MEMO TO:  
G. F. Kemper  
State Highway Engineer  
Chairman, Research Committee

SUBJECT:  
Research Report No. 473; "AASHO Road Test Tandem Axleload Data Adapted to Fundamental Concepts;" KYP-77-56; HPR-PL-1(12), Part III-B.

A recurring question is: "What effects will an increase in the sizes of tires and axleloads have on pavements?" Concern has mounted in regard to the so-called "drop-axle" not having dual wheels or proportioned loading. Presently, there seems to be a trend toward wide tires in lieu of dual wheels. The wide tires first appeared on the front (steering) axle. This trend seemingly represents an attempt to respect the statutory limit of 600 pounds of load per inch of tire width but to violate the axleload or wheel-load limits (KRS 189.222). Whereas a dual-wheeled, single, rear axle having 10-inch wide tires would be limited to a gross load of 20,000 pounds, 600 pounds per inch of tire width would be 24,000 pounds. A tandem set of axles (8 tires) is limited to a gross of 34,000 pounds; 600 pounds would be 48,000 pounds. An advantage is demonstrated clearly when it is shown that a 34,000-pound, tandem axle is not any more damaging than a 18,000-pound, single axle having dual wheels. A great disadvantage arises when a single axle without duals (such as the steering axle or "drop-axle") is loaded heavily without increasing the width of the tires.

In the report enclosed herewith we have analyzed data from the AASHO Road Test to better define the damage factors assignable to tandem axles. Several influences have been considered and documented. The effects of steering axles at the Test Road are somewhat confounded with the load axles. Separate factors are being derived for steering axles; these analyses are being made on the basis of stress-superposition principles.

The practice of treating all axles in tandem sets, or otherwise, as single axles in estimating equivalent loadings should be discontinued. This means that the use of EWL's as a design parameter would have to be discontinued and be supplanted with EAL's.
AASHO Road Test Tandem Axleload Data Adapted to
Fundamental Concepts

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The repetitions of tandem axleloads applied to the AASHO Road Test were
analyzed by the same method previously reported in analyzing the corresponding single
axleload data. The essential findings were:
1. One repetition of a 34-kip (151-kN) tandem axleload appears to cause the
   same damage as one repetition of an 18-kip (80-kN) single axleload.
2. The relationship of log repetitions versus axleload used by Kentucky appear
to be equally valid for single and tandem axleloads.
3. The use of superposition principles, and equivalency of repetitions, in
   combination with terminal serviceability indices permitted analyses of the
tandem axleload data and comparison with equivalent Kentucky thickness
designs converted to the AASHTO structural number.
4. The single axleload analyses were combined with the tandem axleload analyses
   and superimposed by Kentucky equivalent designs. The Kentucky designs,
   based upon elastic theory, encompassed 89 percent of the AASHO Road Test
data.
AASHO ROAD TEST TANDEM AXLELOAD DATA
ADAPTED TO FUNDAMENTAL CONCEPTS

KYP-77-56, HPR-PL-1(12), Part III B

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INTRODUCTION

Thicknesses of flexible pavement structures have been determined by several systems, among which are Kentucky's 1948 and 1959 curves (1, 2), the AASHTO Interim Guide (3), and Kentucky's proposed 1973 design guide (4). The objectives of this paper are (1) to determine the magnitude of the tandem axleload that produces the same equivalent damage as one 18-kip (80-kN) single axleload, (2) to develop appropriate damage factors for tandems using the above tandem axleload as the base value, (3) to compare results obtained from the above design methods, and (4) to resolve apparent discrepancies of EWL-EAL calculations as made in each of the methods.

BACKGROUND

1959 Kentucky Method

The 1959 Kentucky design curves were based upon empirical tests and observations of pavements in 1948 and 1957 and were generally drawn to separate points representing pavements which were performing satisfactorily from those representing unsatisfactory performance. The 1959 curves were an extension of Kentucky's 1948 curves to account for increased traffic volumes. The data indicated that the curves should have been positioned to provide slightly thicker pavements, but engineering judgment could not justify these increases at that time.

1973 Kentucky Design Guide

The 1973 Kentucky design guide is based upon elastic theory, and the curves (5, 6) were drawn to provide structural thicknesses having the same strain values. The limiting values of strain were obtained by matching theoretical strain values with field performance data. The matching was based primarily upon the performance of a 23-inch (580-mm) pavement composed of 7 3/4 inches (195 mm) of asphaltic concrete and 15 1/4 inches (395 mm) of dense-graded aggregate placed on a soil having a CBR of 7 to withstand a field loading of 8 x 10^5 applications of 18-kip (80-kN) axleloads.

AASHO Road Test

A stated objective of the AASHO Road Test (7) was to determine significant relationships between the numbers of repetitions of specified axleloads of different magnitudes and arrangements and the performance of different thicknesses of uniformly designed and constructed asphaltic concrete surfaces on different thicknesses of bases and subbases when on a basement soil of known characteristics. Special studies were also made of pavement fatigue. It should be noted that none of the objectives of the AASHO Road Test mentioned the development of a pavement thickness design system. The emphasis was upon pavement structural fatigue analysis and comparison of load-damage effects.

The following equation (3) was derived to express the relationship between repetitions (N), axleload (L), structural number (SN), and terminal serviceability (Pt):

\[
\log W_t = 5.93 + 9.36 \log (SN + 1) - 4.79 \log (L_x + L_2) + 4.33 \log L_2 + G/B_x,
\]

where

\[
G_t = \frac{\log((4.2 - P_t)/(4.2 - 1.5))}{B_x} \quad \text{and} \quad B_x = 0.40 + (0.08(L_x + L_2)^{3.23} / ((SN + 1)^{5.19}(L_2)^{3.23})
\]

For single axles, this equation reduces to

\[
\log W_t = 5.93 + 9.36 \log (SN + 1) - 4.79 \log (L_x + 1) + G_t/B_x
\]

Equations 1 and 2 were used to develop nomographs ("design charts").

Fatigue data from the AASHO Road Test (7, Appendix A) were analyzed (8) to determine (i) the basis for the development of Equations 1 and 2 and (2) how these data compared to the 1973 Kentucky design guide. Figure 1 illustrates the comparison of the repetitions-axleload relationship for the 1959 Kentucky curves, the 1973 Kentucky design guide, and the 1974 AASHTO Interim Guide (3). Figure 2 illustrates the same three relationships of Figure 1 as traffic equivalency factors, or damage factors, equivalent to an 18-kip (80-kN) single axleload.

The AASHO Road Test was constructed on a soil assigned a soil support value of 3.0, which corresponds to a Kentucky CBR of 5.2. This permits a direct comparison of AASHTO structural numbers with 1959 and 1973 Kentucky designs. The 1973 Kentucky design guide thicknesses at a CBR of 5.2 and an asphaltic concrete modulus of 480 ksi (3.31 GPa) were converted to equivalent SN's, using values of a1, a2, and a3 of 0.44, 0.14, and 0.11, respectively, by the equation (3)

\[
SN = a_1d_1 + a_2d_2 + a_3d_3
\]

where d1, d2, and d3 are thicknesses of various layers in the pavement structure.
Figure 1. Repetitions versus Single-Axleload Equivalencies.
Figure 3 is an example of the AASHO Road Test (7) fatigue data for a terminal serviceability of 2.5 and 18-kip (80-kN) single axleload. The 1973 Kentucky curve, in terms of SN, and the Equation 2 solutions are shown on Figure 3 as solid and dashed lines, respectively. The data ranged for single axleloads of 6 kips (27 kN) to 30 kips (133 kN) and for five terminal serviceability values of 1.5 to 3.5 for each axleload.

Using the 1973 Kentucky damage factors from Figure 2, the five axleload plots were superimposed to produce Figure 4 on which all data points had a terminal serviceability value of 2.5. The 1973 Kentucky curve is superimposed on Figure 4 and readily fitted the 18-kip (80-kN) data, but veered away from the lighter and heavier axleload data.

The AASHO Road Test data (7) for five values of terminal serviceability, such as Figure 4, illustrated that the relationship of increasing axleload with increasing \( P_t \) coincides with the "rutting criteria" adopted in the 1973 Kentucky design criteria. The 1973 Kentucky thickness design curves provide for variable terminal serviceabilities dependent upon expected equivalent axleload repetitions. Higher values of terminal serviceability are used for heavily traveled routes (because of the need for minimum of rutting, maintenance, and traffic restrictions); the terminal serviceability is allowed to decrease progressively to the minimum level for lightly traveled routes where geometrics restrict speed limits and rutting is not such a prominent and dangerous factor.

The 1973 Kentucky traffic equivalency factors shown in Figure 2 permitted superpositioning of plots similar to Figure 3 to produce Figure 5. The combinations of terminal serviceability and axleload are shown in Figure 5. The following observations were made:

1. the 480-ksi (3.31-GPa) asphaltic concrete modulus Kentucky curve encompasses approximately 93 percent of all AASHO data points (Kentucky moduli lines for 270, 305, 375, and 600 ksi (1.86, 2.10, 2.59, and 4.14 GPa) have also been superimposed);

2. the 18-kip (80-kN) single-axle curve for \( P_t = 2.5 \) from Figure 6 (7) was superimposed onto Figure 5, showing that the curve encompasses 59 percent of the data points, has the same general shape suggested by the data points except for the 6-kip (27-kN) set and is almost a direct fit of the family of asphaltic concrete elastic moduli lines;

3. the combination of 1 and 2 above confirms that the 1973 Kentucky design guide (4) does provide for variable terminal serviceability levels, according to the EAL level, with a high probability of success in the design life;

4. elastic theory provides a sound basis for accurately describing the observed performance data of both Kentucky highways and the AASHO Road Test;

5. one level of terminal serviceability should not be used for the wide range of EAL's, as suggested by AASHTO thickness design nomographs;
Figure 3. Relationship between Repetitions of an 18-kip (80-kN) Single Axleload and Structural Number for Terminal Serviceability of 2.5, AASHO Road Test Seasonally Weighted Data (Reference 7, Appendix A).
Figure 4. Relationship between Repetitions of Single Axleloads and Equivalent Repetitions of 18-kip (80-kN) Single Axleloads for Terminal Serviceability of 2.5.

Figure 5. Relationship between Repetitions of Single Axleloads of Various Terminal Serviceabilities and 18-kip (80-kN) Single Axleloads for a Terminal Serviceability of 2.5.
Figure 6. Main Factorial Experiment, Relationship between Design and Axle Applications (Reference 7, Figure 22, page 27).
6. AASHTO nomographs provide for approximately a 60-percent probability of successful pavement performance throughout the design life; and
7. the semi-logarithmic relationship between single axleload and repetitions used in the 1973 Kentucky design guide is not only a reasonable assumption but has been confirmed by the analysis of the AASHO Road Test data (7).

Kentucky has not developed its own damage factors for tandem axleloads, nor has it determined the magnitude that produces the same damage as one repetition of an 18-kip (80-kN) single axleload. The purpose of this investigation is to provide these answers.

ANALYSIS

Single-Tandem Axleload Equivalency

Analysis of the single axleload data (8) from the AASHO Road Test (7) proved to be rewarding enough to warrant an analysis of the tandem axleload data (Appendix A, 7). AASHTO (3) had determined that an 18-kip (80-kN) single axleload and a 33.124-kip (147-kN) tandem axleload both produced the same damage. Thus, the 32-kip (142-kN) tandem axleload data were plotted for Pτ of 1.5, 2.0, 2.5, 3.0, and 3.5 as shown in Figures 7-11, respectively. The dashed line is the solution of Equation 1 and the 480-ksi (3.31-GPa) line is the same Kentucky solution shown in Figures 3-5. The similarity among Figures 3 and 7 through 11 prompted plotting of the 24-kip (107-kN), 40-kip (178-kN), and 48-kip (214-kN) for the five values of Pτ mentioned above. The same trends mentioned earlier (and in Reference 8) were evident.

The first problem was to determine what tandem axleload produced the same equivalent damage as an 18-kip (80-kN) single axleload. The criteria to be satisfied were

1. the level of serviceability must be equal,
2. the same number of repetitions must be used,
3. one value of an AASHTO SN must be chosen to evaluate the equivalent effects of single and tandem axleloads, and
4. the tandem axleload damage factors must be compatible with the 1973 Kentucky (4) single axleload damage factors.

Kentucky has associated 18-kip (80-kN) single axleloads and a level of serviceability of 2.5 together. Having determined (8) that the 1973 Kentucky design guide (4) and the AASHO Road Test results (7) were compatible, the same serviceability value of 2.5 was chosen. As shown in Figures 3 and 9, the AASHO Road Test data (7) at a serviceability of 2.5 had a span of repetitions from 1,000 to 1,000,000; and 100,000 repetitions was chosen for analysis only because that point is the middle of the log scale. From Figure 3, the 480-ksi (3.31-GPa) line intersects the 100,000 repetitions line at a SN value of 3.07. Thus, the criteria values were determined.

The 480-ksi (3.31-GPa) line encompassed 93 percent of the AASHO Road Test single axleload data (Figure 5); and, as shown in Figure 3, one data point was above the 480-ksi (3.31-GPa) line. The 480-ksi (3.31-GPa) line was superimposed on Figure 9, and similar figures, for a serviceability value of 2.5 and tandem axleloads of 24 kips (107 kN), 40 kips (178 kN), and 48 kips (214 kN). A line of equal offset to the 480-ksi (3.31-GPa) line was constructed such that one data point was above the constructed line. The SN value at 100,000 repetitions was graphically determined and transferred to Figure 12. These four values were connected with a smooth curve. Thus at a SN = 3.07, Figure 12 shows that an 18-kip (80-kN) single axleload would be equivalent to a 34-kip (151-kN) tandem axleload.

Tandem Axleload Equivalency Factors

Tandem axleload equivalency factors must be compatible in methodology with the single axleload damage factors. Thus, the Kentucky single axleload relationship of axleload vs log repetitions (Figure 1) required the use of the same axleload vs log repetitions format for tandem axleloads. