Development of Traffic Parameter for Structural Design of Flexible Pavements in Minnesota

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•THE LOADING on a highway pavement is composed of applications of axle loads of various weights. The axle loads range from less than 2,000 lb on a single axle to more than 50,000 lb on a set of tandem axles. To determine the load effect on a pavement during its design life it is necessary to obtain the number of loads and the weight distribution operating over the pavement. For some design procedures this is done by assigning a specific load to the highway section. Another method is to relate the design to the amount of total traffic in average daily traffic (ADT) and the number of heavy trucks expected to use the highway (HCADT). The latter is the method used for the present Minnesota flexible pavement design procedure (1).

At the AASHO Road Test it was possible to determine the relative effect of the loadings used because a particular section of road was subjected to repetitions of one magnitude of load. The relative effect of the loads on the performance of pavement sections can be used to convert each load repetition to an equivalent number of repetitions of a base load. For a number of design procedures, including the AASHO Interim Guide, an 18,000-lb axle is used as the base load (2, 3, 4).

Even though a fairly precise determination can be made of the load equivalency factors, the calculation of the total equivalent 18,000-lb single axle loads is approximate because the distribution of axle loads on a pavement can only be estimated. When all loads on a road section are the same, such as at the Road Test, there is no problem involved with determining the summation of equivalent axle loads, but when actual highway loadings are being considered, approximations must be made to estimate the distribution of axle weights within a given truck type and the distribution of the various truck types over a particular section of road. During the last five years a comprehensive study has been made of flexible pavement design and performance in Minnesota. This study was based on measurements and observations on 50 test sections, all on existing state highways. As a part of this study it was necessary to have a determination of the traffic loads on each section. The distribution of the various truck types for the 50 test sections could not be determined accurately from the available statewide data.

Therefore, a traffic study was started in 1964 by the Planning Research Section of the Minnesota Department of Highways for these test sections. The traffic study has been used to obtain the distributions mentioned plus the total volume of traffic to use the roadway at each test section. The distribution and volumes are used to (a) calculate the total equivalent 18,000-lb axle loads that the section has been subjected to since it was last resurfaced, and (b) determine what traffic parameters best predict the total equivalent loads on a pavement section and how accurately these parameters predict the equivalent axle loads.

The first part of this paper is a presentation of the traffic study made on the Minnesota test sections and analysis of the data. The analysis has been programmed for the CDC 6600 computer. The statewide weight distribution and volume distribution data for the year can be put into the program to bring the traffic for each test section up to date. This is done in general by assuming that 1964, which is the year the traffic study was run, is the base year and that the distributions on each test section vary as the statewide distributions for subsequent years.

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It has been assumed that a comprehensive traffic study cannot be made when a pavement is to be designed. In the second part of this study correlations have, therefore, been made between the equivalent axle loads and (a) average daily traffic (ADT), (b) the heavy commercial average daily traffic (HCADT), and (c) the summation of Types 4 plus 5 trucks. It is shown that the equivalent loads can be predicted with increasing accuracy using the first three parameters in order as listed. The errors in these predictions are related to design thickness.

TOTAL LOAD IN TERMS OF EQUIVALENT 18,000-LB SINGLE AXLE LOADS

To analyze the performance of the Minnesota test sections based on the concepts of the AASHO Road Test and based on a good estimate of the load effect on the pavements, it is necessary to estimate the total equivalent number of 18,000-lb axle loads since the pavement section was built. Even though accurate determinations of the load equivalency factors based on the performance of the sections at the Roat Test have been made, the calculation of the total equivalent loads for a highway section is approximate because the distribution of the axle loads or the numbers of the various axle loads cannot be obtained exactly.

A traffic study on the Minnesota test sections was performed by the Planning Research Section of the Minnesota Department of Highways in 1964 to fill in an estimate of these distributions on the test sections.

The traffic study included the following operations on 41 of the 50 test sections:

1. Weigh all trucks passing a location during a 16-hour period on a weekday in each of three seasons.
2. Classify vehicles during 16-hour periods on a weekday, Saturday, and Sunday in each of the four seasons.
3. Count traffic for seven consecutive days in each of the four seasons to provide average daily traffic volumes (ADT).

Only 41 traffic stations were used because nine of the locations could represent distributions for two test sections.

The procedure to determine the total number of equivalent wheel loads over a section since it was constructed as summarized in the following has been performed on each test section through 1964, 1965, 1966, and 1967. It is assumed that it is desirable to update this information in future years. The method outlined has therefore been put into a computer program that, when statewide data for a given year have been added, adds on the traffic estimate for each test section using the 1964 traffic study as a base and modifies the weight and volume distributions based on ratios of the statewide data. The computer program is available on request from either the Civil Engineering Department of the University of Minnesota or the Minnesota Department of Highways Planning Research Section.

