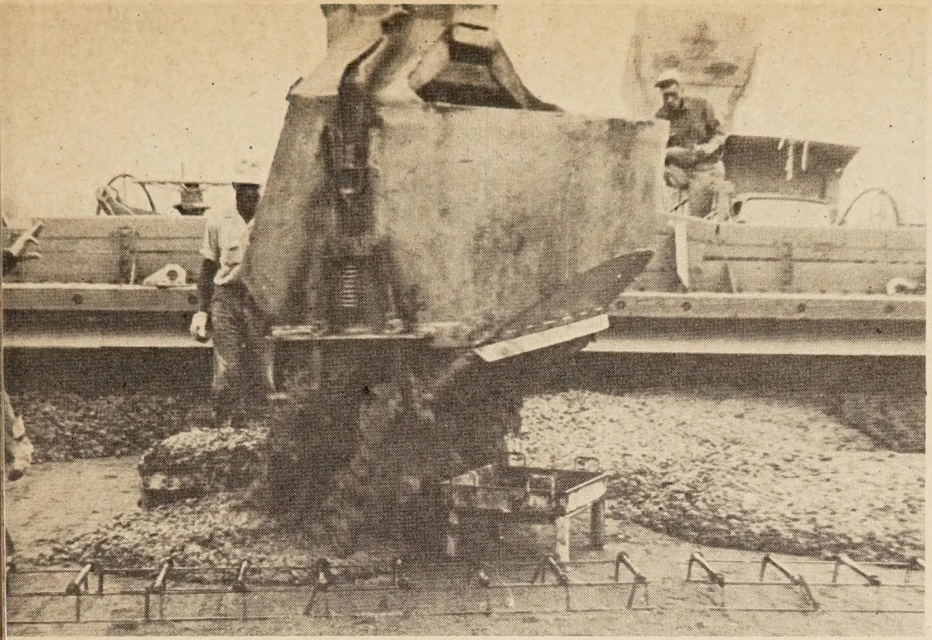


Figure 1.—One of the methods used in obtaining sample concrete.

ed originally that three pans be placed e subgrade, slightly separated to cover ea over which a bucket load of concrete l be distributed. However, some diffi- was found with this method of sampling. the pans were placed directly on the ade, the wave of concrete from the t frequently knocked the pans aside. me projects, to correct this difficulty, ans were held in place by concrete led against their sides. Another method to be effective was mounting the pans gs about 12 inches high, as shown in 1.

ne States adopted the practice of having ucket load dumped on the subgrade in a ribbon or in an oval-shaped pile. Samples possibly representing different sections of the bucket-load were then taken from the concrete. At first it was questionable whether the samples so obtained could be considered to represent the first, middle, and last third of the concrete batch discharged from the mixer. However, it was pointed out that the first third of the concrete discharged from the bucket might not be the same as the first third of the concrete discharged from the mixer. Due to restraint of the sides of the bucket, the first third of concrete discharged from the bucket may include some of the second third of the concrete discharged into the bucket. For this reason, no consideration was given in this report to differences between the methods used to obtain these one-third-bucket-load samples. Although such differences existed, it may be considered that the collective samples for each mixing time and overload are reasonably representative of the entire mixing load.

ble 4.—Average mixing time, in seconds, as given by those States where mixing and transfer times were recorded [1]

State	Nominal mixing time	No overload		10 percent overload		20 percent overload		Average actual mixing time
		Transfer time	Actual mixing time	Transfer time	Actual mixing time	Transfer time	Actual mixing time	
Alabama	30	11	30	15	30	11	29	30
	50	11	49	11	49	11	49	49
	90	11	79	11	75	11	79	78
alifornia	30	10	21	10	23	10	24	23
	50	10	40	10	39	10	38	39
	70	10	60	10	60	10	60	60
Delaware	40	9	41	9	41	9	41	41
	70	9	70	9	70	9	70	70
	90	9	90	9	90	9	90	90
istrict of Columbia	30	12	29	12	30	12	30	30
	50	12	45	12	45	12	50	47
	70	12	70	12	70	12	69	70
ansas	50	10	39	10	54	10	51	48
	60	10	60	10	57	10	53	57
	70	10	60	10	62	10	61	61
	90	10	75	10	76	10	77	76
hio 1	40	8	41	9	43	8	42	42
	50	8	51	9	54	9	51	52
	75	9	66	9	66	9	65	66
hio 2	50	10	50	10	50	12	49	50
	75	10	65	10	65	12	64	65
irginia 1	30	------	27	------	28	------	28	28
	60	------	58	------	60	------	60	59
	90	------	89	------	87	------	90	89
irginia 2	30	------	29	------	36	------	------	32
	60	------	58	------	63	------	------	60
	90	------	93	------	96	------	------	94

Florida (30, 60, 90 sec.), Michigan (30, 50, 70 sec.), Nebraska (30, 50, 60, 90 sec.), and West Virginia (30, 40, sec.) did not include transfer time in mixing times stated. New York included a transfer time of 9 sec. in mix- mes of 40, 50, 60, 90, and 120 sec. No information of transfer time was furnished by Washington (45, 60 sec.).

Effect of Mixing Time on Strength

As shown in table 2, the States used widely different nominal mixing times, and some differences in overloads. There also was a variance in the materials used and in the methods of testing compressive and flexural strengths. To place each set of data on a uniform basis for comparison, the strength obtained for a 60-second mixing time, or with no overload, was adopted as the standard of comparison. Strengths obtained for other mixing times, or for overloads, were then compared with these values.

In six of the studies, a 60-second mixing time was not used. To permit comparison of the data obtained with those for the other projects, the determined strengths were plotted against mixing time and a curve drawn through the points. The value shown on this curve at intersection with the 60-second abscissa was taken as the base measure.

To keep the reporting of data concerning mixing time within reasonable bounds, some liberties have been taken in their presentation. The mixing times are shown at 5-second intervals, and a value for strength obtained with an actual mixing time of 48 seconds, for example, is shown for 50 seconds. However, if there was only one determination of strength of concrete for a given time of mixing, this was not shown in the charts. In many instances the elimination of these single values removed wild results and showed to better advantage the trend of the remaining mutually supporting data.

Data reported by each State of the effect of mixing time on the compressive and flexural strength of concrete are shown in figures 2 and 3. The varying strengths reflect the materials used and the methods of testing employed. Some States used cantilever beam testing machines, and obtained flexural strengths much higher than those using center-point loading.

Data averaged for all of the studies to show the effect of mixing time on the compressive strength are plotted in figure 4. The curve in each portion of the figure presents the best considered average. In the lowest portion of the figure, the curve represents an average of the other three curves. Similar curves for flexural strength are shown in figure 5.

The same finding; that the compressive and flexural strengths of concrete prepared with the mixers and materials used were at a maximum for a mixing time of 60 seconds, is evident in figures 4 and 5. Marked increase or decrease in mixing time resulted in a reduction in strength, but this reduction was of no great moment. For a mixing time of only 30 seconds, the compressive strength was reduced only 6 percent and the flexural strength only 5 percent. For a mixing time of 90 seconds, the compressive strength was reduced only 7 percent and the flexural strength only

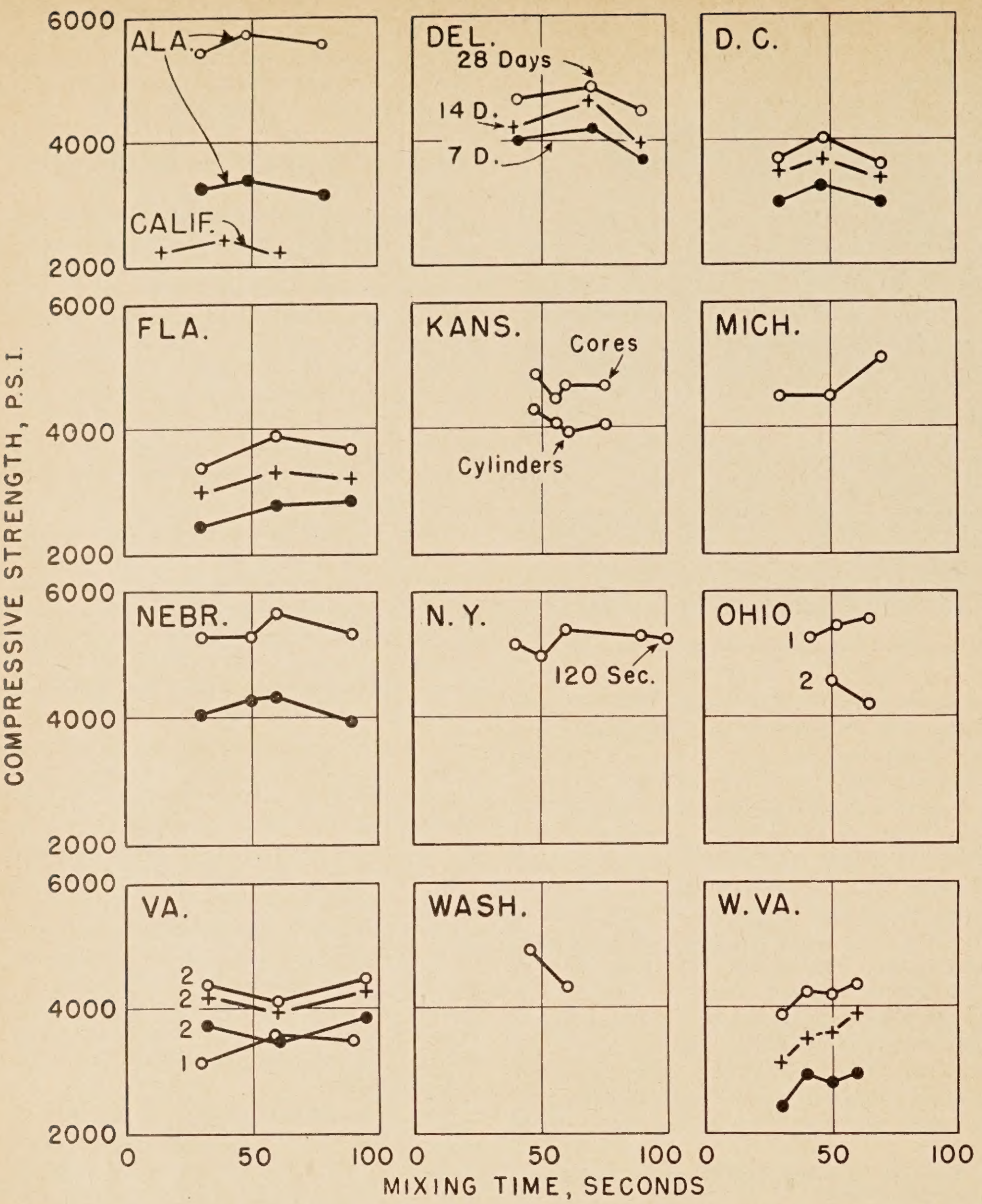


Figure 2.—Effect of mixing time on compressive strength, by State.

3 percent. A reduction in mixing time to 50 seconds caused a reduction in compressive strength of about 0.5 percent and no decrease in flexural strength.

Figures 6 and 7 present the effect of ov
load on the compressive and flexural strengt
of the samples tested. The curve representi
the average for all determinations of co
pressive strength shows that a decrease of
percent in strength resulted for an overlo
of 10 percent. For a 20-percent overload,
decrease in strength of only 1 percent resulte
In the flexural strength determinations, ov
loads of 10 and 20 percent each caused
reduction in strength of only 2 percent.

Some inquiry has been made of the reas
for the lower compressive strength of concre
prepared with an overload of 10 percent th
with an overload of 20 percent. It w
speculated that the greater overload caus
the drum to operate more efficiently; howev
if this were the reason a mixer with an ov
load of 10 percent would be expected
operate more efficiently than one with
overload. Such was not found to be the ca
if strength tests of concrete are used to juc
the efficiency or rather the effectiveness o
mixer. Some other reason must apply
these test results.

Most specimens were prepared, cured, a
tested in accordance with standard AST
methods. No concern need be given to t
phase of each investigation, as the data w
apparently affected but little by variations
the preparation of specimens. With this
cepted, it may be assumed that variations
the strength of the concrete are due to
mixing procedures used, or the weather co
ditions over which there was no control.

Further study was given to the effect
overload on the compressive strength of c
crete, reported in table 5. It was obser
that in Florida the strength for no overl
was considerably higher than that for
percent overload at all ages and for 20 perc
overload at an age of 7 days. It was belie
that a detailed study of the results from t
State might be warranted. It was also no
that in the Virginia No. 2 study and in
West Virginia study the results for a
percent overload ranged from slightly lowe
considerably lower than for no overload,
that no tests were made for an overload o
percent. It was believed that these res

Table 5.—Effect of overload on compressive strength

State	Tests at 7 days for unit compressive strength					Tests at 14 days for unit compressive strength					Tests at 28 days for unit compressive strength				
	No overload	10 percent overload		20 percent overload		No overload	10 percent overload		20 percent overload		No overload	10 percent overload		20 percent overlo	
		Strength	Strength ratio [2]	Strength	Strength ratio [2]		Strength	Strength ratio [2]	Strength	Strength ratio [2]		Strength	Strength ratio [2]	Strength	Streng ratio
	p.s.i.	*p.s.i.*		*p.s.i.*		*p.s.i.*	*p.s.i.*		*p.s.i.*		*p.s.i.*	*p.s.i.*		*p.s.i.*	
Alabama	2, 890	2, 950	102	3, 320	115	------	------	------	------	------	5, 720	5, 260	92	5, 740	100
California	------	------	------	------	------	2, 300	2, 240	97	2, 130	93	------	------	------	------	----
Delaware	4, 010	4, 020	100	3, 760	94	4, 280	4, 310	101	4. 120	96	4, 730	4, 640	98	4, 550	96
District of Columbia	3, 140	3, 130	100	2, 950	94	3, 580	3, 560	99	3, 380	94	3, 880	3, 800	98	3, 660	94
Florida	2, 920	2, 470	85	2, 760	95	3, 290	2, 750	84	3, 560	108	3, 760	3, 320	88	3, 940	105
Kansas [1]	------	------	------	------	------	------	------	------	------	------	4, 560	3, 620	80	4, 150	91
Michigan	------	------	------	------	------	------	------	------	------	------	4, 630	4, 920	106	4. 610	100
Nebraska	4, 160	4, 000	96	4, 320	104	------	------	------	------	------	5, 560	5, 390	97	5, 300	95
Ohio 1	------	------	------	------	------	------	------	------	------	------	5, 370	5, 440	101	5, 450	101
Ohio 2	------	------	------	------	------	------	------	------	------	------	4, 300	4, 050	94	4, 790	111
Virginia 1	------	------	------	------	------	------	------	------	------	------	3, 620	3, 330	92	3, 240	90
Virginia 2	3, 740	3, 690	99	------	------	4, 260	3, 990	94	------	------	4, 440	4, 170	94	------	----
Washington	------	------	------	------	------	------	------	------	------	------	------	4, 630	------	4, 660	----
West Virginia	2, 940	2, 560	87	------	------	3, 640	3, 410	94	------	------	4, 240	4, 100	97	------	----
Average	------	------	96	------	100	------	------	95	------	98	------	------	94	------	98

[1] Kansas tested cores at 28 days with the following results: No overload, 5,030 p.s.i.; 10 percent overload, 4,430 p.s.i.; 20 percent overload, 4,530 p.s.i.

[2] Ratio to strength for no ove

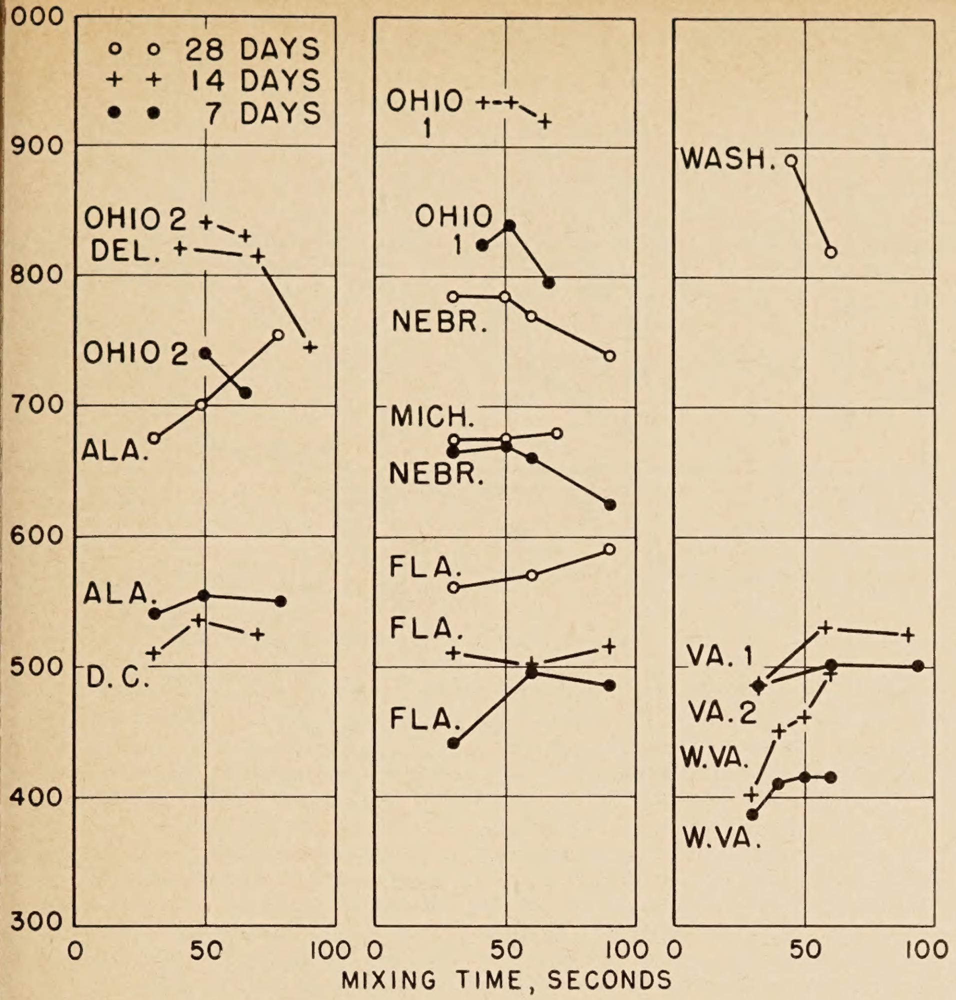


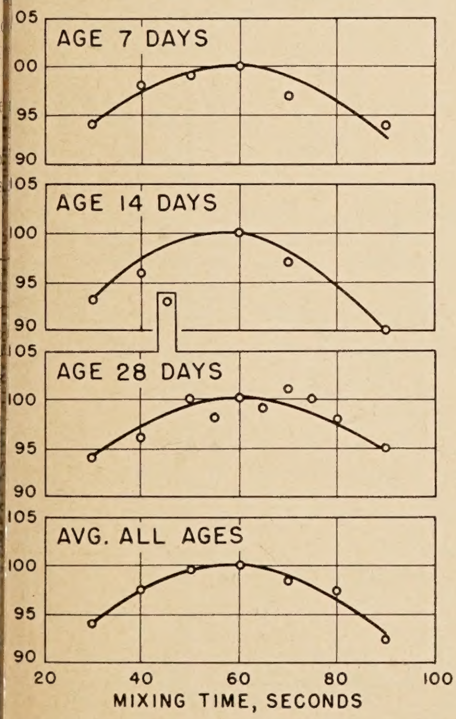
Figure 3.—Effect of mixing time on flexural strength, by State.

ght have influenced the general average an unwarranted extent and that they ght well be excluded from consideration.

To examine more carefully the results of the Florida tests, the compressive strengths obtained for each combination of mixing time and overload were plotted against age at test. It was believed that if there had been any unusual features affecting the test results, these would be shown by some exceptional behavior in rate of gain of strength. As shown in figure 8, all of the Florida tests made for concrete prepared with 90 seconds mixing time produced an unusual behavior in rate of gain of strength. In two of the three cases, the strength at an age of 14 days was lower than that at 7 days. In the third case, the strength at 7 days appears to be quite low and that at 14 days somewhat high. Why these results had this unusual behavior is not known, but there is indication that they were caused by some feature other than the variables of record and it is believed that these results may justifiably be excluded from consideration. Consequently, in consideration of the effect of overload on compressive strength, all three sets of specimens mixed for 90 seconds in Florida were rejected.

Figure 9 presents revised trends of the effect of overload on compressive strength with the questionable and incomplete data excluded. Even with these data excluded, it was found that the strength for an overload of 10 percent was slightly lower than that for an overload of 20 percent, and both overloads furnished less strength than no overload. The maximum amount of reduction in strength is only 4 percent which, in view of the more rapid production of concrete gained by overloading, may be considered of minor consequence.

In the tests to determine the effect of overload on flexural strength, certain test specimens yielded irregular results, as shown in table 6 and figure 10. In no case, however, were all specimens for a given time of mixing involved, and all data obtained were used to determine average trends for all of the studies.



ure 4.—Average effect of mixing time on compressive strength.

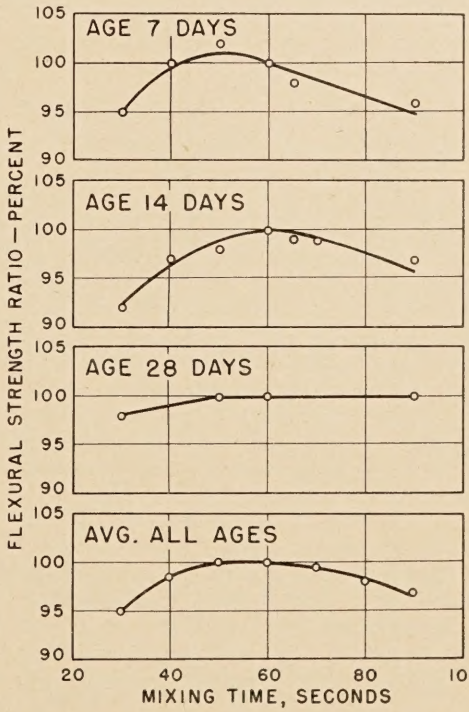


Figure 5.—Average effect of mixing time on flexural strength.

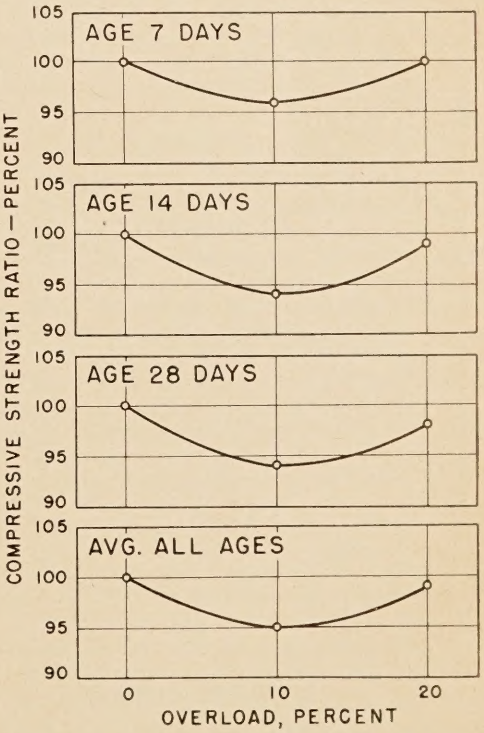


Figure 6.—Average effect of overload on compressive strength.

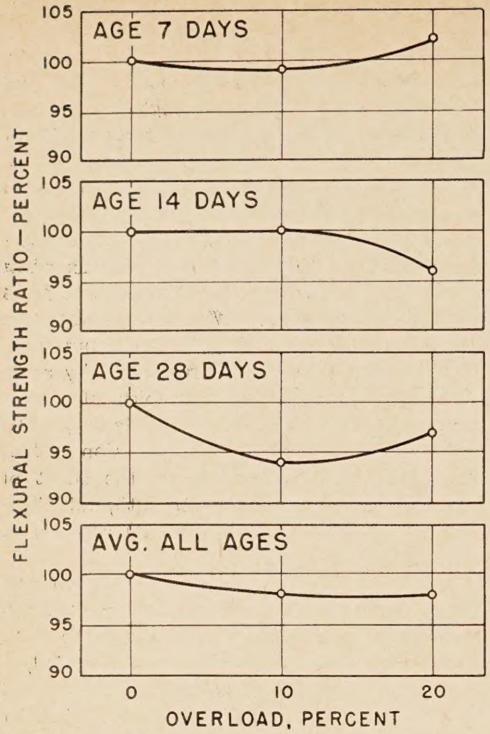


Figure 7.—Average effect of overload on flexural strength.

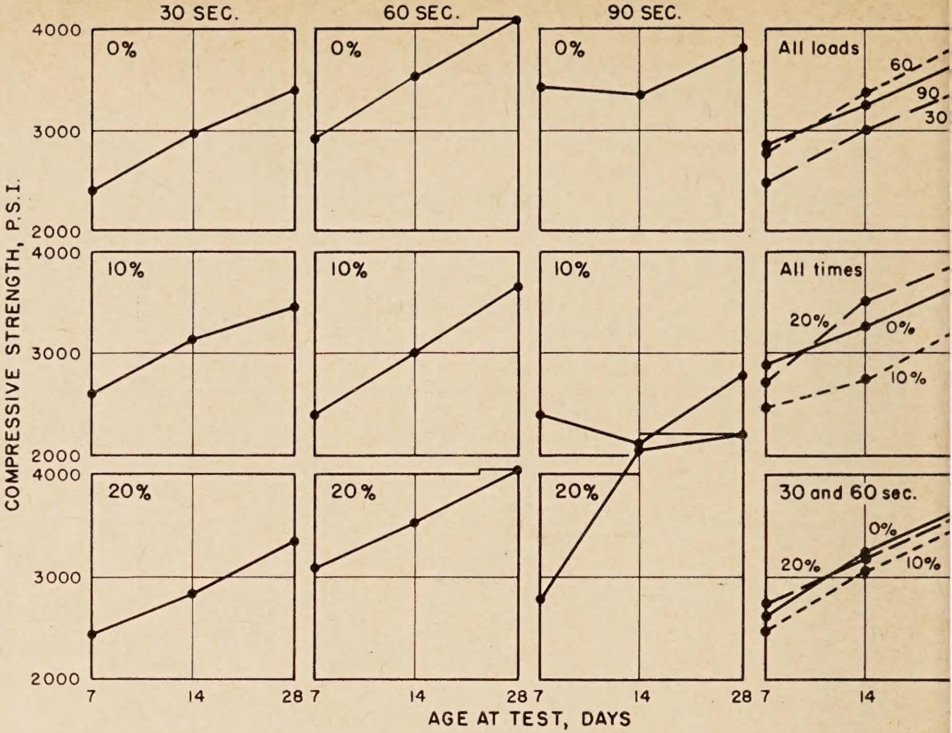


Figure 8.—Compressive strength for each set of variables using Florida test data.

Effect of Make of Paver

It was hoped that sufficient data could be obtained from the projects using the same make of paver to determine whether that make of paver processed concrete in a manner sufficiently different from the other pavers to warrant comment. It was considered desirable to limit the data used to that representing two or more projects and four mixing times.

The results obtained for a single make of paver showing the effect of mixing time on strength are shown in figure 11. By comparison with figures 4 and 5, it will be seen that there is little difference between the curves for this single make of mixer and the curves for all makes over the range of 50 to 70 seconds mixing time. It is probable that more difference in effectiveness mixing will be found between individ mixers of any make than between group mixers of different makes. In two of th studies the mixers used were found, on ini inspection, to contain a considerable amo of hardened concrete. Removal of concrete unquestionably improved the ef tiveness of the mixers.

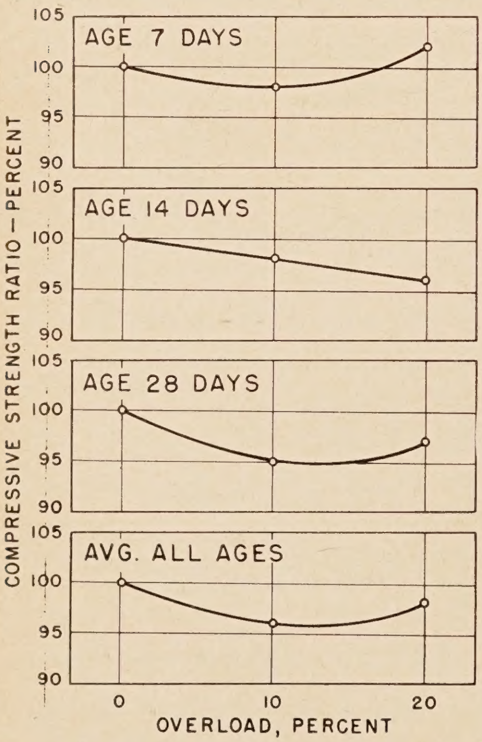


Figure 9.—Average effect of overload on compressive strength excluding questionable and incomplete data.

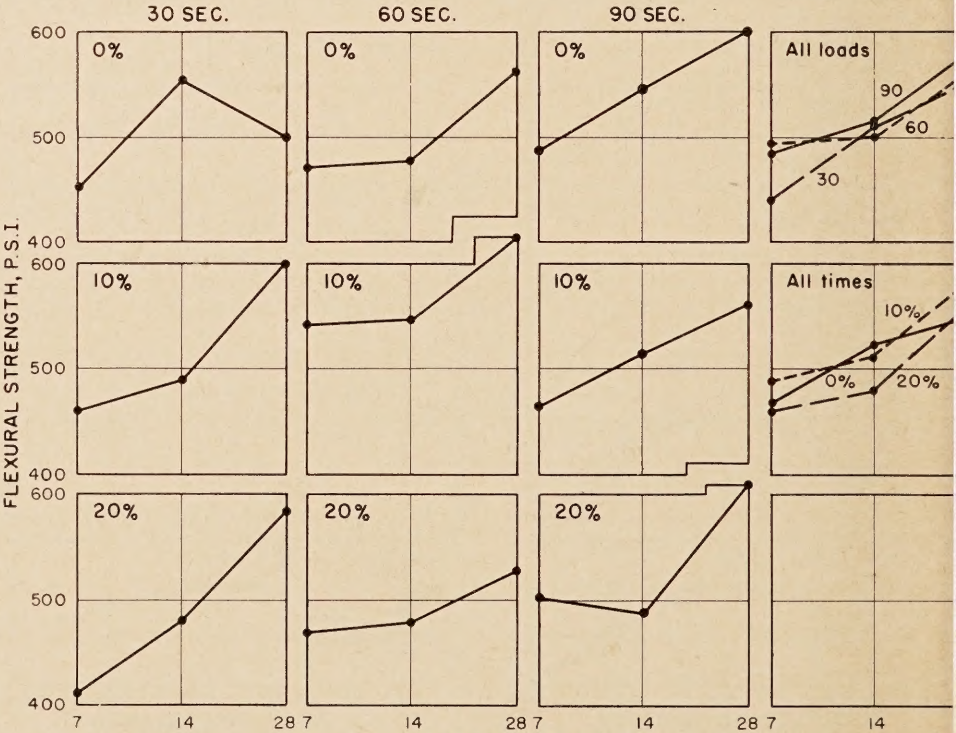


Figure 10.—Flexural strengths for each set of variables.

Table 6.—Effect of overload on flexural strength

State [1]	Tests at 7 days for unit flexural strength					Tests at 14 days for unit flexural strength					Tests at 28 days for unit flexural strength				
	No overload	10 percent overload		20 percent overload		No overload	10 percent overload		20 percent overload		No overload	10 percent overload		20 percent overload	
		Strength	Strength ratio [2]	Strength	Strength ratio [2]		Strength	Strength ratio [2]	Strength	Strength ratio [2]		Strength	Strength ratio [2]	Strength	Strength ratio [2]
	p.s.i.	*p.s.i.*		*p.s.i.*		*p.s.i.*	*p.s.i.*		*p.s.i.*		*p.s.i.*	*p.s.i.*		*p.s.i.*	
Alabama	515	550	107	575	112	------	------	------	------	------	785	640	82	710	90
Delaware	------	------	------	------	------	795	820	103	760	96	------	------	------	------	------
District of Columbia	------	------	------	------	------	545	530	97	500	92	------	------	------	------	------
Florida	470	490	104	460	98	525	515	98	480	91	555	595	107	575	104
Kansas	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
Michigan	------	------	------	------	------	------	------	------	------	------	680	665	98	680	100
Nebraska	680	640	94	640	94	------	------	------	------	------	810	735	90	765	94
New York	------	------	------	------	------	------	------	------	------	------	------	------	------	------	------
Ohio 1	825	800	97	835	101	955	875	92	960	101	------	------	------	------	------
Ohio 2	720	730	101	730	101	840	845	101	820	98	------	------	------	------	------
Virginia 1	------	------	------	------	------	515	520	101	505	98	------	------	------	------	------
Virginia 2	505	485	96	------	------	------	------	------	------	------	------	------	------	------	------
Washington	------	------	------	------	------	------	------	------	------	------	------	865	------	845	------
West Virginia	415	400	96	------	------	430	470	109	------	------	------	------	------	------	------
Average [3]	------	------	99	------	102	------	------	100	------	96	------	------	94	------	97

[1] California, Kansas, and New York reported no tests for flexural strength. [2] Ratio to strength for no overload. [3] The average ratio to strength for no overload at all ages was 98 for oth 10- and 20-percent overload.

Tests for Uniformity of Plastic Concrete

It would be expected that insufficient mixing vould be evidenced by marked differences in he results of tests of the three portions of a ucket of concrete, possibly by greater than ormal weight per cubic foot, and by low ir content. Excessive mixing would be xpected to be detected by excessive fines in he concrete, and possibly by a low air ontent.

Almost all of the States made and reported est determinations which were intended to e used to show the uniformity of the plastic oncrete. These tests included determinaions of the cement content by the Willis-Iime and Dunagan methods, washout tests or fine or coarse aggregates, tests for unit veight of concrete, tests for consistency using he slump cone and Kelly ball methods, and ressure, volumetric, and Chace tests for air ontent.

The data furnished by the States were tudied, and a selection of these data was nade to determine the uniformity of the oncrete produced with the various mixing imes and overloads. For ease in presentation nd comparison, these data are shown in igures 12–20. In each figure, sample data eflecting various characteristics of the conrete are shown with reference to individual combinations of mixing time and overload. Data for the first one-third of the bucket load of concrete are indicated by a circle; for the second third, the data are indicated by a cross; and for the last third, by a triangle. The solid lines in the figures connect the average value for a bucket load.

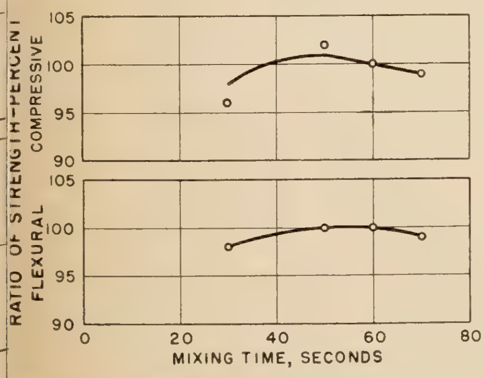


Figure 11.—Effect of mixing time on strength, determined from one make of paver.

Generally, the data plotted for each one-third portion is an average taken from three loads of concrete. These loads, obtained from different batches and on different days, could have been influenced by changing weather conditions, characteristics of the materials used, or by the personal equation of the operators. However, the sample loads indicate a general trend which may be considered adequate for this study and are not intended to cover all minute details which might influence such determinations.

For most of the reporting States, data covering tests for unit weight, washout, and air content were available. In the other States, data for slump were available.

Unit Weight

A marked variation in unit weight of concrete for a single batch of concrete or for several batches mixed under the same conditions would indicate either a harsh concrete or insufficient mixing. If a marked variation was found, and the same one-third portion generally had the greatest or least weight of the samples representing the same bucket load, it was assumed that the mixer was not operating properly and was furnishing undermixed concrete. For a given combination of aggregates, high unit weights, closely grouped, indicated well-mixed concrete.

General trends for all data from short to long mixing times were also of interest. If the trend appeared toward greater weight, an improvement in mixing was assumed. If the trend was toward lesser weight, this was taken to indicate overmixing and reduction in size of the aggregate.

Washout

The results of the washout tests were shown by several different methods. In some cases, the States determined and reported the amount of fine aggregate in the concrete or the grading and fineness modulus of the aggregate. In others, the amount of coarse aggregate was determined. Some States reported the grading of all aggregate, and choice had to be made as to which data would give the most information.

The results of these tests were expected to determine if extended mixing of concrete would abrade the aggregate to a marked extent. This could be demonstrated if there was a decrease in the fineness modulus of the fine aggregate, or an increase in the amount of fine aggregate and decrease in the amount of coarse aggregate. Undermixing of the concrete was indicated by the nonuniformity of the distribution of aggregate in the three portions of a bucket load.

Air content

The air content of the concrete was determined by use of pressure or volumetric methods, including the Chace air meter test as one of the latter methods. When available, data obtained with a pressure meter, or a volumetric method using a large sample of concrete, were preferred over data obtained with the Chace air meter.

The air content of air-entrained concrete was believed to be an excellent indication of the thoroughness of mixing the concrete. Insufficient mixing would be indicated by low amounts of air and by variation of the amounts of air between portions of a batch. With excessive mixing, it was believed that some of the air would be lost, but in this case the air in each portion of a batch would be practically constant.

Slump

The slump is a measure of the workability of concrete. A concrete can have a high water-cement ratio and at the same time have a low slump due to harshness of the mix. In very few instances were the concretes produced in these studies found to have poor workability, and it is believed that these cases can be ignored. The slump can be used with other data to deduce whether thoroughness of mixing was obtained.

Other determinations

Other determinations made on portions of a bucket load of concrete included the Willis-Hime test [1] for the cement content of concrete, and the Dunagan method [2] for determining the composition of concrete. The Willis-Hime test, made by the District of Columbia, New York and Virginia, yielded disappointing results in that they differed greatly from the known cement content. It was found that the principal reason for the results obtained was failure to dry the samples sufficiently. Since all of the water was not driven off, the cement grains still retained water and were not separated from the sand portion of the mortar during the centrifuging operation. This resulted in a test determination showing a low cement content of the concrete.

The District of Columbia made determinations of the composition of the fresh concrete using the Dunagan method. The results varied tremendously and indicated variations within and between batches of concrete which were beyond the realm of the possibility. Without doubt, some feature was overlooked in the performance of these tests which resulted in inappropriate test data.

Review of Uniformity by States

A review of the data for some of the individual State projects was made to determine information of interest with respect to uniformity of concrete. Such information is presented in the following paragraphs.

Alabama

The results from the Alabama project (fig. 12) showed a slight overall decrease in unit weight with increase in mixing time. With an overload of 20 percent, however, higher weights were obtained for each mixing time than for no overload. In 8 of the 9 combinations of mixing time and overload, the last portion of the concrete discharged by the bucket had the greatest weight. These facts collectively were assumed to indicate that the mixer was not operating to best advantage, and that an overload of 20 percent was an aid in obtaining better mixing of the concrete.

Determinations of the material passing the No. 4 sieve in the washout test showed some wide variations within a bucket load of concrete—especially for the 30-second mixing time. Each of the loads had an equal amount of sand, or more in the first one-third of the bucket load than in the second or last third portions. These variations indicated an insufficient mixing for a 30-second period. The general trend for all washout test results showed no increase in amount of fine aggregate with increase in mixing time and overload. This would indicate that even for a 90-second mixing time, there was no more abrasion of aggregates than for shorter periods of mixing time.

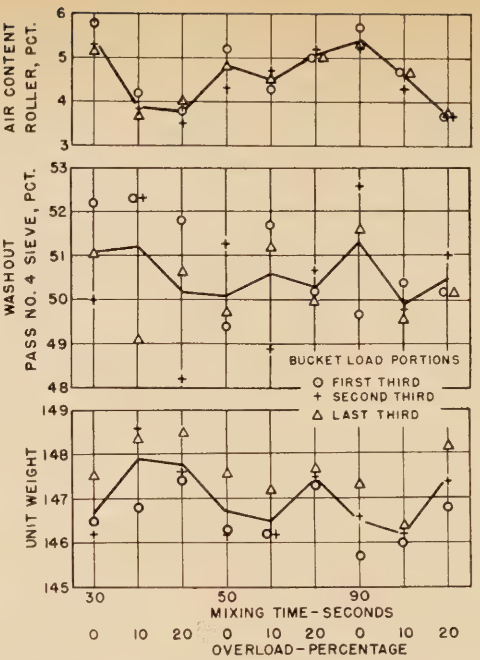


Figure 12.—Test determinations on uniformity of concrete in the Alabama project.

The air content tests, using a volumetric method, produced uniform values for the different portions of a bucket load. In two of the three mixing times, increase in loading resulted in a reduction in the amount of air. The air contents for a 30-second mixing time with no overload and with 20 percent overload were the same as those for the same loads at a 90-second mixing time. It would appear from these results that a 30-second mixing time is sufficient to obtain well-mixed concrete, and that further mixing is of little value.

Delaware

Data from the study in Delaware (fig. 13) showed no overall trend for unit weight except for a higher weight for each mixing time with a 10-percent overload. In 7 of the 9 cases, tl weight of the last portion from the bucket wa equal to or greater than that of other portion This indicated that a greater percentage c stone was present in the last portion ar further suggested that the mixer was nc functioning properly.

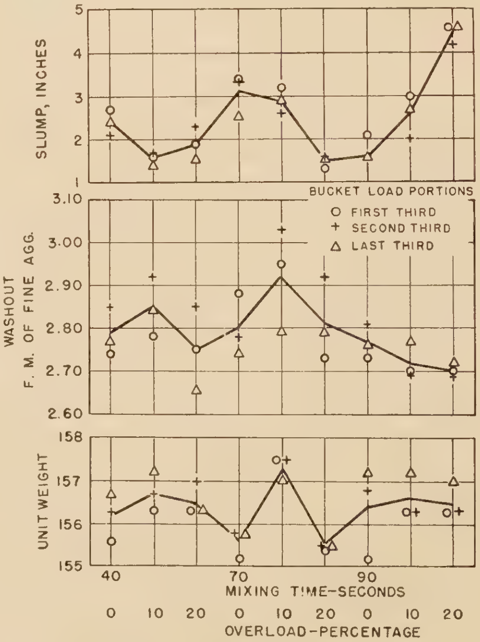


Figure 13.—Test determinations on uniformity of concrete in the Delaware project.

In the washout tests, the high value of fin ness modulus of sand for the 70-second mixir time with a 10-percent overload was matche by a similar high value for unit weight. The: values were considered as sports, representir a nonuniform condition such as the use c unusually coarse sand. The other values fc the washout tests showed no unusual featur other than the prevalence of coarser sand fro the center of the bucket load and the pr gressive decrease in fineness modulus for tl 90-second mixing time.

The progressive increase in fineness of tl fine aggregate was almost matched by an i crease in the slump of the concrete for tl batches involved. Although data for the wat content of the concrete were not immediatel available, the variations in the values fc slump were related to the variations in the un weight values or the fineness modulus of tl fine aggregate. Where an increase or decrea in slump occurred, a decrease or increase i unit weight was found or an increase or d crease in the fineness modulus of the sar occurred. Considering all values given, tl previously mentioned failure of the mixer t furnish well mixed concrete must be repeate It appeared that extended mixing of the co crete did abrade the aggregate to some exten It was also found that the first sample take from each bucket load generally had a lowe than-average unit weight, a finer-than-ave age sand, and a higher-than-average slump.

District of Columbia

The results obtained in the District c Columbia study (fig. 14) were unique in shov

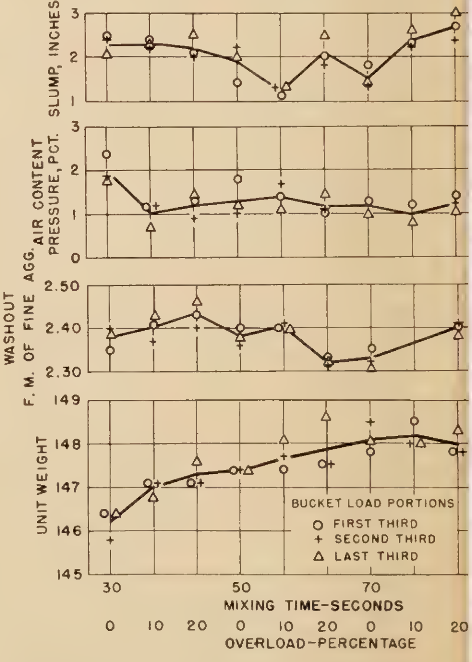


Figure 14.—Test determinations on un formity of concrete in the District c Columbia project.

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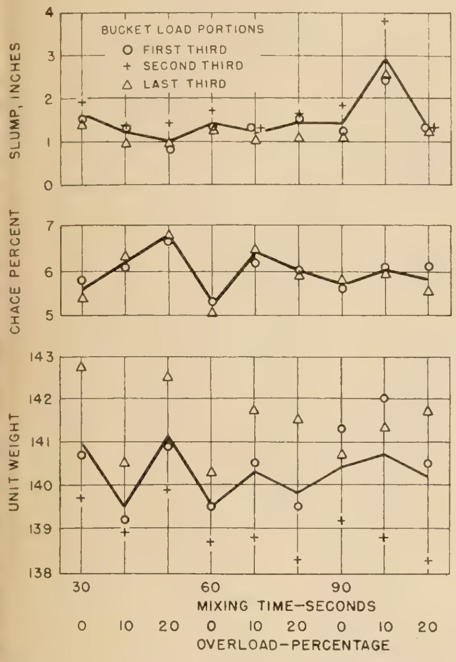
[1] *Cement Content of Freshly Mixed Concrete.* ASTM Bulletin, No. 239, July 1959, pp. 48–49.

[2] *A Method of Determining the Constituents of Fresh Concrete*, by W. M. Dunagan. Proceedings, American Concrete Institute, vol. 26, 1930, pp. 202–210.

g an increase in unit weight for each increase mixing time and overload except for the -percent overload at 70-second mixing time. o corresponding trends were developed in the ta for fineness modulus of fine aggregate, r content, or slump. It appeared that the niformity of concrete was improved by increase in mixing time and load, the additional verload serving to promote the mixing action.



igure 15.—Test determinations on uniformity of concrete in the Florida project.

lorida

The results obtained in the study in Florida fig. 15) in some respects were quite unusual. Except for one nonconforming group of data, uniform results were obtained for the slump of concrete. The tests for air content made by the Chace method, also produced one sport, but otherwise the variations were insignificant. Neither set of data can be used to explain variations found in the tests for unit weight. In the concretes mixed for 60 and 90 seconds, those with a 10-percent overload had slightly greater average weights than those with no overload or 20-percent overload; while in the concretes mixed for 30 seconds, those with a 10-percent overload had the least weight.

In view of the marked variation in unit weight for the separate portions of all batches of concrete, and the fact that the last portion of each bucket load had the greatest weight in 7 of the 9 combinations of mixing time and overload, it appeared that the concrete mix was harsh and failed to respond adequately to increases in mixing time. A possible exception to this may be shown by the low slump. With a slump averaging only 1¼ inches, more variation in unit weight must be tolerated within a batch than for higher slump concrete.

Michigan

Data results obtained in the Michigan study (fig. 16), in which slag was used as the coarse aggregate, reflected in some respects the opinion that slag concrete is usually somewhat harsh. However, similar behavior was detected in data from other projects in which gravel was used.

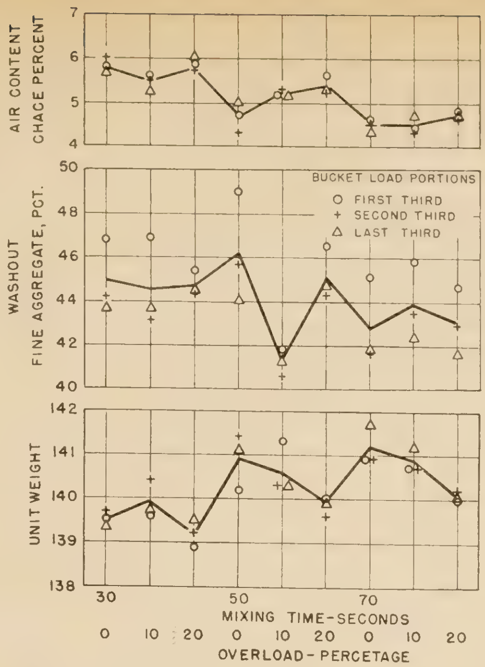


Figure 16.—Test determinations on uniformity of concrete in the Michigan project.

In the tests for unit weight, an increase in time of mixing was accompanied by an increase in the weight of the concrete. In the concretes mixed for 50 or 70 seconds, increase in overload resulted in a decrease in the unit weight, and in the concretes mixed for 30 seconds, those with a 20-percent overload had lower weights than those with no overload. These data indicate that an increase in mixing time and elimination of overload may furnish more uniformly mixed concrete for the particular mixer and concrete used in this project.

The washout tests showed a slight decrease in the amount of fine aggregate with an increase in mixing time and overload. The results of the air content tests showed a reduction in the amount of air with increase in mixing time and overload. This could mean that a 30-second mixing period was sufficient to develop maximum air content in the concrete, and that longer mixing periods permitted some of the air to be lost. It is noted that the data for air content and unit weight are associated. An increase of air content was associated with a decrease in weight, and selection of a most desirable set of mixing conditions definitely does not rest in these determinations.

Nebraska

For the study in Nebraska (fig. 17), the aggregate used was a mixture of sand-gravel and limestone. In conducting the washout tests, one determination made was the amount of crushed limestone found in the mixed concrete.

The tests for unit weight of concrete indicated some large variations both within and among batches. The general trend of these data indicated a slightly higher unit weight for concrete mixed for 60 seconds than for the other concretes included in the study. In 8 of the 9 combinations, the heavier concrete was found in the first portion of a bucket load, indicating that more large aggregate was contained in this portion than in the second or third portions. No relation between unit weight and air content results were found except for one batch mixed for 60 seconds with no overload. This concrete had the highest unit weight as well as the lowest air content.

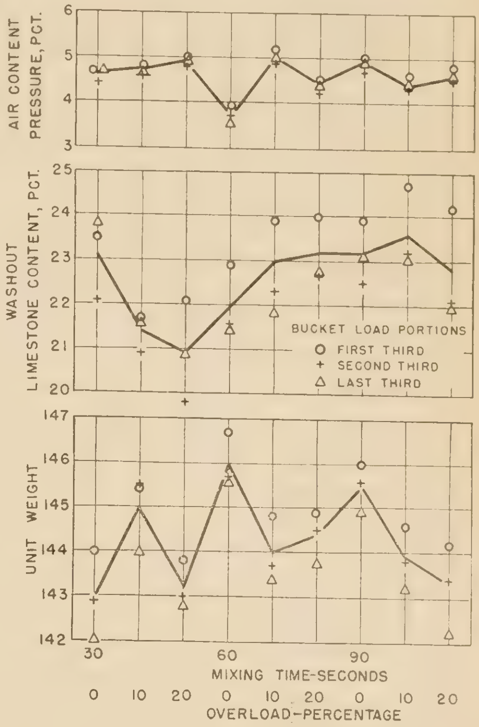


Figure 17.—Test determinations on uniformity of concrete in the Nebraska project.

The Nebraska report stated that a visual inspection of all test batches used did not disclose any poorly mixed concrete. This is of considerable importance as it may indicate that the variations shown in figure 17 may be of no significance with respect to concrete placed on the roadway.

Ohio project No. 1

In the first of the two studies conducted in Ohio (fig. 18), marked variations in unit weight were found, but the data showed no trends which could be associated directly with amount of mixing time or overload. The amount of coarse aggregate recovered from the concrete in the washout tests appeared irregular for the 40-second mixing time, and one group of results for the 50-second mixing time indicated a temporary lack of control at the batching plant. However, the results found for air content appeared to be quite uniform.

It was reported that inspection of the concrete as it was placed on the subgrade revealed only a few batches on which question might be raised regarding uniformity of mixing. Possibly uniformity in grading of the coarse aggregate and in batching the materials were of equal importance to the performance of the mixer.

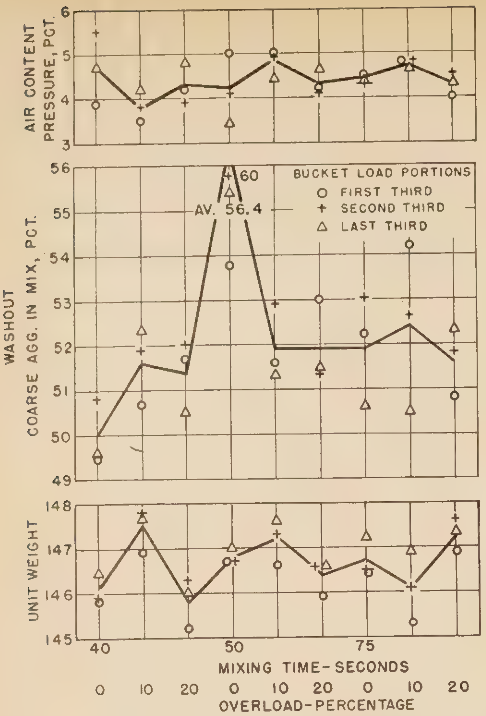


Figure 18.—Test determinations on uniformity of concrete in Ohio project No. 1.

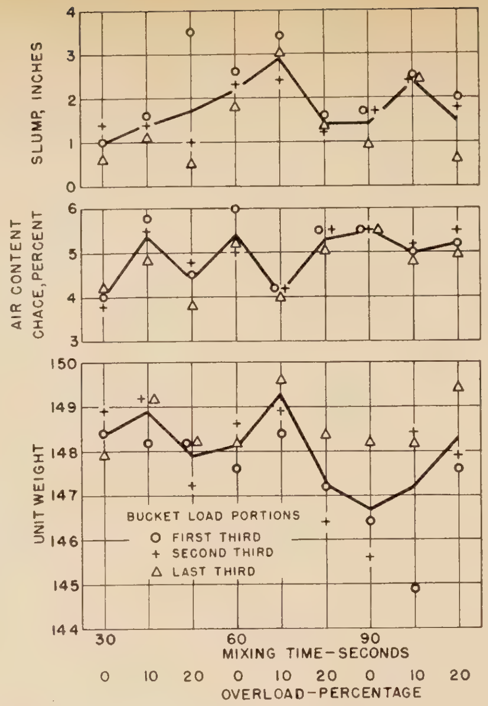


Figure 19.—Test determinations on uniformity of concrete in Virginia project No. 1.

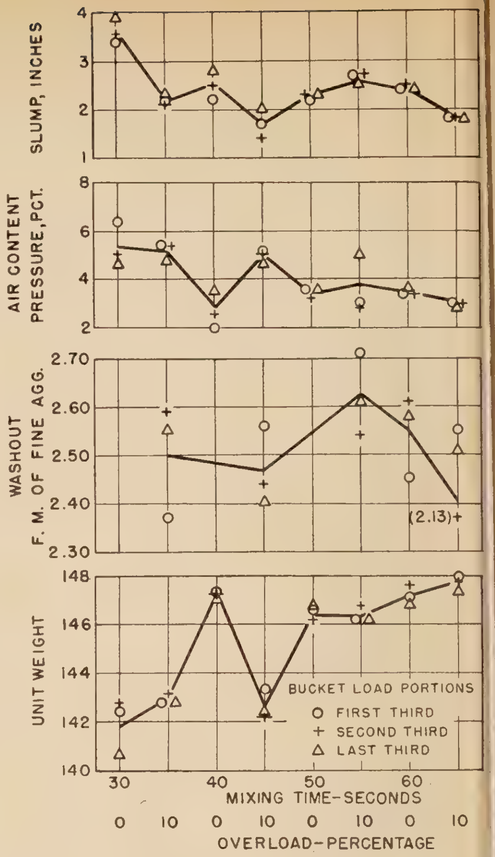


Figure 20.—Test determinations on uniformity of concrete in the West Virginia project.

Virginia project No. 1

It was reported for Virginia project No. 1 that the concrete was harsh and difficult to finish but this was corrected during the study. However, some of the variations of the data shown (fig. 19) may have been caused by this condition. Consequently, only a few comments on these data may be warranted.

It is interesting to note that the unit weight of the 30-second concrete was reasonably uniform, and that greater variations within batches were found for concrete mixed for 90 seconds. On the other hand, the air content for the 30-second concrete varied more from batch to batch than for the 90-second concrete. In the slump tests, the concrete mixed for 30 seconds with a 20-percent overload had a wide range between portions of the bucket load, but this could have resulted from use of the harsh concrete.

West Virginia

The study in West Virginia (fig. 20) was hampered by cold weather and therefore some of the washout tests were not made. The notable variations in unit weight were in close agreement with corresponding variations in air content and slump. In general, the concrete mixed for 50 or 60 seconds was more uniform among batches than the concrete mixed for shorter periods, whereas very uniform concrete throughout a bucket load was found for all mixing times.

Dual-Drum Paver Productivity: A Motion Picture

The Bureau of Public Roads, U.S. Department of Commerce, recently produced a new motion picture, *Dual-Drum Paver Productivity.* The film, based on field research studies conducted by Public Roads, provides evidence that many contractors can substantially increase job output for any given set of job conditions. The key lies in better control of job operating delays.

Action scenes from a variety of concrete paving jobs illustrate job conditions and performance factors encountered where paver productivity ranged from low on some jobs to outstanding on others. Illustrations show how batch plant efficiency and capacity as well as haul road variables affect the size of hauling fleet required to supply the paver. Numerous operating delays are highlighted to show how, and to what extent, they effect paver productivity. Actual job scenes show how these delays have been held to a minimum on high production jobs. The simultaneous showing of contrasting action scenes effectively highlights fast versus mediocre batch truck dumping performance at the skip.

Dual-Drum Paver Productivity is a 16-mm. sound and color film with a running time of 30 minutes. Prints may be borrowed for showings by any responsible organization by request addressed to Photographic Services, Bureau of Public Roads, Washington 25, D.C. There is no charge except for the express or postage fees. Requests should be sent well in advance of the desired showing, and alternate dates should be given if possible. Immediate return after each showing is necessary, so that all requested bookings may be fulfilled.

Prints of the film may be purchased at $122.83 per copy, the price including film, reel, can, and shipping container, and postage within the United States. Inquiries should be addressed to Photographic Services, Bureau of Public Roads, Washington 25, D.C. Payment should not be sent with the inquiry.

How a Dual-Drum Paver Operates

The accompanying series of sketches illustrates the functioning of a dual-drum paver—the machine generally used on-site to mix portland cement concrete for highway pavement—by following a single batch of cement and aggregate completely through the paver. The steps described below are keyed to the Roman numerals at the left of the sketches.

Step I.—The skip is up and batch B is entering compartment 1. Batch A, already in compartment 2, continues mixing. The transfer and discharge chutes are both closed. The empty bucket is returning along the boom.

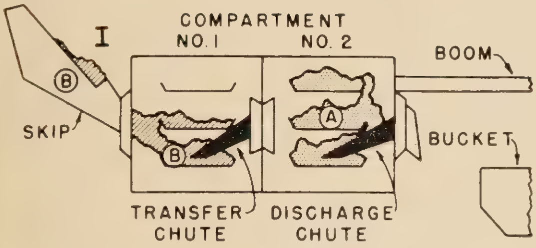
Step II.—Batches B and A continue mixing in compartments 1 and 2, respectively. The skip is down and is receiving batch C from the batch truck. The empty bucket has returned. The transfer and discharge chutes are still closed.

Step III.—The discharge chute has opened, and batch A is being discharged from compartment 2 to the bucket. Batch B continues mixing in compartment 1, and batch C is in the skip, which is still on the ground. The transfer chute is still closed.

Step IV.—The discharge chute has closed and batch A is in the bucket, riding out the boom to be dumped. As the discharge chute closed, the transfer chute opened, and batch B is being transferred from compartment 1 to compartment 2. The skip is moving upward with batch C. These four steps complete one paver cycle.

Steps V, VI, VII.—These steps correspond exactly to steps I, II, and III, respectively. They are included in the series to show the progress of batch B through the paver from the skip, in step I, to the bucket, in step VII.

I



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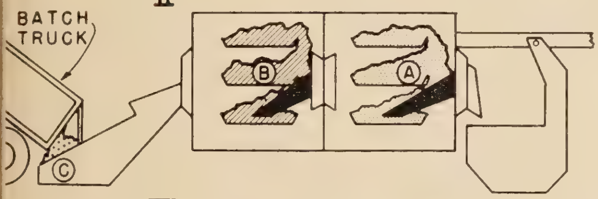

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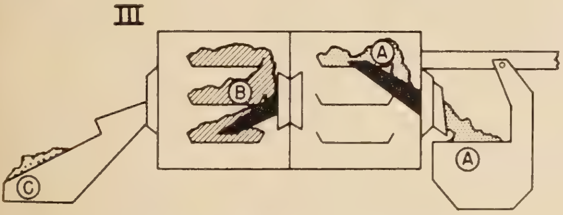

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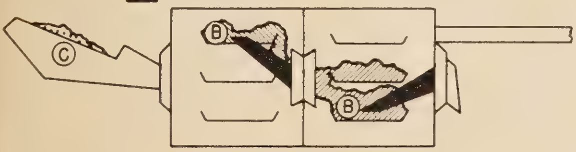

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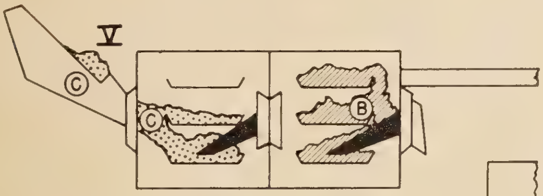

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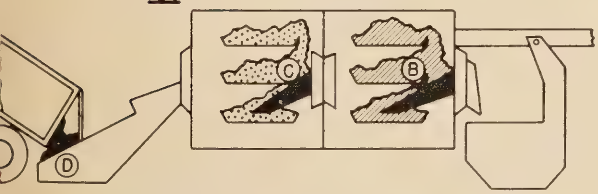

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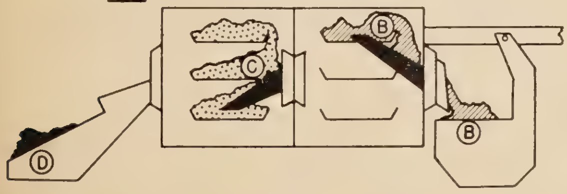

The batchmeter

The sequence of steps in the paver cycle is controlled by a batchmeter, a timing device which, at preset time intervals, actuates the successive operations of the paver or signals to the operator that certain operations can proceed. While there is a variety of types, most batchmeters have generally common principles.

With one popular type, the operator engages a control lever on the batchmeter (or keeps it engaged) to begin the paver cycle. The batchmeter then automatically starts the skip hoist, charges water into the drum, and closes the transfer chute. Next the meter signals when the discharge should be made, and the operator opens the discharge chute (if the bucket is ready). Then the meter, at the proper time interval, automatically closes the discharge chute and opens the transfer chute. As the discharge chute closes, and if the batch truck has emptied the next batch of material into the skip and moved clear, the operator engages the batchmeter control lever (or keeps it engaged) and the next cycle begins.

With another popular type of batchmeter, the operator raises the skip which, on its way up, trips a lever which starts charging water into the drum, actuates the meter, and closes the transfer chute. After a preset time interval the batchmeter automatically opens the discharge chute, unless the operator intervenes because the bucket is not in position. Once the discharge chute has been opened, the batchmeter automatically closes it and opens the transfer chute. At the same time the meter signals to the operator that he can start the next cycle.

Mixing time

The time settings of the batchmeter theoretically control the mixing time which, for any one batch, is the sum of the times it spends in each of the two compartments. Mixing time is usually defined as beginning when all solid materials have entered the drum. This entry time takes from 3 to 11 seconds from the time the transfer chute closes, depending on the nature and moisture content of the aggregates. Some mixing specifications exclude the time of transfer of the batch from the first compartment to the second, which should take about 9 seconds.

The batchmeter cannot, of course, overcome operating difficulties which delay either charging or discharging. If, at the proper moment, the skip is not ready to go up, or the bucket is not in position to receive a mixed batch, the batchmeter timing device is stopped. When the batchmeter resumes, it runs out the full preset amount of the time interval that was interrupted. During the delay, however, the drum continues to turn on "unmetered" time. As a consequence, overtime mixing occurs, usually for the batch in the second compartment. Thus the true mixing time of any batch is the full preset time of the batchmeter plus any additional time occurring because of delays.

It should be noted that the batchmeter is a mechanical device working under adverse conditions of dust, moisture, and heavy vibration, and cannot be expected to parallel the precision timing of a jeweled watch. In addition, it cannot be ignored that the batchmeter's preset timing can be varied or nullified through actions of the paver operator, either inadvertent or deliberate.

Dual-Drum Paving: Cost vs. Mixing Time

BY THE HIGHWAY NEEDS AND ECONOMY DIVISION
BUREAU OF PUBLIC ROADS

Reported [1] by MORGAN J. KILPATRICK,
Chief, Construction Economy Branch

Skilled paving contractors have consistently produced portland cement concrete in dual-drum pavers with controlled mixing time of 45 seconds or less, including transfer time. The increased tempo required for operating the paver with a short cycle and the consequent short mixing time has been achieved in part through use of larger and faster batch trucks, and in part through the contractors' demonstrated awareness of the importance of eliminating unnecessary delays which consume valuable production time.

Monetary savings ranging from 10 cents to $3 per cubic yard of concrete might be realized if mixing time specifications were reduced to 45 seconds from their present levels of up to 120 seconds. In the current highway program, millions of dollars might thereby be saved annually.

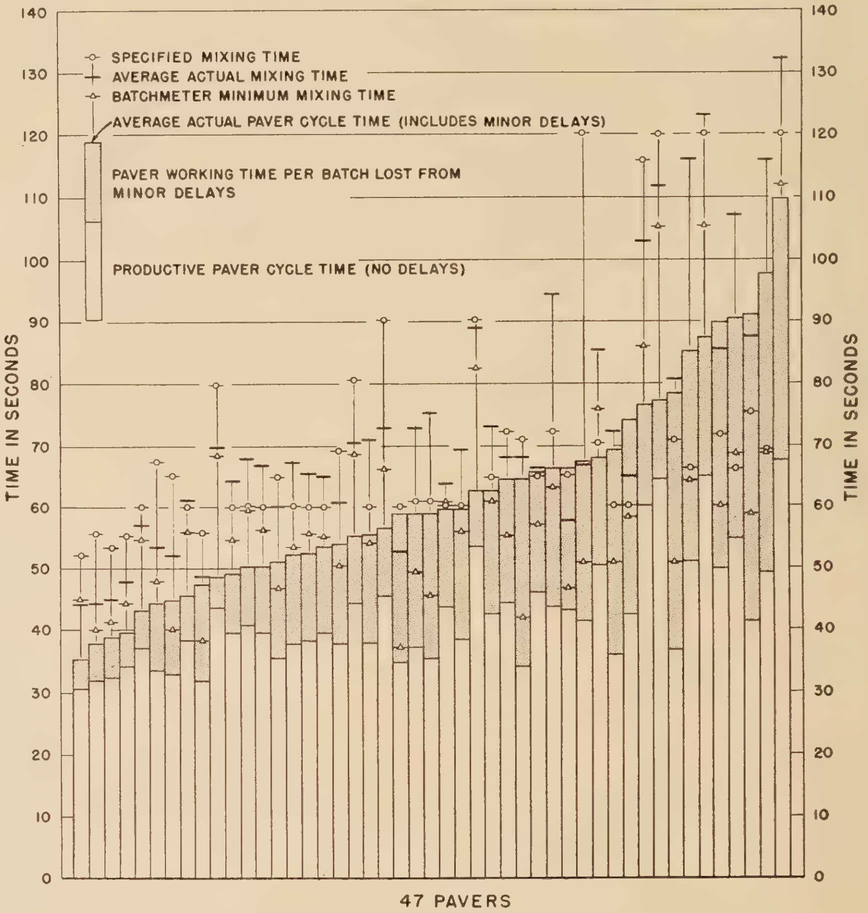

Figure 1.—Performance comparison of 47 dual-drum pavers.

Bureau of Public Roads on-the-job studies of the production of portland cement concrete for highway pavements indicate that some contractors, through adroit management and use of good and well-maintained equipment, achieve sustained high rates of production with dual-drum pavers. The fast paver cycle thus shown to be practical also results in a shorter mixing time for the concrete—less than is now specified by many contracting authorities.

To the engineer the fast cycle poses a problem—that of quality control, usually expressed in terms of mixing time. This is the subject of the article *Study of 34–E Dual-Drum Pavers,* appearing on page 1 of this issue of PUBLIC ROADS, in which it is shown that the longer mixing times now commonly specified can be appreciably reduced without affecting the quality of the concrete.

But there is another consideration involved in the fast cycle—that of economy, which is the subject of this article. Starting from a basis of factual knowledge, it will be demonstrated theoretically that reasonable reduction of specified mixing time will result in the production of concrete, by efficient contractors, with savings ranging up to as much as $3 per cubic yard. Related to the huge highway program now under way, such unit reductions in cost have the potential of saving millions of dollars annually.

Definitions

For clarification, the following definitions are offered. The reader is also referred to the short descriptive article, *How a Dual-Drum Paver Operates,* on page 11 of this issue.

Paver cycle.—The paver cycle is the sequence of paver operations from one charging of the drum to the next.

Skip cycle.—The skip cycle includes those steps of the paver cycle in which the skip is raised, the batch is charged into the drum, and the skip is lowered to the ground where it is then ready to receive the next batch of material dumped by the batch truck.

Mixing time.—As used in this article, mixing time is the time interval from complete entry of a batch of cement and aggregate into the drum to the beginning of discharge of the same batch into the bucket, including transfer time between the two compartments of the drum. (In the article on p. 1, for reasons explained therein, transfer time was excluded from mixing time.) For any given paver cycle, there is a maximum mixing time that can be obtained when the paver is adjusted and operated in a manner consistent with the manufacturer's recommendations. In this article it is assumed that paver operations are in accord with such recommendations.

Key to Fast Paver Performance

In the production of portland cement concrete with dual-drum pavers, a short paver cycle means short mixing time and reduction of the time available in which to perform essential operations at the paver. When the paver cycle is extended by delays a longer mixing time inevitably results, thus nullifying the timesaving advantages of operating with a short cycle. Most delays become apparent at the paver skip and it is here that one can find not only a place to measure qualitatively the contractor's management but also the clue to interdependence of mixing time and batch-truck performance.

The key to fast paver performance thus centers around the ability of the paver operator to run a short skip cycle, the batch-truck driver to dump his batches into the skip on schedule, and to a lesser degree on the coordi-

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[1] This article was presented at the 39th annual meeting of the Highway Research Board, Washington, D.C., January 1960.

nation among these and other operations in front of and behind the paver. Delays resulting from careless or sluggish performance by either the paver operator or the batch-truck driver, and to a lesser extent by others, can effectively stifle the orderly flow of material, extend the paver cycle, and disrupt both supporting and dependent operations.

If the paver operator is slow in lowering the skip, the time remaining for the batch-truck driver to dump his next batch in the skip may not be enough to prevent a delay from occurring, even though he may perform his job well. If, on the other hand, the batch-truck driver fails to keep his truck close to the skip between batches, does not back up promptly when the skip comes down, or fails to have the dump bed raised or at least started up before backing to the skip, he may be too slow in disposing of his batch. The paver operator will then be delayed in raising the skip to begin a new cycle. In each case the paver cycle is extended by the delay, and mixing time is thereby increased.

Many contractors have successfully mastered the problems of getting essential coordination and performance at the skip, as well as keeping attendant supply lines moving. On one markedly successful operation, sustained production by the paver was recorded at a rate of 98 batches per hour. For intermittent periods lasting up to 2 hours, a 110-batch rate was attained. In other words, a batch of concrete was discharged by the paver every 33 seconds, including delay time. When a small number of extended delays, due to lack of batch trucks, was eliminated from the timing, production was at the remarkable rate of one batch every 30 seconds. Remember, this was an average for extended periods and included minor delays. When no delays occured, individual paver cycles were being completed in 24 seconds or even less, with a mixing time of about 27 seconds.

The operation just cited may seem remarkable, but it indicates what can and is being done. Figure 1 shows the performance data for 47 dual-drum pavers on which production studies, usually of 2–4 weeks' duration, were made by the Bureau of Public Roads. Note that each of the four jobs with the fastest performance had a job average cycle time, including minor delays, of less than 40 seconds. It will be seen that on many other jobs batchmeter settings were sufficiently short that a cycle time of less than 40 seconds could have been achieved if the minor delays had been reduced or eliminated.

Relation of Mixing Time to Paver Cycle

The design of the dual-drum paver is such that two batches are mixed simultaneously during a portion of each paver cycle. The mixing time that can be obtained with any given paver cycle is expressed by the formula:

Mixing time $= 2X - D - T - C + L$

Where:

X = paver cycle time.

D = discharge chute open time (typically 9 seconds).

T = transfer chute open time (typically 9 seconds).

C = charging lag time, from close of transfer chute when skip approaches vertical until all solid material is in the drum (job averages of 4 seconds have been attained with dry aggregates).

L = discharge lag time, from opening of discharge chute until concrete appears (averages 1 second).

Obviously, any increase in the time taken for the three elements, D, T, and C, will reduce mixing time in relation to the paver cycle time.

As an example of use of the formula, with a 33-second paver cycle and the indicated values:

Mixing time $= (2 \times 33) - 9 - 9 - 4 + 1 = 45$ seconds.

As previously noted, performance records have shown that on at least one job paver cycles could be completed regularly in 30 seconds which, according to the formula, provided a maximum mixing time of 39 seconds. With the occasional 24-second cycle attained on the job, the mixing time was 27 seconds.

Requirements for a Fast Paver Cycle

The very fast paver-cycle values and consequent mixing times just cited represent actual performance of a single, rather unusual job. An analysis of the performance requirements for maintaining a short paver cycle, based on averages obtained on a number of fast-moving jobs, demonstrates what is fully practical of achievement.

During the paver cycle the skip must be raised, the mixing drum charged, the skip returned to the ground, and then the skip reloaded. This skip cycle took an average of 20 seconds on all jobs studied and often was accomplished regularly in 15 seconds, but seldom in less. The difference in length of time between the skip cycle and the full paver cycle is available for reloading the skip. To do this, the batch truck must back up and cover the skip, dump its batch, and pull away. The paver operator must see that the truck is clear before starting the skip up to begin a new paver cycle.

It was found, in the Public Roads studies, that batch trucks on fast-moving jobs consistently backed into position to dump into the skip in 2 or 3 seconds. As shown in figure 2, it was observed on a very fast job (curve A) that the trucks dumped and pulled away in 3 to 5 seconds. On several other fast jobs (curve B) up to 85 percent of the batches were dumped in less than 8 seconds. It should be noted, however, that such performances were attained only with 4- and 5-batch trucks. The best performance with 2-batch trucks (curve C) took 15 seconds or less for 85 percent of the batches. On other fast jobs the 2-batch trucks took 20 seconds or less for 85 percent of the batches (curve D).

It was also found that after a batch truck cleared the skip, the paver operator took about 2 seconds before he actually started the new cycle.

Combinations of these figures represent possible paver cycle time, from which mixing time can be derived. For example, really fast

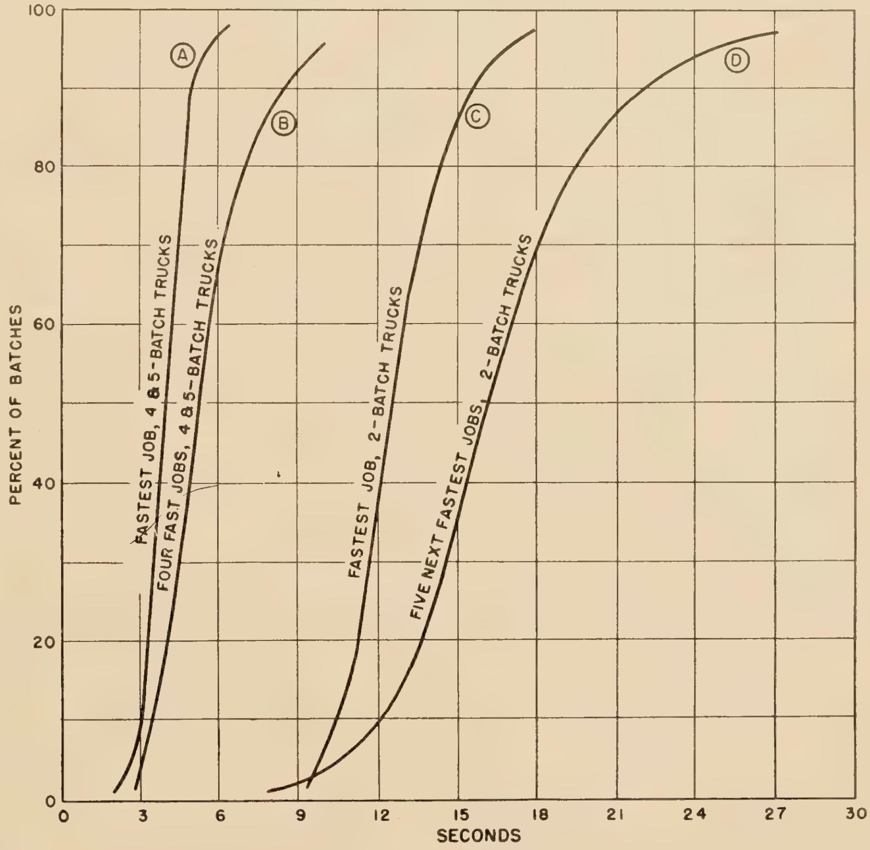

Figure 2.—Cumulative frequency distributions of average time to dump one batch into the paver skip and get the truck out.

operation would include 3 seconds for backup, 5 for dumping, 2 for operator's reaction, and 15 for the skip cycle, totaling 25 seconds for the paver cycle and producing a 29-second mixing time. A more representative fast job using 4-batch trucks, with 8 seconds for dumping and 17 for the skip cycle, would have a 30-second paver cycle and a 39-second mixing time.

With 2-batch trucks the fastest dumping was 15 seconds which, with the 15-second skip cycle time, gives a 35-second paver cycle and a 49-second mixing time. More representative of typically fast operation with 2-batch trucks is an 18-second dumping time and a 17-second skip cycle, producing a 40-second paver cycle and a 59-second mixing time.

Long Cycles, Long Delays

Two methods have been used in this article in arriving at a minimum paver cycle time and the resulting mixing time. In the first, data recorded on one very fast operation revealed that a paver ran for a 2-hour period with an average paver cycle of 30 seconds (excluding time lost in a few extended delays), permitting a mixing time of 39 seconds. Mixing time was further reduced to 27 seconds for individual batches.

In the second approach, paver cycle time and mixing time were derived from performance data obtained from a number of well-operated jobs. A 30-second cycle was found to be entirely practicable and a 25-second cycle was attainable, with 4-batch trucks. These cycles produced mixing times of 39 and 29 seconds, respectively. However, no allowance was made for delays in the calculations.

In considering this problem of delays, it was generally found that more time per batch was lost through delays by pavers with a long paver cycle than was lost by those with a short paver cycle.

This paradoxical fact is evident in figure 3. Curve A in the figure represents the average paver cycle time of each of the 47 jobs studied, including minor delays, while curve B represents paver cycle time excluding delays, averaged in groups of five jobs. Curve C, the difference between the values of A and B, represents the delay time per cycle. It will be noted that the longer the paver cycle time, the greater was the amount of delay, and that conversely the jobs with the fastest cycles had the smallest amount of delay.

The most logical explanation for this seemingly paradoxical trend is that as the permissible production potential increased with shorter paver cycles, management became more alert and responsive to the needs and possibilities for reducing or eliminating delays.

Cost Factors

It is an inescapable fact that delays increase costs. With equal assurance it can be said that mixing time requirements influence costs. The cost of operating a paver outfit tends to be fixed and is almost independent, within reasonable limits, of the rate of production. Labor and equipment costs amount to about $350 per hour, on the average. When production is 50 batches per hour, then, the cost is $7 per batch. However, if production goes up to 70 batches per hour, which is entirely practicable with good batch-truck performance, the unit cost drops to $5 per batch. Thus, with such production improvement, the cost reduction per batch is $2. This amount is a function of the percentage increase or decrease in production and the per-batch difference will diminish as additional batches are added to the hourly production rate. Thus, an increase of 40 batches per hour, from 50 to 90, results in a unit cost of $3.90 per batch, and a reduction in cost of $3.10 per batch. In other words, the first increase of 20 batches is worth $2 per batch, but in the increase of 40 batches the second 20 are only worth $1.10 per batch.

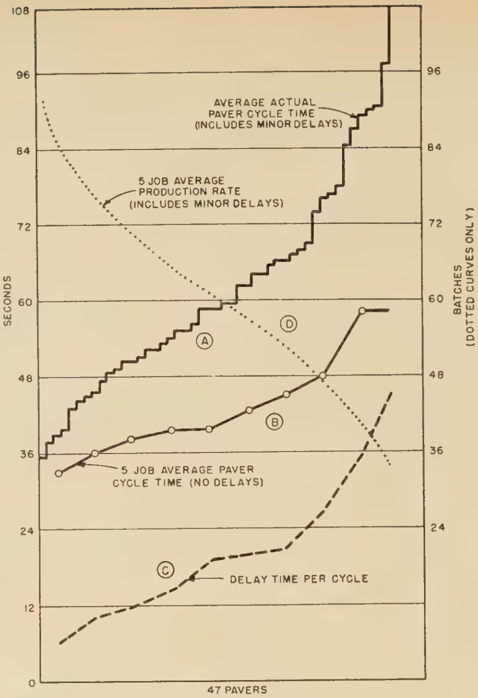

Figure 3.—Comparison of average paver cycle times, including and excluding delay time, for 47 dual-drum pavers.

Data presented in figure 3 also show that hourly production rates, including time lost in minor delays (those of less than 15 minutes each), go down from a high of about 92 batches to a low of 35 per hour as average paver cycle time is increased.

Using data from which figure 3 was derived, for only those pavers which had 50- and 120-second mixing time specifications in force, the production rates averaged 85 and 40 batches per hour, respectively. However, these rates were reduced to 75 and 34, respectively, when the time basis includes certain major delays (those in excess of 15 minutes each) which occurred while a full labor force was employed on these jobs. Using a fixed cost of $350 per hour, the cost differential between 75 and 34 batches per hour becomes $5.63 per batch.

Effect of overload on cost

With a fairly common overload of 10 percent, resulting in a 37.4-cubic-foot batch, the cost differential becomes $4.06 per cubic yard of concrete. Further adjustment is desirable, under certain circumstances, to account for the variation in batch sizes used for different mixing times. In instances where 50-second mixing time is used a 20-percent overload is usually allowed. This will yield a 40.8-cubic-foot batch. Thus, the difference in production cost becomes $4.34 per cubic yard when comparing 40.8-cubic-foot batches at a rate of 75 batches per hour with 37.4-cubic-foot batches at a rate of 34 batches per hour.

Effect of increased production on cost

It may be reasonably assumed that hourly production costs are somewhat less when producing 34 batches per hour than when producing 75. The effect of this consideration is to reduce the cost differential. It could be assumed, for example, that the $350 per hour cost used is for a rate intermediate between 75 and 34 batches per hour, and that the cost would be 10 percent less for the 34-batch rate and 10 percent more for the 75-batch rate. The differential in production cost between the two rates, then, instead of being $4.06 per cubic yard, would drop to $2.98 for 37.4-cubic-foot batches.

It would be impractical to obtain specific cost data for every possible rate of output and, in fact, since a number of assumptions must be made, it would be pointless for the purpose here intended. The unit costs developed above, while based on some factual information and reasonable assumptions, are admittedly hypothetical. However, the method does establish a means for computing production cost differentials due to variations in mixing time specifications.

Data from Federal-aid records

Another source of information on this subject is the data compiled from bid prices per cubic yard and specified mixing times for portland cement concrete placed on Federal-aid projects.

The fairly uniform relation of the two is shown (for the year 1957, the latest available) in figure 4. It will be noted that from a low bid price of $15.75 per cubic yard for 50-second specified mixing time there is a gradual increase of both price and mixing time up to $23.15 for 120-second mixing—a difference, from low to high, of $7.40 per cubic yard. The difference is more apparent than real, however. If it actually is a true indication of the differential resulting from the range in mixing time, then it also means that the labor and equipment cost of running a paver outfit exceeds $700 per hour. Such an hourly cost is unlikely, if not impossible, and cannot be accepted at face value as representing an average.

A more plausible explanation of the $7.40 differential appears to be that part of it could be charged to the mixing time differences and that the balance represents costs generated by regional differences in design practices, hauling distances, and variations in labor productivity, wage rates, climatic conditions, and materials costs. The last mentioned, in particular, influence bid prices but not paver production costs. It is perhaps not without

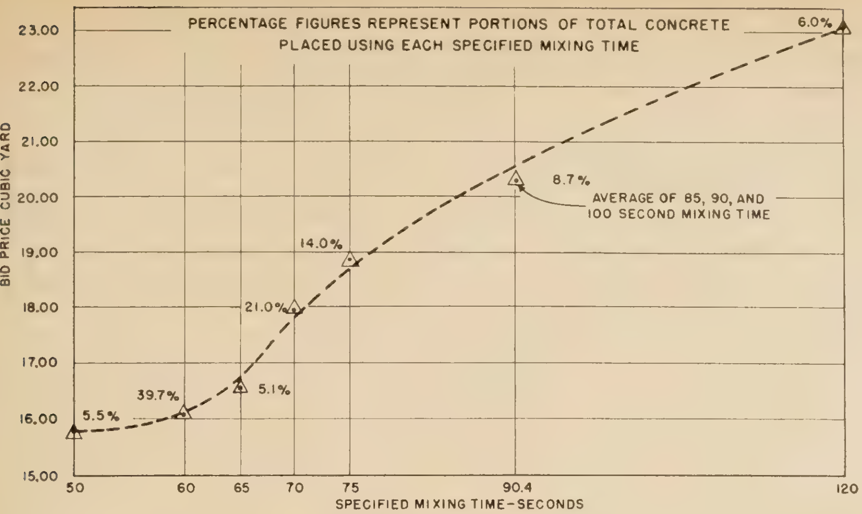

Figure 4.—Distribution of bid price per cubic yard of concrete production according to specified mixing times on Federal-aid projects in 1957.

significance that most States specifying longer mixing times are in the Northeast, whereas those using shorter mixing times are in the South and Southwest where year-round work is possible.

Calculation of Potential Savings

The basic objective of this article is to develop quantitatively the potential savings which might result from reduction in mixing time. It is believed that the fixed cost of $350 per hour for labor and equipment, discussed earlier, offers the most plausible starting point. To allow for variance in production in relation to mixing time, the previously discussed assumptions were used: Production of 34 batches per hour with a 120-second mixing time would cost 10 percent less than the $350 base; production of 75 batches per hour with a 50-second mixing time would cost 10 percent more. Intermediate values were taken from a straight-line projection through these points.

With these premises, the production costs per cubic yard of concrete were calculated for a series of mixing times. These are shown in the first two columns of table 1. It was then a simple matter to derive the approximate production cost reductions that are possible by decreases in mixing times, shown in the remainder of table 1.

It should be remembered that the mixing times shown in table 1 include transfer time. For comparisons with data in the article on page 1, which exclude transfer time, about 10 seconds should be subtracted from mixing times used in table 1. As pointed out in the article on page 1, mixing time of 40 seconds produced concrete with very little strength loss as compared with 60-second mixing; and 30-second mixing time resulted in a strength loss of 5 or 6 percent. In terms of table 1, these values would be 50- and 40-second mixing times, compared to a 70-second base.

Admittedly, it is a bold step to apply the theoretical calculations in table 1 to an entire highway program, but by so doing the point can be driven home. The distribution of concrete production according to specified mixing time on Federal-aid projects (in 1957) is shown in figure 4. It is worth noting, incidentally, that the weighted average of all mixing times was 70 seconds. In the Federal-aid Interstate and primary highway programs, 18 million cubic yards of pavement concrete were laid in 1958, and 20 million would seem a conservative figure to use now.

Working from these bases, the theoretical annual savings in the Federal-aid Interstate and primary programs that would result from reductions in mixing time can be computed. In the first place, if only all higher than 70-second mixing times were reduced just to the 70-second level, the resultant annual savings would total about $4½ million; reduction of all higher mixing times to 60 seconds would save nearly $7½ million. If all mixing times higher than 50 seconds were brought down to the 50-second level, which would result in very little concrete strength loss, the total annual savings would be over $11 million. Similarly, for reduction of all higher mixing times to a 40-second mixing time, which would result in a strength loss of 5 or 6 percent, the savings would total $15 million. It will be noted that the reductions of higher mixing times by 10-second intervals produced increasing increments of savings. Further reductions in mixing time, however, would bring diminishing returns in savings. Such further reductions might also bring unacceptable reductions in concrete strength.

There is no question that the assumptions used here are speculative, although they are based on foundations of fact and considered judgment. There is also no question that a considerable proportion of the contracting industry is capable of converting into increased production the time that would be saved by shorter specified mixing times than are now prevalent. The rate of production is to a large extent governed by the performance of the paver operator and the batch-truck driver. Four-batch trucks, able to maneuver quickly and safely with fully loaded beds in hoisted position, are essential for shorter paver cycles, and they are coming into common use. It can be said that the industry is ready for shorter paver cycles, and resulting shorter mixing times of 50 seconds or less. It is encouraging to note that some States have recently reduced their specified mixing times, and others are now contemplating such changes.

Table 1.—Production cost[1] per cubic yard of concrete according to mixing time, and theoretically possible cost reduction resulting from decreases in mixing time

Base mixing time (*seconds*)	Production cost per cubic yard	Cost reduction per cubic yard possible by decreasing base mixing time to—								
		90 seconds	75 seconds	70 seconds	65 seconds	60 seconds	50 seconds	45 seconds	40 seconds	35 seconds
120	$6.69	$1.85	$2.36	$2.51	$2.64	$2.77	$2.98	$3.08	$3.17	$3.25
90	4.84	------	0.51	0.66	0.79	0.92	1.13	1.23	1.32	1.40
75	4.33	------	------	0.15	0.28	0.41	0.62	0.72	0.81	0.89
70	4.18	------	------	------	0.13	0.26	0.47	0.57	0.66	0.74
65	4.05	------	------	------	------	0.13	0.34	0.44	0.53	0.61
60	3.92	------	------	------	------	------	0.21	0.31	0.40	0.48
50	3.71	------	------	------	------	------	------	0.10	0.19	0.27
45	3.61	------	------	------	------	------	------	------	0.09	0.17
40	3.52	------	------	------	------	------	------	------	------	0.08

[1] Calculated production costs for labor and equipment. Materials not included.

Time and Fuel Consumption for Highway-User Benefit Studies

BY THE DIVISION OF TRAFFIC OPERATIONS
BUREAU OF PUBLIC ROADS

Reported[1] by PAUL J. CLAFFEY
Highway Research Enginee

Travel time and fuel savings are two of the benefits that accrue to highway users through highway improvement. Timesavings result whenever highway improvements reduce travel distance, permit higher speeds, or reduce the frequency of speed changes. Fuel savings are effected when improvements reduce travel distance, mitigate any of the resistances encountered by moving vehicles, or reduce the frequency of stop-and-go and slowdown operations.

During 1959 a study of passenger cars and single-unit trucks was conducted to determine the effect of variation of highway surface type and operating speeds on fuel consumption, and the effect of the elimination of both a stop-and-go and a slowdown operation on fuel and time consumption at various operating speeds. The study also included determination of the fuel consumed while vehicles were stopped with engine idling. Graphic and tabular material developed from the study and presented in this article will serve in estimating time and fuel benefits accruing through highway improvements.

BECAUSE there was a lack of complete data on the variation in time and fuel consumption for all vehicle types and weights, needed for use in highway-user benefit studies, the Bureau of Public Roads undertook a study in 1959 to determine the effects of highway surface conditions and traffic operations on passenger cars and single-unit trucks. The results of that study, arranged for practical use, are presented in this article. Some of the more general findings, which will also be of interest, are reported in the following paragraphs.

General Findings

Much of the savings in time and fuel enjoyed by users as a result of highway improvement arises because of increased vehicle speeds, smoother riding, and reduction of the frequency of stop-and-go and slowdown operations. On paved surfaces the rate of fuel consumption of passenger cars and single-unit trucks (fig. 1) was found to vary inversely with speed for the slower speeds, with the optimum at 25–35 miles per hour, varying according to vehicle type and gross weight. At higher speeds the rate of fuel consumption increased. On gravel surfaces the relation between rate of fuel consumption and speed (fig. 2) was similar, except that the lowest rate of fuel consumption was at 20–25 miles per hour.

The effect of upgrading from gravel to concrete on the rate of fuel consumption (fig. 3) increased with vehicle speed. At speeds of 15 miles per hour the increase in fuel consumption for the gravel surface was less than 7 percent, but at 45 miles per hour it was over 20 percent for passenger cars and pickup trucks and over 30 percent for single-unit trucks with gross weights of 10,000 pounds or more.

Both the additional time and fuel consumption for stop-and-go operations (figs. 4 and 5) increased uniformly with speed. At any speed the excess time consumption varied directly with weight-horsepower ratio. The additional fuel consumption varied with gross weight for single-unit trucks. The passenger car used in the study consumed more fuel than the heavier pickup truck at all speeds, probably because it was equipped with an automatic transmission while the pickup truck had a manual transmission.

The time consumption for a slowdown of 10 miles per hour (figs. 6 and 7) varied inversely with vehicle speed. The additional fuel consumption of passenger cars for slowdowns varied directly with speed for speeds up to 50 miles per hour, while for single-unit trucks it increased with speed up to speeds of 35–50 miles per hour but decreased somewhat at higher speeds.

Time and Fuel Savings

A major objective of highway-user benefit studies is the evaluation of advantages accruing to users as a result of highway improvements. Two of the more important of these advantages are reduced fuel consumption and reduced travel time. The relation between motor vehicles and the roads they travel is so close that even small changes in the characteristics of the road are reflected in the amoun of time and fuel needed for highway trips Minimum values of travel time and motor-fue consumption are possible only when the roadway is ideally suited for the vehicle and t the traffic volumes in which the vehicle operates.

The ideal highway for such purposes would be straight and level, have a smooth surface and be so designed that the movements of each vehicle would be completely unaffected by the presence of other vehicles. Although in practice no highway would be built to such improbable standards, all improvements are directed toward making highways less remote from this ideal. The improvement of a highway enables highway-users to complete thei trips in less time and frequently with less fue consumption. Highway-user benefit analyses if they are to be complete and accurate, must include consideration of these savings.

Travel time savings are brought about through changes in highway facilities which reduce three elements: travel distance, the number of speed changes, and the time lost at traffic signs and signals. Time savings are also brought about by improvements which permit vehicles to be operated safely at higher speeds. Every mile of travel distance eliminated from the highway-user's trips saves time. Elimination of speed changes, such as stops and slowdowns, saves the time consumed while decelerating and accelerating

Nominal highway speed

Nominal highway speed is defined as the modal operating speed of all vehicles of a given class while moving on sections of a highway where they are not slowed or stopped by highway impedances such as traffic signs and signals, sharp curves, etc. Highway changes which improve sight distance or add to highway capacity generally result in increased nominal highway speeds. On any road carrying a traffic volume equal to or greater than its practical capacity, the nominal highway speeds of vehicles will be increased by providing greater capacity through lane widening or additional lanes.

The nominal highway speed for vehicles having high weight-horsepower ratios will be increased mainly through reduction of grades.

Reduction of resistance factors

All improvements which lessen travel distance and the resistances to movement a

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[1] This article was presented at the 39th Annual Meeting of the Highway Research Board, Washington, D.C., January 1960. Dr. Claffey is an Associate Professor of Civil Engineering, Catholic University.

nstant speed, plus those which reduce speed anges, result in motor-fuel savings, as do iprovements which decrease resistance to hicular movement and reduce the energy quirements needed for operation.

A reduction in resistance to movement and e corresponding reduction in fuel use at any ven speed results through improvement hich effect reduction of surface roughness, duction of rate of rise and fall, and reduc- on of curvature. These improvements, how- er, frequently permit higher operating eeds which, because of greater air and roll- g resistances at higher speeds, result in an creased rate of fuel consumption.

The frequencies of stop-and-go and slow- wn time losses are reduced through the ovision of grade separations and access ntrol to reduce the number of access points d through construction of additional lanes relieve congestion. In addition, the fre- iency of slowdown operations is reduced hen curves sharp enough to require vehicles reduce speed are removed through aline- ent changes.

Savings Used in Benefit Studies

The saving in either fuel or time consump- on due to any one type of highway improve- ient is the difference between the amount onsumed if the improvement were made, nd the amount if the improvement were not iade. Where two or more types of improve- ient are made at the same location at the ame time, the savings for each can be com- uted by assuming that the other improve- ient is already completed. For example, if a ighway reconstruction project involving oth upgrading of surface and reduction of ise and fall is considered, the saving in fuel onsumption for operation on the improved urface rather than on the old surface for the ew rate of rise and fall will be the same egardless of the changed rate of rise and fall; nd the saving due to reduction of rise and all on the improved surface is unchanged by he fact that the surface had been improved.

The difference in fuel saving for the condi- ions before and after an improvement is a rue measure of fuel benefit even when the articular improvement makes possible higher perating speeds which usually increase fuel onsumption. An example is surface improve- ient. When a gravel road is improved with high-type surface, the nominal highway peed will increase. The fuel saving that ighway-users will realize through surface mprovement is the difference between the uel consumption on the old surface at the ominal highway speed for the old road efore improvement, and the fuel consumption t the same speed on the improved surface. The fact that users elect to travel faster on he improved road with a corresponding ncrease in the rate of fuel consumed does ot nullify the saving in fuel use, at the lower peed, made possible by the improvement. Any increase in fuel consumption due to the igher operating speed should be considered eparately and included in benefit studies s a negative fuel benefit.

The analysis of user benefits for any highway improvement project can be made most satisfactorily by computing separately the savings for each type of improvement involved and then totaling them. Care must be exercised when summing the savings that the same saving is not counted twice. For example, where a two-lane gravel road is reconstructed as a four-lane divided highway with high-type pavement, both upgrading the surface and increasing the number of lanes permit higher operating speeds with the consequent reduction of time consumption, but the time saving for the higher speed can be included only once.

Required data

For the computation of time and fuel savings resulting from a planned improvement, certain data are required. First, the average gross operating weight of each class of vehicle and the number of vehicles within each class expected to use the route can be obtained by traffic studies and loadometer studies. Second, the information on planned physical changes of the road can be obtained from investigation of the site and by study of the improvement plans.

A third requirement, the effect each type of improvement has on speeds, frequency of speed changes, and the length of stops or delays, can be obtained partially from reported studies (*1*)[2] and from investigation of the traffic operations at the improvement site.

The fourth requirement, determination of the reduction of resistances to movement at constant speeds, can be made from published graphs illustrating fuel consumption as affected by rate of rise and fall for vehicles weighing 10,000 pounds or more (*2*) and for passenger cars (*3*). These data are limited to only certain vehicle classes and gross operating weights, however, and are not sufficiently comprehensive for a general benefit analysis.

Test Vehicles and Procedures

The time and fuel consumption study undertaken by the Bureau of Public Roads in 1959 involved three vehicles—a passenger car, a pickup truck, and a 2-axle, 6-tire, dump truck. These three classes of vehicles accounted for over 98 percent of the vehicle-miles traveled in 1956 by all highway vehicles other than buses and the larger commercial vehicle combinations.[3] Such vehicles were being studied at the same time and for the same purpose by the University of Washington, with financial assistance from the Bureau of Public Roads (*4*).

Data for the passenger car were obtained for a single loading condition, while data for the trucks were obtained for various weight loads—enough to cover the lower range of gross vehicle weights for single-unit trucks. The passenger-car load consisted of two persons, the driver and an observer. The pickup truck was operated with no load except for the driver and observer, and with a load approximately equal to full load capacity. The dump truck was operated with no load and with one-half full load.

Table 1.—Data for vehicles used in the test operations [1]

Type of vehicle	Gross vehicle weight (pounds)	Engine power		Cross-sectional area [2] (sq. ft.)
		Net hp.	R.p.m.	
Passenger car	3, 850	123	4, 200	33
Pickup truck:				
No load	3, 860	120	4, 000	38
Full load	5, 340	120	4, 000	38
Dump truck:				
No load	10, 200	89	2, 800	54
Half load	15, 300	89	2, 800	54

[1] All vehicles were 2-axle, 6-cylinder vehicles. The passenger car had an automatic transmission; the trucks were equipped with manual transmissions.

[2] Frontal area of vehicle, derived by multiplying overall height by overall width.

The passenger car was a 6-cylinder 1957 standard 4-door sedan with a 3-speed automatic transmission. At the time of the tests it had been in service for 2 years, during which time it had traveled a distance of 30,000 miles. The weight and additional pertinent information for the three vehicles are given in table 1.

The pickup truck used was a 6-cylinder, manual shift 1959 model with a GVW (gross vehicle weight) of 4,900 pounds. The 6-cylinder, 1950 medium-type dump truck had been in service for 50,000 miles. Both trucks were checked on a dynamometer prior to the tests and the efficiency of combustion measured with an exhaust analyzer at a wide range of loads. At the time of the tests the vehicles were operating at near optimum efficiency.

Test run procedures

Data on the time and fuel consumption of these vehicles were obtained from a series of test runs made over a nearly straight section of Virginia route 350 south of Washington, D.C. This is a divided highway with four 12-foot lanes of portland cement concrete, with well-built shoulders of firmly compacted gravel 10 feet wide. The test runs were made between two fixed end points set 8,000 feet

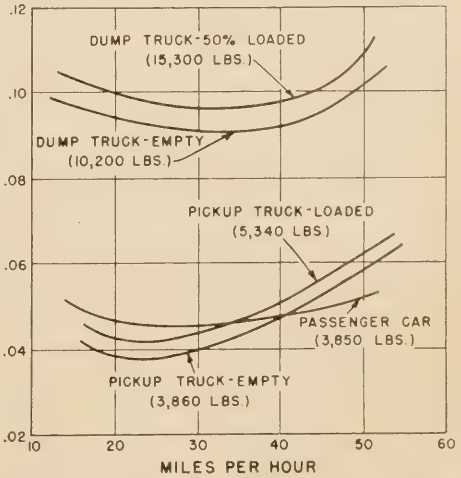

Figure 1.—Fuel-consumption rates at constant speed on a level, straight, concrete surface.

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[2] Italic numbers in parentheses refer to the references on p. 21.

[3] *Traffic and Travel Trends, 1956,* by T. B. Dimmick. PUBLIC ROADS, *vol. 29, No. 11,* Dec. 1957.

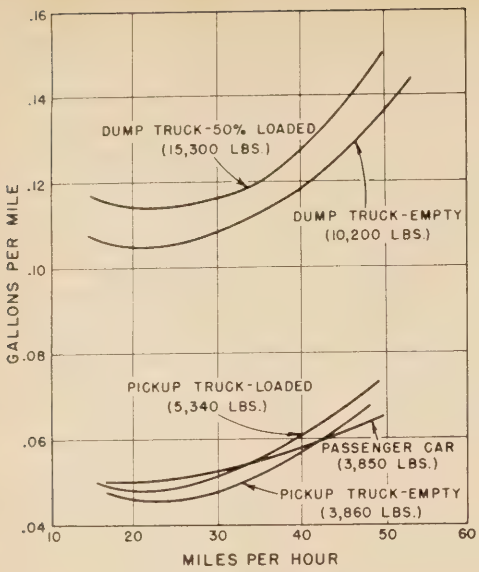

Figure 2.—Fuel-consumption rates at constant speed on a level, straight, gravel surface.

(1.515 miles) apart. These points were at nearly the same elevation and the rate of rise and fall between them was less than 0.2 foot per 100 feet.

The following types of test runs were made between end points of the test section: Constant speed runs on the paved surface at indicated speeds of 15, 25, 35, 45, and 55 miles per hour; constant speed runs on the gravel shoulder at the same speeds; stop-and-go runs on the paved surface at indicated operating speeds the same as for the constant speed runs; and slowdown runs (10 mile per hour speed reduction only) on the paved surface at the same operating speeds. Three runs of each type were made for each vehicle and load in each direction at each of the given speeds. The idling fuel consumption was obtained for each vehicle at engine speeds of 450, 550, 650, and 750 revolutions per minute.

The runs were made by driving the vehicle over the test section, measuring the amount of travel time and fuel consumed between end points and recording the direction of travel, time of day, fuel temperature, and run speed as indicated on the vehicle speedometer. the constant speed runs no other data w taken. On the stop-and-go and slowd runs the vehicle was brought to a stop or speed reduced by 10 miles per hour immediately accelerated back to schedu speed, as many times as possible, passing b end markers at run speed. Additional d recorded for these runs were the time dur which acceleration took place after each s or slowdown, the number of stops and sl downs, and the number of gear changes each acceleration. The rates of speed cha used for both the stop-and-go and slowdo operations during deceleration and accele tion were those of the typical driver un ordinary conditions (*5*).

Recording the date and time made it pos ble to determine wind direction and veloc at the time of each run by reference to wi data collected by the U.S. Weather Bureau a nearby station.

The first step in the analysis of the field d was to compute the true speed of each test r The indicated run speeds, read on the spee

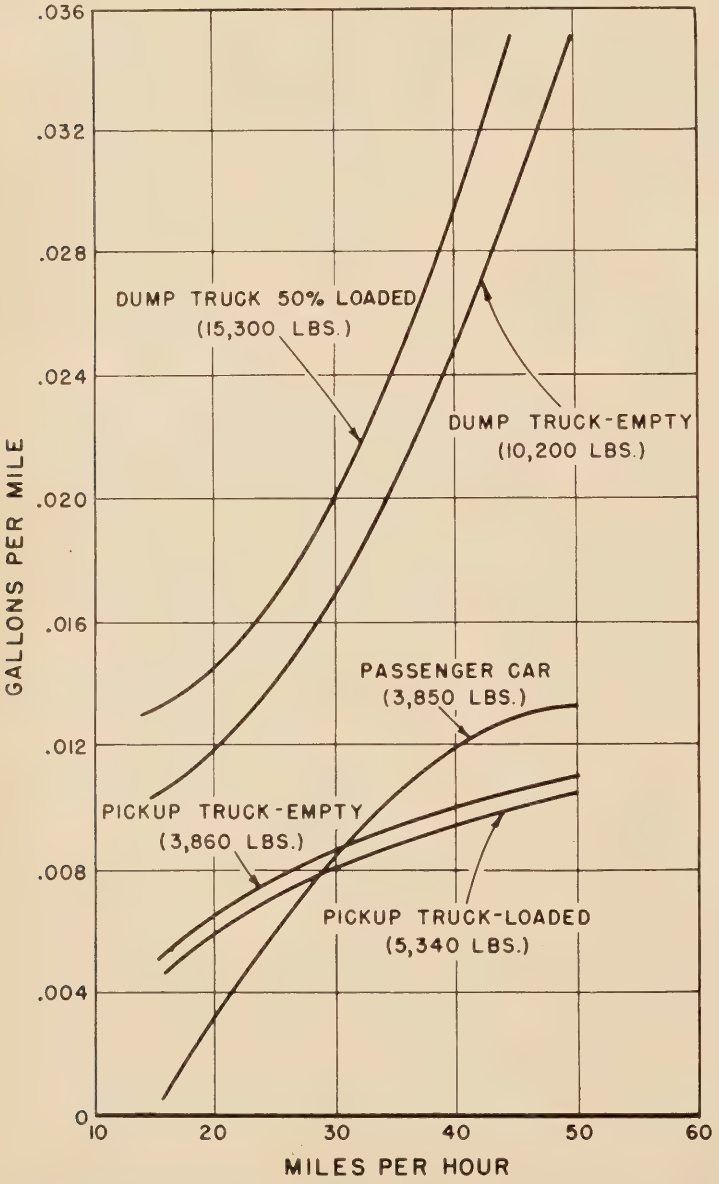

Figure 3.—Savings in fuel consumption at constant speeds effected by improvement from a gravel surface to a concrete surface.

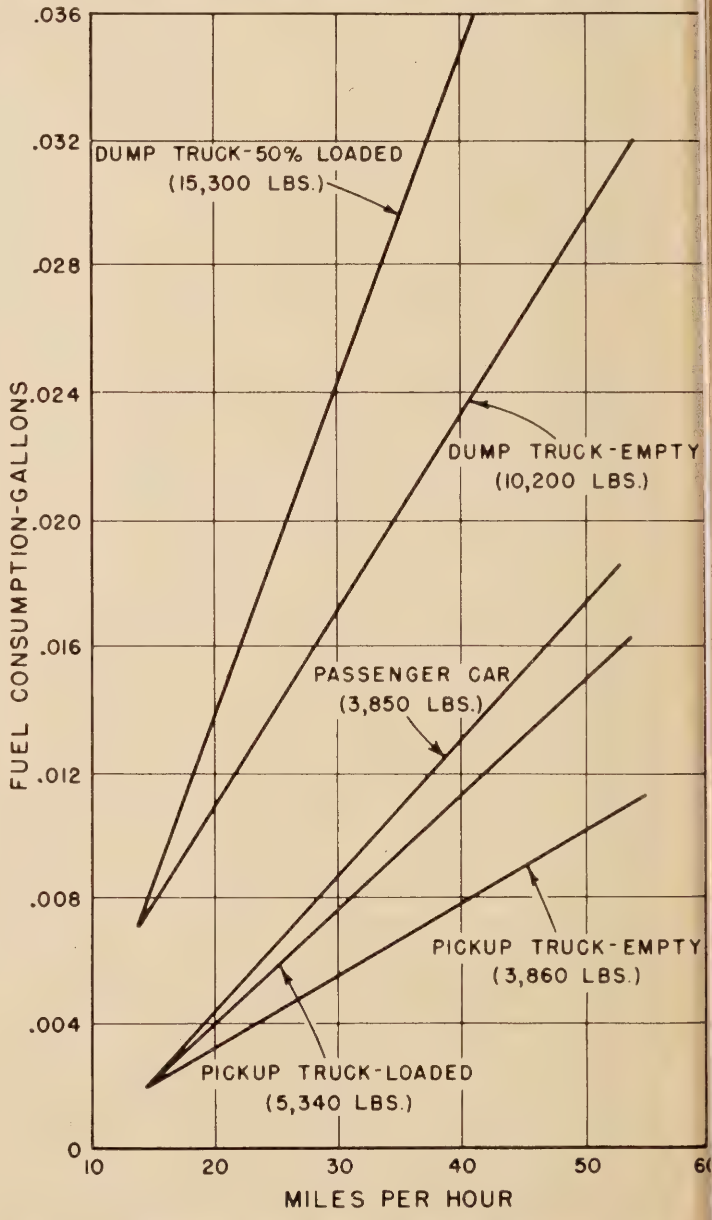

Figure 4.—Excess fuel consumed by a vehicle coming to a stop an then returning immediately to former speed.

neter, were recognizedly inaccurate but were ed during the test because it was easier for e driver to maintain a given speed consist- tly if he had a definite speed to attain rather an attempting to hold the speedometer nee- e at such a point on the dial that the run eed would be the true speed. The true eed was computed from the known run dis- nce and the run time recorded for the con- ant speed runs.

Fuel consumption was measured directly ıd accurately by noting the amount of fuel awn out of the reservoir of a burette type elmeter. Since the volume of fuel measured ıried with the temperature, all fuel readings ere corrected to 30° C. (86° F.)—the average el temperature during the period of the tests.

Application of Test Results

Corrected fuel-consumption values in gallons r mile were computed for each constant eed run on both the paved and gravel sur- ces. Curves drawn from the averages of ese values for each run speed for each vehi- e type and weight, plotted against true speed, e shown in figures 1 and 2.

The curves in figures 1 and 2 may be used to timate the change in rate of fuel consump- on in gallons per mile which will result when ominal highway speeds are increased through ghway improvement on roads carrying affic volumes somewhat less than their ca- ıcity volume. Since nominal highway speed the average operating speed between points here vehicles are slowed or stopped by high- ay impedances, the application of these curves is not restricted by the effect of such highway impedances.

In the case of highway improvements where more lanes are to be added to provide greater capacity, when capacity before improvement is less than the 30th hour volume, figures 1 and 2 may be used to estimate the fuel consumption after improvement when vehicle speeds are relatively uniform. However, the lower speeds before improvement are largely due to congestion and include frequent decelerations and accelerations. The rate of fuel consumption before improvement may be estimated by adding to the values found in figures 1 and 2 the amount of additional fuel consumed by slowdowns. The average number of slowdowns may be determined by making suitable speed-delay studies over the route before improvement, and the additional fuel consumption due to a slowdown may be estimated by using the curves in figure 6 (p. 20).

The curves presented in figure 3 show the fuel savings in gallons per mile effected by improvement from a gravel surface to a paved surface. The ordinates of these curves equal the difference between the fuel consumption for operation on a paved surface and operation on a gravel surface at the same speeds.

In using figure 3, the saving due to surface improvement should be read from the curves for the nominal highway speed of the gravel-surfaced road before improvement. A reduction in road roughness, of course, will permit higher speeds and most users take advantage of this even though higher speeds increase fuel consumption for speeds above approximately 35 miles per hour. It is at the discretion of the highway user whether he operates on the improved surface at the same speed as on the rougher surface and saves on fuel use, or operates at a higher speed and pays for the higher speed (and thus time saving) through increased fuel consumption. In either case the saving is made available to the user. The nominal highway speed of modern vehicles on a gravel or loose surfaced road is between 30 and 35 miles per hour; for any particular road under study it should be obtained by making a spot speed study.

Stop-and-go operations

The additional fuel consumed for a stop-and-go operation was found by dividing the number of stop-and-go operations made on each run into the difference between the amount of fuel used for the stop-and-go run and the average amount of fuel used for the constant speed runs on the paved surface at the same run speed. This difference was the additional amount of fuel used by a vehicle to come to a stop and accelerate back to the constant speed. The fuel consumption curves for stop-and-go operations at various speeds are presented in figure 4.

A similar procedure was used to compute the additional time consumption for a stop-and-go operation. Figure 5 shows curves of excess stop-and-go time consumption as a function of true speed. The time and fuel consumption shown in figures 4 and 5 do not include the time or fuel consumed while a vehicle is stopped, but only the additional consumption for the actual stop-and-go maneuver.

Engine idling consumption rates

The idling fuel-consumption rates of the test vehicles are presented in table 2. The data shown were obtained with the vehicle stationary and the engine warm. For the trucks, the rates were obtained in forward gear with the clutch disengaged. The rate for the passenger car equipped with an automatic transmission was measured with the transmission in neutral position and also in drive position with the brakes set. Idling fuel-consumption values are given for four different engine speeds—the average of these being recommended for use in benefit studies.

Figures 4 and 5 and table 2 are particularly useful for estimating the savings which will result if an intersection controlled by traffic signals or stop signs is eliminated through construction of a grade separation structure.

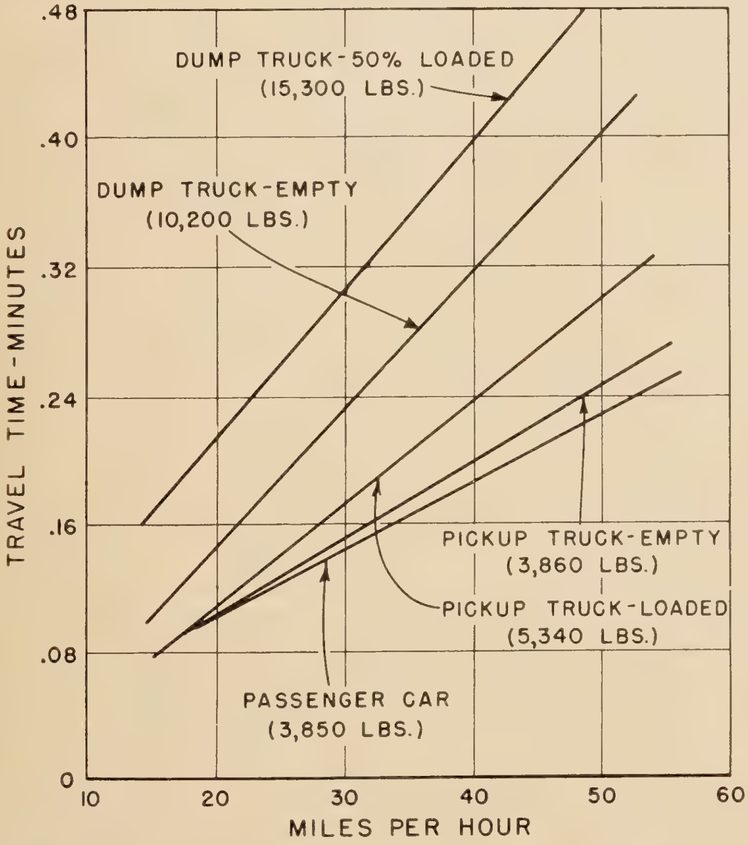

Figure 5.—Excess time consumed by a vehicle coming to a stop and then returning immediately to former speed.

Table 2.—Fuel consumption rates for idling vehicle

Engine revolutions per minute	Fuel consumption in gallons per minute				
	Passenger car			Pick-up truck	Dump truck
	Transmission in neutral	Transmission in drive	Average		
450	0.005	0.005	0.005	0.006	0.009
550	.006	.008	.007	.007	.010
650	.006	.009	.007	-----	.011
750	.007	.014	.010	.008	.013
Average	.006	.009	.007	.007	.011

Slowdown operations

The additional fuel and time consumption curves for a slowdown of 10 miles per hour with immediate resumption of speed, at various speeds, are shown in figures 6 and 7. Periods of operation at reduced speed are excluded. The procedures used for computing these values due to slowdowns were similar to those used for computing the fuel and time consumption of stop-and-go operations.

The applicability of the curves in figures 6 and 7 is limited to improvements that eliminate highway impedances which cause vehicles to reduce speed by about 10 miles per hour. This limitation is not serious, however, since most slowdowns of importance in highway-user benefit studies are about 10 miles per hour. Preliminary analysis of data taken from extensive speed-delay studies made in 1958–59 with a passenger car showed that speed reductions of up to 3 miles per hour were a normal part of uniform driving and were not eliminated through highway improvements, and that the average of the speed reductions in excess of 3 miles per hour was about 10 miles per hour. In addition, it was recently established that the average speed reduction of motortrucks when slowed by highway or traffic impedances is 11.4 miles per hour (6).

The curves in figures 6 and 7 may be used to estimate savings in fuel and time consumption through the elimination of a variety of speed reduction factors. In the case of a curve elimination, test runs should be made before improvement to determine the average amount of slowdown caused by the curve. Where crossroads or driveway entrances are to be eliminated, test runs should be made to establish the average percentage of driveways at which through vehicles are forced to reduce speeds because of other vehicles entering or leaving, and the average value of such speed slowdowns.

If the average speed reductions found for curves and driveway entrances are between 8 and 12 miles per hour, figures 6 and 7 may be used to compute fuel and time savings. If the average speed reduction is more or less than 8 to 12 miles per hour, the fuel and time savings may be estimated by assuming that the magnitude of these savings is proportionate to the magnitude of the speed change.

Practical Illustrations

Two examples will illustrate how figures 1–7 and table 2 may be used to compute the fuel and travel-time savings arising from particular improvements.

Example A.—On a 10-mile length of 2-lane road 24 feet wide, the existing gravel surface is to be replaced by a concrete pavement. Average annual daily traffic on the route is 4,000 vehicles per day; 80 percent of the vehicles are passenger cars and 20 percent are 2-axle, single-unit trucks having an average gross vehicle weight of 10,000 pounds. The nominal highway speed on the route before improvement was found to be 35 miles per hour for all vehicles. It is expected that this will be increased to 45 miles per hour after improvement. Compute the average annual

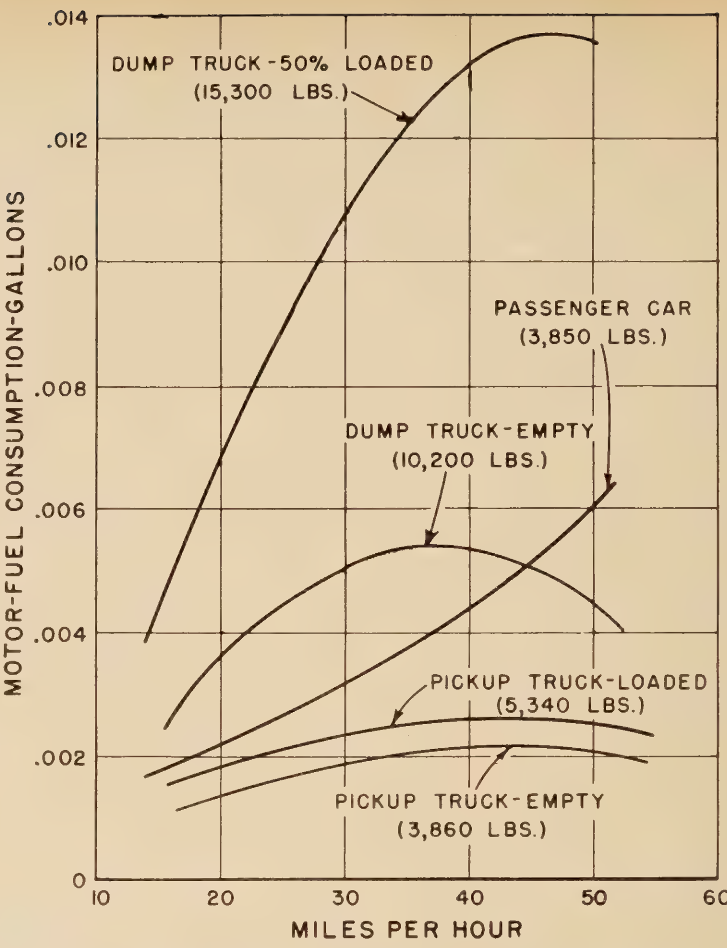

Figure 6.—Excess fuel consumed by a vehicle reducing speed by 10 miles per hour and then returning immediately to former speed.

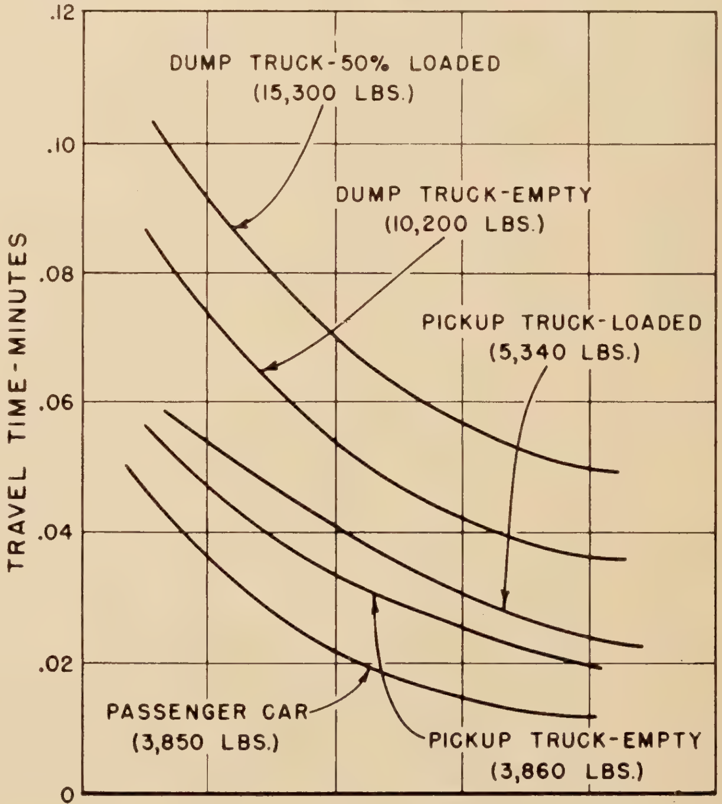

Figure 7.—Excess time consumed by a vehicle reducing speed by 10 miles per hour and then returning immediately to former speed.

l savings which may be attributed to this provement.

Solution.—Annual number of vehicles using route:

senger cars------------------ 4,000×365×80%=1,168,000
cks------------------------ 4,000×365×20%= 292,000

From figure 3, fuel savings due to surface provement at nominal speed of 35 miles hour are 0.010 gal. per vehicle-mile for ssenger cars and 0.021 gal. for trucks. om figure 1, the increases in fuel consumpn due to speed increase from 35 to 45 p.h. are 0.003 gal. per vehicle-mile for ssenger cars and 0.004 gal. for trucks.

Annual fuel savings for the 10-mile imvement:

senger cars---- 1,168,000×10×(0.010−0.003)=81,760 gal.
icks---------- 292,000×10×(0.021−0.004)=49,640 gal.

The total annual fuel savings thus amount 131,400 gallons. At 30 cents per gallon, s represents an annual savings of $39,400.

Example B.—A grade-separation structure planned at the interesection of a 4-lane ided parkway and a 2-lane crossroad where ffic signals now control vehicle movements. e average annual daily traffic volumes on 4-lane and 2-lane routes are 20,000 and 00 vehicles per day, respectively. All hicles on the parkway are passenger cars; percent of those on the crossroad are pasger cars and 20 percent are 2-axle, singleit trucks having an average gross weight of 000 pounds. The nominal highway speed the parkway is 45 miles per hour and on crossroad, 30 miles per hour. Turning vements at this intersection are so few in mber that they may be neglected. It was termined from a study of traffic movements at on both routes traffic signals caused 25 rcent of the vehicles to stop, with an avere time loss while idling per stop per vehicle of 20 seconds or 0.33 minute. Compute the annual fuel and time savings which will result from this improvement.

Solution.—Annual number of vehicles stopped on the parkway at the intersection:

Passenger cars---------------- 20,000×365×25%=1,825,000

Annual number of vehicles stopped on the crossroad at the intersection:

Passenger cars------------- 4,000×80%×365×25%=292,000
Trucks------------------- 4,000×20%×365×25%= 73,000

From figure 4, unit fuel savings per stop-and-go for passenger cars are 0.015 gal. at nominal speed of 45 m.p.h. and 0.009 gal. at 30 m.p.h.; for trucks, 0.017 gal. at 30 m.p.h. From figure 5, unit time savings per stop-and-go for passenger cars are 0.21 min. at nominal speed of 45 m.p.h. and 0.14 min. at 30 m.p.h.; for trucks, 0.23 min. at 30 m.p.h. From table 2, fuel consumption while idling for passenger cars is 0.007 gal. per min.; for trucks, 0.011 gal. per min.

Annual fuel savings for passenger cars on the parkway:

Stop-and-go------------ 1,825,000×0.015=27,375 gal
Idling------------------ 1,825,000×0.33×0.007= 4,216 gal.

Annual fuel savings for passenger cars on the crossroad:

Stop-and-go--------------- 292,000×0.009=2,628 gal.
Idling-------------------- 292,000×0.33×0.007= 674 gal.

Annual fuel savings for trucks on the crossroad:

Stop-and-go---------------- 73,000×0.017=1,241 gal.
Idling--------------------- 73,000×0.33×0.011= 265 gal.

The total annual fuel savings thus amount to 36,399 gallons. At 30 cents per gallon, this represents an annual savings of $10,900.

Annual time savings for passenger cars on the parkway:

Stop-and-go---------------- 1,825,000×0.21=383,250 min.
Idling---------------------- 1,825,000×0.33=602,250 min.

Annual time savings for passenger cars on the crossroad:

Stop-and-go---------------------- 292,000×0.14=40,880 min.
Idling-------------------------- 292,000×0.33=96,360 min.

Annual time savings for trucks on the crossroad:

Stop-and-go------------------------ 73,000×0.23=16,790 min.
Idling----------------------------- 73,000×0.33=24,090 min.

The total annual time savings thus amount to 1,163,620 minutes. Taking, for the sake of example, a value of 1½ cents per minute, the annual time savings are worth $17,400. Thus the total annual fuel and time savings occasioned by construction of the grade-separation structure can be valued at $28,300.

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Fuel and time consumption rates for trucks in freight service. See pp. 22–31 of this issue of Public Roads.

Fuel and Time Consumption Rates for Trucks in Freight Servic

BY THE DIVISION OF TRAFFIC OPERATIONS
BUREAU OF PUBLIC ROADS

Reported [1] by MALCOLM F. KEN
Transportation Economi

The number of times a truck must change its speed in a mile of travel increases with the density of traffic, according to an analysis of data derived from studies conducted in 1957 and 1958 of rural and urban travel in five States—data necessary in the analysis of highway-user benefits.

Using a congestion index, which indicates that speed changes per mile increase uniformly with average daily traffic for different types of highway, together with the rates of fuel and travel time consumed during a change in vehicle speed, the added cost of operating at nonuniform speed could be assessed.

This article also shows that, for the gross vehicle weights observed, smaller and less powerful engines give better fuel economy, but their use carries a penalty of increased time-consumption (lower road speeds) at the higher gross vehicle weights. Trucks with diesel engines were found to travel about 50 percent more miles on a gallon of fuel than trucks with gasoline engines of approximately equivalent power and gross weight characteristics.

ONE of the greatest voids in the data available for the analysis of highway-user benefits accruing through the improvement of highway facilities has been reliable fuel- and and time-consumption rates of commercial motor vehicles operating in actual service. To help fill this void the Bureau of Public Roads developed a program for obtaining this information. Ohio State University, the Universities of Michigan and Washington, and a transportation consultant from the University of Maryland were engaged to measure fuel consumption and overall travel time of selected trucks in rural and urban line-haul service and in city pickup and delivery service, under traffic conditions ranging from restricted to free flowing. This study group obtained the cooperation of private, government-owned, and for-hire highway freight carriers. Three of the studies were conducted simultaneously during the summer of 1957, and one during the summer of 1958.

A principal concern of highway planners of a few decades ago was the surfacing of dirt roads. Today, a principal concern is the elimination of frictional factors that impede the free flow of traffic on paved roads. Eliminating stops occasioned by stop signs and traffic lights, the widening of pavements or the adding of more lanes, the designing of highways with easier grades and curves, and the upgrading of other features that cause reduction in normal driving speeds, are factors that are now of primary importance.

In addition to improving the safety and efficiency of traffic flow, such improvements result in direct benefits to road users. Savings in motor fuel and time costs are two of the principal benefits that result, and they are directly affected by the elimination of frictional factors that impede the free flow of traffic. The over-all purpose of the studies described in this report was to provide data on fuel consumption and travel time for various vehicle types and traffic conditions, which could be used in the economic analyses of road-user benefits.

Summary of Findings

Major findings of the studies are summarized in the following paragraphs.

1. The fuel consumption in gallons per mile of motor trucks operating in rural and urban line-haul service increased with the power of the engine for equivalent gross vehicle weights.

2. Operating over identical rural line-haul routes, diesel-powered trucks were found to travel about 50 percent more miles on a gallon of fuel than gasoline-powered trucks of approximately equivalent power and gross vehicle weight. In terms of fuel consumption, this means that diesel-powered trucks consumed about 66 percent of the gallonage used by gasoline-powered trucks.

3. The consumption of gasoline per mile by trucks was 25 to 30 percent higher in urban areas than in rural areas.

4. The average truck speeds, including all stops and slowdowns, were found to be 37 miles per hour in rural line-haul operation, 19 miles per hour in urban line-haul operation, and 11 miles per hour in city pickup and delivery. For free-flowing traffic, the comparative speed for trucks in rural line-haul operation was 40 miles per hour.

5. The usefulness of speed changes per mile as a congestion index was demonstrated by proving that speed changes per mile increased uniformly with average daily traffic for different types of highways. Knowing the numb of speed changes saved, the proportion of sto and slowdowns, and the magnitude of eac it is possible to use this index to compute t added cost of fuel and time caused by spe changes, when the extra fuel and tin consumed during a speed change is known.

6. The stops on rural highways, made fro the average truck speed, represented 11 pe cent of all deviations from desired speec whereas the stops on urban streets represent 45 percent of all deviations from desir speeds.

7. The average number of speed chang per mile was found to be 1.66 for rural lin haul, 4.97 for urban line-haul, and 6.91 f city pickup and delivery operations.

Definition of Terms

To avoid misinterpretation of the resul certain terms used in this article are define

Fuel consumption.—Gallons of gasoline diesel fuel consumed per mile of highw travel. The conversion from gallons per m to miles per gallon can easily be made sin one is the reciprocal of the other.

Travel time.—Minutes required to tra 1 mile. Minutes per mile can be convert to miles per hour by dividing 60 by t minutes per mile.

Stop.—Bringing a motor vehicle to complete stop.

Slowdown.—A reduction in speed of a mot vehicle of more than 3 miles per hour witho coming to a stop.

Speed change.—All motor vehicle accele tions and decelerations effecting a spe change of more than 3 miles per hour, includi both stops and slowdowns.

Average gross vehicle weight.—The avera of the individual gross vehicle weights several vehicles, all falling within the sa class interval of gross vehicle weight.

Engine cubic-inch displacement.—The cro sectional area of a cylinder multiplied by t length of piston stroke, which gives t cylinder displacement; multiplied by t number of cylinders.

Net horsepower.—The brake horsepower the engine, operating with all its norn accessories, that is available at the clutch its equivalent. It is the gross horsepow minus the horsepower absorbed by f compressor, generator, etc. For all practi

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[1] This article was presented at the 39th annual meeting of the Highway Research Board, Washington, D.C., January 1960.

Table 1.—Route termini, route numbers, distances, and rates of rise and fall of rural highways traveled by observed line-haul trucks

Termini		Numbered routes	Mileage [1]	Rate of rise and fall [2]
From	To			
Washington, D.C.	Baltimore, Md.	Md. 193, U.S. 1	32.6	1.58
Do.	Richmond, Va.	Va. 350, U.S. 1	95.5	1.42
Columbus, Ohio	Cleveland, Ohio	Ohio 3, 61, U.S. 42	128.4	1.41
Do.	Parkersburg, W. Va.	U.S. 33, 50	108.8	.63
Do.	Wheeling, W. Va.	U.S. 40	119.9	1.70
Detroit, Mich.	Lansing, Mich.	U.S. 16	80.5	.59
Do.	Toledo, Ohio	U.S. 25	55.4	.16
Do.	Three Rivers, Mich.	U.S. 112, 12, Mich. 60	151.7	.48
Seattle, Wash.	Aberdeen, Wash.	U.S. 99, 410	95.5	1.25
Do.	Bellingham, Wash.	U.S. 99	75.5	1.28
Do.	Centralia, Wash.	U.S. 99	74.7	1.09
Do.	Chehalis, Wash.	U.S. 99	80.7	1.09
Do.	Everett, Wash.	U.S. 99	18.5	1.87
Do.	Longview, Wash.	U.S. 99, 830	120.7	.95
Do.	Mt. Vernon, Wash.	U.S. 99	53.9	1.24
Do.	Olympia, Wash.	U.S. 99	53.1	1.29
Do.	Portland, Oreg.	U.S. 99	161.2	.93
Do.	Tacoma, Wash.	U.S. 99	23.9	1.59
Do.	Yakima, Wash.	U.S. 10, 97	139.1	1.35

[1] Between municipal boundaries of terminal cities.
[2] In feet per 100 feet of distance.

rposes, net horsepower is assumed to be 90 cent of the gross horsepower.

Total rise and fall.—The arithmetic sum of vertical rise and fall in feet for any section highway. The rise in one direction of vel will become the fall in the opposite ection. The total rise and fall is the same ardless of the direction of travel.

ate of rise and fall.—The total rise and fall any section of highway in feet divided by length of section in hundreds of feet. It not to be confused with the percent of grade. is equivalent to the average percent of de only when either the rise or fall is 100 cent of the total rise and fall.

Description of Test Routes

he four studies were conducted in the eral areas of Maryland-District of Colum--Virginia, Ohio, Michigan, and Washington. e line-haul (intercity) routes with their gins, destinations, route numbers, mileages, rates of rise and fall are shown in table 1. e urban extensions of the line-haul routes Cleveland and Columbus, Ohio, Detroit, ch., Baltimore, Md., Washington, D.C., ttle, Wash., and some smaller munici-ities were studied separately from rural -haul operation. These generally followed numbered routes until diversion was essary to reach the trucking terminal or ivery warehouse.

ity pickup and delivery service was died in Detroit, Columbus, Seattle, and shington, D.C. All such operations were irregular routes except for the postal ivery service trucks which followed the e routes each day to the various substations Columbus. The types of service varied m large tractor-truck semitrailer combi-ions delivering grocery products from ehouses to retail stores and motor fuel n wholesale storage tanks to retail filling tions, to panel and van-type trucks engaged package or linen delivery service. Rise fall rates were estimated for Columbus, roit, and Washington, D.C., at approxi-tely 0.5 foot per 100 feet. Rates of rise fall for routes were recorded for Seattle, and ranged from 1.9 to 2.3 feet per 100 feet. However, the variations in rates of rise and fall among routes were not of sufficient magnitude to cause significant changes in fuel and time consumption.

Description of Test Vehicles

The gasoline- and diesel-powered tractor-truck semitrailer combinations, made available by commercial carriers for line-haul observation, are described in table 2 according to type, engine displacement, and net brake horsepower. City pickup and delivery gasoline-powered vehicles, consisting of panel and other single-unit trucks and tractor-truck semitrailer van and tank combinations, are similarly described in table 2.

Where the size and weight restrictions of the particular State permitted, three vehicles were observed in each State within each of the following weight groups:

Rural and urban line-haul (pounds)	*City pickup and delivery (pounds)*
20,000–29,999	5,000– 9,999
30,000–39,999	10,000–19,999
40,000–49,999	20,000–29,999
50,000–59,999	Over 30,000
60,000–69,999	

Test Procedures

After receiving permission from fleet owners to use their vehicles for test purposes, in the course of their normal runs, a fuel meter was placed in the cab of each gasoline-powered truck and connected to the fuel lines of the engine between the tank and the carburetor. The fuel meter could be read by a person sitting next to the driver. The fuel tank was filled at the start of each trip and was filled again at the end of the trip; any fuel added enroute was, of course, recorded. This overall record of fuel consumption was used to check the accuracy of the meters.

Diesel-engine trucks, in which excess fuel is recirculated from the engine to the fuel tank, required a different type of meter installation. To circumvent the multimetering of the same fuel, a small-volume, constant-level tank was installed in the fuel line between the engine and the main fuel supply tank. The engine fuel pump drew only from this feed tank, to which all excess recirculated fuel was returned. Fuel consumed by the engine was drawn from the feed tank, and a constant level was maintained in the feed tank through a float arrangement and an auxiliary fuel pump supplying additional fuel from the main supply tank through a fuel meter unit. In this manner, the fuel meter recorded only the actual quantity of fuel consumed by the engine.

Table 2.—Characteristics of commercial motor vehicles made available for study

Number of vehicles	Number of axles and body types [1]	Engine cu. in. dis-placement	Net brake h.p. of engine [2]	Engine r.p.m.
Line-haul, gasoline:				
1	3-S2-2 van.	302	172	3,600
3	3-S2 van	331	128	3,200
1	2-S2 van	377	126	2,800
12	2-S1 van	386	130	2,800
8	3-S1 van	406	156	2,750
4	3-S2 van	450	146	2,600
2	3-S2 van	461	197	3,200
3	2-S2 van	501	165	2,800
1	3-2 van	531	178	2,880
1	3-S2 van	549	230	3,200
4	3-S2 van	590	225	2,800
Line-haul, diesel:				
5	3-S2 van	743	200	2,100
City pickup and delivery, gasoline:				
2	2 panel	214	73	3,200
1	do.	223	126	4,000
1	do.	235	123	4,000
1	2 van	220	89	2,800
5	do.	228	90	3,000
5	do.	248	115	3,400
1	do.	260	90	2,500
1	do.	261	135	4,000
1	do.	263	105	3,400
3	do.	271	114	2,800
2	do.	272	167	4,400
1	do.	282	103	3,200
2	do.	320	103	3,000
1	do.	386	163	3,000
2	2-S1 van	372	139	3,200
2	do.	386	145	3,000
3	do.	406	175	3,200
1	2-S2 van	383	150	2,800
2	do.	450	150	2,800
1	do.	505	175	2,800
2	2-S2 tank	464	170	2,800

[1] Each digit indicates the number of axles of a vehicle or of a unit of a vehicle combination. A single digit, or the first digit of a group symbol, represents a single-unit truck or, if followed by an S, represents a truck-tractor. The S designation represents a semitrailer. A digit, without an S preceding it, in the second or third position of a group symbol represents a full trailer.
[2] Average 140 horsepower for engine sizes 302–406 cu. in., average 171 horsepower for sizes 450–549.

Before the beginning of the test runs each route to be observed was inventoried to locate control points with relation to major changes in traffic flow and to record mileage between control points, rise and fall (through use of an aneroid barometer), number of traffic signs and signals, and number of lanes. Before the start of each run, the observer recorded the vehicle chassis model and year, unladen weight, payload weight, and gross vehicle weight, engine model size and cubic inches of cylinder displacement, and reported net brake horsepower. The weather and condition of the road were also recorded.

The observer, riding in the cab, recorded on each run the following information as he passed the control points: time of day (hour and minute), fuel meter reading (hundredths of a gallon), and odometer reading (tenths of a mile). The magnitude of each speed change of plus or minus 3 miles per hour or more within each section was recorded during the trip. Trips were made at all hours of the day and night, with no change from normal operations being made on account of the study. Drivers were not to change their normal driving habits, and drove at speeds representative of other traffic.

Analysis Procedures

When the fieldwork had been completed, the first step in the analysis procedure was to list the consumption of fuel, travel time, and mileages traveled on each section for each trip, segregating rural from urban data. Speed changes were similarly listed for each section and trip, with stops being shown separately from slowdowns in the Ohio and Washington data. Gallons per mile, minutes per mile, and speed changes per mile were computed separately for line-haul rural trips, for line-haul urban trips, and for city pickup and delivery trips.

Rate of rise and fall

Rise and fall was considered a variable with respect to fuel consumption rates and travel time. No significant variations were found, however, in either parameter for the rather narrow range of rates of rise and fall studied. As shown in table 1, rates of rise and fall for the rural highways studied ranged from 0.16 for the route between Detroit and Toledo, to 1.87 for the route between Seattle and Everett. Of the total mileage studied, 40.6 percent had a rate of rise and fall below 1.0, 47.7 percent had rates from 1.0 to 1.5, and 11.7 percent had rates from 1.51 to 1.87. The average rate of rise and fall for all rural sections studied was 1.22. The results reported for this study reflect the average values for all highwa sections without regard to variations in ris and fall.

Table 3.—Number of trips and total miles observed for gasoline- and diesel-powered motor vehicles, classified by gross vehicle weights

Weight classes (pounds)	Average gross vehicle weight	Gasoline-powered vehicles		Diesel-powered veh.cles	
		Number of trips	Total miles observed	Number of trips	Total miles observed
Line-haul vehicles:					
17,000-18,999	17, 000	15	1, 111	------	------
19,000-23,999	21, 300	55	3, 085	------	------
24,000-29,999	27, 000	25	2, 398	1	60
30,000-37,999	34, 500	123	11, 740	6	545
38,000-47,999	42, 000	98	8, 906	12	1, 641
48,000-53,999	51, 200	64	5, 381	8	668
54,000-61,999	59, 500	42	3, 520	9	1, 125
62,000 and over	67, 900	31	2, 111	12	1, 503
Total	------	453	38, 252	48	5, 542
City pickup and delivery vehicles:					
4,400-4,999	4, 600	13	231	------	------
5,000-8,999	6, 000	25	1, 172	------	------
9,000-12,999	10, 500	89	1, 775	------	------
13,000-16,999	14, 500	51	603	------	------
17,000-20,999	18, 500	6	67	------	------
21,000-24,999	22, 500	1	33	------	------
25,000-30,499	27, 500	80	480	------	------
30,500-36,999	33, 300	18	232	------	------
37,000-39,999	38, 500	3	81	------	------
40,000-45,999	42, 100	5	171	------	------
51,000-51,999	51, 300	3	154	------	------
54,000-59,999	57, 000	40	64	------	------
62,000-69,999	66, 000	32	70	------	------
Total	------	366	5, 133	------	------

Table 4.—Summary of fuel-consumption rates for line-haul trucks operating over rural highway, classified by gross vehicle weights and engine power characteristics [1]

Gross vehicle weight (pounds)	Fuel-consumption rates in gallons per mile for vehicles with engine displacement of—							
	302–406 cu. in. gasoline-powered (140 hp.)		450–549 cu. in. gasoline-powered (171 hp.)		590 cu. in. gasoline-powered (225 hp.)		743 cu. in. diesel-powered (200 hp.)	
	Actual rate	Computed rate [2]	Actual rate	Computed rate [2]	Actual rate	Computed rate [2]	Actual rate	Computed rate [2]
17,000	0. 150	0. 154	0. 152	0. 173	------	--------	------	--------
21,300	. 163	. 163	. 189	. 185	------	--------	------	--------
27,000	. 170	. 175	. 210	. 200	0. 243	0. 241	0. 146	0. 153
34,500	. 196	. 191	. 229	. 219	. 247	. 253	. 176	. 162
42,000	. 214	. 207	. 246	. 239	. 278	. 266	. 176	. 171
51,200	. 233	. 226	. 256	. 263	. 273	. 280	. 164	. 182
59,500	. 233	. 244	. 289	. 285	. 287	. 294	. 189	. 193
67,900	------	--------	. 298	. 307	. 314	. 307	. 212	. 203

[1] Average rate of rise and fall, 1.2 feet per 100 feet.

[2] Computed rates are based on the following formulas: 302–406 cu. in., 0.1177+0.00212W; 450–549 cu. in., 0.1288+0.00262W; 590 cu. in., 0.1975+0.00162W; and 743 cu. in., 0.1194+0.001229W. (W=GVW in thousands of pounds.)

Vehicle weight groupings

It was not possible to set up a precis schedule of vehicles and gross vehicle weight to be observed, since the demand for commercial freight in normal operations did not permit the selection of a specified gross vehicl weight. It was hoped that the plan to observe a minimum of three vehicles for each o several weight-class intervals would result i an even distribution within the class interval This, however, was not the case and it wa necessary to form new gross vehicle weigh groupings in the analyses. The most significant groupings for the line-haul and picku and delivery vehicles, together with th number of trips and total miles observed i each grouping, are shown in table 3. It i evident that sizable mileages were logged i each type of service and that a reliable bas exists for the development of fuel consumption and travel time rates.

Engine size groupings

The gasoline-powered vehicles observed o line-haul operations were grouped, for purposes of analyses, into three engine displacement size groups consisting of 302–406 cubi inches, 450–549 cubic inches, and 590 cubi inches. Vehicles with 743-cubic-inch displacement diesel engines were also studie as a group. The net horsepower for th four groups of engine displacement wer determined to be 140 horsepower for th 302–406-cubic-inch size group, 171 horsepowe for the 450–549-cubic-inch size group, 22 horsepower for the 590-cubic-inch size group and 200 for the 743-cubic-inch diesel engine

A grouping of city pickup and deliver vehicles by power characteristics was considered but found impractical for the purpose of analysis because of the irregularity of th service, which resulted in wide variations i the speed of operation, number of deliveries stops per mile, idling time, and the rate o discharge of cargo.

Average Fuel Consumption Rates

A summary of the average rates of fue consumption is shown in table 4. Two fue consumption values are shown for each grou of vehicles with similar power characteristic One is the actual rate and the other is th computed rate, shown in figure 1 as straigh line relationships, which were derived fro the actual average values. The rates of ris and fall were 1.18 feet per 100 feet for th 302–406-cubic-inch group, 1.20 feet per 10 feet for the 450–549-cubic-inch group, 1.2 feet per 100 feet for the 590-cubic-inch grou and 1.22 feet per 100 feet for the 743-cubic inch diesel engine. The variation in rise an fall appeared to be rather insignificant an therefore a valid comparison of the motor-fu consumption rates for the several grouping of vehicles is practical.

It may be noted that the vehicles with th larger power plants used appreciably mor gasoline for a given average weight. Fo

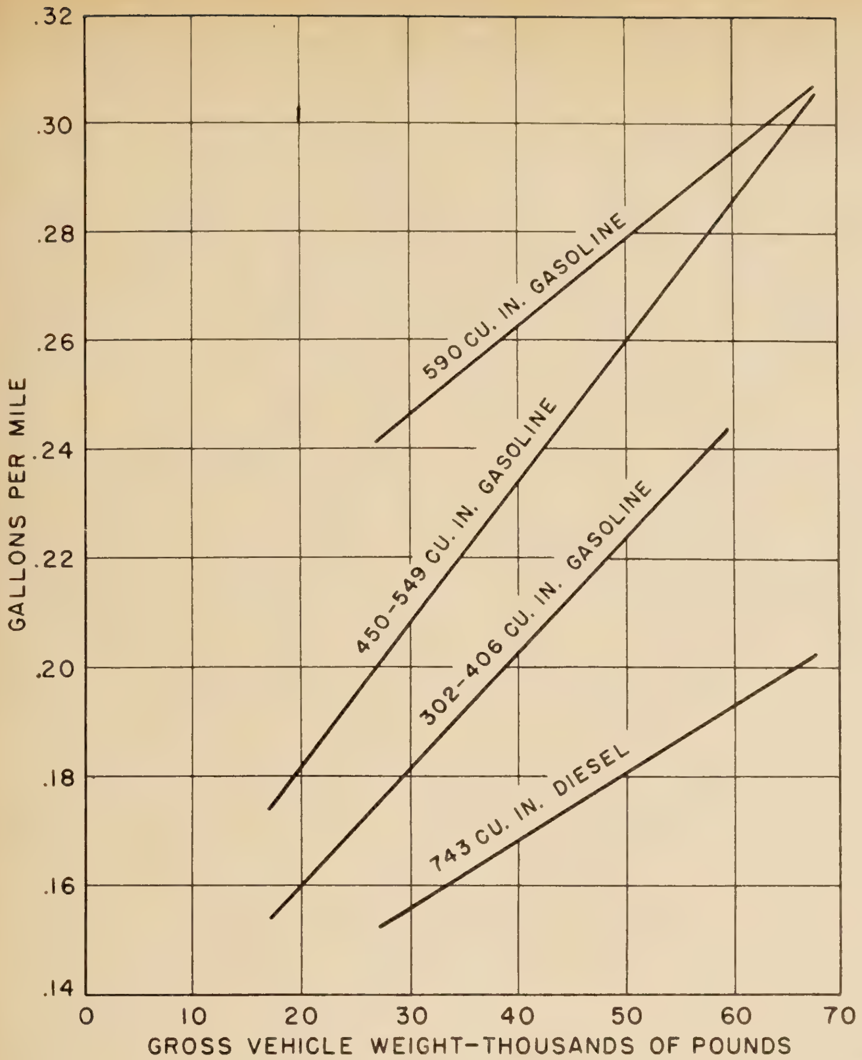

Figure 1.—Motor-fuel consumption rates of rural line-haul trucks by size of engine for 1.2 rate af rise and fall.

nstance, in figure 1 it is seen that gasoline-powered vehicles in the lowest engine power group with an average GVW (gross vehicle weight) of 40,000 pounds had a fuel-consumption rate of 0.202 gallon per mile. This compares with 0.233 gallon per mile for vehicles in the medium power group, which represents a 15-percent increase; and with 0.262 gallon per mile for vehicles in the largest gasoline-engine power group, a 30-percent increase.

Also, it may be seen that the fuel-consumption rate increased with gross vehicle weight. In the medium power group, for instance, a vehicle weighing 20,000 pounds consumed approximately 0.181 gallon per mile, while a vehicle weighing 60,000 pounds consumed 0.285 gallon per mile. However, despite the fuel-consumption rate increase with gross vehicle weight increase, there was a decrease in the fuel consumption per 10,000 pounds of gross vehicle weight. For example, in the medium power group a 20,000-pound vehicle consumed 0.181 gallon per mile, or 0.091 gallon per mile per 10,000 pounds, while a vehicle weighing 60,000 pounds which consumed 0.285 gallon per mile actually consumed only 0.048 gallon per mile per 10,000 pounds, indicating that as gross vehicle weight is increased the fuel economy per unit of gross weight is improved.

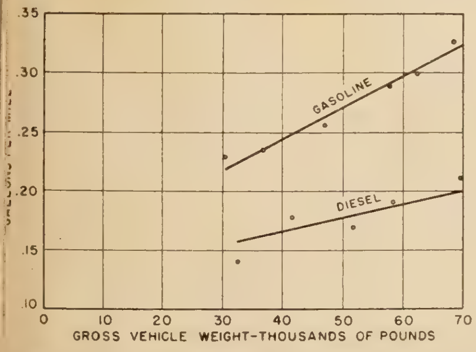

Figure 2.—Comparison of gasoline and diesel fuel consumption rates of rural line-haul trucks operating over the same routes.

Gasoline and diesel fuel comparison

For the same gross vehicle weight averages, the diesel-powered vehicles consumed considerably less fuel than the gasoline-powered vehicles with approximately the same power characteristics. For example, a vehicle with a 590-cubic-inch gasoline engine and an average GVW of 60,000 pounds consumed approximately 0.294 gallon per mile, while a vehicle with a 743-cubic-inch diesel engine and a similar weight consumed 0.193 gallon per mile. In this case the diesel consumption rate was 66 percent of the gasoline consumption rate. However, the foregoing comparison does not represent results obtained over identical routes.

A comparison of gasoline and diesel fuel consumption rates for vehicles traveling over identical routes was possible from the data obtained in the State of Washington. The diesel-powered combination units traveled a total of 5,542 miles on 48 trips. Twenty-eight of these trips, totaling a distance of 3,617 miles, were traveled over the same routes used by gasoline-powered trucks on 32 trips, totaling 3,966 miles. By grouping gross vehicle weights into class intervals, it was possible to obtain average consumption values that were directly comparable with respect to rise and fall rates and gross vehicle weight. Of the vehicles with gasoline engines, 21 trips were made by vehicles with engines of 461-cubic-inch displacement, 3 with engines of 450-cubic-inch displacement, and 8 with engines of 590-cubic-inch displacement. For the 32 trips, the average net horsepower of the vehicles with gasoline engines was 199 horsepower, as compared with the 200-horsepower diesel engines. The results are summarized in table 5 and the relationships derived from the average rates of fuel consumption are shown in figure 2.

Table 5.—Gasoline and diesel fuel consumption rates for line-haul trucks traveling over the same rural routes, classified by gross vehicle weights [1]

Gross vehicle weight (pounds)	Number of trips	Total miles traveled	Total gallons consumed	Actual rate, miles per gallon	Computed [2] rate, miles per gallon	Actual rate, gallons per mile	Computed [3] rate, gallons per mile
Gasoline:							
30,400	1	63	14. 34	4. 393	4. 452	0. 228	0. 221
36,800	2	284	66. 77	4. 253	4. 224	. 235	. 237
46,800	7	993	254. 89	3. 896	3. 867	. 257	. 263
57,900	14	1, 831	529. 23	3. 460	3. 472	. 289	. 292
62,500	1	142	42. 45	3. 345	3. 308	. 299	. 303
68,300	7	653	213. 25	3. 062	3. 101	. 327	. 318
Total or average	32	3, 966	1, 120. 93	3. 538	--------	. 283	--------
Diesel:							
32,600	1	65	9. 15	7. 104	6. 723	0. 141	0. 158
41,500	7	923	163. 89	5. 632	6. 229	. 178	. 168
51,600	6	618	105. 17	5. 876	5. 668	. 170	. 179
58,100	8	1, 146	219. 87	5. 212	5. 306	. 192	. 187
69,900	6	865	182. 15	4. 749	4. 651	. 211	. 200
Total or average	28	3, 617	680. 23	5. 317	--------	. 188	--------

[1] Average rate of rise and fall, 1.17 feet per 100 feet.

[2] Computed miles-per-gallon rates are based on the following formulas: gasoline, $5.53486-0.03563W$; diesel, $8.5345-0.05556W$.

[3] Computed gallons-per-mile rates are based on the following formulas: gasoline, $0.14217+0.00258W$ diesel, $0.12106+0.00113W$. (W=GVW in thousands of pounds.)

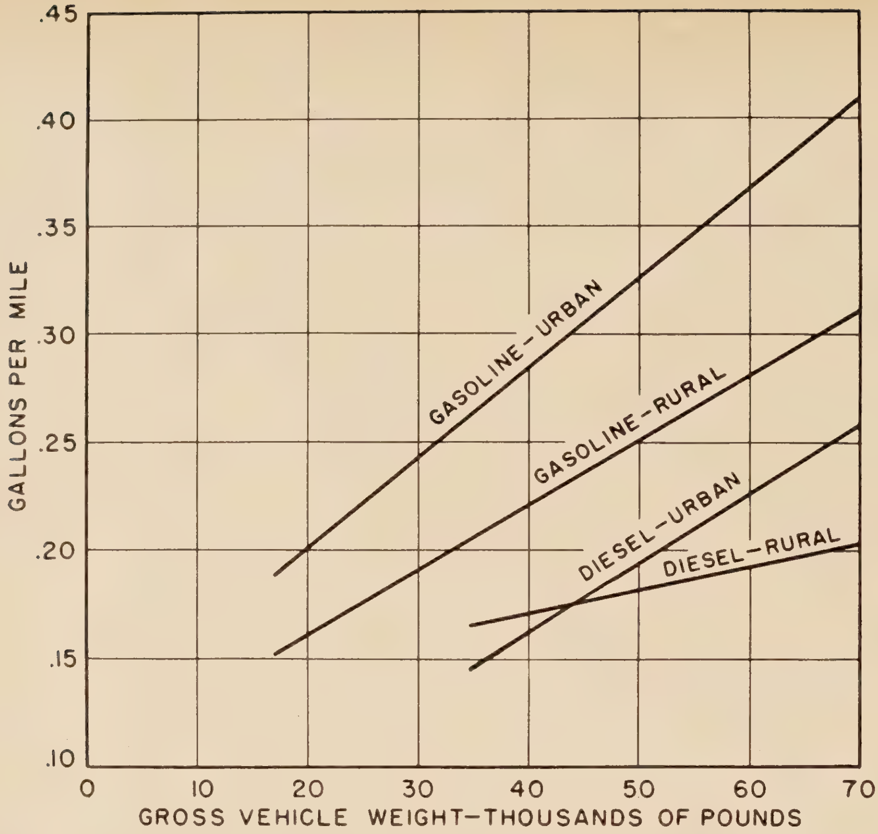

Figure 3.—Comparison of rural and urban motor-fuel consumption rates of line-haul trucks.

For a GVW of 70,000 pounds, as shown in figure 2, the gasoline consumption rate was 0.322 gallon per mile, or 3.11 miles per gallon; and the diesel consumption rate was 0.200 gallon per mile, or 5.00 miles per gallon. In effect the diesel-powered vehicles traveled about 53 percent more miles per gallon of fuel than did the gasoline-powered vehicles. A similar comparison for a GVW of 50,000 pounds indicated that the diesel-powered vehicles traveled about 52 percent more miles per gallon of fuel than gasoline-powered vehicles. A comparison of the average rate for all gasoline-powered vehicles for all 32 trips with that for all diesel-powered trips shows that 51 percent more mileage was obtained by diesel-powered vehicles on the same gallonage of fuel. This relative value is based on the total miles traveled and total gallons consumed shown in table 5. The average diesel consumption rate of 0.188 gallon per mile was 66 percent of the average gasoline consumption rate of 0.283 (also shown in fig. 1).

Rural and urban comparison

The fuel consumption rates for all gasoline- and diesel-powered trucks observed in line-haul rural and urban travel are shown in table 6. The computed rates, obtained from the straight-line relationships shown in figure 3, were derived from the average actual rates. Referring to figure 3, the fuel consumption rates for gasoline-powered vehicles in urban travel appear to be considerably greater than the gasoline consumption rates in rural travel. The fuel consumption percentage differences in rural and urban travel range from a 25-percent difference for a GVW of 20,0 pounds to a 32-percent difference for a GV of 70,000 pounds.

A comparison of the rural and urban fu consumption rates for diesel-powered truc observed in line-haul service, however, sho that there was little percentage differen where the GVW was from 40,000 to 50,0 pounds, but where the GVW approache 70,000 pounds there was a 27-percent high consumption rate in urban travel.

Again, figure 3 shows the fuel consumptio advantage of the diesel engine.

City pickup and delivery vehicles

City pickup and delivery motor-vehic gasoline consumption rates are shown i figure 4 for two different rates of rise and fal The straight-line values were derived fro actual average values. In Seattle, where th rate of rise and fall averaged 2.1 feet per 10 feet, the gasoline consumption was 18 percen higher at 10,000 pounds GVW and 14 percen higher at 40,000 pounds GVW than the consumption rate in the other three cities whe the rise and fall was about 0.5 feet per 100 fee It will be noted that gasoline consumptio increased as gross vehicle weights increase as was the case for line-haul operation. I may also be noted that the consumption rat approximate very closely the values shown i figure 3 for gasoline-powered vehicles in urba line-haul service. Consumption rates fo

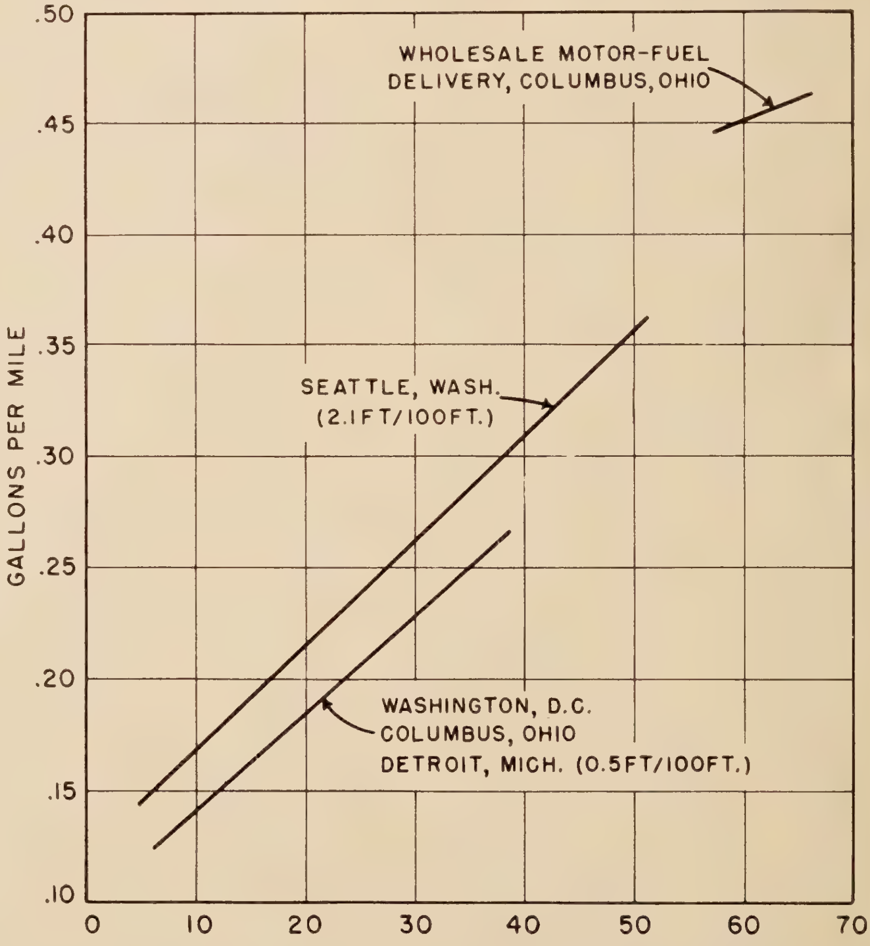

Figure 4.—Motor-fuel consumption rates at different rates of rise and fall for city deliver vehicles.

Table 6.—Gasoline and diesel fuel consumption rates for rural and urban line-haul operations, classified by gross vehicle weights

Gross vehicle weight (pounds)	Gasoline and diesel fuel consumption rates in gallons per mile							
	Gasoline-powered vehicles				Diesel-powered vehicles			
	Rural travel		Urban travel		Rural travel		Urban travel	
	Actual rate	Computed rate [1]	Actual rate	Computed rate [1]	Actual rate	Computed rate [1]	Actual rate	Computed rate [1]
17,000	0.150	0.152	0.175	0.189	----	----	----	----
21,300	.166	.165	.218	.207	----	----	----	----
27,000	.184	.182	.232	.230	----	----	----	----
34,500	.206	.204	.263	.261	0.176	0.167	0.147	0.146
42,000	.229	.227	.291	.292	.176	.174	.179	.169
51,200	.243	.254	.332	.330	.164	.184	.180	.198
59,500	.280	.279	.365	.364	.189	.192	.225	.224
67,900	.308	.304	.395	.399	.212	.200	.255	.250

[1] Computed rates are based on the following formulas: gasoline, rural, 0.10115+0.00299W; gasoline, urban, 0.11865+0.00413W; diesel, rural, 0.13180+0.00101W; diesel, urban, 0.03924+0.00310W. (W=GVW in thousands of pounds.)

Table 7.—Comparison of motor-fuel consumption rates of three studies of trucks operating over rural highways,[1] classified by gross vehicle weights

Average gross vehicle weight (pounds)	Motor-fuel consumption in gallons per mile from indicated studies							
	1958 five-State study					1937 Oregon study		1948 Pennsylvania study
	Gasoline-powered vehicles				Diesel-powered vehicles	Gasoline-powered vehicles	Diesel-powered vehicles	Gasoline-powered vehicles
	Engine cubic inch displacement of—			Average				
	302-406	450-549	590					
20,000	0.160	0.181	----	0.161	----	----	----	0.135
30,000	.181	.207	0.246	.191	0.156	0.203	0.128	.170
40,000	.202	.234	.262	.221	.169	.251	.157	.200
50,000	.224	.260	.279	.251	.181	.295	.183	.228
60,000	.245	.286	.295	.281	.193	----	----	.255
70,000	----	.312	.311	.311	.205	----	----	.282

[1] Rate of rise and fall for Oregon data was 1.0; for the other study data it was 1.2.

wholesale motor-fuel delivery vehicles are shown separately in figure 4 as they were not considered for this study as multi-stop city delivery vehicles.

Comparison with previous studies

Fuel-consumption rates obtained in this study have been compared with results found in two previous studies—a 1937 Oregon study (*1*), and a 1948 Pennsylvania study (*2*).[2] The comparison of these consumption rates are given in table 7 and illustrated graphically in figure 5. For comparative purposes, the average consumption rates found in the 1958 study, rather than the rates found for the individual groupings of vehicles, were used. Considering the entire gross vehicle weight range, the consumption rates obtained in the 1958 study were found to be approximately 10 percent higher than corresponding data reported in the Pennsylvania study, which were obtained by controlled tests on new vehicles. The higher motor-fuel consumption rates in commercial operation as compared with the controlled test operation can be ascribed partly to a greater prevalence of speed changes in commercial operation than had been encountered in the test truck operation, and partly to the fact that the commercial truck engines were not kept to the high degree of performance efficiency as the controlled test trucks, which were regularly maintained by factory mechanics.

It appears that the results in the Pennsylvania study, which covered a much wider range of gross vehicle weights and rates of rise and fall, may be increased by 10 percent and used to represent the fuel characteristics of vehicles now in actual commercial service.

Gasoline consumption rates in the 1937 Oregon study and the 1958 study were quite similar in the lower gross vehicle weights but the Oregon study gasoline consumption rates were higher by nearly 20 percent for the gross vehicle weights at 50,000 pounds. Diesel-fuel consumption figures in the Oregon study were lower than the 1958 study diesel consumption rates by as much as 30 percent in the lower weight ranges but were almost identical for gross vehicle weights at 50,000 pounds.

Average Time Consumption Rates

The travel time consumption rate of commercial motortrucks in rural line-haul operation was analyzed in two different ways. The first analysis was made to determine the travel time of vehicles for all trips, without considering rise and fall or traffic friction. This analysis was made in a manner similar to that used for determining the fuel-consumption rates. Actual and computed travel time consumption rates are given in table 8. In figure 6, straight lines are used to relate travel time and gross vehicle weight for each of the engine characteristic groups. It is seen that vehicles with engine displacement size of 302-406 cubic inches, which traveled

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[2] Italic numbers in parentheses refer to the list of references on p. 31.

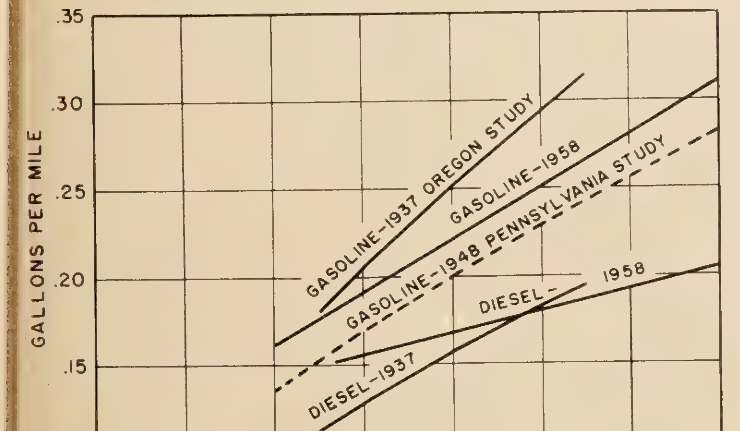

Figure 5.—Comparison of data from 3 reports on motor-fuel consumption rates of line-haul trucks.

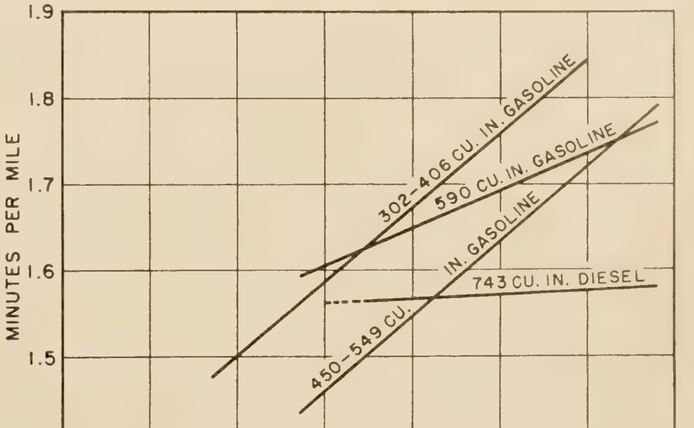

Figure 6.—Comparison of average time consumption rates of rural line-haul trucks by engine size for 1.2 rise and fall.

Table 8.—Rates of travel time consumption for trucks in rural line-haul service in 5 States, 1957–58 [1]

Gross vehicle weight (pounds)	Travel time-consumption rates in minutes per mile for vehicles with engine displacement of—								
	302–406 cu. in., gasoline (140 h.p.) engine		450–549 cu. in., gasoline (171 h.p.) engine		590 cu. in., gasoline (225 h.p.) engine		Gasoline engine average—Actual rate	743 cu. in., diesel (200 h.p.) engine	
	Actual rate	Computed rate [2]	Actual rate	Computed rate [2]	Actual rate	Computed rate [2]		Actual rate	Computed rate [2]
17,000	1.434	1.478	------	--------	------	--------	1.434	------	--------
21,300	1.506	1.514	------	--------	------	--------	1.506	------	--------
27,000	1.649	1.563	1.467	1.436	1.606	1.593	1.592	------	--------
34,500	1.619	1.627	1.520	1.501	1.590	1.626	1.596	1.636	1.567
42,000	1.687	1.691	1.526	1.566	1.662	1.659	1.620	1.460	1.571
51,200	1.728	1.769	1.626	1.645	1.738	1.699	1.692	1.616	1.576
59,500	1.859	1.840	1.660	1.717	1.724	1.735	1.696	1.569	1.580
67,900	------	--------	1.859	1.790	1.761	1.771	1.797	1.598	1.585
Average	1.638	--------	1.586	--------	1.696	--------	1.625	1.559	--------

[1] Average rate of rise and fall, 1.2 feet per 100 feet.

[2] Computed rates are based on the following formulas: 302–406 cu. in., 1.333+0.008516W; 450–549 cu. in., 1.203+0.008642W; 590 cu. in., 1.476+0.004347W; and 743 cu. in., 1.549+0.000526W.

Table 9.—Summary of travel time consumption rates, by gross vehicle weights and power characteristics, for urban line-haul freight vehicles and city delivery vehicles

Time-consumption rates in minutes per mile for urban line-haul vehicles with engine displacement of—						Time consumption rates in minutes per mile for city delivery vehicles	
Gross vehicle weight (pounds)	302–406 cu. in., gasoline engine	450–549 cu. in., gasoline engine	590 cu. in., gasoline engine	Average gasoline engine	743 cu. in., diesel engine	Gross vehicle weight (pounds)	All gasoline engines
17,000	3.207	2.868	------	3.105	------	4,600	8.854
21,300	2.909	3.473	------	2.987	------	6,000	5.736
17,000	3.388	2.818	2.957	3.182	2.556	10,500	6.181
34,500	3.260	2.973	2.378	3.136	2.353	14,500	5.125
42,000	3.274	3.082	2.728	3.167	2.597	18,500	4.500
51,200	3.513	2.914	2.283	3.253	2.901	22,500	5.502
59,500	4.533	2.987	2.532	3.435	3.043	27,500	4.847
67,900	4.486	2.630	2.815	3.039	2.784	33,300	4.184
Average	3.306	2.997	2.671	3.156	2.740	Average	5.443

at a rate of 1.59 minutes per mile with a GVW of 30,000 pounds, traveled at 1.85 minutes per mile when the GVW was 60,000 pounds. Vehicles in the 450–549-cubic-inch engine size group traveled 1.46 and 1.72 minutes per mile at corresponding weights. The straight-line relationships for these two engine groups were approximately parallel, indicating a constant rate of increase in travel time consumed with increase in gross vehicle weights.

The vehicles with 743-cubic-inch diesel engines maintained a much more constant speed with respect to gross vehicle weights than those with the larger gasoline engines, showing an increase of only 0.02 minute per mile from 30,000 to 60,000 pound GVW.

The travel time consumption rates of commercial vehicles in urban line-haul and in city pickup and delivery service are shown in table 9. Although time-consumption rates were not found to vary in a uniform manner with gross vehicle weight, it was noted that as the power characteristics of engines increased the time consumption decreased.

Table 10.—Average speeds of gasoline- and diesel-powered trucks, experiencing less than two slowdowns per mile and no stops in Ohio and Washington rural line-haul operation [1]

Gross vehicle weight (pounds)	Time-consumption rates [2]							
	302–406 cu. in. gasoline engine		450–549 cu. in. gasoline engine		590 cu. in. gasoline engine		743 cu. in. diesel engine	
	Minutes per mile	Miles per hour	Minutes per mile	Miles per hour	Minutes per mile	Miles per hour	Minutes per mile	Miles per hour
17,000	1.34	44.8	------	------	------	------	------	------
21,300	1.38	43.5	------	------	------	------	------	------
27,000	1.43	42.0	1.35	44.4	1.36	44.1	------	------
34,500	1.50	40.0	1.40	42.9	1.38	43.5	1.483	40.5
42,000	1.57	38.2	1.44	41.7	1.40	42.9	1.486	40.4
51,200	1.65	36.4	1.50	40.0	1.43	42.0	1.490	40.3
59,500	----	----	1.56	38.5	1.45	41.4	1.493	40.2
67,900	----	----	1.61	37.3	1.47	40.8	1.497	40.1

[1] Average rate of rise and fall, 1.3 feet per 100 feet.

[2] Rates were computed by the following formulas. 302–406 cu. in.: m.p.m., 1.18035+0.00916W; m.p.h., 49.1986−0.25747W.
450–549 cu. in.: m.p.m., 1.17435+0.00643W; m.p.h., 49.2757−0.17956W.
590 cu. in.: m.p.m., 1.2909+0.00264W; m.p.h., 46.0567−0.07742W.
743 cu. in.: m.p.m., 1.4696+0.00040W; m.p.h., 41.1719−0.01905W. (W=GVW in thousands of pounds.)

Referring to the average time-consumption rates for all gasoline-powered vehicles (tables 8 and 9) it will be seen that vehicles in rural line-haul service traveled at an average rate of 1.625 minutes per mile, or 36.9 miles per hour; vehicles in urban line haul traveled at 3.156 minutes per mile or 19.0 miles per hour; and all city pickup and delivery vehicles at 5.443 minutes per mile or 11.0 miles per hour. Similar figures for diesel-powered vehicles were 1.559 minutes per mile, or 38.5 miles per hour for rural line-haul operation, and 2.740 minutes per mile, or 21.9 miles per hour for urban line-haul operation.

Average speeds in free-flowing traffic

The second analysis made of travel time for rural line-haul operations involved the desired speeds at which vehicles traveled in free-flowing traffic when they apparently were unrestricted except by speed limits or safe driving speeds. It was possible to study the speeds by analyzing time-consumption rates on certain highway sections in Ohio and Washington where trucks traveled without experiencing more than two slowdowns per mile and no stops. The average operating speeds under these conditions were related to the four groupings of engine sizes and power characteristics and to gross vehicle weight, as shown in table 10 and figure 7.

Travel time, in minutes per mile, increased sharply as the gross weight of gasoline-powered commercial trucks in the lowest range of engine size and power increased. Conversely, of course, average road speeds decreased sharply. However, as the engine horsepower and gross vehicle weight increased, the travel time increase was less pronounced. This is reflected by the steepness of the slope of the lines per 10,000-pound increase in GVW. For the lowest gasoline-powered engine size, the rate increased 0.09 minute per mile for each increase of 10,000 pounds in GVW. For the medium gasoline-powered engine size, the corresponding increase was 0.06 minute per mile, and for the 590-cubic-inch engine gasoline-powered vehicles and the diesel-powered vehicles the increases were 0.03 and 0.01 minute per mile, respectively.

The relative performance of the four groupings of vehicles (fig. 7) point up the consideration that while better fuel economy is attained with smaller engines for the gross vehicle weights investigated, the penalty of using smaller engines is an increase in travel time consumption at higher vehicle weights.

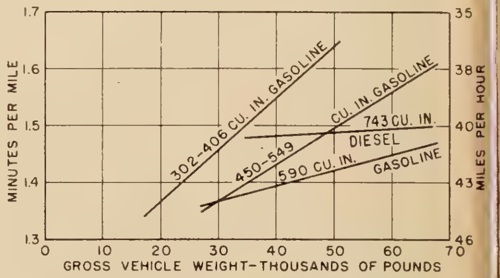

Figure 7.—Average time consumption rates for trucks operating in free-flowing traffic on rural line-haul service with an average rate of rise and fall of 1.3 feet per 100 feet.

Time-consumption rates compared

Another important use of the current study data was in comparison with the average time-consumption rates reported in the 1948 Pennsylvania study (*2*). Travel-time-consumption rates are graphically illustrated for the two studies in figure 8, using the average rates for all vehicles.

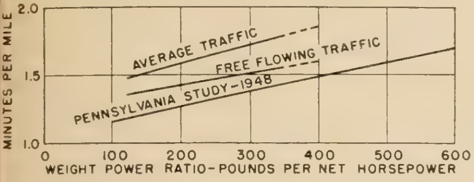

Figure 8.—Comparison of 1957–58 travel time rates for rural line-haul gasoline-powered trucks for 1.2 rate of rise and fall with 1948 Pennsylvania study data based on 1.3 rate of rise and fall.

The time-consumption rates obtained in the 1958 study, considering the average travel time for all conditions of traffic, are labeled "average traffic" in figure 8 and were found to be 26 percent higher than corresponding data reported in the Pennsylvania study. A comparison of greater significance, however, can be made between the 1958 study, identified in figure 8 as "free-flowing traffic," and those of 1948 Pennsylvania study, because both were made under similar conditions. The time-consumption rates of gasoline-powered trucks traveling in free-flowing traffic were 10 percent higher than corresponding data reported in the Pennsylvania study.

Effect of Traffic on Performance

One of the main objectives of the study was to investigate the effect of varying traffic volumes on the performance of commercial vehicles. Other studies (*1—4*) have made a good start in determining the fuel consumption and travel time for uniform speeds, stops and starts, and slowdowns; and in finding out how certain factors, such as gradient, rise and fall, horizontal curvature, gross vehicle weight, and engine characteristics, effect fuel and time consumption. However, little has been available in the literature as to the effect of varying traffic volumes.

It was hoped that this study would provide a means for estimating the added operating cost brought about by frictions in the traffic stream. The basic approach was one of considering the number of speed changes per mile for varying volume conditions, the percentage of the total number of speed changes that were stops and starts, and the average speed change in terms of miles per hour of a stop or slowdown. It was reasoned that if such information could be provided, the added cost for having to operate other than at a uniform speed could readily be assessed.

Speed changes per mile

What are probably the most significant results of this study, speed changes per mile, were computed for trucks with different gross weights operating over three types of rural highways with varying average daily traffic and are shown in table 11. An attempt was made to develop similar data for urban operation, but the lack of traffic data for the irregular routes traveled made this impossible.

The average values of speed changes per mile (from table 11) are shown in figure 9 as straight-line relationship established for the three types of highways. The benefits accruing from the elimination of impediments to free-flowing traffic are clearly illustrated by comparing the speed changes per mile on the 4-lane divided, controlled-access facility with those on the 4-lane undivided, uncontrolled-access facility. For an average daily traffic of 15,000 vehicles, there were an average of 2.0 speed changes per mile on the 4-lane uncontrolled-access highway as compared with a rate of about 0.8 on the 4-lane controlled access highway. Speed changes per mile on 2-lane highways increased from 2.0 to 2.8 where the average daily traffic increased from 5,000 to 10,000. In contrast, speed changes per mile on the 4-lane uncontrolled-access highway increased from 1.5 to 1.8 over the same average daily traffic range.

Data for 4-lane divided highways with no access control were not obtained in sufficient quantity for analysis. It is reasonable to expect that the relationship for this type of highway would fall between that for the two 4-lane highways shown in figure 9, and would probably lie closer to the 4-lane undivided, uncontrolled-access highway.

Analysis of speed changes

Of considerable importance among the data obtained were the percentages of total speed changes representing stops and slowdowns. Speed changes caused by stops and slowdowns are presented in table 12 from results of the studies made in Ohio and Washington, the only States where stops were recorded. On the average, complete stops occasioned about 11 percent of the speed changes in rural line-haul operations and about 45 percent in urban line-haul operations.

Compiled from the limited data available, an analysis of speed changes in miles per hour was made and it was found that an average stop in rural areas was made from a speed of 26 miles per hour. On city streets the average stop was made from a speed of 18.9 miles per hour. The average change in speed for slowdowns in both rural and urban areas was 11.4 miles per hour.

To illustrate the significance of a speed change in terms of motor-fuel consumption and to confirm that fuel consumption increases with an increasing number of speed changes per mile, gasoline-consumption rates were computed for road sections having different rates of speed change per mile, for different gross vehicle weights. The average rates are presented in table 13 for the three types of operation.

The straight-line relationships established for the data in table 13 are shown in figure 10. It is seen that an increase of one speed change

Table 11.—Speed changes per mile made by trucks operating over three types of rural highways with varying average daily traffic

Average daily traffic on indicated highways	Highway section mileage	Number of trips	Total miles traveled	Speed changes per mile for vehicles with average gross vehicle weight (1,000 pounds) of —						
				17.0	23.1	27.4	36.3	43.7	52.2	Average
4-lane divided, controlled access:										
46,700	6.56	54	354.24	1.56	2.05	------	2.38	2.71	2.36	2.19
23,300	3.62	54	195.48	.62	.83	------	1.17	1.90	1.99	1.24
12,700	8.19	54	442.46	.38	.62	------	.53	.66	.74	.60
4-lane undivided, uncontrolled access:										
15,700	31.71	54	1,712.34	1.73	1.79	------	2.12	2.35	2.34	2.03
10,300	48.78	54	2,634.12	1.59	1.55	------	2.07	2.03	2.12	1.82
5,200	5.67	52	153.79	------	1.19	------	1.58	1.47	1.73	1.53
2-lane:										
8,800	27.30	56	1,528.80	------	------	2.75	2.74	2.61	2.69	2.71
6,000	57.58	56	3,224.48	------	------	2.24	2.14	2.15	2.31	2.18
2,000	20.52	56	1,149.12	------	------	1.59	1.48	1.35	1.70	1.50

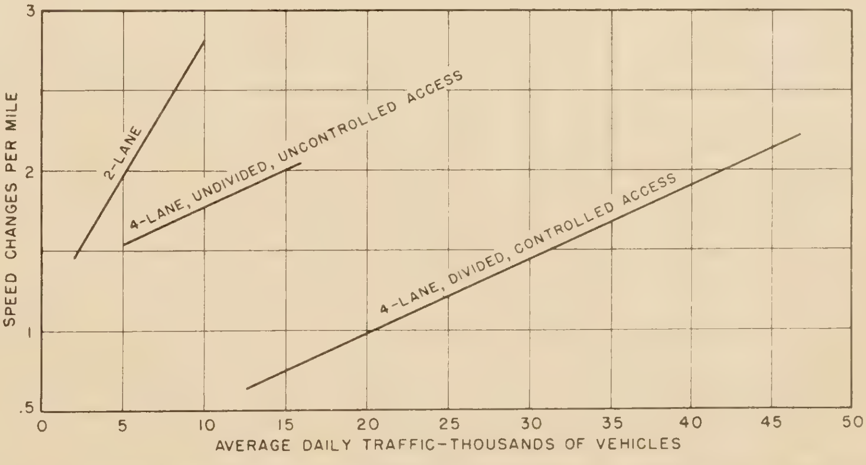

Figure 9.—Average speed changes per mile for rural line-haul trucks, by average daily traffic and type of highway.

Table 12.—Number and percentage of speed changes occasioned by slowdowns and stops of trucks in Washington and Ohio rural and urban line-haul travel

Speed Changes	Washington			Ohio			Total		
	Slow-downs	Stops	Speed changes	Slow-downs	Stops	Speed changes	Slow-downs	Stops	Speed changes
Rural line-haul:									
Number	5, 358	795	6, 153	8, 036	935	8, 971	13, 393	1, 731	15, 124
Percent	87. 1	12. 9	100. 0	89. 6	10. 4	100. 0	88. 6	11. 4	100. 0
Urban line-haul:									
Number	1, 220	613	1, 833	1, 581	1, 688	3, 269	2, 801	2, 301	5, 102
Percent	66. 6	33. 4	100. 0	48. 4	51. 6	100. 0	54. 9	45. 1	100. 0

per mile for a vehicle weighing 30,000 pounds traveling on a rural highway resulted in an average fuel-consumption increase of 0.010 gallon per mile. The corresponding increase for vehicles in urban line-haul operation was 0.021 gallon per mile, and for city delivery vehicles the average increase was 0.0056 gallon per mile. The greater rate of speed change for urban line-haul operation as compared to rural line-haul operation is probably due to the higher incidence of stops and slowdowns. City pickup and delivery vehicles consume less gasoline per speed change than the urban line-haul vehicles because stops and slowdowns are of lesser magnitude, as evidenced by an average speed of 11 miles per hour.

Also of importance is the indication that fuel consumption attributable to a speed change increases with gross vehicle weight. For example, the fuel consumed for an increase of one speed change per mile for rural line-haul operations was 0.0092 gallon for vehicles with 20,000 pounds GVW and 0.0142 gallon for 50,000 pounds.

Data for travel time-consumption rates due to one speed change per mile were also developed, and are shown in table 14. The average time-consumption rate did not appear to increase with gross weight but the average value for all gross vehicle weights increased as the speed changes per mile increased.

The average time consumed in one speed change for rural line-haul operation was found to be 0.26 minute, or 15.6 seconds; for urban line-haul operation 0.27 minute, or 16.2 seconds; and for city pickup and delivery operation 0.38 minute, or nearly 23 seconds. In spite of the fact that the speeds from which stops and slowdowns were made were higher in rural than in urban line-haul operation, the time consumption per speed change is about equal, probably because the percentage of total speed changes that are stops is much higher in the urban line-haul.

The increased fuel- and time-consumption rates for one speed change have been developed principally for illustrative purposes, although they can be used in estimating benefits. When data are available from controlled tests (*3—4*) on a variety of vehicles, the data herein presented may be refined.

Table 13.—Gasoline-consumption rates for trucks in line-haul and city pickup and delivery operation for various rates of speed change per mile

Average gross vehicle weight (*pounds*)	Gasoline-consumption rates in gallons per mile for indicated number of speed changes per mile						
	1	3	4	5	7	9	12
Line-haul, rural:							
17,000	0. 134	0. 142	------	0. 160	0. 181	------	------
34,500	. 180	. 198	------	. 226	. 250	------	------
42,000	. 200	. 222	------	. 255	. 279	------	------
53, 000	. 228	. 257	------	. 300	. 322	------	------
57,000	. 239	. 270	------	. 311	------	------	------
68,000	. 268	. 305	------	------	------	------	------
Average	. 197	. 220	------	. 251	. 279	------	------
Line-haul, urban:							
17,000	0. 143	0. 149	------	0. 153	------	------	------
26,000	. 159	. 180	------	. 198	------	0. 324	------
28,000	------	------	------	------	0. 246	------	------
52,000	. 206	. 268	------	. 328	. 409	. 426	------
58,000	. 217	------	------	------	------	------	------
59,000	------	. 292	------	------	. 457	------	------
61,000	------	------	------	. 373	------	------	------
62,000	------	------	------	------	------	. 465	------
Average	. 185	. 224	------	. 269	. 333	. 382	------
City pickup and delivery:							
6,000	------	------	0. 111	------	------	------	0. 145
10,500	------	------	. 131	------	------	------	. 167
18,500	------	------	. 165	------	------	------	. 206
27,500	------	------	. 204	------	------	------	. 250
33,300	------	------	. 229	------	------	------	. 279
Average	------	------	. 143	------	------	------	. 168

Cost of a Speed Change

The approximate cost of a stop is included in this article more as a matter of interest than with the idea of establishing valid cost values. Many sections of rural highway studied were traveled by line-haul vehicles without experiencing any stops and with less than two slowdowns per mile. Likewise, certain urban sections of highway studied were traveled by line-haul vehicles with a high incidence of stops but with less than two slowdowns per mile.

In order to estimate the cost of a stop the entire fuel consumption rate for the rural travel with no stops was subtracted from the fuel-consumption rate for urban travel where a high incidence of stops occurred. The difference is attributed solely to the effect of stops because slowdowns were the same in both instances. It should be remembered though, that the average stop was made from 26 miles per hour in rural areas and 19 miles per hour in urban areas. Dividing the total consumption per mile due to traffic stops by the number of stops per mile gave the consumption rates per stop which are shown in table 15. Gasoline consumed per stop showed a definite increase as the GVW increased. For example, if a cost per gallon of fuel of 30 cents is used, the cost of a stop would range

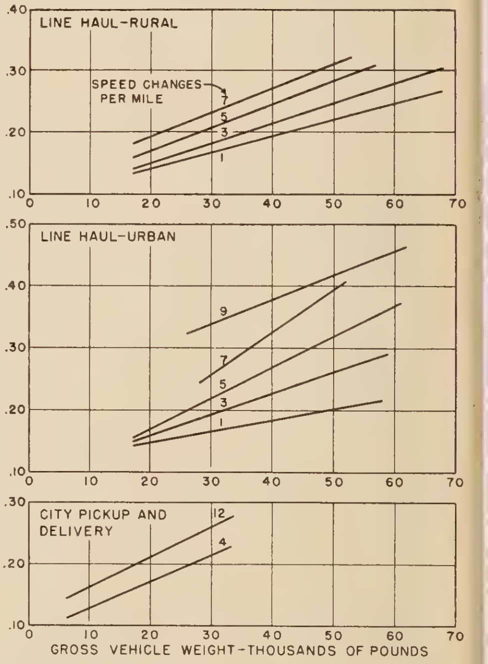

Figure 10.—Gasoline consumption rates, by rate of speed change per mile and by gross vehicle weight, for line-haul and city delivery vehicles.

ble 14.—Average travel time-consumption for trucks in line-haul and city pickup and delivery operations for various rates of speed changes per mile

Type of travel	Average time consumption in minutes per mile for the indicated number of speed changes per mile							Average time lost per speed change (minutes)
	1	3	4	5	7	9	12	
Rural	1.48	1.89	------	2.33	3.05	------	------	0.26
Urban	2.35	2.69	------	3.20	3.81	4.53	------	.27
City pickup and delivery	------	------	4.39	------	------	------	7.43	.38

m one-half cent for a GVW of 17,000 pounds more than 2 cents for a GVW of 51,000 unds.

Knowing the number of speed changes ved, the proportion of stops and slowdowns, d the magnitude of each, it is possible to mpute the added cost of fuel and travel time a speed change if the extra fuel and time nsumed during the speed change is known. hus, using speed changes per mile as a easure of congestion, the benefits may be mputed that accrue from highway improve ents that reduce congestion. It is realized at at present the tool is rough, but it can be refined. This is planned, using digital recorders instead of human observers.

Table 15.—Gasoline consumption rates for trucks in line-haul operation due to traffic stops, by gross vehicle weight

Gross vehicle weight (pounds)	Gallons per stop	
	Actual rate	Computed rate [1]
17,000	0.014	0.017
21,300	.030	.024
27,000	.034	.034
34,500	.044	.046
42,000	.054	.058
51,200	.076	.073

[1] Computed from straight line formula $0.001625W-0.0103$. (W=GVW in thousands of pounds.)

References

(*1*) Beakey, John

The effect of highway design on vehicle speed and fuel consumption. Oregon State Highway Commission Technical Bulletin No. 5, Salem, 1937.

(*2*) Saal, Carl C.

Time and gasoline consumption in motor truck operation. Highway Research Board, Research Report No. 9–A, 1950.

(*3*) Claffey, Paul J.

Time and fuel consumption for highway-user benefit studies. See pp. 16–21 of this issue of Public Roads.

(*4*) Sawhill, Roy B.

Motor transport fuel consumption rates. Highway Research Board paper, 39th Annual Meeting, Jan. 1960.

New Publication: Highway Progress, 1959

The Annual Report of the Bureau of Public Roads, Fiscal Year 1959, newly titled *Highway Progress, 1959*, is now available from the Superintendent of Documents, U.S. Government Printing Office, Washington 25, D.C. at 40 cents a copy.

Reflecting the central role of highway transportation in our entire way of life, the greatly expanded construction program launched by the Federal-Aid Highway Act of 1956 continued its vigorous growth during the fiscal year.

Highway usage also increased, with motor-vehicle registrations forecast to reach a record high of 70.4 million in the calendar year 1959, and travel by these vehicles pointing toward at least 700 billion vehicle miles.

The Bureau of Public Roads had set a fiscal year goal of $3.075 billion in Federal-aid obligations for surveys and plans, right-of-way acquisition, and construction. Actual obligations of the year reached $3.223 billion, as compared with a $2.749-billion total for the previous year.

During the fiscal year 1959, completions of all classes of Federal-aid and Federal projects provided improvements on 32,828 miles of roads and streets—with the growing use of multilane highways—that total represented the equivalent of 71,336 miles of single-lane construction. Individual projects included examples of the most spectacular and the most complex construction in highway history. Construction put in place during the year called for $2.875 billion of Federal funds, an increase of 74 percent over the previous year.

Projects for the construction of 30,923 miles of improvements also were set up during the year under the Federal-aid and Federal highway programs.

These extensive Federal-aid operations were supported largely with funds authorized by the Federal-Aid Highway Acts of 1956 and 1958. On August 1, 1958, Federal-aid funds for fiscal year 1960, amounting to $3.5 billion, were apportioned to the States. This brought the total of Federal-aid apportioned since passage of the 1956 Act to $10.55 billion.

Federal-aid improvements under the continuing primary, secondary, and urban programs progressed on a larger scale than ever before, but the Interstate System held its position as the focal point of public interest in highways. As sections were opened to traffic, more and more motorists began experiencing the advantages of the controlled-access freeway with its relief from cross traffic, its greater comfort and safety, and significant savings in travel time and vehicle operating costs. Residential, commercial, and industrial centers developed adjacent to the Interstate right-of-way—further indication of the catalytic role of motor transport.

Locating such important highway facilities was not left to chance. These complex Interstate System projects usually require several years of preparatory work—planning and surveying, plus design and right-of-way acquisition—before actual construction begins. The progress report on the Federal-aid highway program, presented to Congress during the fiscal year, showed that by December 31, 1958, improvements substantially meeting approved standards and at least adequate for current traffic, had been completed on 4,831 miles of the Interstate System and that during the calendar year 1958, there were 2,078 miles of high type pavement placed under construction.

At the end of the fiscal year progress of the Interstate System program was threatened by two financial problems. The first was immediate, and eminated from a sharply accelerated rate of spending called for by th Federal-Aid Highay Act of 1958.

Under the basic 1956 Act, the Federal-ai program is financed on a pay-as-you-go basi from Federal highway-user taxes which g into the highway trust fund. Net income o the trust fund during the fiscal year wa $2.2 billion while expenditures from the fun for Federal-aid highways amounted to $2. billion. This was the first year that expenditures had exceeded receipts. Apportionments for fiscal 1960, made under the 195 Act, considerably outweighed anticipate revenues to the trust fund. It was recognize that this action would deplete the surplu accumulated through earlier years of th trust fund and would preclude apportionmen of any funds for the Interstate System for th fiscal year 1961. As the fiscal year 195 ended, congressional action to remedy thi situation was pending.

There was, in addition, a long-range problem of financing the Interstate System program. The new estimate of the cost of completing the Interstate System presented t the Congress during fiscal year 1958 showe that Federal and State matching financin required after July 1, 1956, amounted t $37.6 billion, as compared with the $27.4 billion figure contemplated in the Federa Aid Highway Acts of 1954 and 1956.

During fiscal year 1959 the Bureau of Publi Roads submitted the *Third Progress Report o the Highway Cost Allocation Study*. Schedule for presentation to Congress early in 1961 together with a new detailed estimate of th cost of completing the Interstate System, it i expected that these reports will be of rea assistance to the Congress in its consideratio of appropriate scheduling and financing o Interstate and other Federal-aid highwa programs.

Errata

The table *State Legal Maximum Limits of Motor Vehicle Sizes and Weights Compared With AASHO Standards*, which appears on pages 250–251 of Public Roads magazine, vol. 30, No. 11, December 1959, requires a correction in footnote references.

In the entries for Maryland and Ohio, the footnote references 31 and 44 should be deleted from the column "Axle load-pounds, Tandem, Statutory limit." In the entry for North Dakota, footnote reference 44 should be added in the "5-axle" and "Other combination" columns under the heading "Practical maximum gross weight."

U.S. GOVERNMENT PRINTING OFFICE: 1960

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