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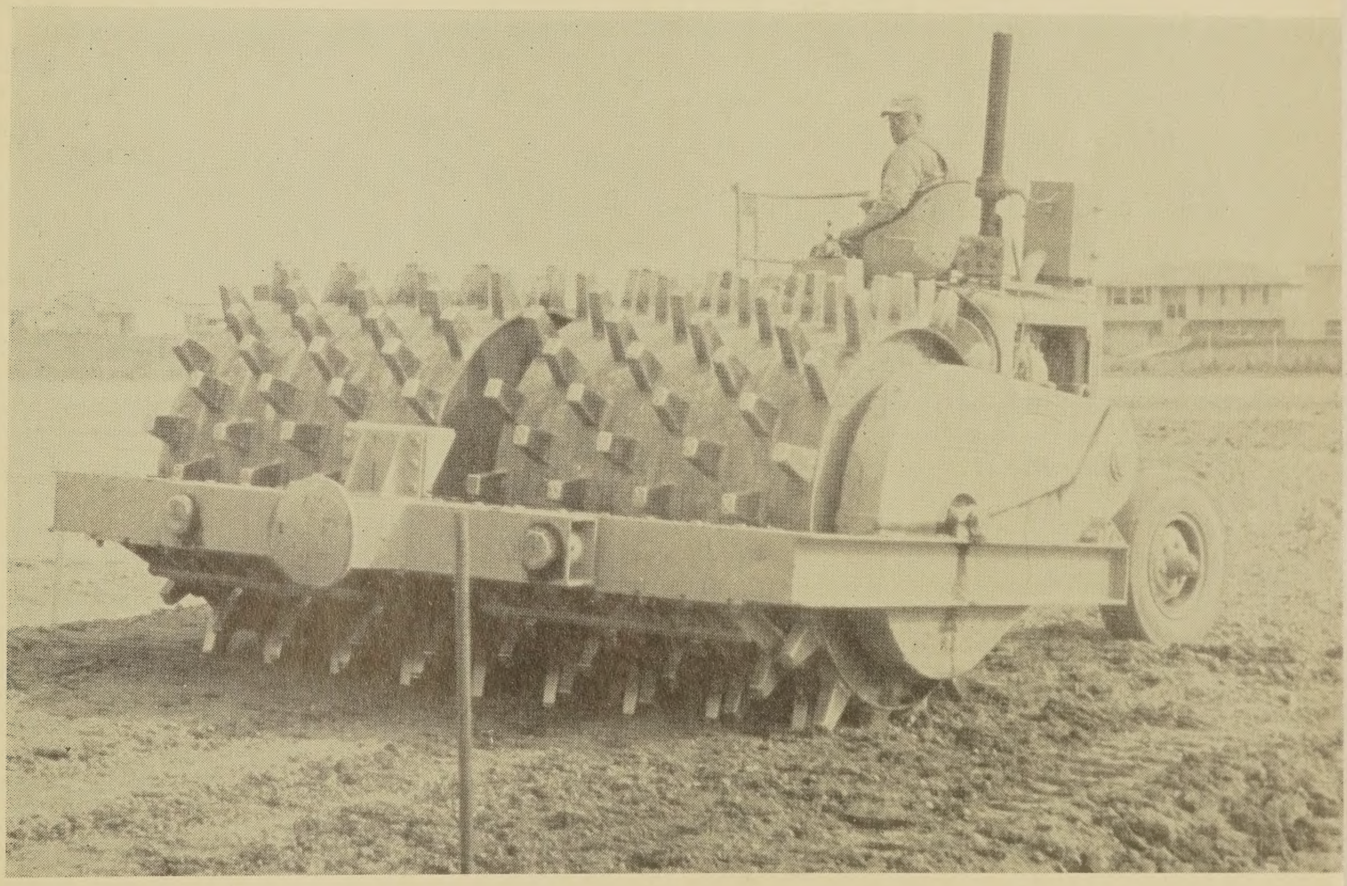

Compaction of a 6-inch silty-gravel test course by a dual-drum self-propelled sheepsfoot roller. Compaction is being done as part of a pilot study for an HPR cooperative compaction research project at Hazelcrest, Illinois.

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IN THIS ISSUE

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Shrink-Swell Potential of Soils

BY THE STRUCTURES AND APPLIED MECHANICS DIVISION BUREAU OF PUBLIC ROADS

Reported by[1] GEORGE W. RING, III,
Highway Research Engineer

This article describes a laboratory study conducted to develop a new test method for measuring the shrink-swell potential of a soil, independent of its molding moisture and density. The method consists of measuring the volume change that occurred when the soil was dried after cyclic wettings and dryings to achieve an equilibrium condition. As the shrink-swell potential test requires from 1 to 100 weeks to complete, swell-potential test results on 12 soils were compared to results obtained by 8 standard test methods in an attempt to find a rapid and reliable substitute. Good relationships were obtained with plasticity index, Georgia volume change, surface area, and linear shrinkage. Of these eight, linear shrinkage shows the most promise as a rapid, reliable substitute for the longer shrink-swell potential method.

Introduction

THE PERFORMANCE of engineering structures is sometimes affected by the hrinking and swelling of soils. Pavements ecome wavy as the result of differential olume change of the subgrade. Uneven hrinking or swelling of the foundation soils ause unsightly and dangerous cracks to evelop in buildings. Pipelines are deformed, isalined, and occasionally ruptured by olume change of the soil in which they are mbedded. Sometimes concrete canal linings rack when water seeps through construction ints and causes uneven swelling of the nderlying clays that have a high change of olume. Engineers need to know whether e soils to be used in construction may eate problems because of excessive volume ange.

This is a report on a laboratory study to evelop a method of evaluating the shrink-vell potential of a soil—a measure of how uch the soil may change in volume as oisture content changes. The report inudes (1) a brief literature survey reviewing echanics of volume change of soils, (2) reılts of a new test developed to measure olume change of soils when they are alterately wetted and dried (shrink-swell otential), and (3) a comparison of the results this test to many standard tests used to easure shrinking and swelling characteristics soils.

When a soil swells or shrinks, three primary tions appear to occur. These, as illustrated figure 1, are: (1) elastic bending or unnding of soil particles, (2) interlayer exnsion or contraction of certain layered clay minerals, (3) osmotic imbibition, which is a change in the thickness of water films on the exterior surfaces of soil particles. All of these are usually associated with changes in moisture content of the soil, although elastic bending may occur to a limited extent without moisture change. There may or may not be an associated change in the volume of the air in the soil.

Mechanisms of swelling have been studied by many investigators. Gilboy (*1*)[2] suggested that the amount of elastic deformation that occurs in a soil under a given load may depend on particle shapes that promote bending and unbending (figure 1, part A). His experiments with mixtures of mica and dune sand showed that the consolidation and rebound of the compacted mixtures were proportional to the amount of mica present. The results of his tests on three different mixtures are, as follows:

Mica in Mixture	*Decrease in Void Ratio Under 10 kg./cm.^{2}*	*Increase in Void Ratio When Load is Removed*
Percent	*Percent*	*Percent*
10	36	26
20	47	31
40	51	42

From X-ray diffraction studies, Bradley, Grim, and Clark (*2*) noted that one clay mineral, montmorillonite, expanded by taking on molecular layers of water internally (fig. 1, part B). Fink and Thomas (*3*) studied this phenomenon and found that the unit thickness of one layer of a lithium bentonite (montmorillonite) crystal increased about 780 percent when allowed to absorb water. Ladd (*4*) showed that a saturated clay soil swelled less in salt solutions than in water. He attributed this to the fact that less liquid was imbibed (fig. 1, part C) when the soil was soaked in the salt solution. Compacted Vicksburg buckshot clay, soaked in a 5-molar solution of $CaCl_2$, swelled about 6 percent less than when it was soaked in water. Allen and Johnson (*5*) determined that the amount of swell of a compacted soil was greatly affected by the initial moisture condition of the soil and to a lesser extent by the initial density. A soil compacted in a dry condition swelled much more than when compacted to the same density in a wet condition. Similar results were obtained by Holtz and Gibbs (*6*).

Conclusions

On the basis of the new work reported herein, these conclusions have been made:

The objective of this study appears to have been reasonably well achieved: An alternate wetting-and-drying procedure was developed to establish the shrink-swell potential of soils. The wide range of soil types used for this study provided a broad enough base to indicate that the linear-shrinkage test has real potential as a substitute for the very time-consuming wetting-and-drying method.

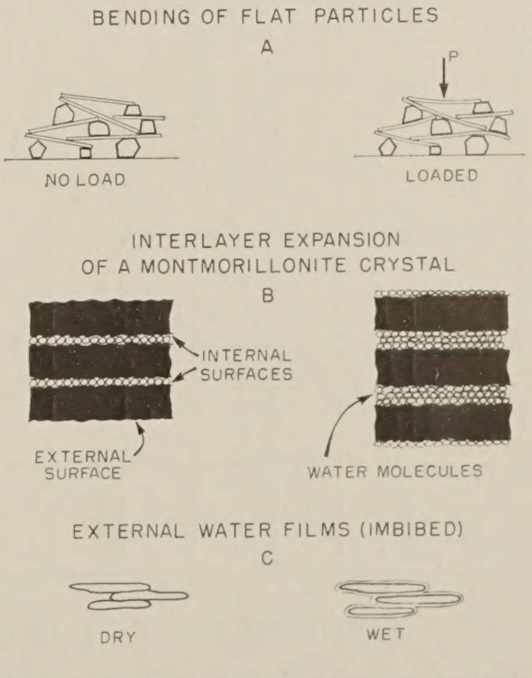

Figure 1.—Some mechanisms of volume change.

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[1] Presented at the 44th annual meeting of the Highway search Board, Washington, D.C., January 1965.

[2] References indicated by italic numbers in parentheses are listed on page 105.

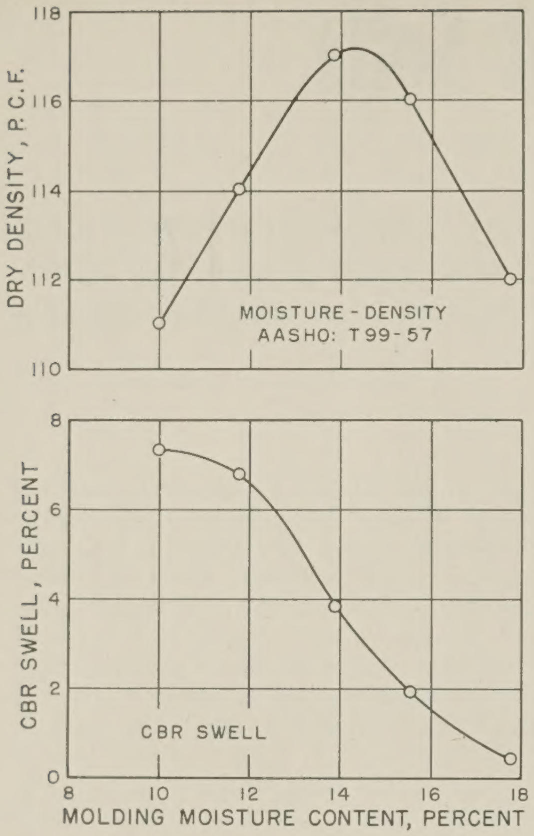

Figure 2.—Variation of swell with molding moisture and density of Hybla Valley clay.

Shrink-Swell Potential

The study discussed here is concerned primarily with the problem of predicting potential shrinkage and swelling of soils, as this activity affects roadways and other types of structures. In the bulk volume of a soil-water-air mixture, shrinkage is the decrease caused by drying, and swelling is the increase caused by wetting. Measuring an inherent property of soils, such as shrink-swell potential, is difficult, not only because of the many types of mechanical actions taking place but also because the measurements may be radically affected by environmental conditions. For example, figure 2 shows how the swelling f one soil, as measured during the Califora Bearing Ratio (CBR) test, changed as te compacted density and molding moiste content changed. It was necessary to mimize these effects to determine a true measue of shrink-swell potential.

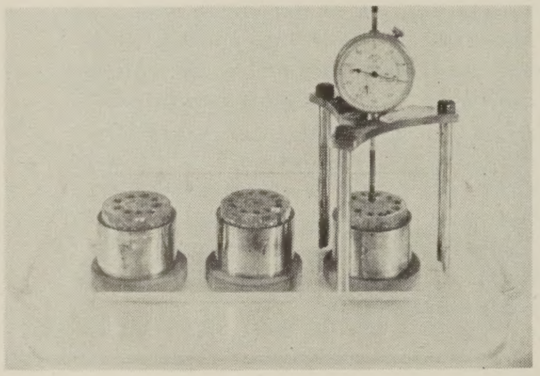

Figure 3.—Apparatus for cyclic wetting and drying test.

Existing laboratory test methods for detmining the shrink-swell properties of scs usually fall into one of two categories: eitlr a volume change test or a swell-pressure te. Information on 10 volume change tests ad 4 swell pressure tests is shown in tables1 and 2, respectively. Some volume chare tests measure swelling; other volume chare tests measure shrinkage. The Georgia methd (7) for determining volume change measus both swelling and shrinkage. Two identil specimens are compacted, then one is soakd while the other is dried. The test results determined from the combined volume chare of the two specimens. H. C. Porter) suggests that alternately wetting and dryg a soil rapidly may achieve an equilibrium cdition, regardless of the initial moisture ad density of the soil specimen.

Consequently, to determine the mt suitable test for measuring shrink-swl potential, the Georgia volume change test ad Porter's findings were investigated furth. The tests were intended to be rapid ad

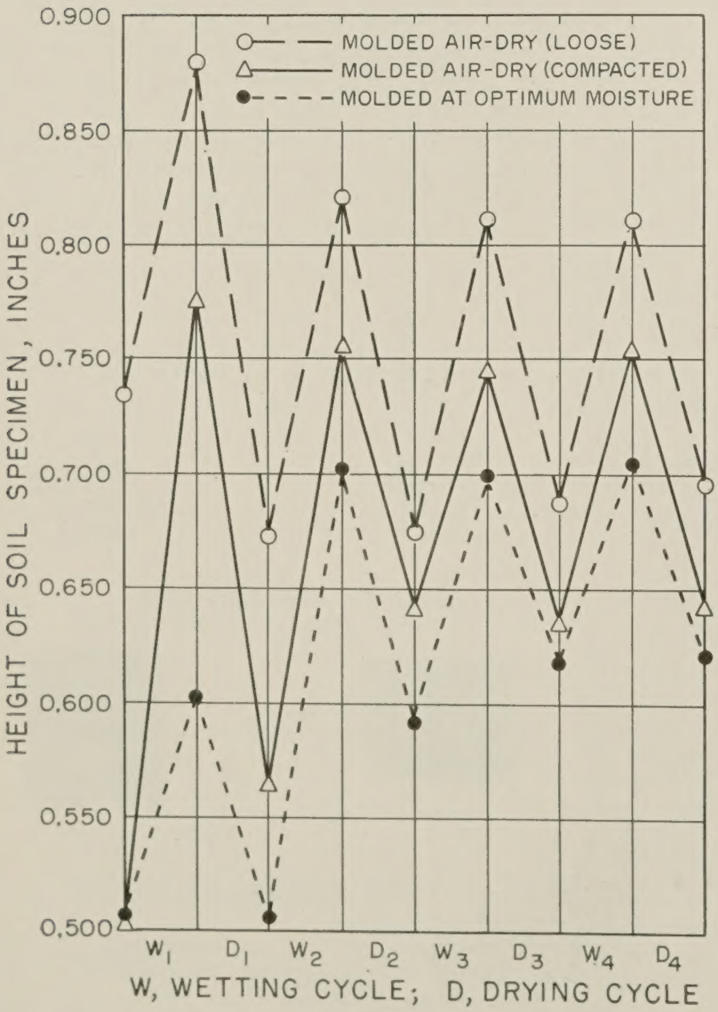

Figure 4.—Height change of 3 specimens of Iredell clay when alternately wetted and dried under a 0.25 p.s.i. surcharge.

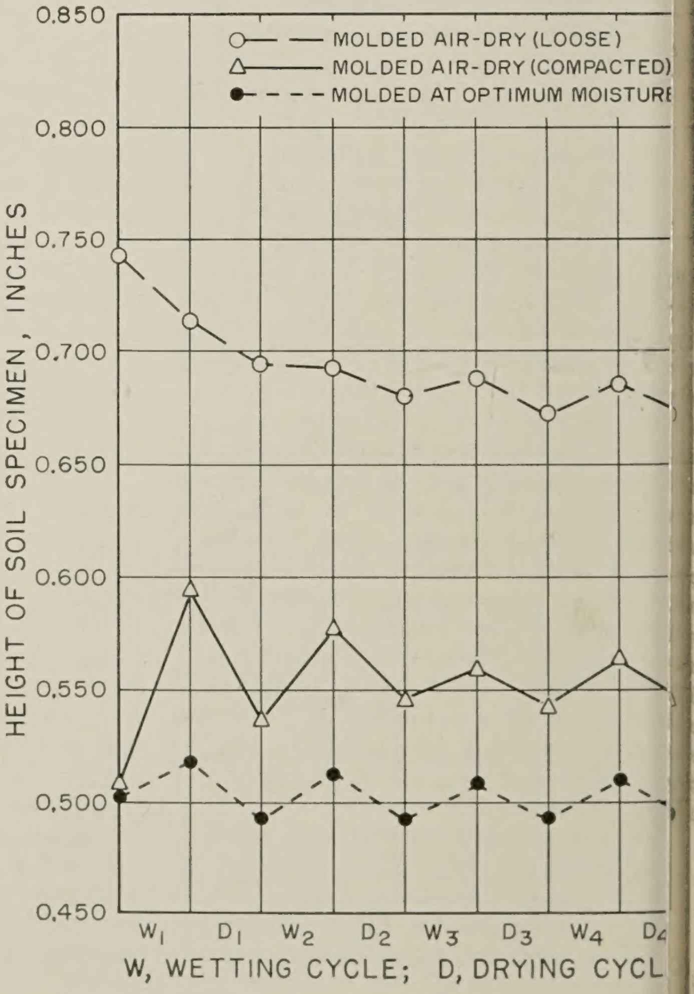

Figure 5.—Height change of 3 specimens of Cecil when alternately wetted and dried under a 0.25 p. surcharge.

Table 1.—Types of volume change tests

General type	Specific examples	Size of test specimen	Initial moisture content of soil	Soaking or drying time	Use of test results	Test procedures
Free swell	Method proposed by Winterkorn and Baver.	0.5 gram	Dessicated over P_2O_5.	24 hours	Identify swelling soils	Soil lightly tamped into glass Jena tube and permitted to absorb liquid of known dielectric constant. Test repeated with liquid having different dielectric constant. Relative amounts of the two liquids absorbed indicates swelling activity of soil.
	Free swell in graduate of water.	Variable, generally 1 to 10 grams.	Air dry	24 hours	Determine relative swelling potential of soils.	Soil slowly added to 100 ml. graduate of water. After soaking, volume of soil-water mixture is measured on the graduate.
Swell or consolidation with surcharge (confined laterally).	CBR	6-in. dia. by 4⅝- to 7-in. length.	Optimum (AASHO: T 99) or field moisture content.	4 days	Identify swelling soils for flexible pavement design.	Soil is compacted into mold, usually by dynamic compaction (for undisturbed samples, mold is forced into soil), trimmed, and soaked under a surcharge. Change in height is determined.
	AASHO: T 116	4-in. dia. by 1.5625-in. length.	Variable—usually at optimum moisture content (AASHO: T 99).	Until swell is no more than 0.001 in. in 18 hours; maximum 7 days.	Measure relative amount of swell for different conditions of moisture and density.	Similar to above, smaller mold, usually statically compacted.
	Different types of odometers.	Variable, usually from 1.5- to 4-in. dia. and 0.5- to 1.5-in. length.	Variable, to fit problem.	Variable	Determine rate and amount of consolidation or swell.	Similar to two procedures noted above, except specimens are smaller and test conditions are more variable.
Swell and shrinkage.	Georgia volume change.	4-in. dia. by 1-in. length.	Optimum (AASHO: T 99).	48 hours	Classify embankment soil, subgrade, and base course materials for pavement design.	Two identical specimens dynamically compacted. One specimen soaked and permitted to swell; the other specimen is oven dried at 110° C. Total volume change is then calculated.[1]
Volumetric shrinkage.	AASHO: T 92	1.75-in. dia. by 0.50-in. length.	Liquid limit to 1.1 x liquid limit.	Air dry to change in color, then oven dry at 110° C. to constant weight (usually 4 hours or more).	Calculate: (1) shrinkage limit, (2) shrinkage ratio, (3) volumetric change, and (4) linear shrinkage.	Soil-water mixture is placed into dish of known volume and tapped firmly to release entrapped air. After drying, volume of dry soil pat is determined by measuring displacement.
Linear shrinkage	Texas Bar Linear Shrinkage Test.	5-in. length by ¾-in. square.	Slightly wetter than liquid limit.	Air dry to change in color, oven dry at 105° C.	Identify high volume-change soils.	Soil is mixed with sufficient water so that a groove in a half-inch thick pat just closes without jarring. Soil is placed in rectangular mold and dried. Length of dry soil is measured and compared to original length.
	Saturated linear shrinkage.	10-in. length by 1-in. dia. (semi-circular).	Sufficient to provide free water after thorough mixing.	Air dry at 70° F. for 4 hrs., then oven dry at 105° C. for 24 hours.	Identify high volume-change soils.	Soil is mixed with sufficient water until free water is visible on surface. Thirty minutes after mixing, excess water is decanted; soil is remixed and placed in mold. Dry length of soil is compared to original length.
Change in thickness of clay mineral crystal.	X-ray diffraction test.	A few milligrams.	Variable	Not applicable	Study primarily of elemental soil properties.	Measured reflections from a beam of X-rays directed at different angles onto thin layer of soil (clay) shows thickness of basal layer spacings in crystalline structure.

Total volume change(V) is calculated:

$$V=\left(\frac{V_2-V_1}{V_1}+\frac{V_3-V_4}{V_3}\right)100$$

where,
V_1=Original volume soaked specimen.
V_2=Final volume of soaked specimen.
V_3=Original volume of dried specimen.
V_4=Final volume of dried specimen.

ple. The first tests were made by the orgia method. In these tests, some medium low plasticity soils exhibited high swelling aracteristics when soaked, evidently as the ult of the compaction of the specimen. so, some high plasticity soils swelled much re during a second soaking than during first soaking period. Because of these urrences, an approach based on Porter's dies was thought to possibly be more ical. A test procedure was devised to ermine whether alternate wetting and ing, as suggested in Porter's studies, would ieve an equilibrium condition of shrinking l swelling, regardless of initial moisture and sity condition. In this procedure, three cimens of each soil were molded to the tial moisture and density (percentage of SHO: T 99) conditions, as follows:

Specimen	*Moisture content*	*Density percent*
1	Optimum	100
2	Air dry	100
3	Air dry	64–83

pecimens No. 1 and 2 were compacted tically to a height of 0.5 inch and a diameof 2.0 inches. The height of the uncomted specimen (No. 3) depended on the

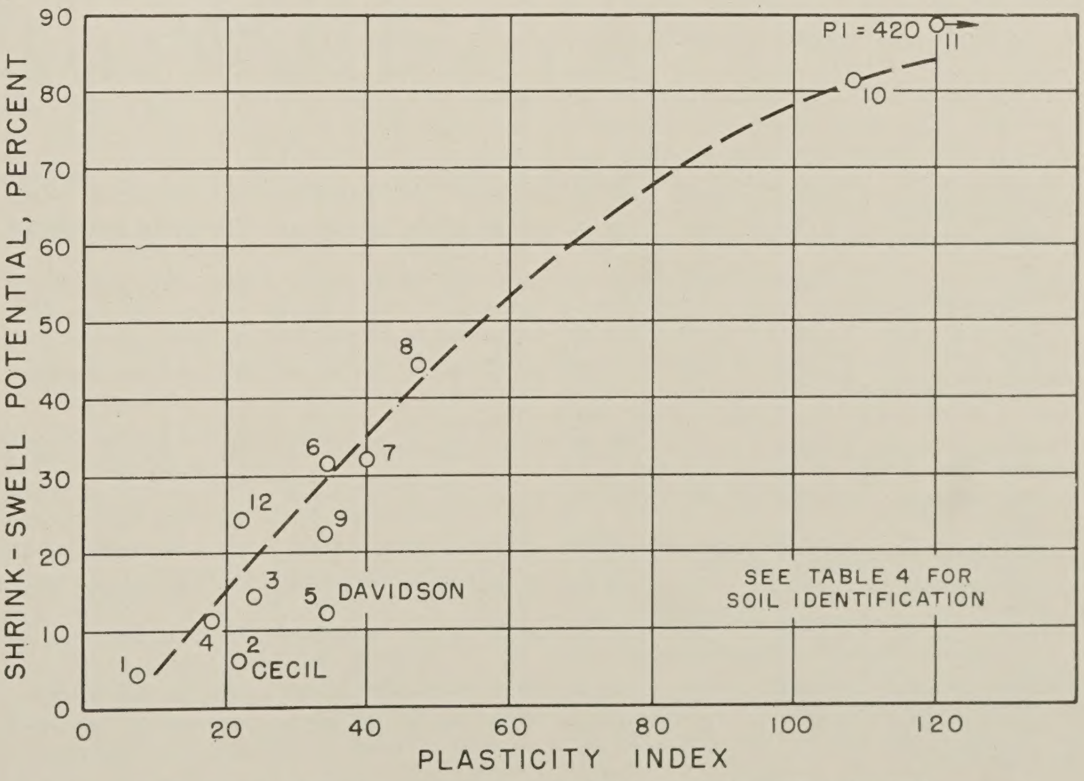

Figure 6.—Relation of plasticity index to shrink-swell potential.