Truck Factors

Truck factors have been calculated for each of five types of trucks for each test section in 1964 using the weight data from the traffic study. A truck factor (TFS) is defined as the average number of equivalent 18,000-lb axle loads that the pavement section is subjected to with one passage of that truck type. If, for instance, a Type 5 truck factor is 1.5, then on the average every Type 5 truck that passes over the test section would have the effect of 1.5 18,000-lb axle loads when the effect of its five axles are summed together. For the traffic analysis, trucks are classified into the following six types:

Type	Description
0	Single unit, 4-tire
1	Single unit, 2-axle, 6-tire
2	Single unit, 3-axle
3	Tractor-truck or semitrailer, 3-axle
4	Tractor-truck or semitrailer, 4-axle
5	Tractor-truck or semitrailer, 5-axle

The weighing part of the 1964 traffic study was done at four times (cycles) during the year: (a) early spring, during load restrictions; (b) late spring, after load restrictions; (c) summer; and (d) fall. The weighing done for the early spring was actually done in the spring of 1965, but was assumed as part of the 1964 data.

A computer program called TRUFAC was set up to calculate truck factors for each cycle for each test section using the weight data. TRUFAC essentially accepts the number of axles in 2,000-lb weight classes for single axles and tandem axles, multiplies the number of axles in each weight class by the load equivalency factor for that weight class, sums the products, and divides by the number of trucks in that truck type classification giving the average number of equivalent 18,000-lb axle loads for that type truck. This final value is the truck factor. The equivalency factors have been obtained (5) to show the relative effect of the various axle loads on the performance of a pavement section as indicated by the AASHO Road Test equations.

Truck factors have been determined for Types 1 through 5 trucks using TRUFAC. The truck factors calculated for individual seasons at each test section were weighted assuming the following time distribution: 2 months for spring, 3 months for fall, and 7 months for the summer truck factor. The late spring value was averaged with the summer value to obtain a summer truck factor for weighting.

To study the variations in truck factors, the highways were broken down into three classes and the variations in truck factor with season for these groups were considered. The three classifications are the following:

Class A—Highways carrying interstate trucks and very few local trucks.
Class B—Medium-high traffic roads with some interstate trucks and some local trucks.
Class C—Low traffic loads with almost all local trucks.

There are 8 sections classified as Class A, 15 sections as Class B, and 18 sections as Class C.

Table 1 summarizes the truck factors obtained on these classes of roads for the three cycles of the year. Two things are of interest in this table. First, the spring restrictions have a slight effect on the truck factors for Classes A and B roads and have a greater effect on Class C roads, which are generally restricted in the spring. Second, in all cases the fall truck factors are significantly higher than the spring or summer values (primarily because of harvest time). These variations justify the use of seasonal truck factors and the weighting of them by time to determine a yearly truck factor. In a number of cases the yearly truck factor for Class C roads was quite different from the overall average for a given truck type. In cases where an extremely high or low value represented a very small number of trucks, designated maximum or minimum values of truck factor for the various truck types were used. It was reasoned that over the years a truck factor nearer the average would be appropriate. Table 2 gives the minimum and maximum limits on truck factors set up. These limitations primarily affected Class C roads.

TABLE 1

SUMMARY OF SEASONAL TRUCK FACTORS BY ROAD CLASSES

Road Class	Season	Truck Type 1	2	3	4	5
A	Spring	0.210	0.273	0.947	1.249	1.682
	Summer	0.277	0.492	0.745	1.362	1.640
	Fall	0.291	0.701	1.410	1.750	1.948
B	Spring	0.144	0.213	0.544	1.428	1.850
	Summer	0.215	0.273	0.811	1.408	1.893
	Fall	0.216	0.304	0.837	2.062	2.199
C	Spring	0.113	0.232	0.126	0.659	0.411
	Summer	0.184	0.311	0.186	1.097	1.827
	Fall	0.278	0.424	0.665	1.077	1.988
All	Spring	0.150	0.240	0.687	1.253	1.678
	Summer	0.219	0.352	0.619	1.329	1.737
	Fall	0.256	0.454	1.028	1.761	2.034

Weight Distributions

TABLE 2

MINIMUM AND MAXIMUM TRUCK FACTORS USED FOR 1964 YEARLY TRUCK FACTORS

Limit	Truck Type				
	1	2	3	4	5
Minimum	0.100	0.150	0.208	0.500	0.500
Maximum	0.500	0.800	None	2.250	2.300

The variation in weight of the five types of trucks back to 1952 has been estimated by using statewide weight distributions for each type of truck obtained from the annual traffic reports of the Minnesota Department of Highways Planning and Programming Division. Before 1963, the tables did not include a breakdown between tandem and single axle loads, which made it impossible to calculate directly the statewide truck factors (SWTF) for Types 2, 4, and 5 trucks from the traffic reports.

In the Bureau of Public Roads 1965 Truck Weight Study (5), a procedure was suggested for projecting tandem axle effect back for previous years when only the all-axle category was available. This method consists of calculating the ratio of single axles to all axles in each weight category for the earliest year this information is available (1963). This ratio is then used to estimate the number of single axles in each weight group for each type of truck. The remainder of all axles divided by two is assumed to be the number of tandem axles in that weight group. This procedure was used to estimate the statewide truck factors for each type truck for each year previous to 1963. The results from this method of estimating tandem axles have been incorporated in the computer program for estimating variation in truck factor.

A plot of the truck factors is shown in Figure 1. Of special interest is the increase in weight of the Type 4 and Type 5 trucks in the last three or four years. The ratio of the statewide truck factors for a given year to the 1964 statewide truck factors is used to modify the truck factors for each test section for the year of interest. This has been done for each test section back to the year when it was last overlaid. Provision for this calculation has also been made in the computer program so that statewide truck factors are used to modify the test section truck factors as the statewide traffic reports are made available in each future year.

Truck Type and Volume Distributions

The 1964 truck type distribution has been determined for each test section using the volume data from the 1964 traffic study. The distribution is set up as the percentage of heavy commercial traffic that includes Types 1, 2, 3, 4, and 5 trucks. The percentages obtained for each season have been weighted to calculate a 1964 percent distribution for each test section.

It is assumed that the volume distribution of heavy commercial trucks can vary from year to year. To estimate the variation from year to year the statewide volume data are used. These data were again obtained from the annual traffic reports. The "axles counted" data are used to determine this statewide yearly distribution. The variation of distribution from year to year is determined by taking the ratio of these percentages to the 1964 percentage and multiplying the 1964 test section distributions by these ratios. The sums of these calculated distributions are apportioned up or down to 100 percent so that the calculated percentages can be used along with the HCADT to determine the number of each type of truck for each test section and each year. A plot of the state-

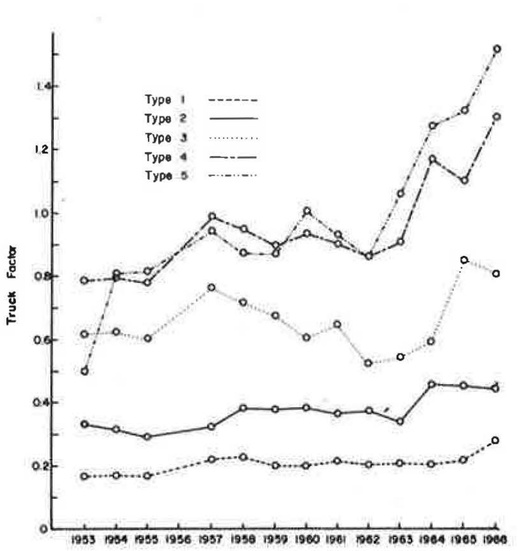

Figure 1. Statewide truck factors.

wide yearly percentage distributions is shown in Figure 2. The general increase in the percentage of Type 5 trucks in the last four years is of interest. The use of statewide distribution data is recommended for updating the traffic volume data each year in the future. Provision has been made in the computer program for inclusion of these data from the annual statewide traffic reports.

The total HCADT for each test section in 1964 is obtained from the traffic study. The HCADT does not include 4-tired, 2-axle trucks (defined as Type 0 trucks).

The variation in HCADT is estimated by using traffic flow maps furnished by the Traffic and Planning Section of the Minnesota Department of Highways. Again, using 1964 as the common denominator, ratios of CADT from the traffic flow maps were obtained for each test section location and each year back to when the individual test was constructed. CADT, which includes Type 0 trucks, was used because this is the value along with total ADT that is shown on the maps. Ratios of CADT can be assumed to be the same as ratios of HCADT because the percentage of Type 0 trucks has remained essentially constant from 1952 through 1967.

From the preceding information, the number of heavy commercial trucks per day (HCADT) traveling in one direction (i.e., over the test section) can be determined for each test section and each year. This is referred to in the program as HCADT (J, K) where J refers to each test section 1 to 50 and K refers to the year from 1952 to the present year (PY). When HCADT (J, K) is multiplied by each of the percent distributions for each year, the number of each type of truck is obtained for each test section and each year. This set of values is referred to as ANOTKS (I, J, K).

With TFS (I, J, K) and ANOTKS (I, J, K) determined from the previous paragraphs, an estimate of the equivalent 18,000-lb axle loads contributed by each truck, each year, on each test section can be obtained by multiplying corresponding elements of these arrays. The resulting array is represented by DTEAL (I, J, K), the daily total equivalent axle loads for each type truck (I), each test section (J), and each year (K).

The summation

$$\sum_{I=1}^{5} \text{DTEAL (I, J, K)} = \text{DTEAL (J, K)} \tag{1}$$

gives the daily equivalent axle loads for each test section and each year. To get the total equivalent 18,000-lb axle loads for a given year, the DTEAL (J, K) is multiplied by 365, giving the YTEAL (J, K).

To obtain the summation of equivalent axle loads for a test section, the summation

$$\sum_{K=YC}^{PY} \text{YTEAL (J, K)} = \text{SYTEAL} \tag{2}$$

is made, where YC is the year constructed and PY is the present year. This is called the SYTEAL (summation of yearly total equivalent axle loads). The YTEAL for the year constructed is divided by two because it is assumed that traffic ran for half the year of construction. Table 3 is a list of the 1967 yearly 18,000-lb axle loads for each test section plus the estimated summation of the equivalent 18,000-lb axle loads for each test section through 1967. This table shows the wide variation in traffic found on the Minnesota test sections.

To carry this procedure through the next year (in this case, 1968), it is necessary to

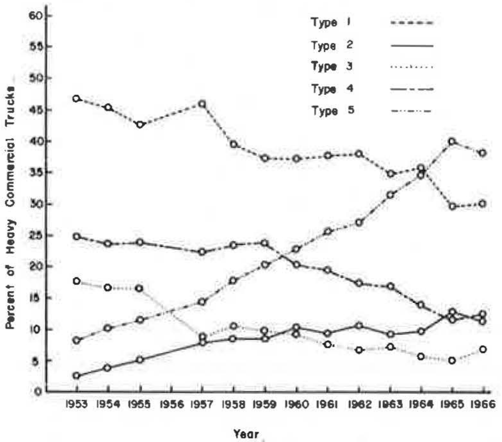

Figure 2. Percent distribution of heavy commercial traffic.

TABLE 3

1967 YEARLY EQUIVALENT 18,000-LB AXLE LOADS AND SUMMATION OF EQUIVALENT 18,000-LB AXLE LOADS THROUGH 1967

Test Section	Year Built	1967 Yearly N18	Σ N18 Through 1967	Test Section	Year Built	1967 Yearly N18	Σ N18 Through 1967
1	1958	113, 510	851, 724	28	1956	–	34, 647[b]
2	1954	–	69, 930[b]	78[a]	1965	7, 128	15, 788
52[a]	1965	24, 182	53, 016	29	1956	–	20, 898[b]
3	1961	25, 596	107, 049	30	1961	222, 115	995, 833
4	1958	16, 511	98, 957	31	1959	12, 367	84, 338
5	1958	6, 576	44, 215	32	1957	6, 194	50, 261
6	1960	162, 168	669, 927	33	1957	40, 906	272, 691
7	1961	14, 658	97, 143	34	1959	134, 589	737, 715
8, 9	1953	40, 112	388, 359	35	1958	15, 677	88, 628
10	1958	3, 867	25, 587	36	1961	42, 189	187, 263
11	1961	9, 536	61, 314	37	1961	32, 944	131, 606
12	1956	6, 966	60, 526	38	1956	48, 511	325, 947
13, 14	1962	31, 574	123, 679	39, 40	1953	19, 625	145, 253
15	1960	328, 581	1, 530, 470	41	1955	–	640, 540[b]
16	1957	65, 530	539, 128	91[a]	1964	218, 369	630, 200
17, 18	1959	76, 480	385, 125	42	1962	12, 565	45, 906
19	1957	99, 046	743, 533	43	1959	553	4, 036
20	1955	70, 612	371, 262	44	1963	7, 269	27, 841
21, 22	1961	25, 303	141, 060	45	1959	6, 674	25, 825
23	1961	131, 402	488, 325	46	1961	6, 773	26, 819
24	1956	4, 198	36, 830	47	1957	20, 501	166, 545
25	1956	2, 294	26, 054	49	1955	32, 856	260, 985
26, 27	1961	1, 457	7, 025	50	1954	7, 911	53, 047

[a]Sections overlaid since 1963 continued to be observed with a number of 50 plus the original number.
[b]Total equivalent 18,000-lb axle loads before being overlaid.

have (a) the annual statewide traffic report for that year, and (b) the traffic flow map or some estimate of the CADT for each test section. The annual traffic report is used to determine the truck factor ratios (changes in weight distribution) of the trucks by type and the volume distribution change of the various type trucks necessary to modify the results of the 1964 traffic study to make it applicable for the present year. The annual traffic reports are usually available in April of the following year. The traffic flow maps are only available for the even years. For an intervening year, such as 1965, the same CADT could be assumed without a great error. With the 1966 traffic flow map available, it is then possible to interpolate between 1964 and 1966 to get a better estimate for 1965. These data can be changed easily in the computer program.

The procedure developed in this section is valid for updating the traffic value on each test section as long as there is no abrupt change in the traffic pattern for the given section. For instance, if an Interstate highway opened parallel to a section, the heavy traffic would most likely be altered materially. The traffic flow map for that year would show the decrease (if any) in the total volume, but would not indicate the decreased number of Types 4 and 5 trucks nor possibly their general decrease in weight caused by the shifting of through traffic to the Interstate highway. If a change in traffic pattern such as this occurs, it is advisable to make another traffic study at the test section location. To ensure that no extraneous traffic conditions have developed on any of the test sections, it would be advisable to conduct another traffic study every 5 or 10 years. The frequency at which these traffic studies are made is dependent on the funds available for such a study. The field work represented here costs approximately $85,000. A future study would only have to be run three times per year rather than four, but more time would be required to obtain complete information on some of the low-traffic sections.

Based on the results of the study made in 1964, a future study could be modified in the following ways. As shown previously, there is a significant difference in truck factors between spring, summer, and fall. It would therefore be advisable to weigh and count trucks in each of these seasons. The spring cycle should be during the spring restriction period and the fall cycle preferably should start after September 1. It would be advisable to make weight distribution determinations only on test sections where more than ten of each type of truck can be weighed during a reasonable length of time. Volume distribution data should be gathered until at least one of each type of truck has

passed the given location. This is important in areas where very low traffic occurs, because it is known that sometime one of a given type of truck will pass by. When one Type 5 truck every three or four days is added up over the life of the pavement it may be the major contributor to total loads to which the pavement is subjected.