Table 2.—Types of swell pressure tests

Test	Size of test specimen—diameter × length	Initial moisture content of soil	Soaking time	Change in height or expansion permitted—per 1 p.s.i. pressure	Use of test results	Comments on test
	Inches		*Hours*	*Inches*		
AASHO: T 190	4 × 2.5	Determined by exudation pressure criteria. Moisture content is usually close to optimum by AASHO: T 99.	16 to 20	0.00264	In thickness design of flexible pavements.	Specimen compacted by kneading compactor and static loading. Placed in expansion frame; swells in one direction against calibrated spring steel bar.
Strom and Hennes swell pressure test.	4 × 1.5 to 2.5	Variable	16	May be varied	Not stated	Compacted similar to above. Placed in pressure cell and surrounded by air or water, depending on amount of restraint desired. Side wall friction occurring in AASHO: T 190 claimed to be eliminated. Pressure measured by gage.
FHA swell index (soil PVC meter).	2.75 × 0.85	Air dry or at optimum (AASHO: T 99).	2	0.001	Identify high swelling or shrinking soils.	Specimen compacted into ring by impact compaction, trimmed to size. Soil expands against proving ring when soaked in water. The resultant swell index (pressure) is related to the potential volume change (noncritical; marginal; critical; very critical) of soil.
Odometer placed in universal testing machine.	Varied, but usually 1.5 to 4 × 0.5 to 1.5.	Varied to fit problem.	Variable [1]	0.0001 to 0.00001	Research, special problems.	Type of compaction, specimen size, soil density, and moisture conditions differ to fit equipment and/or problem.

[1] Usually no more than 1 week.

Table 4.—Shrink-swell potential of 12 soi

Soil		Shrink-swell potential
No.	*Type*	*Percent*
1	Portneuf	4.0
2	Cecil	5.7
3	Hybla Valley	13.9
4	Williams	10.8
5	Davidson	11.7
6	Parsons	13.3
7	Winterset	31.9
8	Iredell	46.9
9	Potomac	22.4
10	Ca Bentonite	81.3
11	Na Bentonite	89.0
12	Berthoud	24.0

soil type, as the soil for the specimen w poured loosely into the mold. The sa amount of soil was used for all three spe- mens. After being molded, all the specime were subjected to four cycles of altern wetting and drying, figure 3. Wetting w continued on each soil until swelling a- parently ceased. This period of time rang from about 200 minutes for low plastic soils to 200,000 minutes (140 days) for t bentonites. Drying was at 110° C. Althou the drying temperature may be regard by some as too severe, tests on Parsc and Davidson soils showed that this tempe- ture had little or no effect on subsequent cyc of wetting and drying. The volume cha

Table 3.—Test data for soils used in shrink-swell potential study

BPR sample No., soil, and source	Soil class		Mechanical analysis, soil finer than—(mm.)						Plasticity index	Liquid limit	Specific gravity	AASHO: T 99		Shrinkage		Linear shrinkage	Volume change		Shrink-swell potential	Surface area of material finer than 0.42 mm.		Clay minerals in material finer than 2 microns	
	AASHO	Unified	2.0	0.42	0.074	0.020	0.005	0.001				Optimum moisture content	Maximum dry density	Limit	Ratio		Georgia	AASHO: T 116		External	Internal	Predominant	Accessory
			Pct.	*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Pct.*				*Pct.*	*P.c.f.*			*Pct.*	*Pct.*	*Pct.*	*Pct. of wet volume*	*m.²/g.*	*m.²/g.*		
S 30470, Portneuf silt loam, Idaho.	A-4(8)	ML-CL	100	99	97	51	22	13	4	26	2.72	16	107	19	1.73	3	4.3	7.0	4.0	25	27	Montmorillonite	Illite and kaolinite.
S 14335, Cecil clay, Ala.	A-7-5(17)	MH	100	91	65	50	38	28	22	63	2.84	27	90	25	1.57	12	14.6	3.8	5.7	35	18	Kaolinite	Degraded mica and free iron oxides.
S 35732, Hybla Valley clay, Va.	A-7-6(11)	CL	100	92	58	41	32	22	24	47	2.76	14	117	16	1.83	11	12.3	5.9	13.9	36	113	Montmorillonite	Small amounts of illite and kaolinite.
S 30038, Williams loam, N. Dak.	A-6(12)	CL	100	96	77	57	40	24	18	38	2.73	18	108	16	1.80	11	13.5	3.0	10.8	44	36	Montmorillonite	Illite and kaolinite.
S 37000, Davidson clay loam, Va.	A-7-5(20)	MH	100	99	95	88	80	74	34	70	2.89	30	91	24	1.60	14	12.3	1.5	11.7	48	39	Degraded mica	Kaolinite, amorphous iron oxides and quartz.
S 30375, Parsons silt loam, Okla.	A-7-6(20)	CH	100	99	94	75	59	53	34	62	2.65	28	91	9	1.98	19	29.2	6.0	31.3	47	106	Montmorillonite	Kaolinite.
S 30907, Winterset silty clay loam, Iowa.	A-7-5(20)	CH	100	99	98	80	52	42	40	70	2.73	25	94	9	2.02	21	25.2	11.0	31.9	51	141	Montmorillonite	Illite and kaolinite.
S 30932, Iredell silt loam, Va.	A-7-5(20)	MH-CH	100	97	91	80	71	60	47	82	2.85	25	94	9	2.07	26	46.1	15.1	46.9	80	157	Montmorillonite	Kaolinite and halloysite.
S 16313, Potomac clay, D.C.	A-7-6(20)	CH	100	100	97	87	52	41	34	60	2.83	22	99	16	1.88	19	22.9	25.3	22.4	33	93	Kaolinite	Illite and mont morillonite.
S 36004, Bentonite (calcium ion), Miss.	A-7-6(20)	CH	100	100	100	(1)	(1)	(1)	108	167	2.83	45	75	13	1.78	35	(2)	30.1	81.3	103	532	Montmorillonite	None.
S 36005, Bentonite (sodium ion), Wyo.	A-7-6(20)	CH	100	100	100	(1)	(1)	(1)	421	515	2.81	51	69	36	1.23	39	(2)	28.5	89.0	51	521	Montmorillonite	None.
S 35332 and S 35365 (combined), Berthoud, Mont.	A-7-6(14)	CL	100	100	95	79	64	30	22	44	2.74	20	102	13	1.96	16	22.0	13.3	24.0	42	105	Vermiculite and montmorillonite.	Kaolinite and illite.

[1] Could not be determined by hydrometer method. Not determinable by Georgia method.

able 5.—Relationships of standard test results to shrink-swell potential

Test method or measurement	Quality of relationship to shrink-swell potential	Remarks
Plasticity Index.	Good	May overestimate shrink-swell potential of soils containing iron oxides and inactive clays.
Shrinkage limit.	Fair	Underestimates shrink-swell potential of bentonitic soils.
AASHO: T 190.	Poor	Molding moisture and density conditions not suitable for prediction of shrink-swell potential.
CBR	Fair	Relationship with shrink-swell potential slightly improved for specimens molded to AASHO: T–180.
AASHO: T–116.	Fair	May overestimate the shrink-swell potential of soils sensitive to method of compaction.
Georgia volume change test.	Good	May overestimate shrink-swell potential of micaceous soils; method not suitable for bentonite soils.
Surface area.	Good	May overestimate the shrink-swell potential of high-activity clays mixed with sands.
Linear shrinkage.	Good	Test fairly rapid and easy to perform.

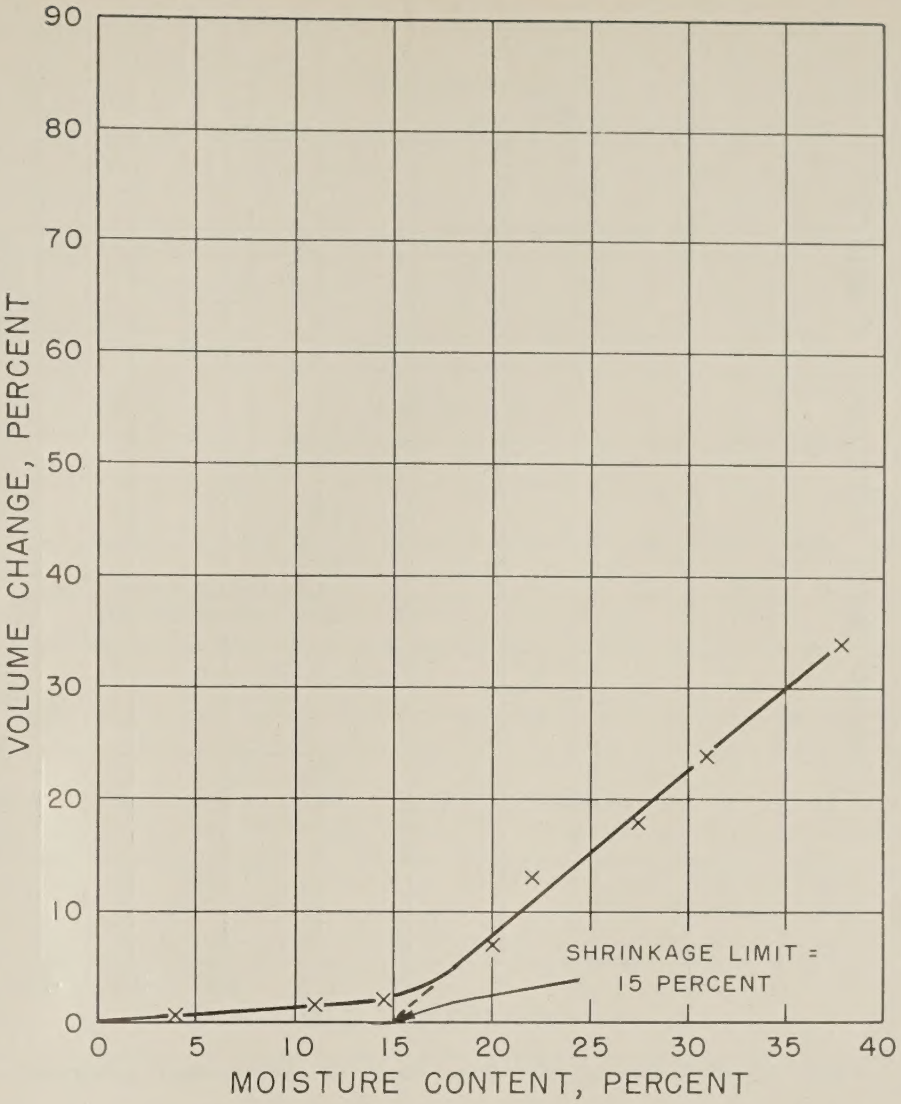

Figure 7.—Phenomenon of shrinkage limit.

f the specimens was determined during he fourth drying period. The volume of he wet specimens was calculated from their ieasured height and diameter; the volume f the dry specimens was measured by mercury isplacement. The total volume change was xpressed:

$$\text{otal vol. change} = \frac{\text{Vol. wet specimen—Vol. dry specimen}}{\text{Volume wet specimen}} \times 100$$

Tests were made on 12 soils to confirm the quilibrium hypothesis postulated from 'orter's work. The texture of these soils anged from a loessial silt having a PI of 4 low shrink-swell potential) to a bentonite aving a PI of more than 300 (very high shrink-well potential). Test data and other characeristics of the 12 soils are shown in table 3. 'he volume change of the soil specimens was ieasured under a 0.25 p.s.i. surcharge to rovide a reasonable restraint without maskig volume change.

Wet-dry cyclic changes in height for two f the soils that had very different volume-hange characteristics are shown in figures 4 and 5. Primary observations in this test series were: (1) The fat clay (Iredell) specimen molded at optimum moisture content swelled much more after being dried than when it was initially at optimum moisture content; (2) during the first soaking, the specimens of both soils compacted when air dry showed a change in height that was disproportionately greater than subsequent height changes; (3) in both cases, the height change of all specimens became essentially constant after several cycles of wetting and drying—at this point, the effects of the difference in initial density and moisture content appeared to have been minimized.

Because the equilibrium shrink-swell condition was achieved by the procedure described in the foregoing paragraphs, shrink-swell potential is defined as the volume change (in percent) that occurs under a 0.25 p.s.i. surcharge during the fourth drying in four cycles of wetting and drying of a soil compacted at optimum moisture content to 100 percent of the AASHO: T 99 maximum density. The shrink-swell potential for each of the 12 soils used in this study is listed in table 4.

Up to this point, the study was directed to a method of determining shrink-swell potential uninhibited by molding moisture, density, particle orientation, or the like. The method involved alternate wetting and drying of the soil and required one or more weeks to complete a test. In an effort to shorten the time required to obtain an estimate of shrink-swell potential, it was hoped that a relationship could be developed with the results obtained by some other test method that could be performed in a shorter time. For this reason, the same 12 soils were tested by 8 standard or universally accepted volume-change or swell-pressure tests, and the results were compared with the shrink-swell potential.

A method proposed by Seed, Woodward, and Lundgren (*9*), for determining swelling potential only, consists of compacting a soil to maximum density at optimum moisture content and measuring the percent of swelling after the specimen has soaked under a 1-p.s.i. surcharge. The authors concluded that for practical purposes, however, the swelling potential of a soil could be predicted from the plasticity index, but that the actual amount of swelling a soil may have in the field can only be determined from swelling tests conducted under conditions that are as similar as possible to anticipated field conditions.

In the study reported here, data obtained from shrinking and swelling tests showed that the plasticity index is also a good predictor of shrink-swell potential. In addition, the data

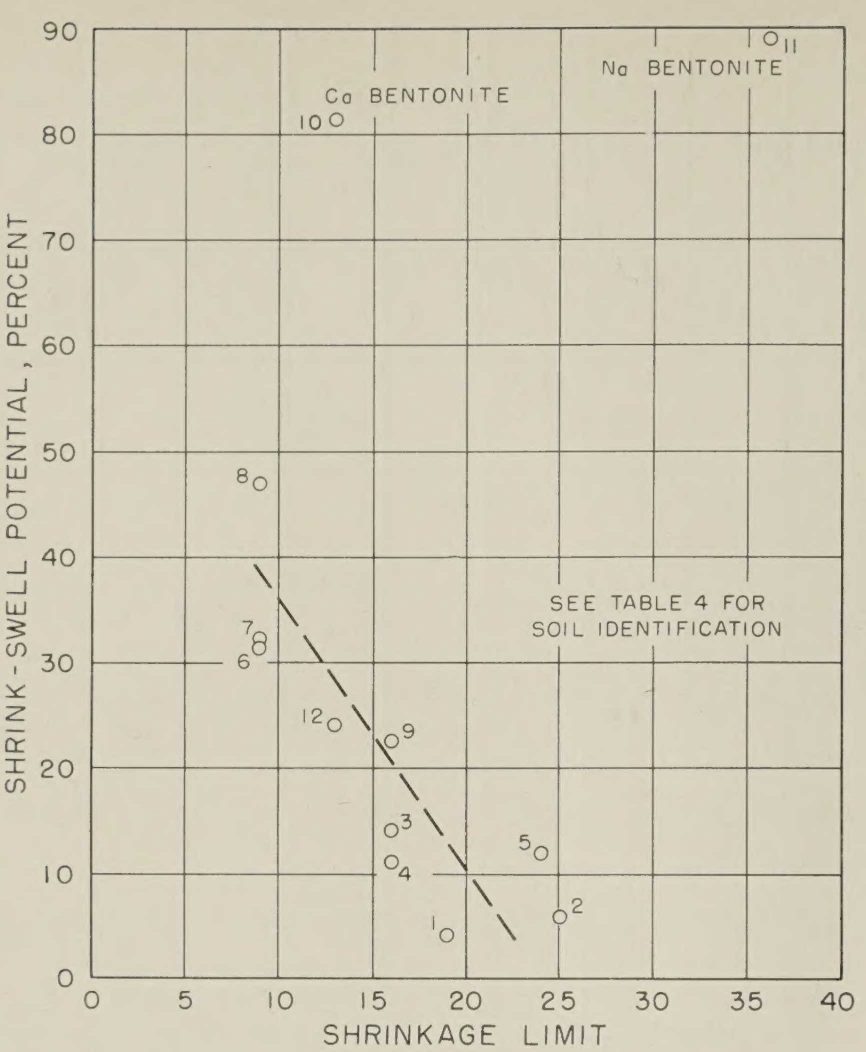

Figure 8.—Relation of shrinkage limit to shrink-swell potential.

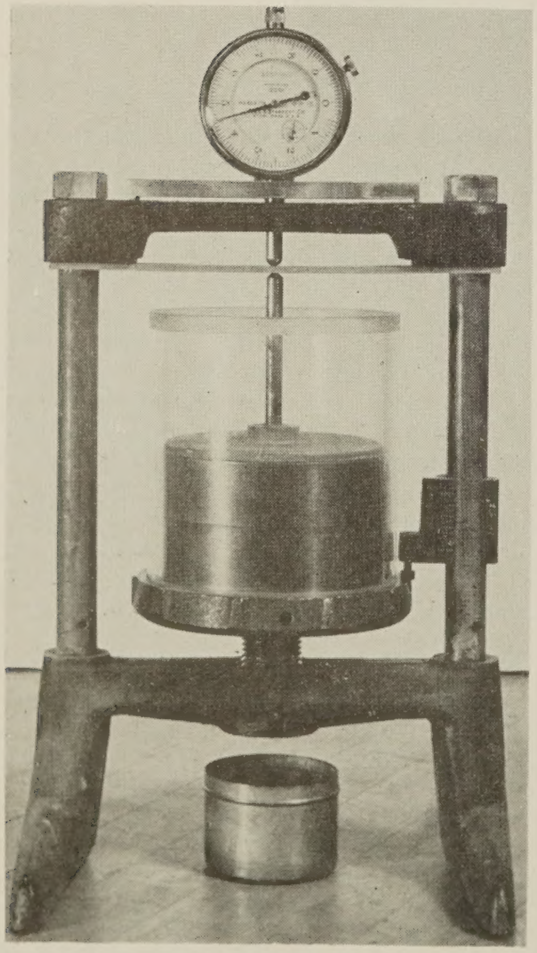

Figure 9.—Apparatus for AASHO: T 190—expansion pressure test.

compiled showed: (1) The results obtained from a variety of other types of tests on soils having a wide range of shrink-swell potential, and (2) factors affecting these test results. Limitations of some of the methods and the test results are discussed.

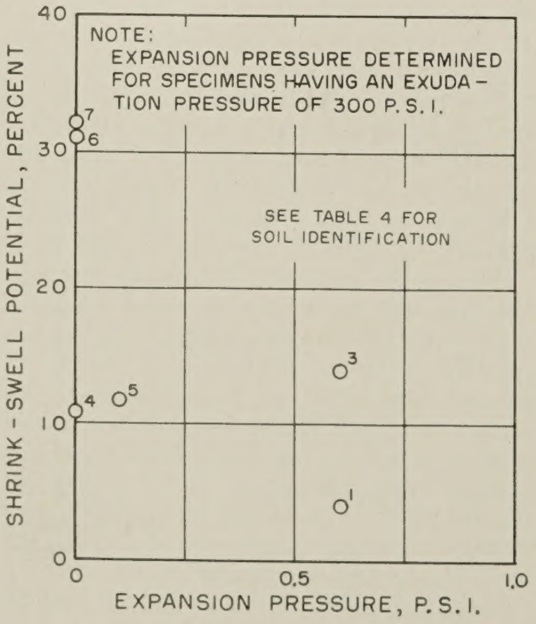

Figure 10.—Relation of expansion pressure by AASHO: T 190–61 to shrink-swell potential.

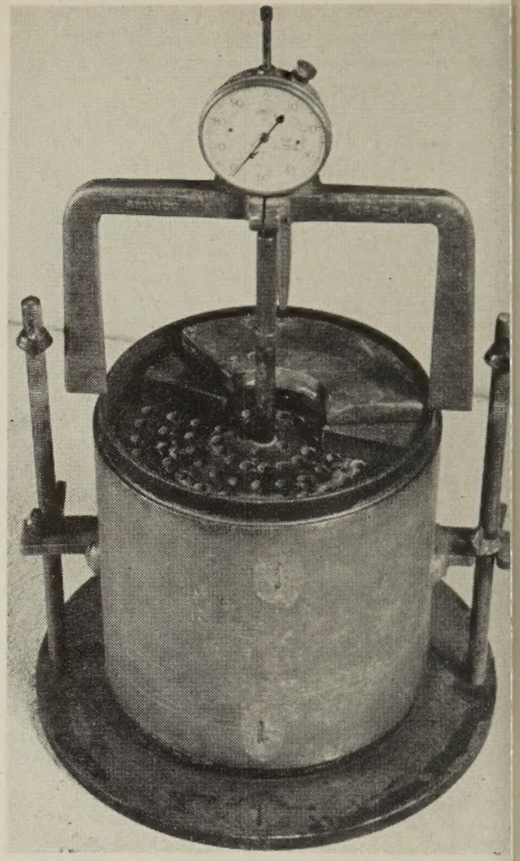

Figure 11.—Apparatus for CBR volume change test.

Test Results Compared

In the following part of this article t shrink-swell potential test results are compar to the results obtained from standard tests the same 12 soils. In an attempt to find rapid, reliable substitute, the standard tes were evaluated for their ability to predict t shrink-swell potential. The eight tests studi are listed as follows, with AASHO test desi- nations where applicable: Plasticity ind (PI), T 91–54; shrinkage limit (SL), T 92–

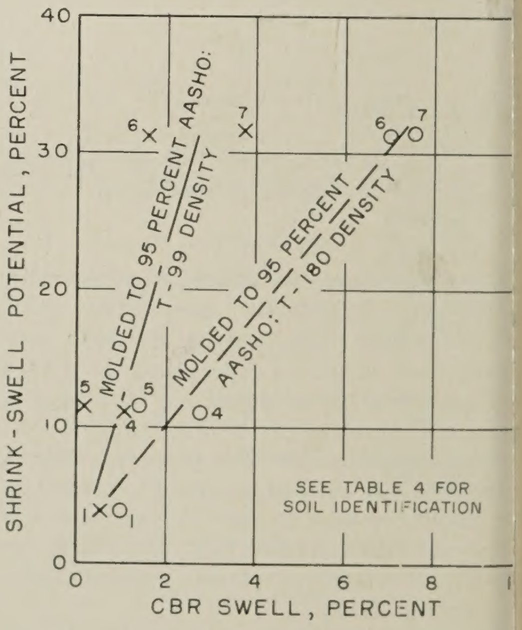

Figure 12.—Relation of CBR swell to shrin swell potential.

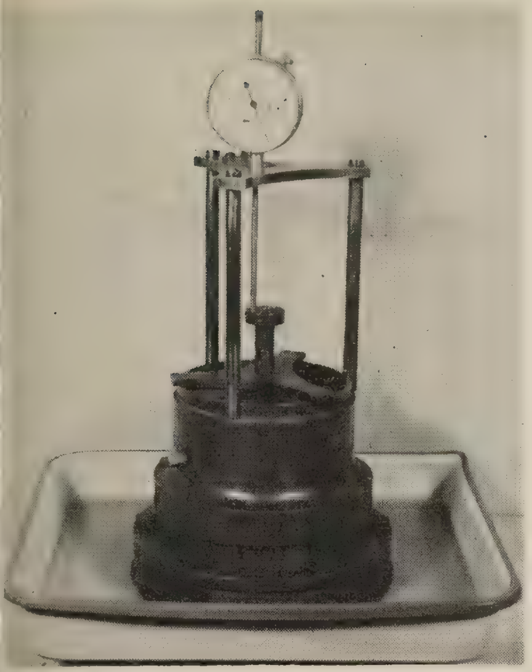

Figure 13.—Apparatus for AASHO: T 116—Volume Change Test.

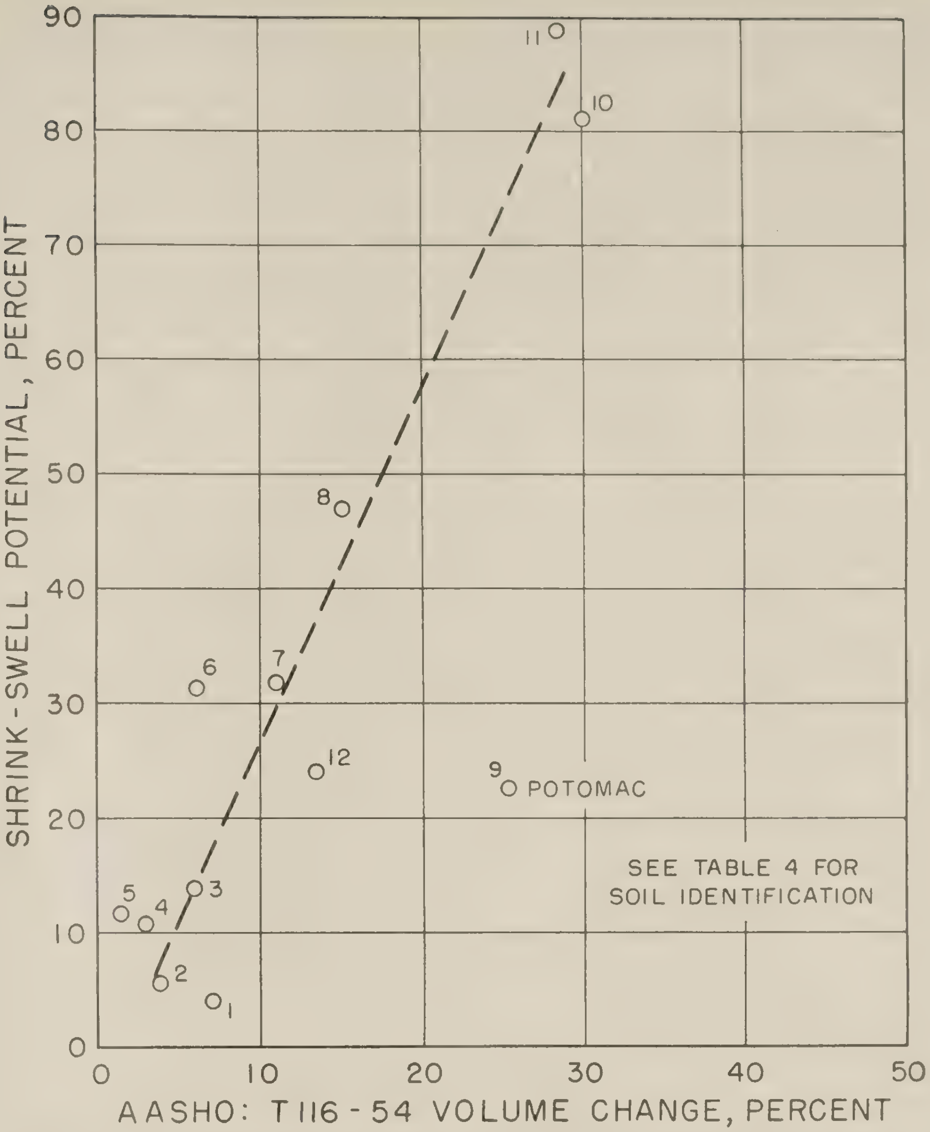

Figure 14.—Relation of AASHO: T 116–54 volume change to shrink-swell potential.

expansion pressure, T 190–61; CBR volume change, T 193–63 with modification; volume change of soils, T 116–54; Georgia volume change; total surface area; and linear shrinkage.

Plasticity index

The plasticity index (PI) is the range of moisture content over which the soil is in a plastic condition. Figure 6 shows the relationship of PI to the shrink-swell potential for the 12 soils tested. The relationship for 10 of the soils was fairly good. Based on the relationship for these 10 soils, the other 2, Cecil and Davidson, had only about one-half the shrink-swell potential that would have been anticipated on the basis of their PI's. Perhaps this was because these soils had high contents of iron oxide. The Davidson soil closely resembled lateritic soils normally developed in the tropics.

Shrinkage limit

The shrinkage limit (SL) is the calculated moisture content below which a soil has only a small change in volume as moisture content is further reduced. Figure 7 shows a plot of volume change versus moisture content; SL is indicated at the intercept of zero volume change and 15 percent moisture content. The SL of soils is generally inversely related to PI and fineness of soils. Figure 8 shows the relationship of shrink-swell potential to SL for all 12 soils. The relationship was fair, except for the two bentonites that showed much higher shrink-swell potential than would have been expected from their SL's.

AASHO: T 190

The expansion pressure test described in AASHO: T 190 measures swell pressure (fig.). Figure 10 shows little relationship between shrink-swell potential and expansion pressure, as determined by AASHO: T 190 procedures. In general, when these procedures are used, silty and permeable lean clay soils have medium to high swelling characteristics, and relatively impermeable fat clay soils have low to medium swelling characteristics. Specimens of fat clays tended to dry and shrink on the bottom during the soaking period. Covering the bottom of these soils with a rubber disk caused higher swelling pressures. Soaking times longer than 16 to 20 hours also caused higher swelling pressures for fat clays.

CBR Volume Changes

The CBR test measures the change in height that occurs when a compacted soil specimen is soaked, usually for 4 days (fig. 11). The soaking procedure is conducted primarily to place the soil in the weakest condition it may attain under pavements, although the measurement of height change during soaking apparently gives a fair indication of how much trouble can be anticipated because of volume change. Figure 12 shows the relationship of swelling during the CBR test to shrink-swell potential test results. For the limited data, the relationship was better for CBR specimens molded to 95 percent of the AASHO: T 180 maximum density than for those molded to 95 percent of the AASHO: T 99 maximum density.

AASHO: T 116

The test for determination of volume change of soils, AASHO: T 116, is similar to the CBR swelling procedure, except that the specimen is smaller, the soaking period is longer, and the specimens are usually compacted statically instead of dynamically. A soaking specimen is shown in figure 13. The relationships between the results of this test and shrink-swell potential are shown in figure 14. The Potomac clay soil did not appear to fit the relationship, possibly because this soil was very sensitive to loading conditions and type of compaction.

Georgia Volume Change

The Georgia test was developed to classify subgrades for road construction. Two identical specimens of each soil are compacted at optimum moisture content. One specimen is allowed to dry; the other is soaked, as shown

Figure 15.—Georgia volume change test: one specimen soaking, one specimen drying.

in figure 15. The soil classification is based on the combined volume change of the two specimens and its laboratory compacted density. The volume change of 9 of the 12 soils studied showed a fair to good relationship with shrink-swell potential (fig. 16). The Cecil soil had a different relationship, perhaps because the mica in this soil caused high swelling characteristics the first time it was wetted after being compacted. The Na and Ca bentonites could not be tested by the Georgia method because the top of the soaked samples curled and cracked as a result of the inability of the specimens to soak up water quickly enough to prevent the top of the specimens from drying.

Total Surface Area

Measurement of the total surface area is not a standard test method, but the results correlate so well with shrink-swell potential that these measurements are included here as a matter of interest. Total surface area is the sum of the external and the internal surface areas (see fig. 1, part B), expressed in square meters per gram of soil passing the No. 40 sieve. The values reported were measured by the Diamond and Kinter (*10*) glycerol retention method. The relation of total surface area to shrink-swell potential is shown in figure 17. The gradation of the Hybla Valley clay caused the shrink-swell potential to be about one-half the anticipated value based on the total surface area. Although the clay portion of this soil was chiefly montmorillonite, a material having a high surface area, there evidently was sufficient sand to form a resistance to shrinkage.

Linear Shrinkage

Linear shrinkage is the decrease in length of a bar of soil-water mixture that is dried until shrinkage ceases; it is expressed as a percentage of the original length of the bar. In addition to being a test that is fairly rapid and easy to accomplish, the dry length of the specimen at the end of the test, compared to the length of the mold, provides a physical sense of the soil's susceptibility to shrinkage or swelling (see fig. 18).

For purposes of this study, linear shrinkage tests were made on soil that was slightly wetter than the liquid limit. Teflon[3] molds were used that were 20 cm. long by 2.54 cm. diameter and had a semicircular cross-section. They were lubricated with 0.3 g. petroleum jelly and the specimens were dried in an oven at 70° C. ±5°. The drying temperature was selected on the basis of results of tests indicating that linear shrinkage was affected only slightly by differences around the 70° C. This procedure produced a very good correlation of linear shrinkage with shrink-swell potential (fig. 19).

Review of Relationships

The results of the eight standard tests studied are related to shrink-swell potential with different degrees of success. Table 5 lists the general quality of the relationships and presents possible explanations as to why certain soils did not readily conform. Four of the tests—plasticity index (PI), Georgia volume change, surface area, and linear shrinkage—were closely related to shrink-swell potential. Of these four, the PI requires only a few hours to perform when rapid drying equipment is available; but the linear shrinkage requires about 16 hours (overnight drying). However, by the PI relationship, the shrink-swell potential of fine-grained but inactive clays was apparently overestimated by about two to one. Also the PI is not so easily related to shrink-swell potential as is an actual volume change test such as linear shrinkage. Linear shrinkage is the easiest to perform of any of the tests studied.

The relationship of linear shrinkage to shrink-swell potential was very good for the linear shrinkage test method described in this article. However, further investigations, not reported here, were devoted specifically to factors influencing the linear shrinkage test. The primary purpose of these investigations was to find a modified procedure that would provide an even better correlation. Results obtained by an alternate procedure, devised as a result of the supplementary studies, did not correlate as well with shrink-swell potential as those obtained by the test method herein described. The study, however, did show the variables and their quantitative effect on linear shrinkage test results. A limited supply of an informal report on the supplementary study is available. Interested researchers may obtain copies without cost by addressing requests to the Bureau of Public Roads, Washington, D.C., 20235, attention: Materials Division, Office of Research and Development.

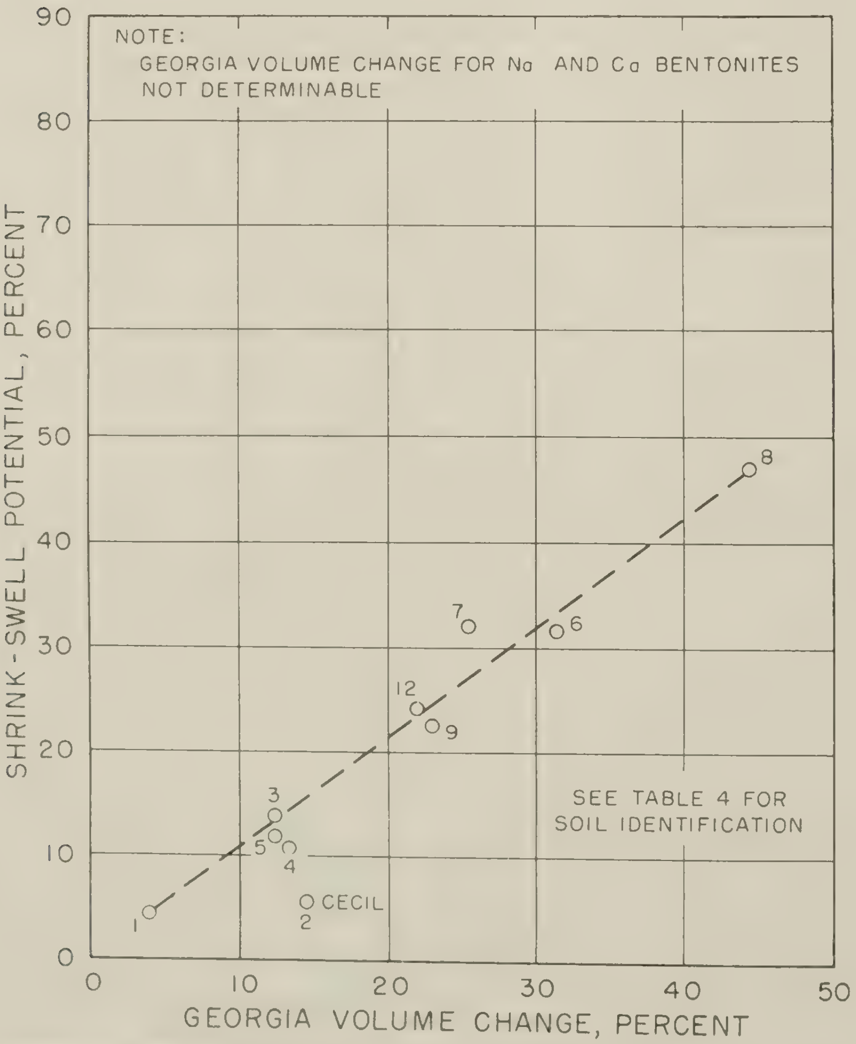

Figure 16.—Relation of volume change by Georgia method to shrink-swell potential.

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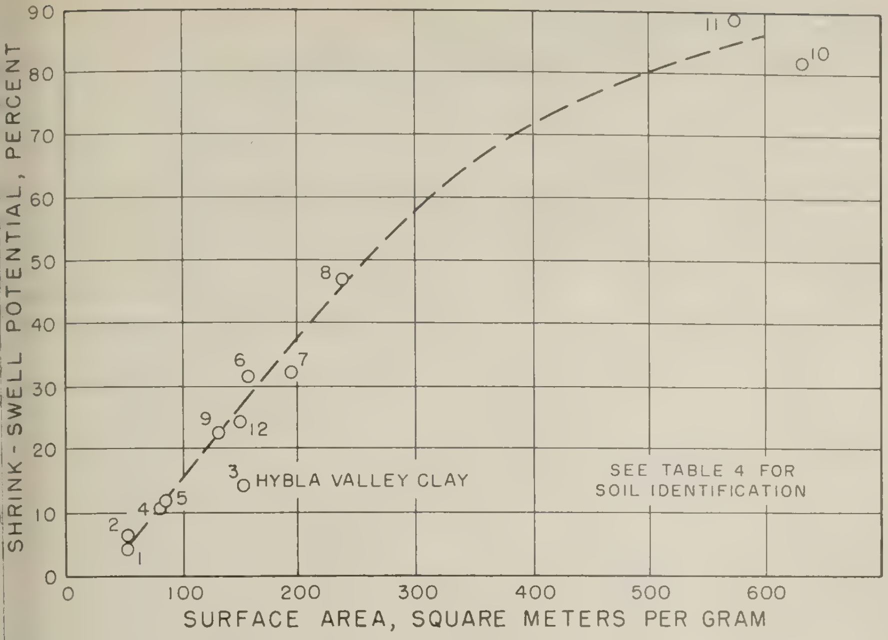
[3] Trade name for polymerized tetrafluoro ethylene, a synthesized plastic.



igure 17.—Relation of total surface area to shrink-swell potential.

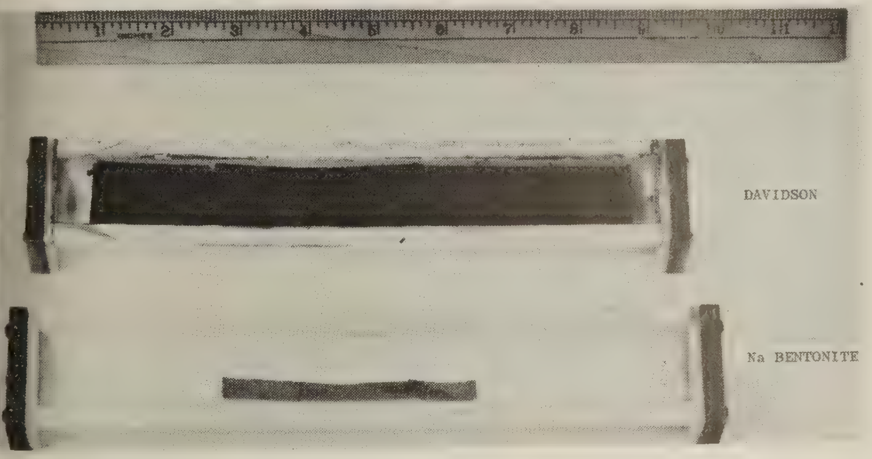


Figure 18.—Dried linear shrinkage specimens of two soils.

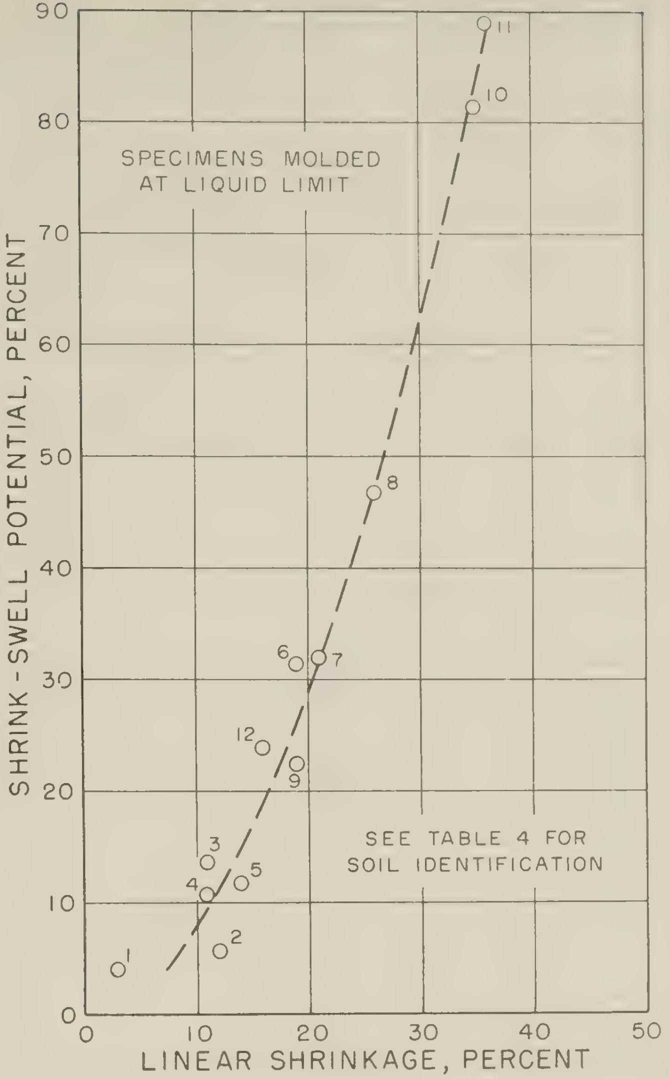


Figure 19.—Relation of linear shrinkage to shrink-swell potential.

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Friction Reducing Mediums for Rigid Pavement Subbases

Reported by[1] ALBERT G. TIMMS
Highway Research Enginee

BY THE STRUCTURES AND
APPLIED MECHANICS DIVISION
BUREAU OF PUBLIC ROADS

Increased interest in the use of prestressed concrete pavements has been accompanied by an awareness of the need for friction reducing mediums between the subbase and the slab in order to minimize the required prestressing force. The Bureau of Public Roads has tested several different mediums in a winter-spring study and a summer study. The findings from these studies are discussed in this article.

In the studies, concrete slabs 6 feet square were moved horizontally, alternately forward and backward, several times to simulate the movement of pavements in service. The thrust necessary to cause horizontal movement and the magnitude of displacement caused by the thrust were measured from the first detectable movement until free sliding of the slab began.

All the slabs used in the test were 5 inches thick but weights were added for two sets of tests so that the effects of 8- and 11-inch slabs were obtained. Resistance to slab movement was determined for the seven underlying materials: a plastic subgrade, two types of granular subbases, and four types of mediums on a granular subbase. Most of the tests were made at a very slow rate of loading, but for comparison purposes some tests were run at medium and fast rates.

The least resistance was recorded when the medium was either a thin layer of sand or a double layer of polyethylene sheeting on a thin, leveling course of sheet asphalt. Both of these mediums were considered effective in reducing friction between the subbase and the slab.

Introduction

AS EARLY as 1924 the Bureau of Public Roads conducted studies to determine the magnitude of the resistance offered by the underlying material to the horizontal movement of concrete pavement slabs. Data from these early studies clearly showed that the resistance differed considerably according to the type of material upon which the pavement rested. Increased interest in the use of prestressed concrete pavements has been accompanied by an awareness of the need for mediums between the subbase and the slab that have a low resistance to slab movement.

For many years pavement designers have known that mediums having a low resistance to slab movement will reduce materially the direct tensile stresses induced in concrete slabs by resistance to movement during contraction. Because direct tensile stresses are generally very small for the relatively short slabs of conventional concrete pavements, little use was made of friction reducing mediums until the advent of the use of prestressed concrete pavements.

Prestressed concrete pavement slabs having lengths up to 800 feet require mediums that have a low friction coefficient for the most efficient use of the prestressing force. A medium that would reduce the frictional resistance of the subbase by 50 percent could make possible a 30- to 40-percent reduction in the required prestressing force.

Previous investigators have established that the resistance to slab movement could be decreased by different means. In 1924 Goldbeck (*1*)[2] reported that the elimination of ridges and depressions in the subgrade or the introduction of a sand layer between the subgrade and the pavement caused an appreciable decrease in the coefficient of friction. Recently, Stott (*2*), of the Road Research Laboratory of Great Britain, presented the results of a comprehensive investigation of different materials used as sliding layers over granular subbases, including polyethylene sheeting, paraffin wax, bitumen, and lubricating oil.

Heretofore, a thin layer of sand has been the most commonly used medium to reduce friction between the subbase and the slab. However, many engineers now believe that sand layers should not be used under the relatively thin prestressed highway pavements because of the possibility of aggravation of edge pumping. In recognition of the importance c friction reducing mediums for construction c prestressed concrete pavements, the Burea of Public Roads undertook a study designe to develop comparative data on several type of mediums that have been proposed b designers of such pavements.

Conclusions

The following conclusions are based on th analysis of the data developed in the stud reported here:

- For granular subbase materials, th magnitude of the coefficient of sliding frictio was unaffected by (1) differences in sla thicknesses of 5, 8, or 11 inches or (2) b seasonal differences in subgrade moisture co tent. When the friction reducing mediu was a double layer of polyethylene sheetin on a thin leveling course of sheet asphalt, th thickness of the slab did not cause any di ference in the magnitude of the coefficient c friction. The effect of seasonal differences i subgrade moisture on the friction coefficie was not determined when the polyethyle sheeting was used.
- For a thin layer of sand on a granula subbase, the coefficient of friction was u affected by rate of application of the thrusti force (rate of loading), which ranged from 1 to 90 minutes for total applied force. T effect of rate of loading on the coefficient c friction was not determined for the oth mediums used.
- The coefficient of friction for the initi movement of a slab was appreciably great than for subsequent movements; essenti stability of resistance was obtained after on 2 or 3 cycles of movement.
- Mediums of both a thin layer of sand a of a double layer of polyethylene sheeting c a thin leveling course of sheet asphalt we effective in reducing friction between the su base and the slab.

Scope of Study

Resistance to slab movement was dete mined for a plastic subgrade, two types granular subbases, and four types of mediu on a granular subbase. These underlyi materials were: (1) Subgrade soil consisti of micaceous clay loam and referred to this article as plastic soil; (2) a granular su base consisting of material that met t

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[1] Presented at the 43d annual meeting of the Highway Research Board, Washington, D.C., January 1964.

[2] References indicated by italic numbers in parentheses are listed on page 111.

Bureau of Public Roads grading and plasticity requirements for Federal highway projects (*3*); (3) a granular subbase consisting of a blend of washed sand and gravel; (4) a granular subbase, same as No. 2, and a 1-inch sand layer covered by 1-ply building paper; (5) a granular subbase, same as No. 2, and a layer of emulsified sand asphalt about 1 inch thick; (6) a granular subbase, same as No. 2, and a thin leveling course of sheet asphalt covered by a double layer of polyethylene sheeting that contained a special friction reducing additive; and (7) a granular subbase, same as No. 2, and a layer of sheet asphalt about one-half inch thick. The physical properties and AASHO classification of the subgrade and subbase materials, and information on the sheet and emulsified asphalts, are listed in table 1.

For each underlying material, force-displacement curves were developed from data obtained by moving concrete slabs, 6 feet by 6 feet, horizontally, alternately forward and backward several times to simulate the behavior of pavements in service. The force or thrust necessary to cause horizontal movement of the slab and the magnitude of displacement caused by the thrust were measured from the first detectable movement until free sliding began.

Table 1.—Physical properties of subgrade and subbase materials, and sheet asphalt and emulsified asphalt [1]

Properties	Subgrade	Granular subbase	Sand in sheet asphalt	Sand in emulsified asphalt
Mechanical analysis:				
Passing, sieve size:				
3-inch .... percent..	--------	100	--------	--------
2-inch .... do....	--------	98	--------	--------
1½-inch .... do....	--------	96	--------	--------
1-inch .... do....	--------	91	--------	--------
¾-inch .... do....	--------	84	--------	--------
⅜-inch .... do....	100	70	--------	100
No. 4 .... do....	99	61	100	95
No. 10 .... do....	98	54	98	87
No. 40 .... do....	94	36	68	37
No. 80 .... do....	--------	--------	30	9
No. 200 .... do....	78	15	12. 5	4
Liquid limit	40	33	--------	--------
Plasticity index	15	16	--------	--------
Classification	A-6(10)	A-2-6(0)	--------	--------
Penetration	--------	--------	60-70	60-70
Asphalt content .... percent..	--------	--------	8. 8	7. 5

[1] No information was available for the subbase of blend washed sand and gravel.

The testing program was divided into a winter-spring study and a summer study, when the absorbed moisture in the subbase and subgrade were at the maximum and minimum, respectively, of the annual cycle of moisture change. All slabs were 5 inches thick. To develop data on force-displacement curves for 8- and 11-inch thick slabs, 100-pound weights were dispersed uniformly on top of the 5-inch slabs to provide the equivalent weights. A general view of the test slabs and a 5-inch slab loaded to the weight equivalency of an 11-inch slab are shown in figure 1.

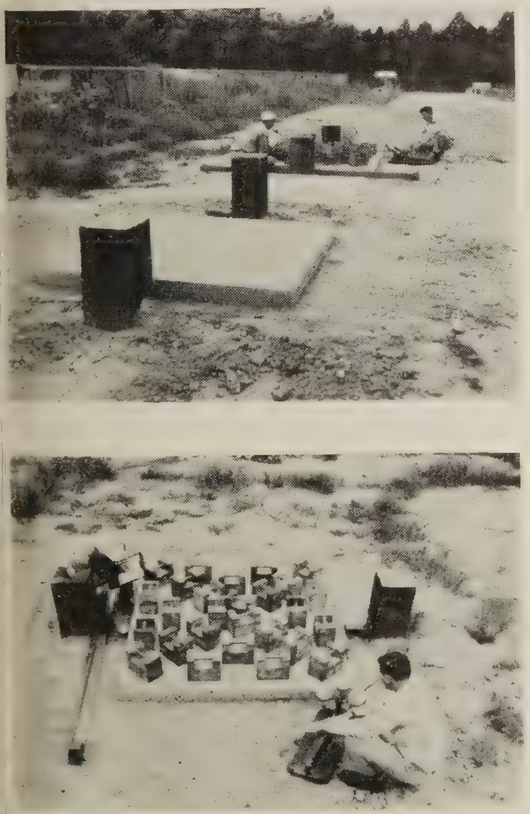

Figure 1.—Upper: General view of slabs between abutments.

Lower: A 5-inch slab loaded to the weight equivalent of an 11-inch slab.

Test Procedure

A schematic arrangement of the test slabs and the testing apparatus is shown in figure 2. Five wooden posts, 1-foot square, were set 3 feet deep in the ground on 9-foot centers to serve as reaction abutments for the hydraulic jack used to apply the thrusting force. The subbases and sliding mediums were placed symmetrically in 8-foot squares between the wooden posts. The 6-foot square, 5-inch thick concrete slabs were cast in place and centered in the 8-foot squares. The thrusting force was applied by a hydraulic jack to the concrete slab through a 3-foot long, 4-inch channel bearing plate. Horizontal displacement was measured by a micrometer dial on the side of the slab opposite the thrusting force.

In most of the tests the thrusting force was applied continuously for 5-minute in-

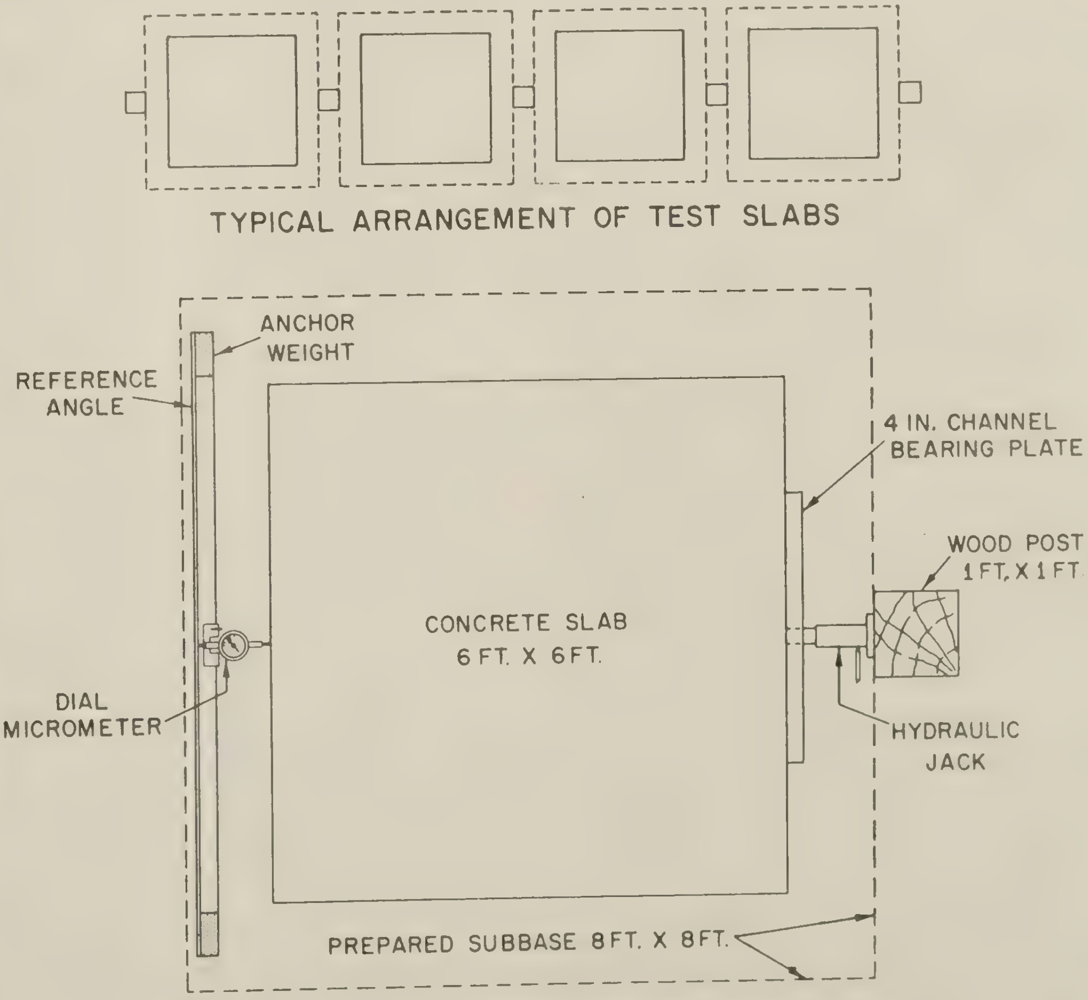

Figure 2.—Arrangement of test slabs and testing apparatus.

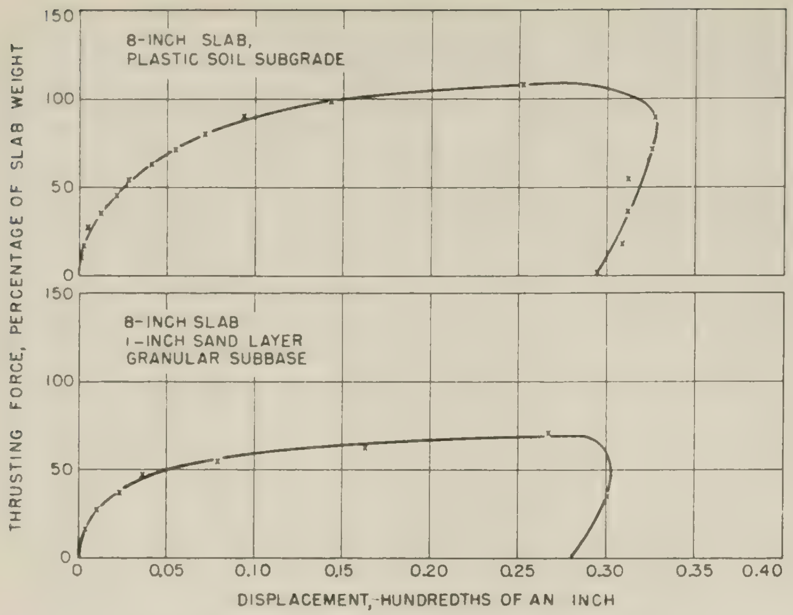

Figure 3.—Typical force-displacement curves.

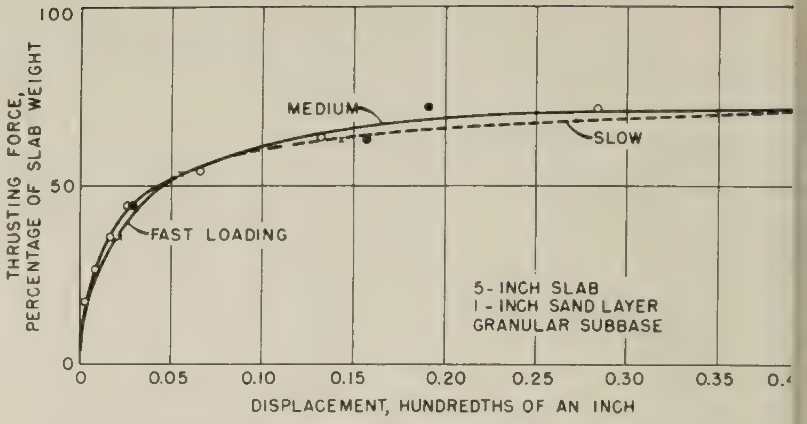

Figure 4.—Effect of rate of loading on force-displacement relations.

tervals and the load increased in increments of 200 pounds on 5-inch slabs, 320 pounds on 8-inch slabs, and 440 pounds on 11-inch slabs. The thrusting force was held constant during the 5-minute interval between the added increments. The displacement of the slab was measured immediately after the application of each increment of force and immediately before the next increment was applied. These two readings were averaged for a single displacement value. Incremental loading was continued until the slab was sliding freely and the thrusting force could not be increased.

The thrusting force was removed every 5 minutes in load decrements of 400 pounds for the 5-inch slabs, 640 pounds for the 8-inch slabs, and 880 pounds for the 11-inch slabs. When the thrusting force was released, the slabs tended to move in a reverse direction. This return movement was recorded in selected tests; it was measured immediately after the removal of each decrement of force and just before the removal of the next decrement.

Force-displacement diagrams at two additional rates of loading were also developed for the 5-inch slab on the granular subbase and sand layer. One loading rate was very fast—a force of 200 pounds was applied every 10 seconds; the other loading rate was twice as slow as the described rate—200 pounds every 10 minutes.

In general, the slabs were moved back and forth three times, a total of six instrumented runs. The slab under test was protected from the elements by a canvas shelter, which was removed when figure 1 was photographed.

Test Results

The data obtained in the testing of the slabs are shown in different ways in figures 3 to 11, inclusive. These figures illustrate certain characteristics of force-displacement behavior that have been reported previously by other investigators (*2*, *4*).

Figure 3 shows typical data developed in two of the tests. Each point on the curves represents an average for results of six displacement tests, three in a forward and three in a backward direction. As the increments of force were applied, the successive increments of displacement increased in a ratio that closely approximated a parabola. After free sliding occurred, the thrusting force could not be increased beyond the force at which the slab began to slide. The slab returned slightly toward its original position upon release of the thrusting force. This return movement was believed to have been the result of elastic deformation of the soil and, as mentioned previously, was measured in only a few of the tests because such information had little value for the purpose of this study.

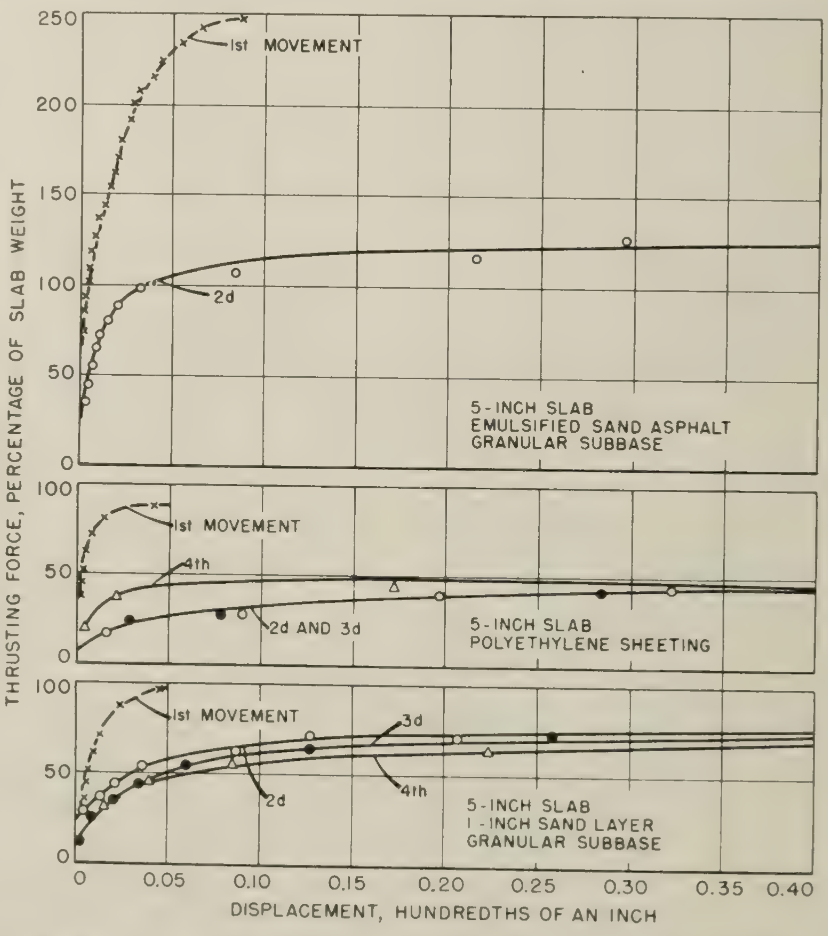

Figure 5.—Effect of successive slab movements on force-displacement relations.

Rate of Application of Thrustin Force

The effect of rate of loading on the d placement of a slab cast on the granul subbase and sand layer is shown in figure The total thrusting force was applied approximately 1½, 45, and 90 minutes for t fast, medium, and slow loading rates, respe tively. Analysis of data collected show that the rate of loading had no apprecia effect on the displacement of slabs on sa layers. This finding agrees with that of St (2) who observed that restraint offered by friction reducing layer of sharp sand was n

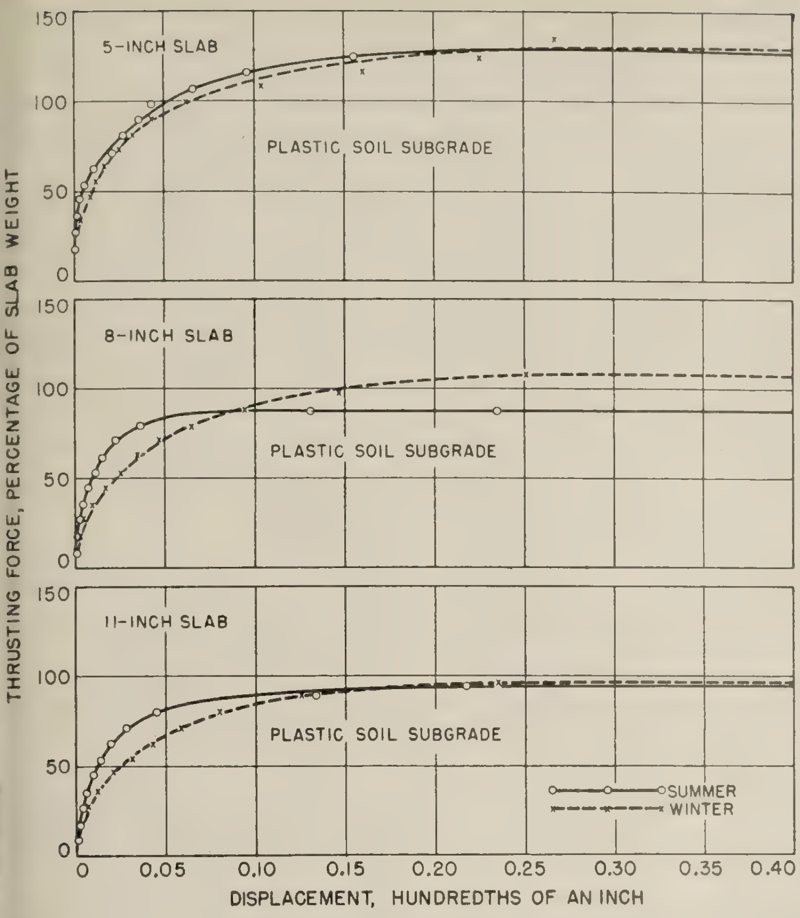

Figure 6.—Force-displacement curves for concrete slabs on plastic soil.

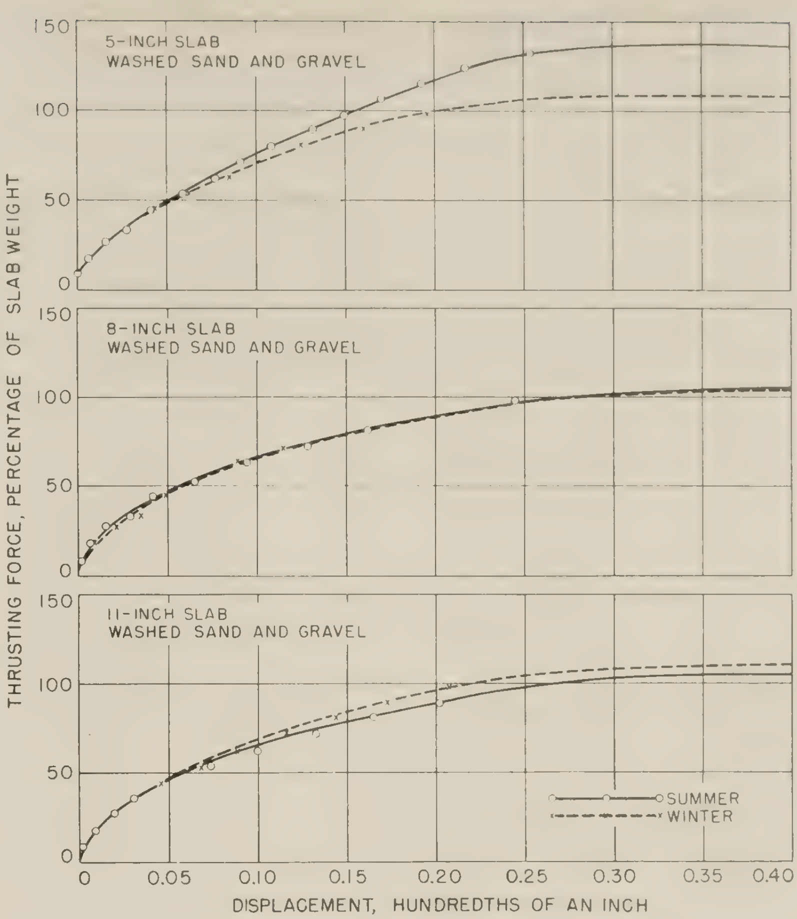

Figure 8.—Force-displacement curves for concrete slabs on blend of washed sand and gravel subbase.

markedly affected by differences in the rate of slab movement between 0.08 inch and 0.5 inch per hour.

Successive Slab Movements

As mentioned previously, the test slabs were moved back and forth several times. Examples of data obtained from these successive movements are shown in figure 5 for each of the 5-inch thick slabs cast on the sand layer, polyethylene sheeting, and emulsified sand asphalt. When free sliding occurred at first movement, the slabs moved so rapidly under the built-up thrusting force that accurate force-displacement measurements were unattainable. Therefore, plotted data on the first movement curves terminate at the point where free sliding began.

As expected, all three of the proposed friction reducing mediums produced greater resistance to slab displacement in the first movement than in the following movements (fig. 5). It is evident, however, that a condition of essential stability of resistance was obtained after only two or three movements. The data also show that the magnitude of the coefficient of friction—thrusting force at free sliding expressed in terms of percentage of slab weight—was considerably greater for the emulsified sand asphalt than for the subbases of the polyethylene sheeting and the sand layer.

Tests of the emulsified sand asphalt were discontinued after the second movement of the slab because of the large thrusting force required to cause free sliding. Likewise, tests of the sheet asphalt were concluded after the first movement of the slab because the thrusting force required to start free sliding was three times the weight of the slab. Both of these mediums bonded to the bottom of the slab; this indicated the need for use of an intermediate sliding medium beneath prestressed pavements.

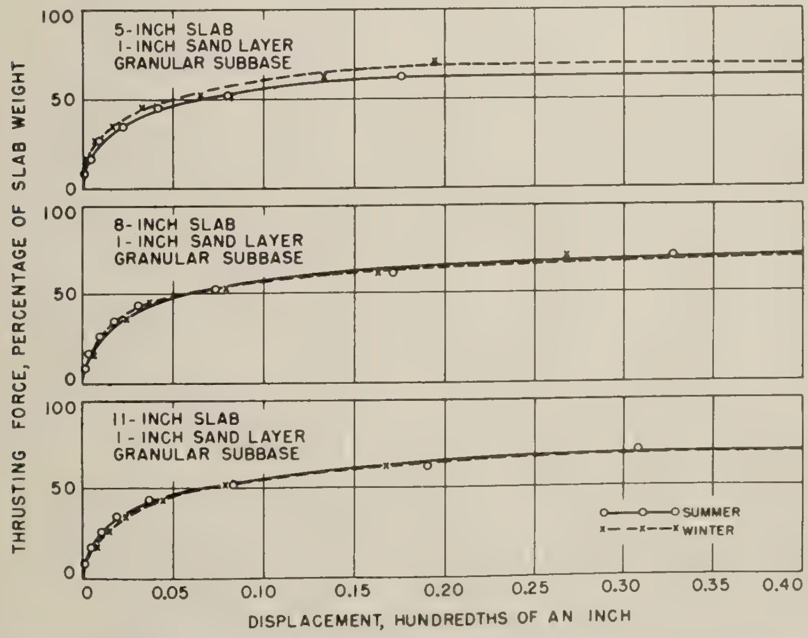

Figure 7.—Force-displacement curves for concrete slabs on granular subbase, BPR grading and plasticity requirements.

Winter-Summer Comparisons

Force-displacement relations were obtained in the summer and again in the winter-spring period for 5-, 8-, and 11-inch thick concrete slabs on the: (1) plastic subgrade soil, (2) granular subbase, (3) blend of washed sand and gravel subbase, and (4) the sand layer on a granular subbase. A 5-inch slab was cast on each of the underlying materials and, in turn, weighted to the equivalent of 8- and 11-inch slabs. The data developed in these tests are shown in figures 6 through 9. Each plotted point is the average value of displacement of five slab movements. The first movement of the slab in each of the six runs was not included in the average. Conse-

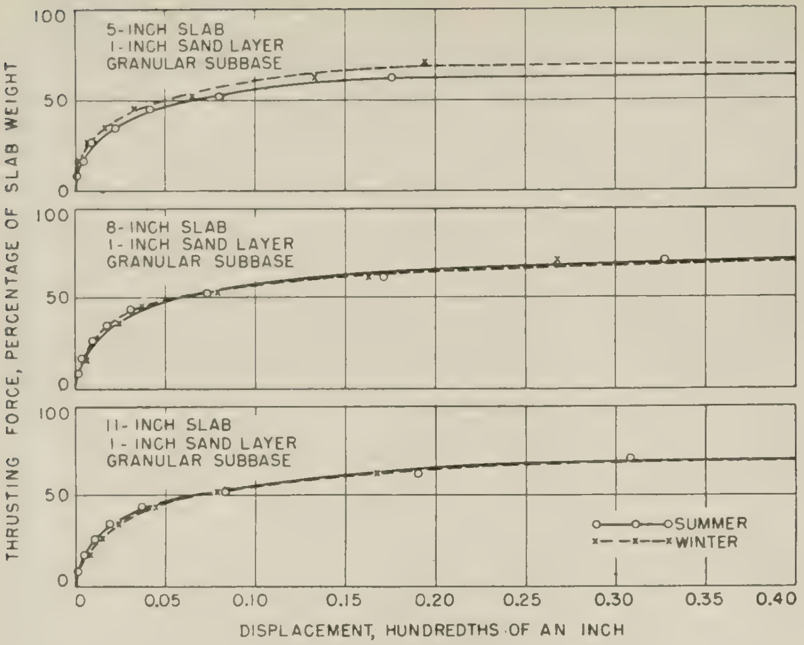

Figure 9.—Force-displacement curves, concrete slab on granular subbase, and 1-inch sand layer.

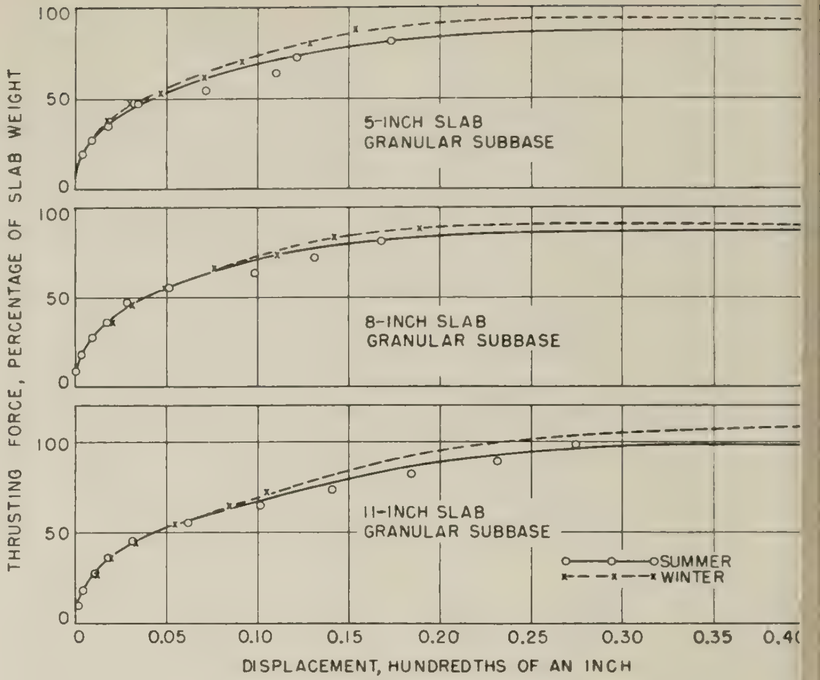

Figure 10.—Force displacement curves, leveling course of shee asphalt covered by double layer of polyethylene sheeting.

quently, the force-displacement values represent a condition of essential stability of resistance to slab movement. The subgrade was not frozen at the time of the winter-spring tests.

The force-displacement relations for the slabs on the plastic subgrade soil are shown in figure 6. For a displacement up to about 0.1 inch, less thrusting force was required to move the slabs on the subgrade in the winter than in the summer. However, in the free sliding range, the thrusting force necessary to move the slabs in the winter was at least equal to that required in the summer. The moisture in the top half inch of the subgrade soil was 22 and 25 percent, respectively, at the time of the summer and the winter-spring tests. The coefficient of friction tended to decrease in magnitude as the slab thickness was increased. This same tendency was observed by Teller and Sutherland (*4*), who noted that such a decrease in friction coefficient might be related to resistance to movement caused by an elastic or semielastic deformation within the soil itself.

Force-displacement relations for slabs on the granular subbase are shown in figure 7. The surface of granular subbases may differ considerably in roughness according to the type of granular material and construction practices. In the study discussed here, the surface of the granular subbase was relatively smooth and sandy in texture. The relatio
recorded in the tests show that (1) the mag-
tude of the friction coefficient for the granu
subbase, unlike that for the plastic subgra
tended to remain constant as the slab thickn
was increased, and (2) the shape of t
force-displacement curve for the granu
subbase, again unlike that for the plas
soil, was unaffected by moisture conditio
related to the season of the year.

The force-displacement relations for t
tests in summer and winter-spring for t
slabs on the blend of washed sand and gra
and for the slabs on the 1-inch sand lay
are shown respectively in figures 8 and
Except for the winter data on the 5-inch sla
the force-displacement relations for the ble
of washed sand and gravel were very simi
to those for the granular subbase. The da
as shown in figure 9, conclusively establish
that the coefficient of friction for the slabs
the subbase of 1-inch sand layers on granu
subbases were unaffected by seasonal diff-
ences in subgrade moisture or by slab thi-
nesses. These conditions appear to be typi
for slabs on granular materials.

Force-displacement relations were obtai
only in the summer for the slabs on a dou
layer of special polyethylene sheeting ove
thin leveling course of sheet asphalt. Fr
the force-displacement relations, which a
shown in figure 10, it is evident that sl
thickness had little effect on the magnit
of the coefficient of friction.

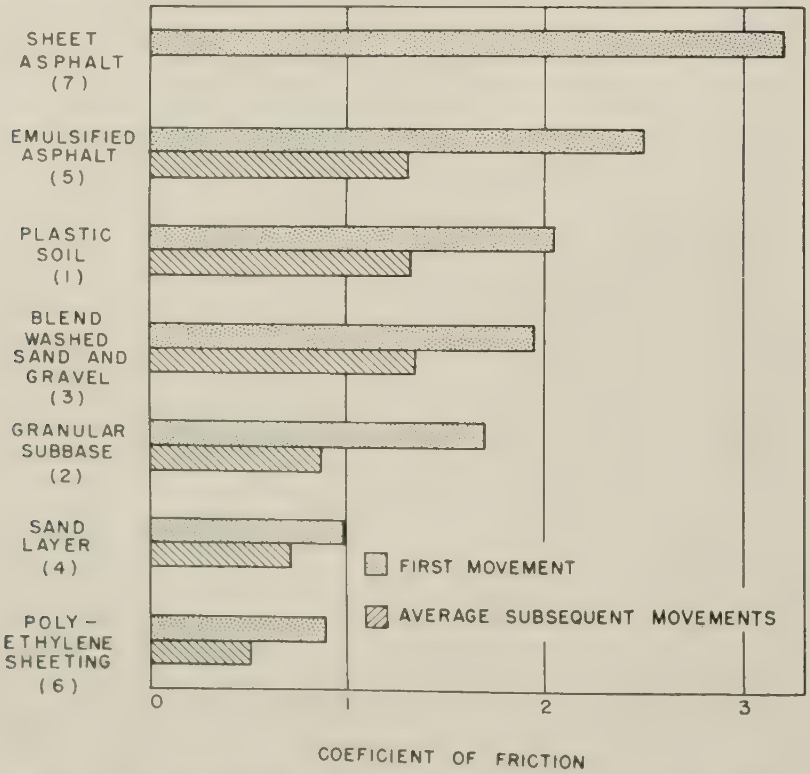

Figure 11.—Summary of coefficients of friction for slabs 5 inches thick.

Summary of Friction Coefficients f
5-Inch Slabs

Coefficient of friction data for the 5-in
thick slabs on each of the seven underlyi
materials studied are summarized in fig
11; the materials are arranged from top
bottom in the descending order of the mag
tude of related coefficient of friction valu
The numbers in parentheses identify the u
derlying materials with the seven listed un

cope of Study, p. 106. These coefficients are he maximum developed in the tests at free liding regardless of the season of the year.

Two significant facts were apparent from he test data—they are illustrated in figure 11: 1) The friction coefficient for the initial novement of a slab was appreciably greater han the coefficient for the average of sub-equent movements, regardless of the under-ying material. This difference in the coeffi-ient for the first movement ranged from 35 ercent greater for the slabs on the 1-inch and medium to about 90 percent for the emulsified asphalt. (2) The lowest coefficients of friction were obtained for the polyethylene sheeting: the coefficient of friction for the first movement was 0.9, and the average for subsequent movements was 0.5. The next to lowest coefficients of friction were recorded for the 1-inch sand layer: 1.0 for the first slab movement and 0.7 for the average of subsequent movements.

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Simplified Procedures for Determining Travel Patterns Evaluated for a Small Urban Area

BY THE OFFICE OF PLANNING
BUREAU OF PUBLIC ROADS

Reported by[1] CONSTANTINE BEN, Geographer, a
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Procedures and results obtained therewith from a two-fold research project aimed at (1) testing whether the gravity model theory would simulate travel patterns for Sioux Falls, South Dakota; and (2) evaluating simplified procedures for calibrating a gravity model for the same area are presented in this article. The application of the gravity model theory in simulating travel patterns for Sioux Falls, South Dakota, is discussed first. In 1956 a comprehensive 12.5 percent Origin-Destination survey was conducted in this small urban area, which had a population of 62,000 at the time of the survey. A three-purpose gravity model based on this full O–D survey was developed and tested. The gravity model distributions were compared with the O–D data and tests were made on trip time length frequency distributions, average trip time lengths, screenlines, and volume counts. In addition, identical tests were made on one- and six-purpose gravity models based on the same comprehensive O–D survey data.

For the second objective, to evaluate simplified procedures for calibrating a gravity model in the same small urban area, data from Sioux Falls and from several other cities were analyzed to determine the minimum acceptable sample size for use with the simplified procedures. The analyses indicated that a 599 home-interview sample might be adequate for calibration of a three-purpose gravity model. Then, the trip information available from the external cordon survey and from a subsample of 599 interviews of the original home-interview survey was used in calibrating the model. The necessary zonal production and attraction figures were determined from detailed socio-economic data by using simplified procedures. Subsequently, the synthetic gravity model distributions were checked against the data obtained from the full home-interview survey.

Although the evaluation showed that the simplified procedures were satisfactory for Sioux Falls, they may not be applicable to cities having different travel characteristics.

Introduction

A THEORY that less data on travel patterns may be sufficient for urban transportation planning than was necessary before the development of travel models provided the premise for the research reported in this article.

Since the early 1940's, the number of transportation planning studies being conducted in urban areas of the United States has been increasing. Basic data on travel patterns, social and economic characteristics of tripmakers, uses of land, and the type and extent of available transportation facilities have been collected. The interrelationships between the different kinds of data have been analyzed, and several theories of urban travel have been formulated. These theories are presented as traffic models (equations) composed of the parameters that influence the generation and distribution of urban trips, as well as the routes of the trips. One of the most widely used theories is the gravity model, which utilizes a gravitational concept to describe the distribution of trips between parts of an urban area.

Although interest has developed in the past few years (1959–63) in the use of a small sample of home-interview data for calibrating traffic models, particularly the gravity mod little has been done to test and evaluate t accuracy and validity of the theories bas on this limited data. For example, in t Hartford Area Traffic Study (*1*),[3] travel da were collected from only 200, or 0.1 perce of the dwelling units within the study ar In the Southeast Area Traffic Study (*2*), su data were collected from 1,384 or 2.0 perce of the dwelling units within its study ar Similar sampling rates have been used other studies (*3, 4*).

Specifically, the research described h had two main objectives: (1) to exami whether a gravity model would adequat reproduce trip distribution patterns for particular small urban area when comp-hensive O–D data were used in the calibrati and (2) to evaluate simplified procedures calibrating a gravity model trip distributi formula for the same urban area.

In researching the first objective, full was made of comprehensive O–D data and t resultant traffic movements calculated w the gravity model were compared with th recorded in the O–D survey.

For the second objective the trip informati available from the external cordon survey a from a subsample of the original hom-interview survey was used to calibrate t model. Simplified procedures were used determine zonal productions and attracti from detailed socio-economic data. check was made to determine whether t results obtained with the model, which w based on limited data, simulated travel pa-terns in the study area. This determinati was made by comparing the resultant tri with comparable data obtained from the O- survey of the same area.

The small urban area selected for t research described here was Sioux Fal S. Dak., which had a 1956 population

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[1] Presented at the 43d annual meeting of the Highway Research Board, Washington, D.C., January 1964.

[2] Mr. Bouchard is presently Director, Rhode Island Statewide Comprehensive Transportation and Land Use Planning Program.

[3] The italic numbers in parentheses identify referen listed on page 123.

2,000 (5). In that year, a comprehensive aome-interview O–D survey was conducted n 12.5 percent of the nearly 20,000 dwelling mits in the area. This survey was conducted t the rate recommended by the U.S. Bureau f Public Roads (6) for urban areas in which he population is 50,000 to 150,000. In ddition to this home-interview survey, the tandard external cordon and truck and taxi urveys were also conducted, as were surveys f the land use and the type and extent of he area's transportation facilities.[4] Data vere available on labor force, employment, etail sales, and the results of a 1960 parking urvey (7). The study area was divided into 4 traffic zones and 10 external stations. 'or summary and general analyses, these ones and stations were combined into 28 istricts, as illustrated in figure 1.

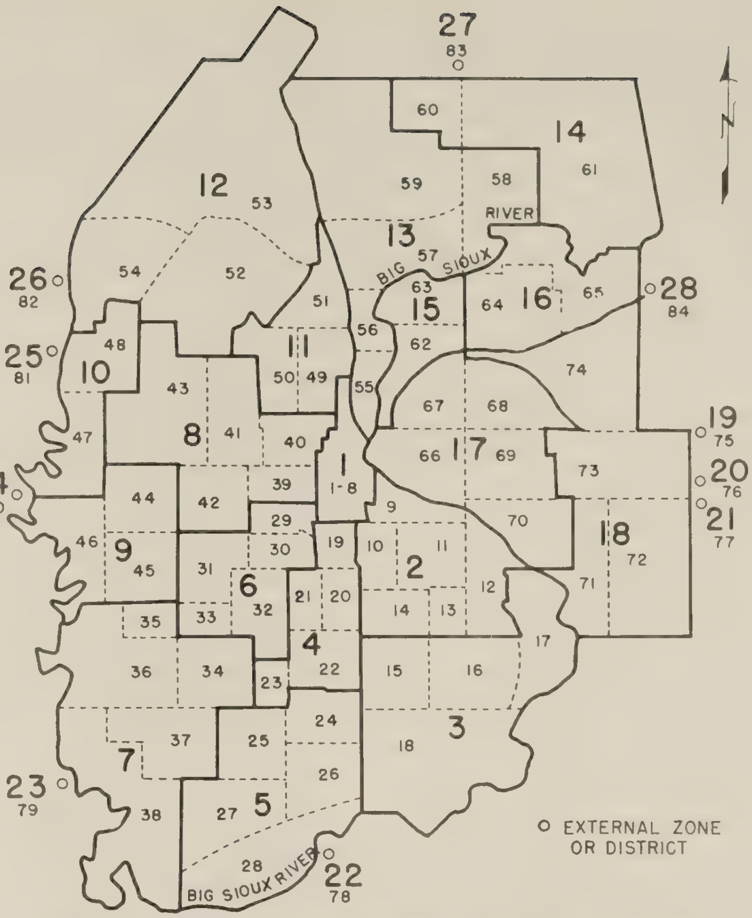

Figure 1.—Sioux Falls, S. Dak. study zones and districts.

Conclusions

Based on results obtained in the research eported herein, the following conclusions ppear to be warranted:

- The gravity model formula provided an dequate framework for determining trip listribution patterns for Sioux Falls.
- A three-purpose trip stratification of ome based work, nonwork, and nonhome ased trips was sufficient for the small urban rea.
- The synthetic procedures used in this esearch to compute zonal trip productions nd attractions were satisfactory for this nall urban area when used in combination ith detailed socio-economic data and with mited travel data from a small sample irvey.
- For Sioux Falls, a 600 home-interview mple used in combination with detailed cio-economic data and the standard exrnal cordon survey provided sufficient data r a three-purpose gravity model calibration. his is a self-contained urban area having a ingle center and no strong travel linkages o other urban areas. The city does not ave any social or economic factors that ight have had a significant effect on travel atterns, and that might have required adjustents to the trip distributions as calibrated by e gravity model formula. Therefore, the ndings for Sioux Falls may not apply to ities having different travel characteristics. urther research should be conducted to etermine whether the findings for this small rban area can have wider application.

The Gravity Model Theory

The gravity model theory can be stated in e following described manner. The trip terchange between zones is dependent upon e relative attraction of each of the zones and pon some function of the spatial separation etween zones. This function adjusts the relative attractiveness of each zone for the ability, desire, and necessity of the tripmaker to overcome spatial separation. Mathematically this theory is stated:

$$T_{ij}=\frac{P_iA_jF_{ij}K_{ij}}{\sum_{i=1}^{n}A_jF_{ij}K_{ij}}$$

Where,

T_{ij}= trips produced in zone i and attracted to zone j.
P_i= trips produced in zone i.
A_j= trips attracted to zone j.
F_{ij}= empirically derived traveltime factors (one factor for each 1-minute increment of traveltime) that are a function of spatial separation between zones. These factors reflect the average areawide effect of the spatial separation on trip interchange.
K_{ij}= a specific zone-to-zone adjustment factor to allow for the incorporation of the effect on travel patterns of social and economic linkages not otherwise accounted for in the gravity model formula.

Five separate parameters are required for calibration of the gravity model before trip interchanges can be calculated. Two of these parameters include the use of the land in the study area and the social and economic characteristics of the people who make trips; these are the number of trips produced and the number of the trips attracted. The third parameter reflects the extent and the level of service provided by transportation facilities in the area—the measure of spatial separation between zones—and is usually denoted by the minimum path traveltime between zones. The fourth parameter, the traveltime factor expresses the average areawide effect of this spatial separation upon trip interchanges between zones.

The fifth parameter in the gravity model formula is the zone-to-zone adjustment factor. It may be incorporated into the model to account for social and economic conditions and political boundaries that might have a significant effect on travel patterns, but are not otherwise accounted for in the model theory. In the study reported here, no need was developed for use of K factors.

Testing the Gravity Model Theory

A gravity model was calibrated from data obtained in the Sioux Falls O–D survey and was tested to determine whether its use would simulate the travel patterns of the O–D survey. The steps followed in this testing were identical to those documented in two recent publications by the Bureau of Public Roads (8, 9). Essentially these were:

- Processing basic data on the travel patterns and transportation facilities in the area, to provide three of the basic inputs to the gravity model formula; namely, zonal trip production, attraction figures, and the spatial separation between zones, as measured by traveltime.
- Developing traveltime factors to express the effect of spatial separation on trip interchange between zones.

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[4] Unpublished data on the capacity and level of service aracteristics of Sioux Falls transportation facilities, retail es figures by zone, and certain employment and labor ce statistics were made available to the U.S. Bureau of iblic Roads by the South Dakota Department of ghways.

Table 1.—Distribution of vehicular trips, Sioux Falls, S. Dak., 1956 [1]

Purpose of trip	Trips made	Traveltime, total	Average travel-time
	Number	*Minutes*	*Minutes*
Home based work	29, 882	209, 128	7. 00
Home based nonwork	65, 759	404, 749	6. 15
Nonhome based	63, 280	360, 736	5. 70
TOTAL	158, 921	974, 613	6. 13

[1] Based on O–D survey, for 24-hour period.

- Balancing zonal attraction factors to assure that the trips attracted to each zone, as calibrated by the gravity model formula, were in close agreement with those shown in the O–D survey data.
- Examining the estimated trip interchanges to determine the need for adjustment to reflect factors not directly included in the model formula.
- Comparing the final trip interchanges obtained by using the gravity model with those obtained in the home-interview survey, to test whether the model would simulate the 1956 travel patterns in the Sioux Falls area.

For this research, the total daily vehicular trips were used that had either origins or destinations within the study area; through trips were excluded. The trips were stratified into the following listed categories: (1) home based auto-driver work trips, (2) home based auto-driver nonwork trips, and (3) nonhome based vehicular trips.

The measure of spatial separation between zones was composed of the offpeak minimum path driving time between zones plus the terminal time in the production and attraction zones connected with the trip. Terminal time was added to driving time at both ends of the trip to allow for differences in parking and walking time in the zones because of differences in congestion and available parking facilities.

Table 2.—Traveltime factor adjustment process—work trips

Driving time	Percent trips, actual	Travel-time factor No. 1	Percent trips, esti-mate No. 1	Adjusted travel-time factor [1]	Travel-time factor No. 2, from figure 2
1	1. 68	162	1. 24	219	220
2	2. 93	152	2. 12	210	210
3	6. 09	142	4. 88	177	185
4	10. 28	132	10. 32	131	150
5	12. 61	122	13. 49	114	125
6	12. 57	112	13. 62	103	110
7	13. 91	102	13. 26	107	100
8	11. 22	092	11. 26	92	085
9	10. 91	082	11. 42	78	079
10	4. 20	072	6. 04	50	067
11	4. 40	062	5. 33	51	061
12	3. 98	052	3. 52	59	057
13	1. 53	042	1. 56	41	050
14	1. 34	032	1. 09	39	048
15	1. 70	022	0. 74	51	045
16	0. 04	012	0. 08	06	010
17	0. 01	000	0. 04	00	002
18	0. 00	000	0. 00	00	000
19	0. 00	000	0. 00	00	000
20	0. 00	000	0. 00	00	000

[1] Derived from figures in col. 2 divided by those in col. 4 and multiplied by those in col. 3.

Basic data

Information from the home-interview, external cordon, and truck and taxi surveys was verified, coded, and punched on cards. These cards were edited to ensure that all pertinent information had been recorded correctly, and the edited cards were separated into the three trip-purpose categories. A table of zone-to-zone movements was then prepared for each trip purpose category. Each trip record was examined, and the number of trips from each zone of production to each of the other zones of attraction was accumulated. During this accumulation process, the total number of trips produced by and attracted to each zone was also determined. These zonal trip-production-and-attraction figures were subsequently used to calculate trip interchanges by using the gravity model formula.

Just as the results of the travel pattern inventories had to be processed, so did the data from the transportation facilities inventory. The processing of these data allowed the computation of the spatial separation between zones. Interzonal driving times were obtained by using a standard tree-building computer program. Intrazonal driving times were determined from an examination of the speeds on the highway facilities in each zone. Terminal times in each zone were determined by analyzing the results of the 1960 parking survey (*7*). Terminal time used for central business district zones was 3 minutes and for all other zones, 1 minute.

Traveltime factors

The best set of traveltime factors reflecting the effect of trip length on tripmaking was determined through a process of trial and adjustment. First the trip time frequency distribution was obtained for each trip purpose, by determining the number and percent of trips for each minute of minimum path driving time between all zone pairs. In table 1 this information is summarized for all three trip-purpose categories. Sets of traveltime factors were determined by drawing a line of best fit on the trip time frequency curves and by taking the traveltime factors directly from the line of best fit.

Next the gravity model formula was utilized to calculate estimated trip interchanges and trip time frequency curves using the initially estimated traveltime factors, zonal productions and attractions, and zonal separation information (traveltime). The results obtained indicated close agreement between the actual and the estimated trip time length frequency distribution curves and the average trip time lengths. However, the discrepancies between the actual and the estimated figures were larger than desired by the research staff. (The established criteria were ±3 percent difference on average trip time length, and the trip time length frequency curves closely parallel to each other.) Consequently, a revised gravity model estimate was needed.

To make a revised estimate, new sets of traveltime factors were calculated for each trip purpose category. The percentage of survey trips for each minute of driving time was divided by the percentage of trips obtaine using the gravity model and the results this division were multiplied by the initi traveltime factors, see table 2. These a justed traveltime factors were plotted on lo log paper and a smooth curve was draw through the points as shown on figure 2.

Table 3.—Final traveltime factors by tri purpose, Sioux Falls, S. Dak.—1956

Driving time	Final travel time factors for—		
	Work trips	Nonwork trips	Nonhome based trips
1	220	280	300
2	210	260	270
3	185	220	210
4	150	160	120
5	125	130	100
6	110	090	080
7	100	085	070
8	085	070	060
9	079	060	055
10	067	050	044
11	061	039	038
12	057	035	032
13	050	027	030
14	048	025	026
15	045	021	023
16	010	016	014
17	002	000	005
18	000	000	000
19	000	000	000
20	000	000	000

The new set of traveltime factors, as repr sented by the smoothed curves, was subs quently used in the second calibration of t gravity model. The resultant trip ti length frequency curves and average tr time length figures were again compare with the O–D data. The estimates obtaine during the second calibration were with the established criteria. Consequently, t second estimate of traveltime factors w judged to adequately describe the effect spatial separation on trip interchange b tween zones. These final traveltime facto are shown for each trip purpose in table

Adjustment of Zonal Trip Attractio

Generally, when the gravity model formu is used to distribute the trips, the obtaine zonal estimates do not equal the trips show by the O–D surveys as actually attracted the zones because the gravity model formu does not have any built-in adjustment ensure such results. This difference number of zonal attractions is a difficul inherent in all currently available trip di tribution techniques. Therefore, the numb of trip attractions for each zone was adjust to bring the number of trips distributed to given zone into balance with the number trip attractions of that zone, as determined the survey.

Prior to balancing attractions, the est mated attractions obtained from calibrati No. 2 were compared with the actual tri shown in the survey to determine the di ferences. The two items of information f each zone were plotted for each trip purpos A technique developed by Brokke and Sossl (*10*) was used to judge the adequacy

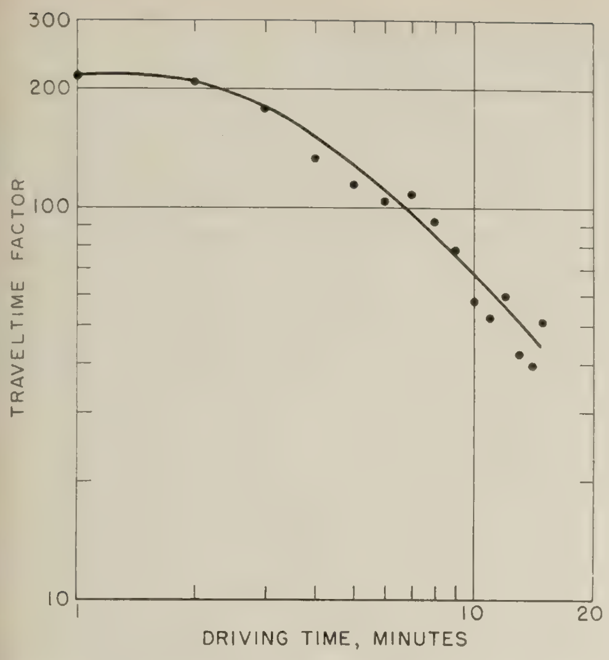


Figure 2.—Revised traveltime factors for work trips, Sioux Falls, S. Dak., 1956.

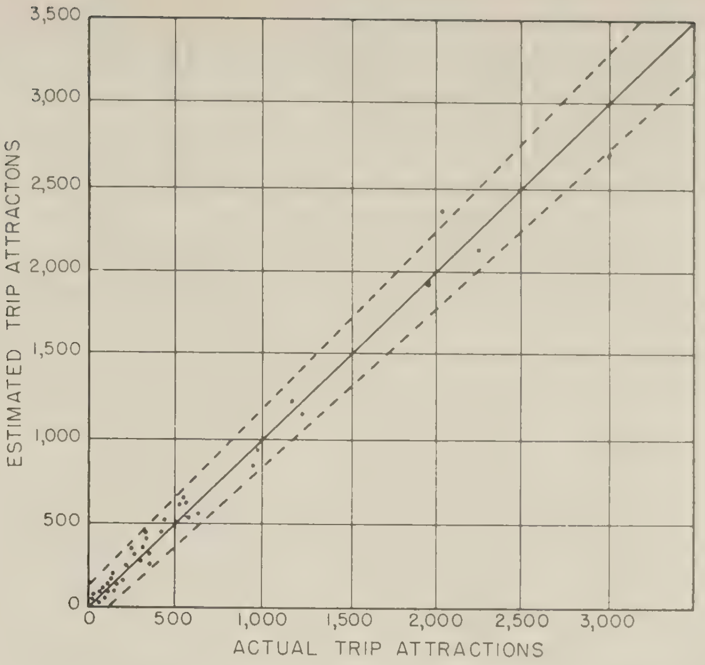


Figure 3.—Work trip attractions, calibration No. 2, Sioux Falls, S. Dak., 1956.

e estimated figures. This earlier work by rokke and Sosslau established a reasonable pproximation of the error that can be exected from O–D surveys of different sample tes, depending on the number of trips easured.

To determine the reliability (the degree of ceptability of the estimates obtained with e gravity model) of the number of trips tracted to each zone in the study area, the MS error for each volume group for the .5-percent sample was plotted and the ints connected by the dashed lines, as own in figure 3. Because two-thirds of the ints indicating the differences between the rvey and gravity model estimated zonal ip attractions fell within these dashed lines, adjustments were required.

Although not required, for the sake of search, the zonal attraction figures for each ip purpose were adjusted in order to obtain more realistic measure of the error in the tual distribution of the number of trips. he adjustment was made by dividing the umber of zonal trip attractions from the -D survey by the number of trips attracted each zone, as developed by the gravity odel, and then multiplying the result by e original zonal trip attraction factor veloped from the O–D survey. The amount adjustment required for each trip purpose is relatively small—in most zones, less than percent and never more than 20 percent. e required adjustment had no discernible ttern.

The interchange figures obtained through e gravity model formula were then recallated, using the adjusted zonal attraction tors. The slight differences between calilations No. 2 and No. 3 showed that the nal attraction factor adjustment had very tle effect on the trip volumes. This can explained on the basis of the rather small justments that were required to balance e zonal adjustment factors.

Geographical bias

In using the gravity model formula, several researchers have discovered the need for adjustment factors to account for special conditions within an urban area that affect travel patterns, such as river crossings. For example, results from a study in Washington, D.C., (*11*) showed that the Potomac River crossings had some influence on trip distribution patterns. Similar findings from a study in New Orleans, La., (*12*) indicated similar problems connected with river crossings. A study in Hartford, Conn., (*1*) indicated that toll bridges crossing the Connecticut River also had a similar effect on travel patterns. In each of these cities, the effects of these conditions were adjusted by time penalties added to those portions of the transportation system for which discrepancies in the model distribution were observed.

Also, in results obtained through using the gravity model formula, some studies have indicated geographical bias that has been caused by factors other than topographical barriers. For example, in the Washington, D.C., study, adjustment factors were needed to account for the medium-income blue-collar workers residing in certain parts of the Washington area and having no job opportunities within the central parts of the city. If work trips for the Washington study had been further stratified, perhaps the need for adjustment factors would have been reduced.

Several tests were conducted on the results of calibration No. 3 to determine the need for any adjustment factors. One of these tests involved the Big Sioux River, which bisects the Sioux Falls area (fig. 1). For the number of trips crossing the Big Sioux River, the total number of trip interchanges in the O–D home-interview survey were compared directly with the number obtained by using the gravity model formula. In addition, both of these numbers were compared with actual counts taken on all the bridges crossing this river. The very close agreement between these three sources of information as shown in table 4 indicated that the Big Sioux River was not a barrier to travel.

Another test for geographical bias was conducted on trips to the central business district (CBD) of Sioux Falls. Trips from each district to the CBD, by trip purpose, as shown in calibration No. 3 of the gravity model, were compared directly with the same information from the O–D survey. Results for work trips are shown in figure 4. No significant bias was present for any of the trip purposes in the model; furthermore, the gravity model estimates were close to the figures compiled in the O–D survey.

Final Tests

The total number of trips obtained from the final calibration of the three-purpose gravity model was assigned to the transportation network, and the same assignment was

Table 4.—Comparison of vehicular trips crossing Big Sioux River, S. Dak., 1956

Facility	Vehicular trips			Synthetic gravity model estimate
	Volume count	O–D survey	Gravity model estimate	
Cherry Rock Avenue	1,511	1,640	1,660	1,512
Cliff Avenue, S.	9,132	8,420	9,444	9,208
Tenth Street	14,842	16,296	16,648	16,832
Eighth Street	8,606	6,612	6,080	6,752
Sixth Street	3,864	2,900	3,576	4,564
McClellan Street	3,069	2,596	2,032	1,972
Cliff Avenue, N.	4,699	4,156	3,904	2,048
TOTAL	45,723	42,620	43,344	42,888
Percent difference from volume count	----	−6.8	−5.2	−6.2
Percent difference from O–D survey	+7.3		+1.7	+0.6

Table 5.—Comparison of total trips crossing screenlines for O–D survey, and synthetic, one-, three-, and six-purpose models, Sioux Falls, S. Dak., 1956

Screenline	Trips								
	O–D survey	Synthetic model		One-purpose model		Three-purpose model		Six-purpose model	
Number	*Number*	*Number*	*Percent* [1]	*Number*	*Percent* [1]	*Number*	*Percent* [1]	*Number*	*Percent* [1]
1	7, 952	7, 280	−8. 5	6, 996	−12. 0	7, 344	−7. 6	7, 440	−6. 4
2	21, 012	21, 120	+0. 5	20, 580	−2. 1	20, 460	−2. 6	20, 552	−2. 2
3	13, 516	13, 224	−2. 2	14, 216	+5. 2	13, 900	+2. 8	13, 222	−2. 2
4	11, 384	10, 428	−8. 4	12, 344	+8. 4	12, 060	+5. 9	11, 956	+5. 0
5	9, 744	8, 516	−12. 6	9, 332	−4. 2	9, 252	−5. 0	9, 336	−4. 2
6	8, 784	8, 440	−3. 9	9, 500	+8. 2	9, 392	+6. 9	9, 444	+7. 5
7	6, 280	6, 520	+3. 8	6, 788	+8. 1	6, 824	+8. 7	6, 852	+9. 1
8	6, 568	6, 100	−7. 1	6, 984	+6. 3	7, 032	+7. 1	7, 152	+8. 9
9	2, 264	1, 980	−12. 5	2, 772	+22. 4	2, 676	+18. 2	2, 648	+17. 0
10	17, 448	18, 420	+5. 6	17, 808	+2. 1	17, 592	+0. 8	17, 668	+1. 3
11	5, 868	4, 836	−17. 6	6, 468	+10. 2	6, 532	+11. 3	6, 704	+14. 2
12	5, 592	3, 872	−30. 8	6, 484	+16. 0	6, 412	+14. 7	6, 392	+14. 3
13	13, 656	15, 280	+10. 6	13, 660	0. 0	14, 840	+8. 7	13, 924	+2. 0
14	22, 908	23, 584	+2. 9	25, 096	+9. 6	23, 040	+0. 6	22, 720	−0. 8
15	33, 220	33, 204	0. 0	31, 400	−5. 5	32, 144	−3. 2	34, 005	+2. 4
16	10, 032	10, 996	+9. 6	10, 736	+7. 0	10. 012	−0. 2	10, 120	+0. 8
17	13, 424	14, 220	+5. 9	14, 016	+4. 4	13, 760	+2. 5	14, 012	+4. 4
18	9, 724	12, 200	+25. 5	10, 324	+6. 2	10, 276	+5. 7	10, 424	+7. 2
19	10, 060	10, 720	+6. 6	11, 352	+12. 8	11, 044	+9. 8	11, 092	+10. 3
20	5, 332	5, 476	+2. 7	5, 240	−1. 7	5, 420	+1. 6	5, 556	+4. 2
21	8, 496	8, 364	−1. 5	9, 056	+6. 6	9, 136	+7. 5	9, 200	+8. 3
22	13, 332	14, 192	+6. 5	14, 612	+9. 6	14, 504	+8. 8	14, 672	+10. 0
23	41, 500	41, 468	−0. 1	40, 660	−2. 0	41, 852	+0. 8	39, 995	−3. 6

[1] Percentage difference from O–D survey.

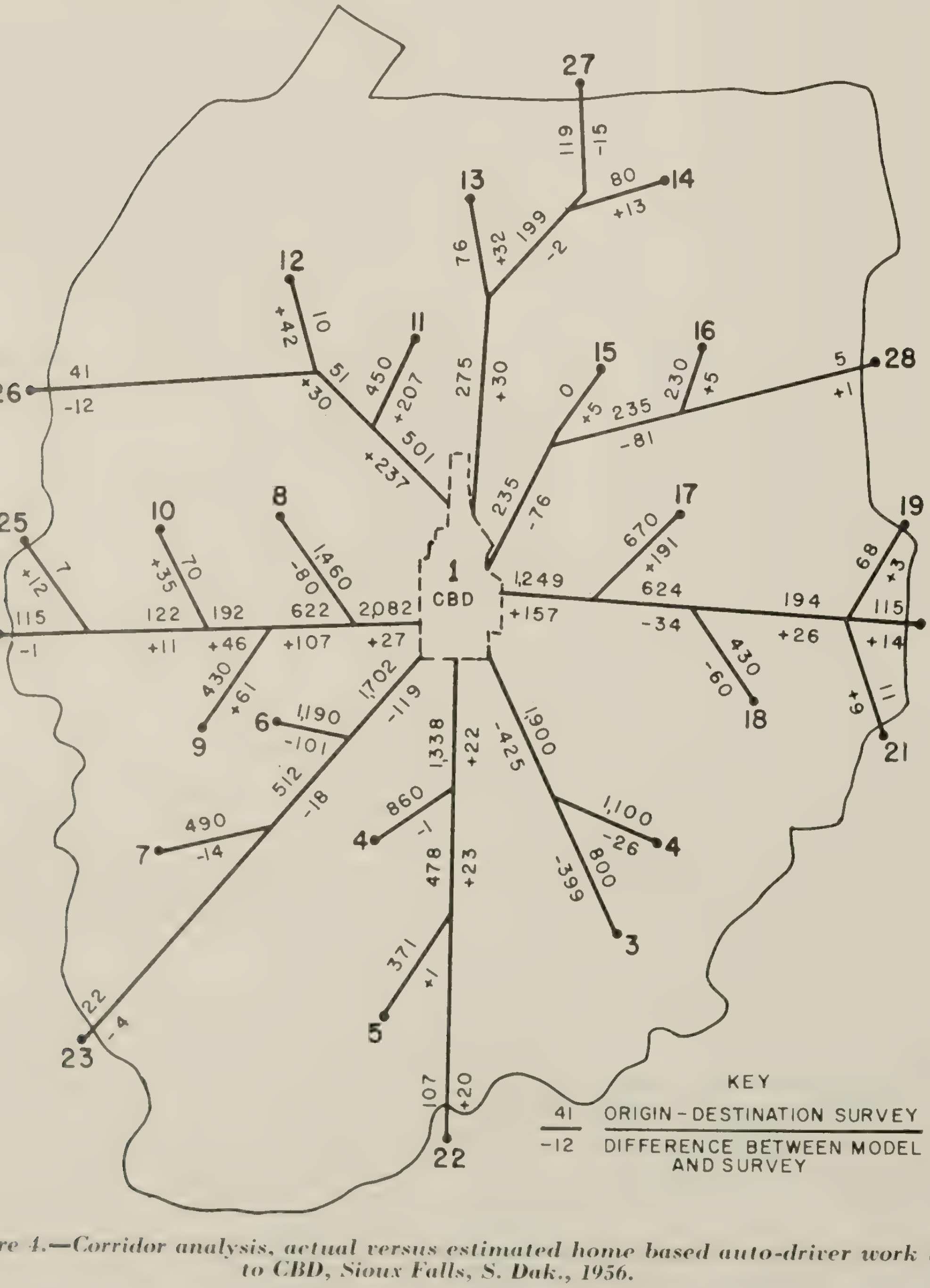


Figure 4.—Corridor analysis, actual versus estimated home based auto-driver work trips to CBD, Sioux Falls, S. Dak., 1956.

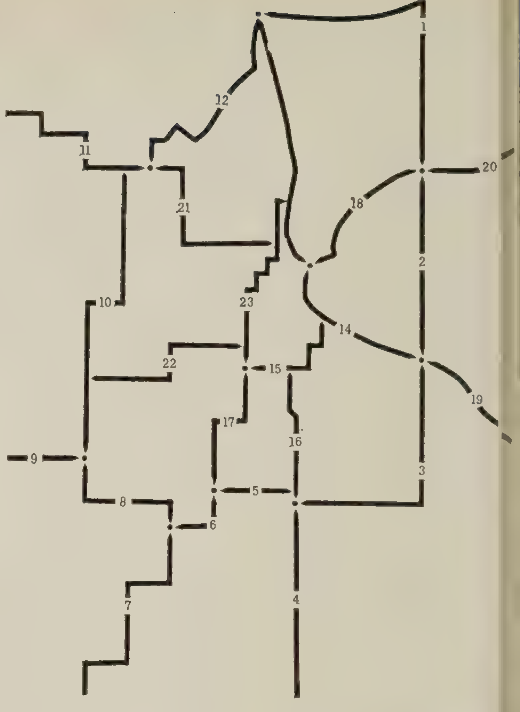


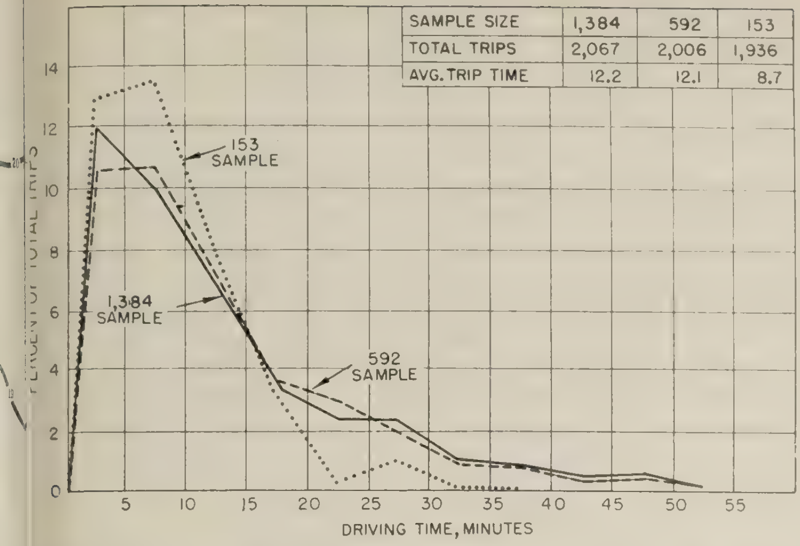
Figure 5.—Location and identification of comprehensive series of screenlines, Sioux Falls, S. Dak., 1956.

made for the total number of trips obtained from the O–D survey. An examination of the results was made by comparing the number of trips crossing a very comprehensive series of screenlines. Figure 5 shows this comprehensive series of screenlines and also identifies each. Table 5 contains tabulations on the actual and the estimated number of trips crossing each of the screen lines identified in figure 5. Only four differences between the surveyed and estimated trip volumes were larger than 10 percent but none had absolute volume discrepancies large enough to affect design considerations.

One final test was made to determine the statistical significance of the differences between the gravity model trip volume estimates and O–D survey data. The results of this test are shown in table 6. When the results were compared with the O–D survey error (*10*), the gravity model estimates held almost the same degree of reliability as the O–D survey data.

When the calibrated three-purpose gravity model was used, the results adequately simulated the trip distribution patterns of the O–D survey. Nevertheless, it is desirable to have a measure of the differences in the results that would have been obtained for lesser and higher degrees of trip stratification than the three trip purposes used in this research. To date, little has been done to investigate these differences. The results of additional analyses performed are not conclusive but do shed considerable light on the subject. In this analysis, gravity models were calibrated for the following listed trip-purpose stratifications:

- One-purpose model—total vehicular trip
- Six-purpose model—(1) home based auto-driver work trips, (2) home based auto-driver shopping trips, (3) home based auto-driver social-recreation trips, (4) home based auto-driver miscellaneous trips, (5) nonhome based vehicular trips, and (6) truck and taxi trips



igure 6.—Trip length frequency distribution, home based auto-driver work trips, southeast area transportation study, Conn., 1960.

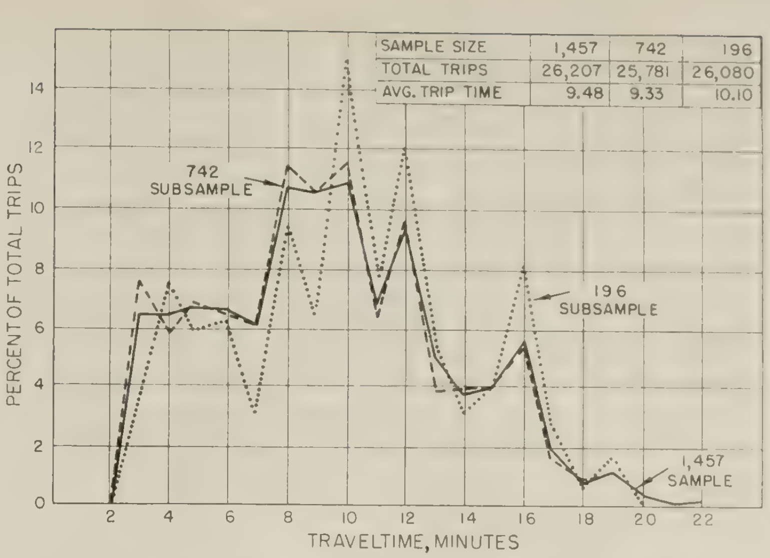


Figure 7.—Trip length frequency distribution, home based auto-driver work trips, N.C. study, 1963.

The same techniques and the same number f calibrations were made in these two models s were made in calibrating the three-purpose iodel. The same tests were also performed n these models as on the three-purpose model; esults had about the same degree of accuracy. 'he absolute and percentage differences etween the number of O–D survey trips rossing the comprehensive series of screennes (fig. 5) and those determined by using the ne-purpose, three-purpose, and six-purpose alibrated models are shown in table 5. The ccuracy of the three-purpose model was ightly better than that of the one-purpose iodel. The use of the six-purpose model, which required an extensive amount of additional effort, produced no improvement in accuracy over the three-purpose model.

'able 6.—Differences between O–D data and gravity model estimates for district-to-district auto-driver trips, for three purposes, by volume groups [1]

Trip volume	O–D survey trips		RMS error	
HOME BASED WORK TRIPS				
Group	*Mean*	*Frequency*	*Absolute*	*Percent* [2]
0–99	21	400	17	80.95
100–199	133	40	47	35.34
200–299	259	13	87	33.59
300–499	402	13	85	21.14
500–1,499	920	8	166	18.04
HOME BASED NONWORK TRIPS				
0–99	27	423	24	88.89
100–199	136	53	83	61.03
200–299	239	28	87	36.40
300–499	380	22	112	29.47
500–999	728	22	231	31.73
1,000–2,999	1,711	9	276	16.13
NONHOME BASED TRIPS				
0–99	25	473	22	88.00
100–199	144	62	63	43.75
200–299	241	30	100	41.49
300–499	385	33	101	26.23
500–999	773	9	119	15.39
1,000–4,999	1,695	9	263	15.52

1956 O-D survey data versus gravity model estimates.
ative difference measured in terms of percent root-mean-
iare error.

Percent RMS error $=100\left(\frac{\sqrt{\frac{\Sigma(d)^2}{n}}}{\bar{x}}\right)$

here,
d=difference between surveyed and estimated
=number of district-to-district movements
=mean of surveyed trips.

Inevstigation of Simplified Procedures

The second phase of the research was accomplished in the following steps:

- The minimum sample size of home-interview survey required to provide the information necessary to develop the gravity model for Sioux Falls was determined. This step involved the analysis of subsample data and the development of curves that could be used to determine the relative error that would occur for different size samples.
- Zonal trip production and trip attraction values for each trip purpose were estimated by utilizing the total trips from the small sample, the split among the three purposes, and certain social and economic characteristics for each zone. Zonal trip productions and trip attractions were developed by using synthetic procedures because these data are not available from small sample data.
- Gravity model trip interchanges were determined for each trip purpose by using the small sample data and the synthetic productions and attractions. The synthetic trip distribution patterns were then compared with the comprehensive O–D survey data.

Overall Travel Characteristics

According to reports on studies of other small home-interview samples, the data collected were adequate for calibrating a gravity model (*1*, *2*). The small home-interview samples provided data useful for developing the total number of trips in the area, as well as the percentage of trips for each trip purpose and travel mode category. These small samples were also reported to have provided sufficient information on the time length of urban trips, which is an important parameter in the calibration of travel models.

Some evidence is available from other reports to substantiate the findings reported in references *1* and *2*. In a recent study by the Connecticut State Highway Department,[5] subsamples of 153 and 592 home interviews were used to compare the total universe of

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[5] Unpublished data on analyses made in connection with the southeast area traffic study (*2*) were made available to the Bureau of Public Roads by the Connecticut State Highway Department.

Table 7.—Comparison of total trip productions for three samples—southeast area traffic study, 1962

Trip purpose	Sample size and percent of dwelling units (sample rate)							
	1,384 2.4 percent		592 1.1 percent			153 0.3 percent		
	Expanded trips	Percent of total trips	Expanded trips	Percent of total trips	Difference [1]	Expanded trips	Percent of total trips	Difference [1]
	Number	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percent*
Home based work	2,067	32.9	2,006	30.9	−3.0	1,936	32.6	−6.3
Other home based	3,218	51.3	3,446	53.1	+7.1	3,139	52.9	−2.5
Nonhome based	990	15.8	1,040	16.0	+5.1	859	14.5	−13.2

Percentage difference from sample of 1,384.

Table 8.—Comparison of total trip productions for six samples—N.C. research project, 1963

Trip purpose	Sample size															
	1,457		742			196			383			248			192		
	Expanded trips	Percent of total trips	Expanded trips	Percent of total trips	Difference[1]	Expanded trips	Percent of total trips	Difference[1]	Expanded trips	Percent of total trips	Difference[1]	Expanded trips	Percent of total trips	Difference[1]	Expanded trips	Percent of total trips	Difference[1]
	Number	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percen*
Home based work	26, 207	38. 9	25, 781	38. 6	−1. 6	26, 080	39. 0	−0. 5	24, 382	38. 5	−7. 0	25, 920	40. 0	−1. 1	27, 498	39. 3	+4. 9
Other home based	27, 760	41. 2	27, 887	41. 7	+0. 5	27, 101	40. 5	−2. 4	27, 983	44. 2	+0. 8	27, 896	43. 0	+0. 5	26, 637	38. 1	−4. 0
Nonhome based	13, 437	19. 9	13, 194	19. 7	−1. 8	13, 720	20. 5	+2. 1	10, 991	17. 3	−18. 2	11, 053	17. 0	−17. 7	15, 802	22. 6	+17. 6

[1] Percentage difference from sample of 1,457.

Table 9.—Comparison of total trip productions for three samples—Pittsburgh, Pa., 1958

Trip purpose	Sample size and percent of dwelling units (sample rate)							
	16,169 4.0 percent		2,021 0.5 percent			404 0.1 percent		
	Expanded trips	Percent of total trips	Expanded trips	Percent of total trips	Difference[1]	Expanded trips	Percent of total trips	Difference[1]
	Number	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percent*
Home based work	796, 195	34. 1	792, 576	33. 9	−0. 5	765, 480	33. 3	−3. 9
Home based other	425, 074	18. 2	440, 784	18. 8	3. 7	436, 920	19. 0	2. 8
Home based soc-rec	288, 047	12. 3	293, 752	12. 6	2. 0	311, 280	13. 5	8. 1
Home based shop	286, 883	12. 3	276, 416	11. 8	−3. 6	289, 640	12. 6	1. 0
Home based school	232, 875	10. 0	218, 264	9. 3	−6. 3	191, 920	8. 4	−17. 6
Nonhome based	306, 915	13. 1	318, 688	13. 6	3. 8	303, 520	13. 2	−1. 1

[1] Percentage difference from 4 percent sample.

Table 10.—Comparison of total trip productions for three samples[1]—Sioux Falls, S. Dak., 1956

Trip purpose	Sample size and percent of dwelling units (sample rate)							
	2,399 12.5 percent		599 3.1 percent			199 1.0 percent		
	Expanded trips	Percent of total trips	Expanded trips	Percent of total trips	Difference[2]	Expanded trips	Percent of total trips	Difference[2]
	Number	*Percent*	*Number*	*Percent*	*Percent*	*Number*	*Percent*	*Percent*
Home based work	25, 161	24. 2	26, 564	24. 4	5. 6	26, 292	26. 4	4. 5
Other home based	50, 782	48. 9	53, 848	49. 4	6. 0	47, 232	47. 4	−7. 0
Nonhome based	27, 924	26. 9	28. 516	26. 2	2. 1	26, 040	26. 2	−6. 8

[1] These figures are from home-interview person trip data only; they do not include information available from the external cordon survey. Auto-driver trip data from both of these sources of data were used in developing trip interchanges synthetically.

[2] Percentage difference from 12.5 percent sample.

trips, as well as the trip time length frequencies for each of three trip purposes. The subsamples were taken from an original home-interview sample of 1,384, in itself a small sample and one that contained inherent sampling error. Some of the results are shown in table 7. This study showed that a sample of 592 home interviews produced approximately the same results for the total number of trips, by trip purpose, as the use of the 1,384 interviews. The trip time length frequency distributions and average trip time lengths for each trip purpose and sample size were also compared and the results showed that the trip time length frequency distributions and mean trip time lengths were very similar for the sample sizes of 1,384 and 592. An example for work trips is shown in figure 6.

Further verification of the procedures used in the two Connecticut studies came from a study made in North Carolina (*13*). The total trips and trip percentages for three trip purposes for subsamples of 192, 196, 248, 383, and 742 were compared. These subsamples were drawn from an original sample of 1,457 home interviews in Fayetteville, N.C. (population 47,106). Some of the results reported were: (1) samples as small as 742 interviews might produce approximately the same data for total trips by purpose as the larger sample of 1,457 interviews (table 8), (2) trip time length frequency distributions and mean trip times were similar for the 742 sample and e 1,457 sample (see figure 7), and (3) a sampl f more than 383 interviews is necessary r adequate reproduction of mean trip times.

Recently the Urban Planning Division f the Bureau of Public Roads made a sim r study of the differences in total number f trips, purpose split, average trip time lengt s, and trip time length frequency distribut n for subsamples of 2,021 and 404 home int rviews from a total sample of 16,169 int rviews.[6] The results of the comparisons of e total number of trips and purpose for e h subsample are shown in table 9. Trip ti e length figures for each of the six purp s in each of the sample sizes tested showed t t these small samples yielded adequate data n these *overall* travel characteristics, results r work trips are shown in figure 8.

The minimum acceptable sample e for the Pittsburgh study, however, was ab t 2,000 interviews, a sample considera y larger than the minimum acceptable sam le size from the Connecticut and North Carol a studies. This larger minimum accepta e sample was not surprising in that per n trips for six trip purposes were analyzed r this major urban area. The smaller C necticut and North Carolina studies requi d the analysis of only auto-driver trips r three trip purposes. A six-purpose str ification requires a larger sample size o develop estimates of the same accur y because of the reduced number of trips n each purpose.

Several subsamples of the Sioux F ls home-interview data were also examined r accuracy of figures on total number of t p productions, average trip time lengths, d trip time length frequency distributions y trip purpose. The results of these analy s for 599 and 199 dwelling-unit subsam s and the Sioux Falls O–D 2,399 sample e shown in table 10 and figures 9, 10, and . These results reinforced the findings of e previously mentioned studies, which indica d that samples as small in number as 0 might be used to determine the *ove ll* average characteristics of travel in t s

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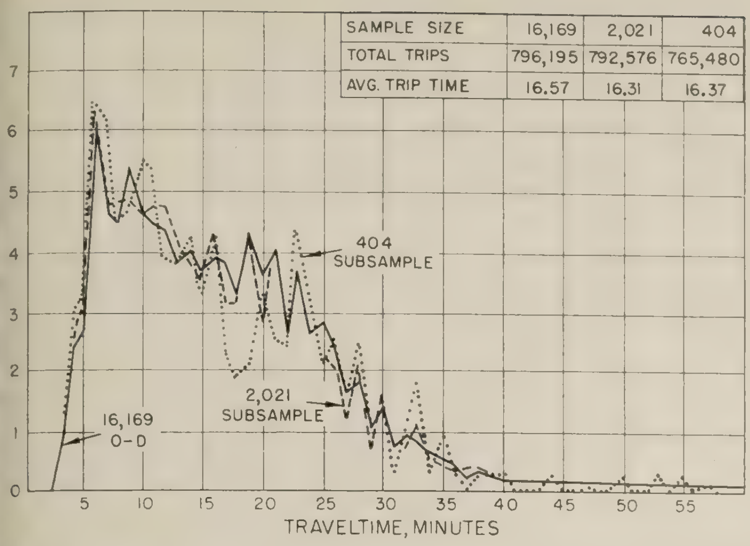
[6] Unpublished summary of procedures and results o n analytical study of subsamples in which data from the Pittsburgh Area Transportation Study were used.



igure 8.—Trip length frequency distributions, home based person work trips, Pittsburgh, Pa., 1958.

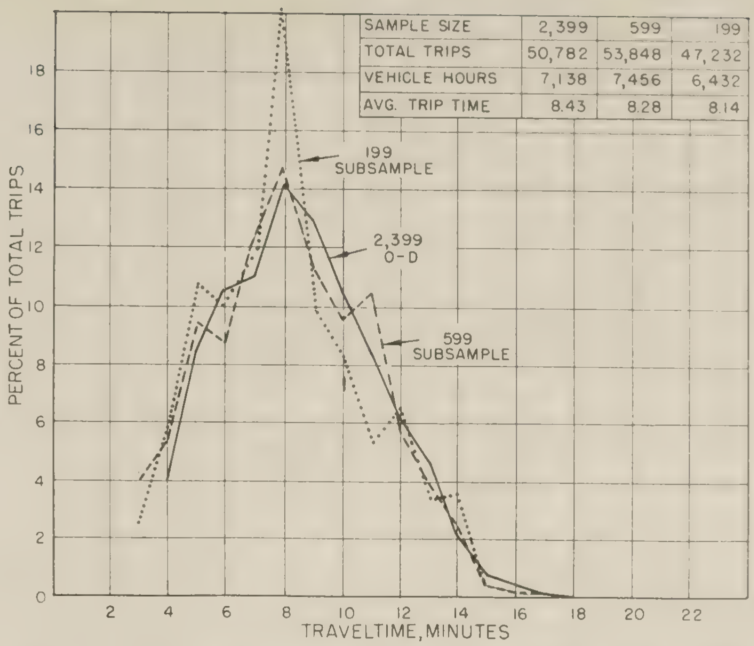
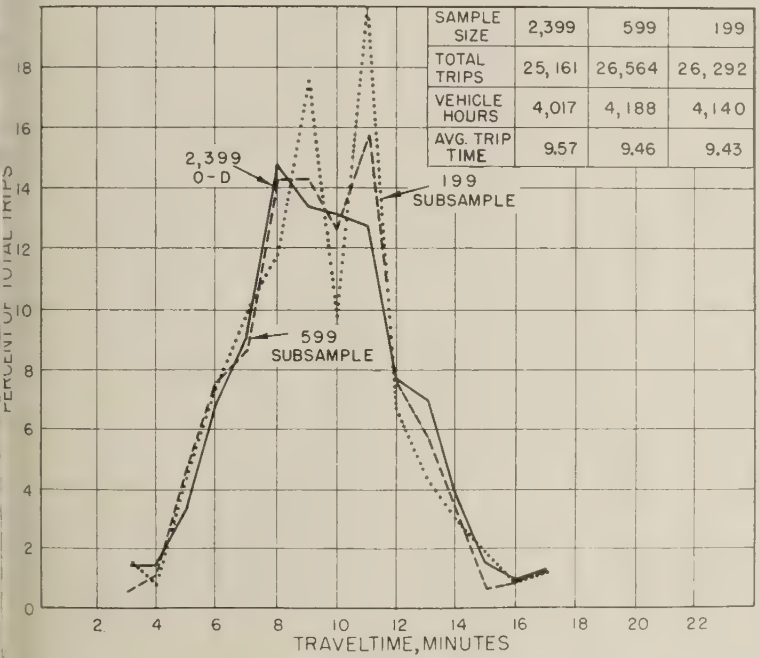


Figure 10.—Trip length frequency distributions, home based nonwork trips, Sioux Falls, S. Dak., 1956.



igure 9.—Trip length frequency distributions, home based auto-driver work trips, Sioux Falls, S. Dak., 1956.

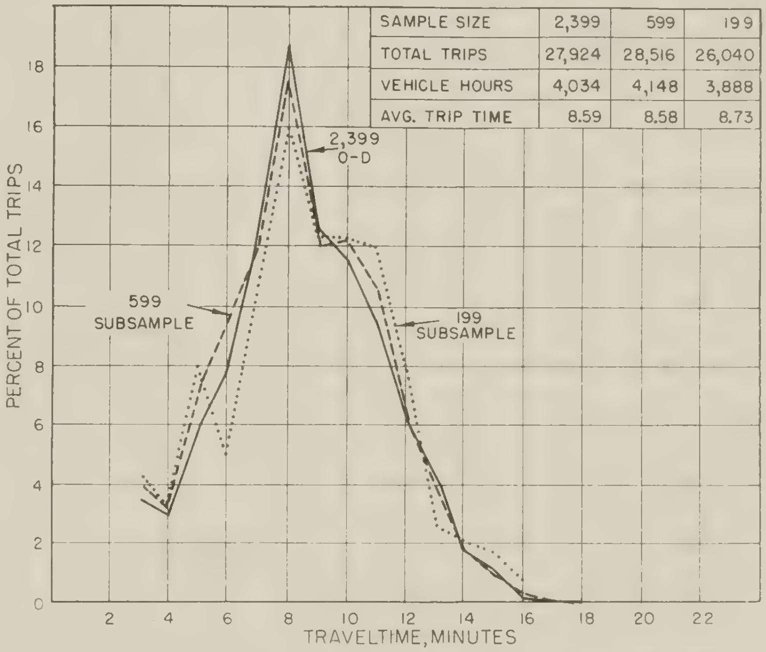


Figure 11.—Trip length frequency distributions, nonhome based trips, Sioux Falls, S. Dak., 1956.

nall urban area when only three trip strati- ations are used.

The results of the tests made with the oux Falls subsamples were analyzed to etermine whether general curves could be eveloped to approximate the error that ould occur in mean trip time length, total ips by trip purpose, and trips per dwelling nit for different sample sizes. The curves ere developed and are shown in figures 12 d 13. They show for Sioux Falls the rror that could be expected to occur in the dicated parameters for different sample es, based on the known variance in the p data. They were developed from the lationship between the standard deviation the mean and the square root of the mple size.

A statistical analysis of small samples of e Pittsburgh, Pennsylvania, trip data was ade to determine the reliability of small samples for making estimates of trip production and average trip time length characteristics. The results of this analysis (figs. 14 and 15) show the reliability of small sample home interview surveys in determining the overall travel characteristics of an urban area.

Zonal Trip Productions and Attracitons

The part of the research discussed in the following paragraphs was based entirely on the sample-size analyses. The results of the 599-interview subsample of the Sioux Falls O–D home-interview survey and the standard external cordon survey were combined with simplified estimating procedures and used in calibrating a synthetic gravity model.

As previously stated, two of the basic parameters required to estimate trip interchanges by using the gravity model formula are the number of trips produced in each zone and the number of trips attracted to each zone for each trip purpose category. Because this information cannot be obtained directly from a small sample home interview, some assumption must be made as to how the total number of trip productions and trip attractions are distributed on a zonal basis. The assumptions made and procedures used to obtain zonal trip production and attraction figures in this research were similar to synthetic procedures that have been previously reported (*4, 14*). In these procedures detailed socio-economic data are used to develop estimates of productions and attractions for use with the gravity model trip distribution technique. For example, data on the labor force was used in developing work trip production figures; employment, for work trip attractions; and retail sales, for nonwork trip attractions.

Table 11.—Vehicular trip productions and attractions, by trip purpose, Sioux Falls, S. Dak., 1956

Trip Purpose	Trips per car[1]	Productions			Attractions		
		Internal[2]	External[3]	Total	Internal[2]	External[3]	Total
Home based work	1.36	27,475	2,175	29,650	28,212	1,438	29,650
Home based nonwork	2.84	57,219	8,010	65,229	60,123	5,106	65,229
Nonhome based	2.98	59,966	4,956	64,922	59,847	5,075	64,922
Total vehicular	7.18	144,660	15,141	159,801	148,182	11,619	159,801

[1] Information includes travel data from both the 600 home-interview sample and the truck and taxi surveys.
[2] These figures were obtained by multiplying the trip rates by the total cars owned by the residents of the study area
[3] These figures are from the standard external cordon survey.

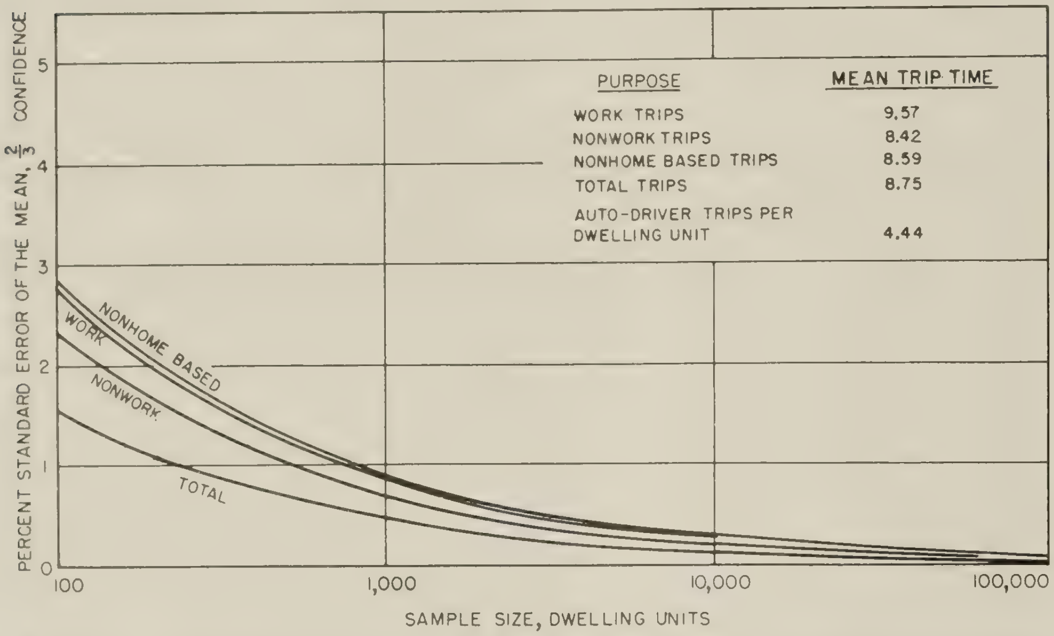


Figure 12.—Percent standard error of mean trip time versus sample size in dwelling units (log scale), Sioux Falls, S. Dak., 1956.

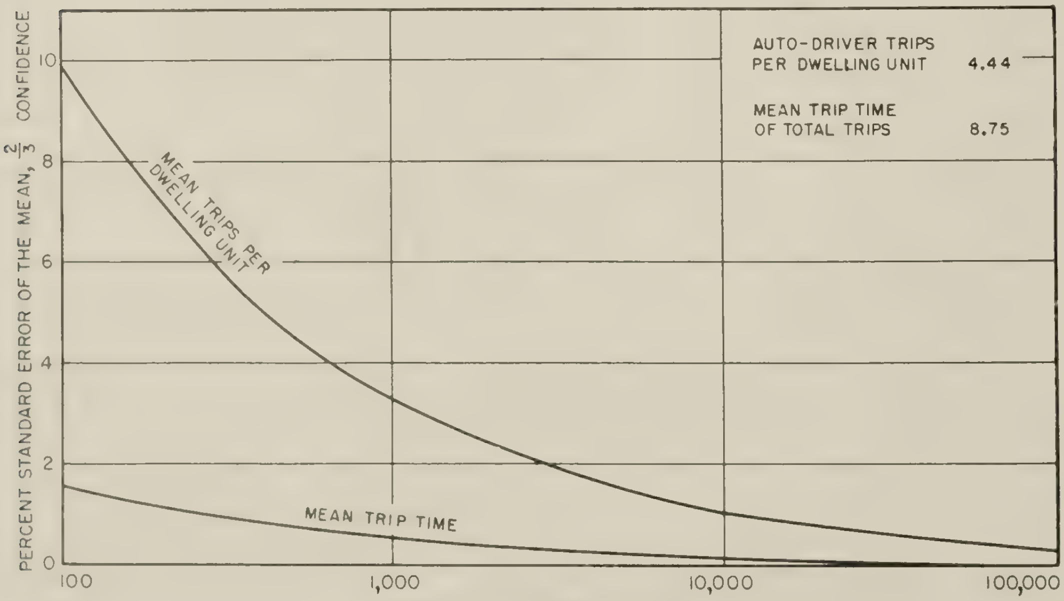


Figure 13.—Percent standard error versus sample size in dwelling units (log scale) for mean trip time and trips per dwelling unit, Sioux Falls, S. Dak., 1956.

The average number of trips made in each car owned by the persons interviewed totaled 7.18 (table 11); 1.36 were work trips, 2.84 were nonwork trips, and 2.98 were nonhome based trips. By applying these rates to the total number of automobiles in the area, a total number of trips, by trip purpose, was obtained. The total number of automobiles for any study area can be obtained from several sources, such as census data (only for the census year), State, county, or city auto registration records, or special surveys. For the

Table 12.—Percentage of all work trips made by transit[1]

Cars per 1,000 persons	Net land per family—in sq. feet					
	10,000	5,000	2,500	1,200	600	30
500	5	7	11	19	33	65
450	7	9	13	21	35	67
400	9	11	15	23	37	69
350	11	13	17	25	39	71
300	13	15	19	27	41	73
275	14	16	20	28	42	74
250	15	17	21	29	43	75
225	16	18	22	30	44	76
200	17	19	23	31	45	77
175	18	20	24	32	46	78
150	19	21	25	33	47	79
125	20	22	26	34	48	8

[1] *From Use of Mathematical Models in Estimating Tr el.* by Alan M. Voorhees, Journal of the Highway Divis n. Proceedings of the American Society of Civil Engineers. vol. 85, No. HW4, December 1959, pp. 131–132.

study reported here, the information was obtained from a comprehensive home-interview O–D survey (1956, Sioux Falls, S. Dak). The resultant estimates of total trip production for each trip purpose are shown in table 11. As total trip productions for the entire study area must equal total trip attractions in the entire study area for each trip purpose category, estimates of total trip attractions were also made and are shown in table 11.

Home Based Auto-Driver Work Trips

Zonal production and attraction figures for home based auto-driver work trips were derived chiefly from employment and labor force statistics.

Zonal trip productions

Zonal work trip productions in the 74 internal zones were derived from zonal labor force information. Labor force data are generally available from census reports, labor statistics, and labor reports. In the research reported here, the information for each zone was taken from data available for Sioux Falls.[7] Information reported in studies made in other areas (*4*, *14*) is that there are about 0.80 daily one-way work trips produced by each person in the labor force. This figure is not 1.0 work trips per person because some persons in the labor force are unemployed, on vacation, or walk to work, etc. Trip patterns shown in the O–D survey data in Sioux Falls were similar. Therefore, to determine the total number of work trip productions in each zone, the number of persons in the labor force in each internal zone was multiplied by 0.8

To determine transit usage the zonal information on car ownership and net residential density was used. An index of transit usage, shown in table 12, was developed from Chicago, Ill., O–D survey data. By using the data from this table, the zonal indexes of transit usage were obtained. The resultant zonal indexes were then totaled and equated to the work trip transit usage for Sioux Falls as determined from the small sample of the

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[7] See footnote 4, page 113.

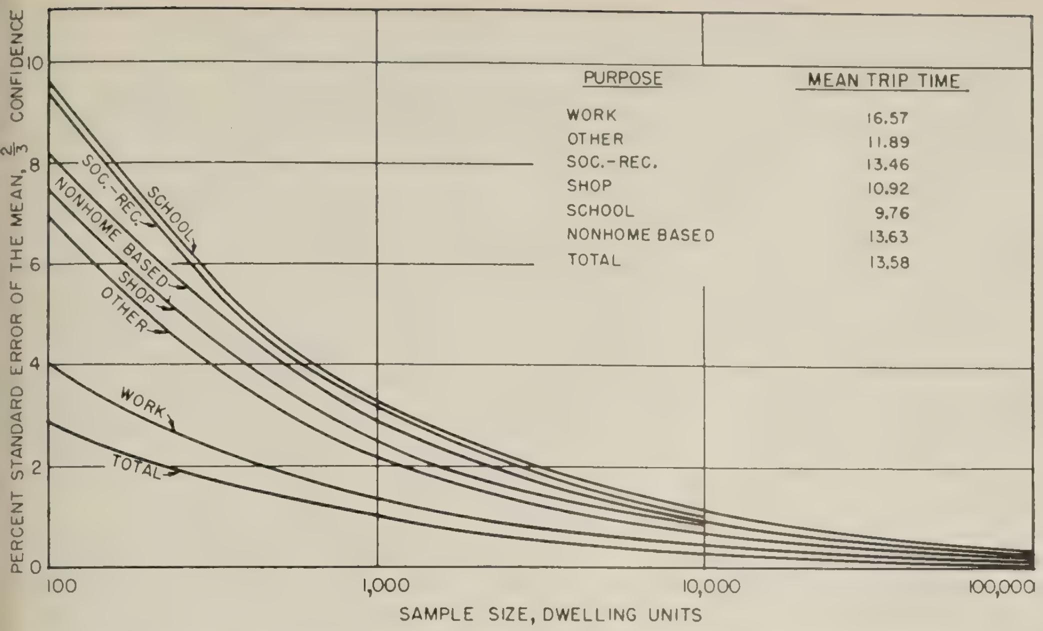


Figure 14.—Percent standard error of mean trip time versus sample size in dwelling units (log scale), Pittsburgh, Pa., 1958.

home-interview survey. The application of his index of transit usage was based on the assumption that a three dimensional plot of he characteristics of variation in transit usage would maintain the same form and shape from one city to another. The number of person work trips made by auto for each zone was then obtained by subtracting these ransit work trips from the total person work trips for each zone. To adjust for car occupancy and to arrive at auto-driver work rips, the number of persons per car was applied to the total number of automobile person work trips previously developed for each zone. The relationship between car ownership and car occupancy is shown in able 13.

For each of the 10 external stations in Sioux Falls, the number of automobile work trips produced by each station was estimated as a percentage of the adjusted total number of trips for all purposes recorded at all stations during a standard external cordon survey. The adjusted total number of trips for all stations was obtained by deducting the number of through trips from the total number of external station trips and analyzing the remaining number of trips. The adjusted total number of external station trips consisted of auto and taxi trips between the external stations and the zones. The percentage of automobile work trips produced by the 10 external stations was determined to be 20 percent of this adjusted external station volume.

To determine the accuracy of these procedures, the number of auto-driver work trip productions estimated for each zone was compared with those from the 1956 O–D survey. These comparisons were also analyzed, using the RMS error criteria, and the analysis showed very close agreement between the actual and the estimated figures. The limits of 1 RMS error are shown as dashed lines in figure 16.

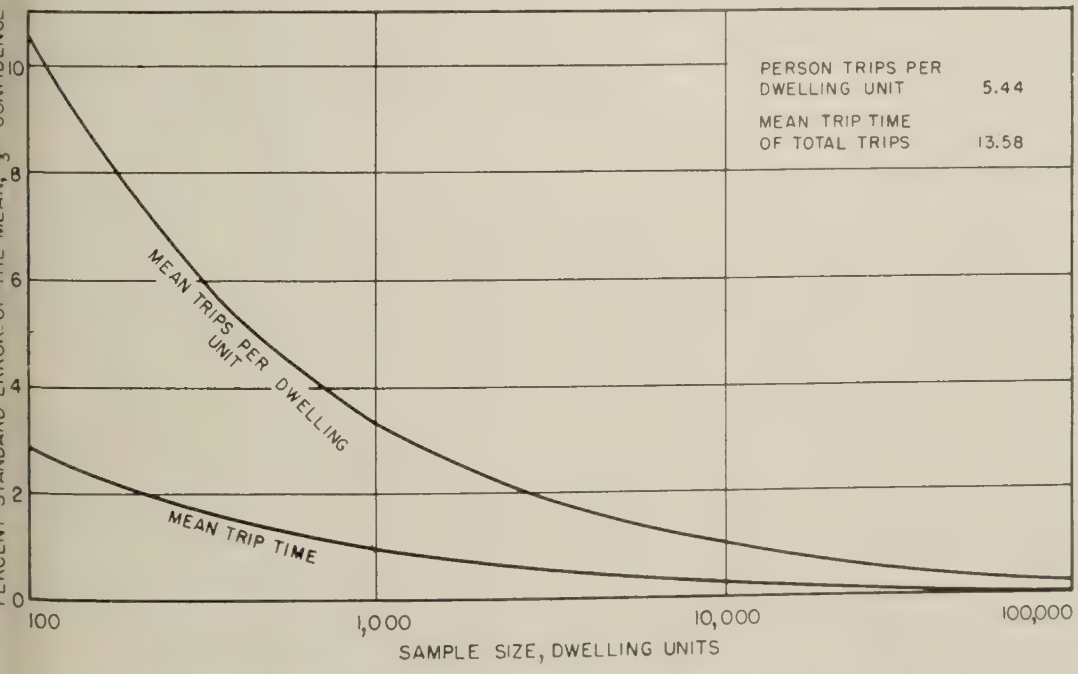


Figure 15.—Percent standard error versus sample size in dwelling units (log scale) for mean trip time and trips per dwelling unit, Pittsburgh, Pa., 1958.

Table 13.—Relationship between persons per car and car ownership for total work trips [1]

Cars per 1,000 persons	Persons per car
500	1.20
450	1.23
400	1.27
350	1.30
300	1.33
250	1.40
200	1.46
150	1.52
100	1.65

[1] *From Use of Mathematical Models in Estimating Travel*, by Alan M. Voorhees, Journal of the Highway Division, Proceedings of the American Society of Civil Engineers, vol. 85, No. HW4, December 1959, pp. 131–132.

Zonal trip attractions

Zonal work trip attractions for each of the 74 internal zones were developed from zonal employment information. Information on the number of people employed in each zone and other statistics had been collected in a special survey by the Sioux Falls Chamber of Commerce. An analysis of these data showed that each employee in Sioux Falls was responsible for about 0.83 one-way person work trips per day. To obtain an estimate of the total number of person work trips attracted to each zone, zonal employment figures were multiplied by 0.83. Corrections were then made for transit usage and car occupancy to arrive at the number of auto-driver work trip attractions—information in table 12 and the tabulation for work trip productions were used. A control figure for the number of work trips to the CBD was also applied. Essentially, the estimated number of auto-driver work trip attractions to the CBD were factored to agree with the number from the small sample and the external survey. All auto-driver work trip attractions to non-CBD zones were factored in a similar manner so that the total number of auto-driver work trip attractions remained the same.

For each of the 10 external stations, the number of auto-driver work trip attractions was determined in the same manner as the number of external station auto-driver work trip productions. The percentage of total station auto-driver trips (minus through trips) that were attracted by the external stations was determined to be 6.0 percent.

To assure the accuracy of these procedures, the total number of auto-driver work trip attractions estimated for each zone was compared with the attractions from the 1956 O-D survey (figure 17). These comparisons were analyzed in the same manner as the work trip productions, and the actual and the estimated figures agreed closely.

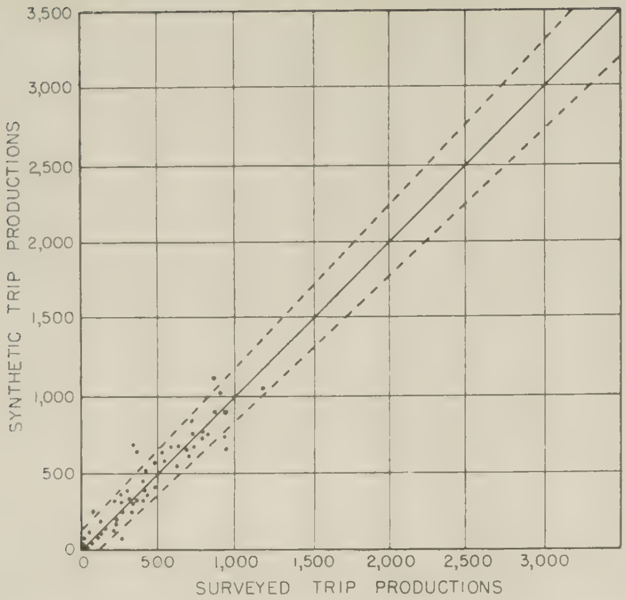
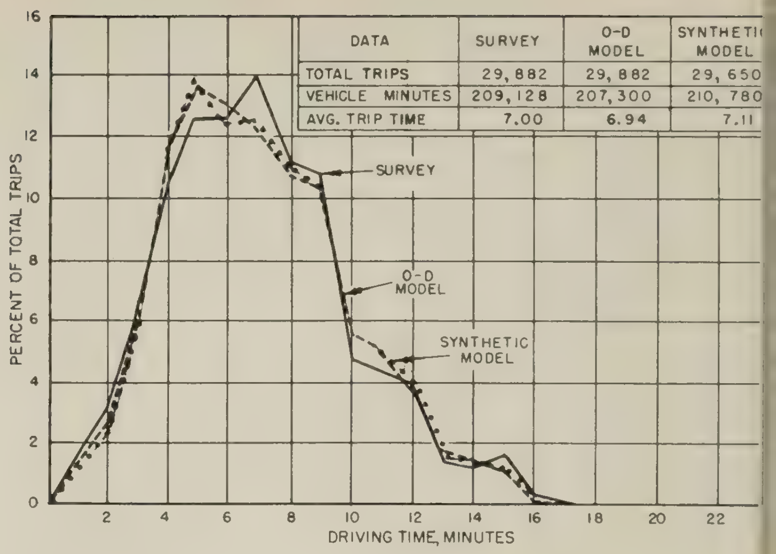


Figure 16.—Synthetic versus surveyed auto-driver home based work trip productions, Sioux Falls, S. Dak., 1956.



DATA	SURVEY	O-D MODEL	SYNTHETI MODEL
TOTAL TRIPS	29,882	29,882	29,650
VEHICLE MINUTES	209,128	207,300	210,780
AVG. TRIP TIME	7.00	6.94	7.11

Figure 18.—Trip length frequency distribution, home bas auto-driver work trips, Sioux Falls, S. Dak., 1956.

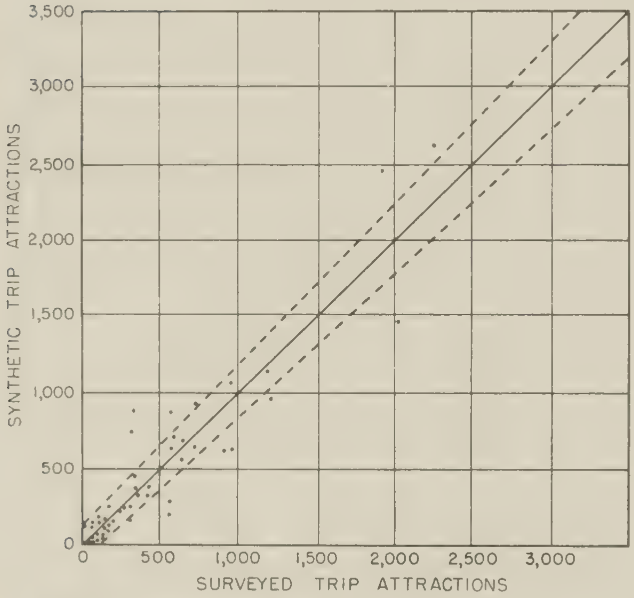


Figure 17.—Synthetic versus surveyed auto-driver home based work trip attractions, Sioux Falls, S. Dak., 1956.

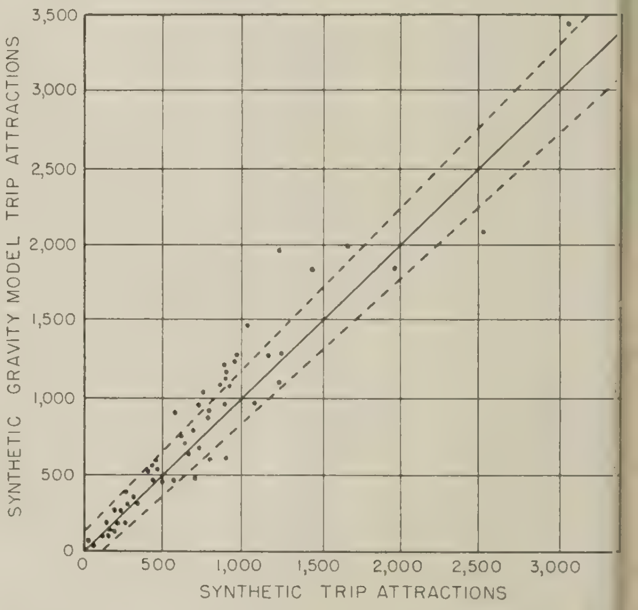


Figure 19.—Synthetic versus synthetic gravity mod home based auto-driver nonwork trip deductio Sioux Falls, S. Dak., 1956.

Home Based Auto-Driver Nonwork Trips

Zonal trip productions

Zonal nonwork trip productions in the 74 internal zones were derived from zonal data on car ownership, which were obtained from the O-D survey. The figure of 2.84 home based auto-driver nonwork trips per car (table 11) was applied to the number of cars owned by the residents in each of the internal zones to determine trip production figures for home based auto-driver nonwork trips. For the 10 external stations, the number of nonwork trip productions—30 percent of the total station volume—was obtained in the same manner as described for those in the external station auto-driver work trip productions.

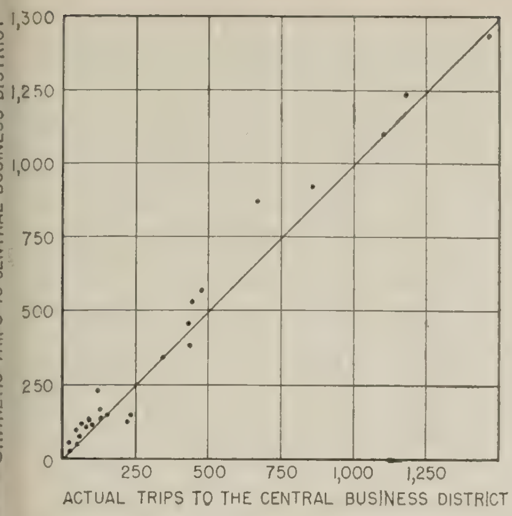
To test the accuracy of these procedures, the total auto-driver nonwork trip production estimates for each zone were compared with the production from the 1956 comprehensive O-D survey and the actual and the estimated volumes agreed very closely.

Zonal trip attractions

Zonal nonwork trip attractions for the 74 internal zones were derived from zonal data on population and retail sales. The total number of internal auto-driver nonwork trip attractions divided into the total population figure for the area produced the population figure per attraction for this purpose. Repeating this process for the total retail sales in the area produced the unit of sales per attraction. Dividing the larger of these rates (population) by the smaller (retail sal) showed that 1.69 units of retail sales we required to attract each nonwork trip, lthough it took 1.00 unit of population o attract each nonwork trip. Using this tenique a weighting factor

(population + 1.69 × retail sales)

was established as an indicator of the num r of auto-driver nonwork trip attractions n each zone. The total number of attracti s for this purpose was prorated to the zones y use of this weighting factor. The number f nonwork trip attractions also was factored o ensure that the number of CBD attracti s was equal to those in the small sample surv y data. The non-CBD attractions were ljusted accordingly to keep the total num r of attractions the same as in the small samp



igure 20.—Actual versus synthetic model nonhome based vehicular trips to CBD, Sioux Falls, S. Dak., 1956.

For the external stations, the number of uto-driver nonwork trip attractions was obained in the same manner as described for ie external station auto-driver work trip roductions. Nonwork trips were 20 percent f the total station auto-driver trips (excluding ie through trips).

To test the accuracy of these procedures, ie total auto-driver nonwork trip attractions stimated for each zone were compared with ie attractions from the 1956 O–D survey. he actual and the estimated volumes agreed easonably well.

able 14.—Differences between O-D data and synthetic gravity model estimates for district-to-district auto-driver trips, for three purposes, by volume groups [1]

Trip volume	O–D survey trips		RMS error	
		HOME BASED WORK TRIPS		
Group	*Mean*	*Frequency*	*Absolute*	*Percent* [2]
0–99	21	400	20	95.24
100–199	133	40	58	43.61
200–299	259	13	119	45.95
300–499	402	13	98	24.38
500–1,499	920	8	186	20.22
		HOME BASED NONWORK TRIPS		
0–99	27	423	28	103.70
100–199	136	53	83	61.03
200–299	239	28	103	43.10
300–499	380	22	166	43.68
500–999	728	22	282	38.74
1,000–2,999	1,711	9	343	20.05
		NONHOME BASED TRIPS		
0–99	25	473	24	96.00
100–199	144	62	82	56.94
200–299	241	30	122	50.62
300–499	385	33	157	40.78
500–999	773	9	289	37.39
1,000–3,999	1,311	8	457	34.86

1956 O–D survey data versus synthetic gravity model imates—relative difference measured in terms of percent t-mean-square error.

Percent RMS Error $=100\left(\frac{\sqrt{\frac{\Sigma(d)^2}{n}}}{\bar{x}}\right)$

here,

= difference between surveyed and estimated trips

= number of district-to-district movements

= mean of surveyed trips.

Nonhome Based Auto-Driver Trips

Zonal trip production and attraction

In several studies it has been reported that auto-driver nonhome based trip production is associated with car ownership (*4*, *14*). Also, from the definition of trip production and attraction for nonhome based trips, production and attraction values should be equal on a *zonal* basis as well as on a study area basis. As trip origins should closely agree with trip destinations on a zonal basis during the 24-hour day, trip productions must also agree closely with attractions. This information was used in determining zonal trip productions and attractions for nonhome based auto-driver trips. Zonal nonhome based trip productions and attractions for the 74 internal zones were derived from the zonal data on car ownership. The figure of 2.98 nonhome based trips per car (from table 11) was applied to the number of cars owned in each internal zone to determine nonhome based trip productions. For the 10 external stations, trip productions and attractions were obtained in the same manner as described for external station auto-driver work trip productions. Nonhome based productions and attractions were 18.5 and 19.0 percent, respectively.

To test the accuracy of this procedure, the total nonhome based trip productions and attractions estimated for each zone were compared with those from the 1956 O–D survey. The actual and estimated values indicated poor agreement. An examination of the internal nonhome based trip productions and attractions from other studies also showed similar poor agreement. This is the most serious weakness of the small sample procedures.

Trip Distribution Patterns

The previously described procedures provide zonal trip production and attraction values for each of the three trip purpose categories. However, before trip interchange patterns could be calculated by using the gravity model, some measure of spatial separation between the zones had to be developed. For this phase of the research, the same information on the minimum path driving times between zones, the intrazonal times, and the terminal times was used as developed in the first part of this research. In addition, some measure of the effect of the spatial separation on trip interchanges between zones (F) was also required. In this phase of the research, full use was made of the traveltime factors already developed for each trip purpose. This was done because of the similarities of the trip time length frequency curves between the total OD sample and the subsample of 599 household interviews.

After all the required parameters had been determined, the gravity model calculations were made to obtain a synthetic trip distribution pattern. This synthetic pattern was compared with the O–D survey data to determine its accuracy. Several tests were involved in the comparisons. First, the synthetic trip time length frequency distributions and average trip time lengths were compared with those from the O–D survey for each trip purpose category; they agreed closely. The results for work trips are shown in figure 18.

The number of trips attracted to each zone, as computed by the gravity model, were compared with those shown by the synthetic procedures, for each trip purpose. The results for nonwork trips, which had the largest scatter, are shown in figure 19. Another test was made of the number of synthetic trips crossing the Big Sioux River. The figures compiled for this test were compared with those from the O–D survey (table 4). Again, the differences were small.

Synthetic trips to the CBD, for each trip purpose, were also compared with the actual O–D movements. The results for auto-driver nonhome based trips are shown in figure 20. No geographical bias was present in the synthetic trip interchanges, and the discrepancies between the two sets of information were very small. Synthetic trip interchanges for total trips were assigned to the minimum path driving time network. The expanded number of trips from the full O–D sample were likewise assigned. These two sources of information were then compared (table 5) by analyzing the differences over a comprehensive series of screenline crossings, these are shown in figure 5.

Finally, a statistical comparison of the actual and the estimated number of trips was made for each trip purpose. The results of the comparisons are shown in table 14. Results were acceptable for all purposes. The accuracy of this synthetic model calibration was equivalent to the accuracy attained with the model calibrated with all the Sioux Falls O–D data (table 6). The accuracy of the synthetic calibration also compared favorably with the results from other studies (*12*, *15*, *16*) when the models were calibrated with the O–D data.

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