Based on the data obtained from the traffic study made in 1964 it has been recommended that the traffic for the Minnesota test sections and any other load determinations based on the equivalent axle load determinations be made at the site being considered and then projected to other years based on statewide variations from year to year. This recommendation is based on a comparison of truck factors in 1964 from a number of the test sections and on the statewide data. Some of the truck factors for 1964 are summarized in Table 4, which gives truck factors for four test sections, the average truck factors for the three classes of roads as defined previously for the overall flexible pavement investigation traffic study, and the statewide traffic from the annual traffic report. Test Sections 1, 15, and 19 are all on US 10 and TS 6 is on US 2 near Duluth. The interesting thing about the three test sections on US 10 is that TS 19 generally has low truck factors compared with TS 1 and TS 15, especially for Types 4 and 5 trucks. It is felt that this low truck factor is caused by the fact that TS 19 is located at a permanent weighing station. Overloaded trucks may be "permanently" avoiding the permanent weighing station. The overall data for the special traffic study also result in somewhat higher truck factors than calculated from the statewide traffic report for 1964. The increase of over 0.50 is significant for Type 5 trucks, as is the increase of about 0.25 for Type 4 trucks. This also may be caused by the use of permanent weighing stations for statewide data collection. These variations show the importance of making traffic surveys for test sections at the location of the sections rather than considering statewide data when the summations of equivalent axle loads are being determined. This is important when considering the loading a research study section has had imposed on it, but is of lesser importance when considering traffic for design purposes.

PREDICTION OF AXLE LOADS FOR PAVEMENT DESIGN

By means of the procedures just presented, the total traffic that has passed over a section of highway can be estimated. The procedure involves a rather comprehensive traffic survey (weight and volume) and the setting up of a computer program that brings the traffic up to date each year. To design a pavement based on equivalent axle loads, it is necessary to estimate the present magnitude of traffic and to be able to project this value into the future over the design period. To do this for design purposes, it is not always practical to run a load distribution study, but it is easier to estimate the ADT, HCADT, or make some estimate of the number of heavy trucks that will be using the road. Using the 1964 traffic study and the variation in statewide traffic, correlations have been developed to show how these traffic parameters correlate with the equivalent 18,000-lb axle loads. The errors in these approximations are converted to

TABLE 4

COMPARISON OF 1964 TRUCK FACTORS

Source	Truck Type				
	1	2	3	4	5
TS 1	0.312	0.151	1.409	1.445	1.789
TS 6	0.464	0.365	0.260	2.242	1.671
TS 15	0.379	0.616	0.161	1.784	1.958
TS 19	0.167	0.236	0.240	0.660	0.710
All Class A	0.267	0.508	0.945	1.440	1.724
All Class B	0.203	0.271	0.773	1.575	1.962
All Class C	0.196	0.326	0.296	1.019	1.631
All Traffic Study Data	0.217	0.359	0.733	1.424	1.801
Statewide from 1964 Traffic Report	0.205	0.452	0.596	1.171	1.276

thicknesses so that the correlations can be evaluated. In the first part of this section, the estimated yearly equivalent loads for the last 12 years are considered to try to estimate the probable future growth of traffic in terms of equivalent axle loads. This factor is necessary for future designs to help determine the load-life of the pavement. The variation in the correlation of HCADT with equivalent loads over the last 10 years is studied and a method is suggested for predicting future growth of equivalent 18,000-lb axle loads based on HCADT.

VARIATION OF RATE OF APPLICATION OF LOADS WITH TIME

To design a highway using the equivalent load concept it is necessary to predict the future growth of traffic in terms of equivalent loads for the design period into the future. As has been shown by the traffic volumes on Minnesota test sections, the number of equivalent loads is not only dependent on the volume of traffic, but also very much dependent on the weight characteristics and the percentage of the different types of trucks.

Two design methods that currently use a growth factor for design with the equivalent load concept are the Asphalt Institute method (4) and the California method (6). A growth factor of 3 percent per year is used, which is inherent in the determination of traffic for the Asphalt Institute design (4, Appendix A). For the California traffic determination, it is assumed that traffic in terms of equivalent wheel loads increases 50 percent in ten years. This is equivalent to a yearly growth factor of 4.14 percent.

To see how these factors compared with the results of the traffic analysis on the Minnesota test sections, the yearly equivalent axle loads for the preceding 12 years were taken as a percentage of the 1965 yearly equivalent axle loads and averaged for the Classes A, B, and C roads as defined previously. The percentages were averaged for each of the classes of sections. It was found that the values for Classes A and B roads were very similar. These two classifications were therefore combined and the averages for this "heavy" category and the Class C (light) category were determined separately. Even though the variation in each of these percentages is based on the same statewide data, there is on the average about a 10 percent higher value of percentage for the light traffic roads. This actually represents a slower growth rate. The lower growth rate for the lower traffic roads can be attributed to the lower percentage of Types 4 and 5 trucks on these roads. The Types 4 and 5 trucks have shown the greatest increase in weight over the last 10 to 12 years. It was found that the growth of the heavy roads can be best represented by a growth factor of greater than 10 percent per year and the lighter traffic roads can be represented by a growth factor of about 8 percent per year. These values of growth factor are considerably higher than those previously mentioned. It is felt that the last 12 years represent a period of abnormally high growth in truck weights and volume of truck traffic. For estimating future traffic growth, a value between 5 and 8 percent would be adequate. This is only an overall value, however, and when a specific estimate is being made, many local factors could materially affect the growth factor anticipated.

Correlation of Equivalent Loads With Other Traffic Parameters

The relationships obtained when 18,000-lb equivalent axle loads are correlated with three traffic parameters on a pavement section are presented in this section. The parameters used for correlation are (a) the two-way average daily traffic at the section location (ADT), (b) the one-way heavy commercial traffic (HCADT as previously defined) at the section, and (c) the daily summation of the number of Types 4 and 5 trucks at the section in one direction.

The initial correlations are made using the data from the 1964 traffic study on the Minnesota test sections. Initial plotting indicated that the data appeared to fall into two categories—one with traffic greater than 150 daily equivalent loads, and the other with less than 150 daily equivalent loads. Test Section 19 was left out of the correlations because the data from this section deviated greatly from the overall trends. Comparison of arithmetic and logarithmic plots and error terms showed that log-log correlations were the best.

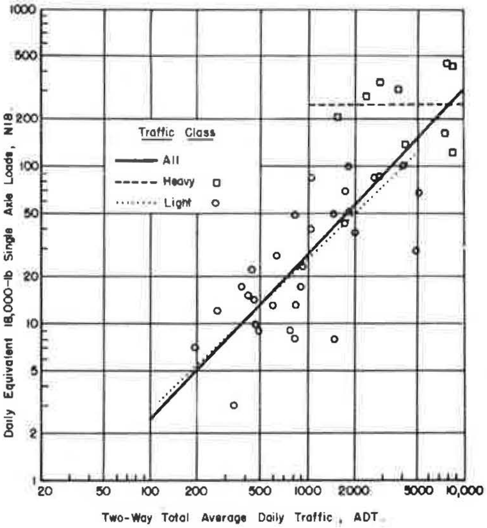

Figure 3. Percent of 1965 annual equivalent 18,000-lb single axle loads for heavy traffic test sections.

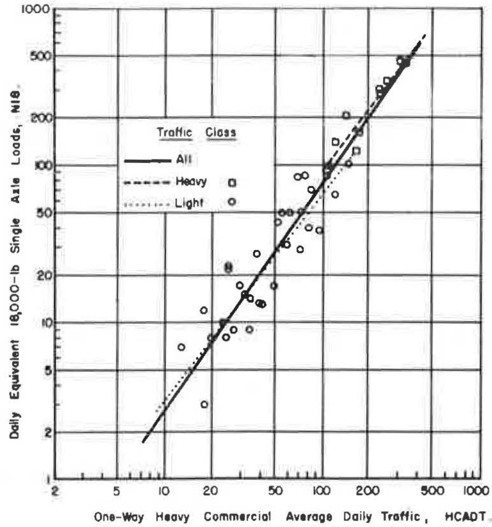

Figure 4. Percent of 1965 annual equivalent 18,000-lb axle loads for light traffic test sections.

Figures 3, 4, and 5 and Table 5 show the correlations of the three parameters and daily N18 using logarithmic axes. The data show that a better correlation is achieved by separating the light and heavy traffic.

Table 6 gives the error thickness of granular base, using Eq. 18 from an Asphalt Institute monograph (7). When log N18 is used, one unit of thickness represents a given standard error because thickness is related to the log N18 in the equation. An error factor is also listed in Table 6 for each traffic parameter and category. This factor represents the percent accuracy to which N18 can be estimated using the given parameter. For instance, the error factor is 1.240 for heavy traffic using HCADT. This means that N18 can be predicted to a percentage accuracy of ± 24 percent (actually × 1.24 or ÷ 1.24). This accuracy represents a thickness of granular base of about 0.6 in.

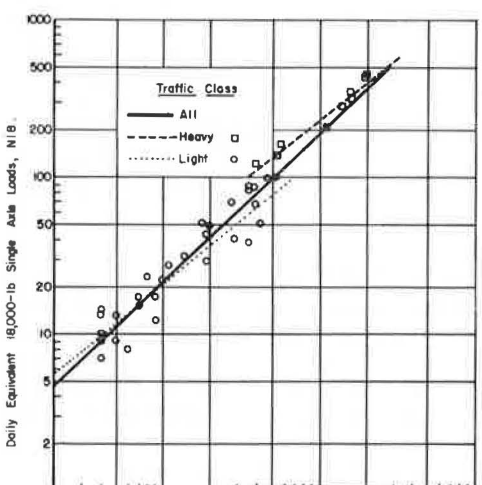

Figure 5. Logarithmic relationship between daily equivalent 18,000-lb axle loads and two-way total average daily traffic.

TABLE 5

CORRELATIONS FOR PREDICTING EQUIVALENT AXLE LOADS WITH LOG-LOG RELATIONSHIPS

Form of Equation: $\log N18 = a_0 + a_1 \log (X)$

X	Traffic Conditions	a_0	a_1	Standard Error
ADT	Light	-1.204	0.853	0.328
	Heavy	2.399	-0.002	0.228
	All	-1.725	1.052	0.367
HCADT	Light	-0.816	1.307	0.229
	Heavy	-0.671	1.317	0.093
	All	-1.006	1.433	0.217
Σ(4+5)	Light	0.506	0.824	0.169
	Heavy	0.819	0.776	0.051
	All	0.396	0.944	0.163

TABLE 6

ERROR IN THICKNESS OF GRANULAR BASE OWING TO STANDARD ERROR OF CORRELATIONS USED TO ESTIMATE N18

Traffic Parameter	Category	Error Factor	Gravel Equivalent Thickness Error (in.)
ADT	Light	2.126	1.8
	Heavy	1.691	1.3
	All	2.328	2.0
HCADT	Light	1.695	1.3
	Heavy	1.240	0.6
	All	1.649	1.2
Σ (4 + 5)	Light	1.475	0.9
	Heavy	1.124	0.3
	All	1.455	0.9

TABLE 7

MINNESOTA TRAFFIC CATEGORIES CONVERTED TO DAILY EQUIVALENT 18,000-LB AXLE LOADS USING THE 1964 CORRELATION

Two-Way HCADT Range	One-Way HCADT Range	Daily 18,000-lb Axle Loads
<150	<75	<43
150-300	75-150	43-107
300-600	150-300	157-392
600-1100	300-550	390-867
>1100	>550	>867

The errors in thickness obtained using the arithmetic relationships were greater than those in Table 6. It is slightly better to break the roads down into heavy and light traffic categories. The better correlation using Σ (4 + 5) as the independent variable is obtained because in most cases the Type 4 plus Type 5 trucks made up about 70 to 90 percent of the equivalent loads on the pavements for 1964.

From the accuracies shown in Table 6, it is apparent that an estimate of equivalent loads using HCADT should be adequate and that slightly better accuracy would result if a good estimate of the number of daily Type 4 plus Type 5 trucks could be obtained.

The following equations have been suggested to predict N18 from HCADT for design purposes.

$$\log N18 = -0.816 + 1.307 \log (HCADT) \quad \text{for HCADT} < 150 \qquad (3)$$

$$\log N18 = -0.671 + 1.317 \log (HCADT) \quad \text{for HCADT} > 150 \qquad (4)$$

For the present Minnesota Department of Highways design procedure, the two-way HCADT is used as a design parameter (1). The HCADT used in this presentation is a one-way HCADT. Table 7 gives the ranges of HCADT presently used converted to daily equivalent 18,000-lb axle loads using this 1964 correlation.

VARIATION IN CORRELATION BETWEEN TRAFFIC AND LOADS

It has been found by the Traffic and Planning Section of the Minnesota Department of Highways that the HCADT on most Minnesota highways is increasing at a rate of 3 percent per year. For the estimation of loading on a pavement using the HCADT, the correlation between HCADT and daily N18 is used. To design a pavement, consideration must be made of the increase in N18 projected into the future through the design period. When HCADT is used to predict N18 over a design period of 20 years, two factors can increase that cause an increase in N18 each year. These are (a) an increase in HCADT which is around 3 percent per year as indicated above (this may vary somewhat depending on local traffic conditions), and (b) an increase or decrease in daily N18 predicted for a given HCADT. A change in correlation could significantly affect the total design N18 over the design period. The correlations to show the effects discussed are considered in the remainder of this section.

The correlation between N18 and HCADT shown in Figure 4 is for the year of the traffic study (1964). To study the variation of this correlation with time, the daily N18 for each test section used in the traffic study was determined for each year from 1956 through 1966. Table 8 gives the results of these correlations for the 11 years. The equation is the same log-log model and results in equally good correlations for each year as shown by the squared correlation coefficients and the standard errors.

To see what these correlations represented in terms of daily N18, the predicted N18 were calculated for each year for one-way HCADT values of 75, 150, 300, and 550.

TABLE 8

RESULTS OF CORRELATIONS BETWEEN N18 AND HCADT FOR 1956 THROUGH 1966 USING NO BREAKDOWN OF TRAFFIC

$\log N18 = a_1 + a_2 \log (HCADT)$

Year	a_1	a_2	Squared Correlation Coefficient	Standard Error
1956	-0.9079	1.317	0.912	0.180
1957	-0.8445	1.293	0.910	0.183
1958	-0.8672	1.342	0.898	0.199
1959	-0.9884	1.385	0.922	0.177
1960	-0.9464	1.362	0.923	0.170
1961	-0.9196	1.352	0.925	0.164
1962	-0.9854	1.362	0.935	0.148
1963	-0.7153	1.259	0.787	0.272
1964	-0.8945	1.373	0.906	0.188
1965	-0.8004	1.355	0.912	0.180
1966	-0.7645	1.359	0.927	0.171

TABLE 9

PERCENT INCREASE IN DAILY EQUIVALENT 18,000-LB LOADS RELATIVE TO HCADT

Period Prior to 1965	HCADT			
	75	150	300	550
10 years	4.2	5.7	6.9	6.7
4 years	12.5	17.3	21.8	25.9
3 years	17.8	15.9	12.5	12.3

These values correspond to the present design limits of 150, 300, 600, and 1100 two-way HCADT. The daily N18 values were plotted on a log scale so that a constant slope represents a constant rate of increase assuming a compound percentage increase. There was not a constant rate of increase over the 11-year period. In fact, there is somewhat of a decrease in the correlations from 1958 through 1962. This can be explained by the fact that more Type 5 trucks relative to Types 3 and 4 trucks were coming into use during that period. The Type 5 trucks generally had a slightly lower truck factor because the loads on tandem axles have a lower load equivalency ratio. In the past four or five years, as trucks have been loaded more efficiently, these loads have gone up and the correlation is at a high level and increasing. To estimate the amount of increase in daily N18 per year relative to HCADT, three lines were drawn through the data from the last 11 years. The lines represent rates of increase for ten years, four years, and three years. The rates of increase represented by the lines are given in Table 9. For the last three years the rate of increase is lower than for the last four years for the two highest categories of HCADT. The increases for three and four years are about the same for the lower two HCADT categories. The rates for the ten-year period are about half or less the slopes of the later years.

To consider the increase in these correlations into the future, a number of factors should be considered. The sag in the relationships from 1958 and 1962 was most likely caused by the greater use of Type 5 trucks. The period from 1962 to the present exemplifies a time when the Types 4 and 5 trucks are being used more efficiently and thus, on the average, these trucks would be heavier. This trend will most likely not continue for more than two or three more years. The percentage increases over 12 percent are thus considered high and a value of 5 to 8 percent per year is recommended. This percent increase along with the 3 percent increase in HCADT per year yields an 8 to 11 percent increase in N18 per year. When the maximum allowable axle loads are considered it can be seen that these values would be exceeded after three or four years at a rate of increase of 15 percent and after about ten years at a rate of 10 to 12 percent per year. Using an overall rate of increase of 5 percent results in a factor of 2.5 in 20 years and using 12 percent results in an 8.6-fold increase. It is felt that the lower percent increase should be used so that gross overdesign will not occur. If it is found that there is more increase in loading and the pavement is failing because of it, an overlay can be added after any number of years of service.

SUMMARY AND CONCLUSIONS

At the AASHO Road Test it was possible to determine the relative effect of the loadings used because a particular pavement section was subjected to repetitions of only one magnitude of load. The relative effect of the loads on the performance of pavement sections can be used to convert each load repetition to an equivalent number of repetitions of a base load. These load equivalencies can be used to convert mixed traffic to a number of equivalent 18,000-lb axle loads. A procedure has been developed for de-

termining on a computer the total equivalent 18,000-lb axle loads on each test section. To do this it was necessary to determine the load and volume distribution of traffic on the individual test sections rather than using statewide data. Annual statewide data can be used to modify the distributions determined from the traffic study. Both the number and weight of the Type 5 trucks have increased as shown in Figures 1 and 2. The weights of Types 1, 2, and 3 trucks are about the same over the last 15 years.

The equivalent 18,000-lb axle loads can best be predicted from the daily sum of Type 4 plus Type 5 trucks on a section of road. However, the prediction using the HCADT is only slightly worse and is recommended for designing flexible pavements. The log-log relationships shown as Eqs. 3 and 4 can be used for the correlation and should be updated each year. It is recommended that the HCADT continue to be used for traffic determinations and that an increase of 5 percent in N18 relative to HCADT and an increase of 3 percent in HCADT be used for design purposes if no other particulars are known about the design traffic. It is thus recommended that an annual growth factor of 8 percent in N18 be used for design purposes. With subsequent correlations of the Minnesota test sections in future years, the growth factor can be verified or modified.

Further studies should be continued in an attempt to relate the truck factors to the type of road, location, etc. The additional studies should not be made at permanent weighing stations because these are apparently being avoided by some heavy trucks. With the traffic values being calculated each year, other correlations between type of road and the weight distributions should be considered. A study should also be considered for which every vehicle is counted and classified and every truck is weighed over a period of a week or even a month to see how accurate various samples of this total would be in predicting equivalent 18,000-lb axle loads.

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REFERENCES

1. Flexible Pavement Design Standards. Minnesota Department of Highways Design Manual, St. Paul, July 1, 1964.
2. AASHO Interim Guide for the Design of Flexible Pavement Structures. American Association of State Highway Officials, Oct. 1961.
3. Shook, J. F. Development of Asphalt Institute Thickness Design Relationships. Proc. AAPT, Dallas, Texas, 1964.
4. Thickness Design—Asphalt Pavement Structures of Highways and Streets. The Asphalt Institute, Manual Series No. 1, March 1964.
5. 1965 Truck Weight Study (RCS 38-20-7). Bureau of Public Roads Instructional Memorandum 50-1-65, April 19, 1965.
6. Materials Manual of Testing and Control Procedures, Vol. 1. California Division of Highways, Sacramento.
7. Developments in Thickness Design of Asphalt Pavement Structures. The Asphalt Institute, Oct. 1963.
8. Kersten, M. S., and Skok, E. L., Jr. Application of AASHO Road Test Results to Design of Flexible Pavements in Minnesota. Paper presented at 48th Annual Meeting and included in this Record.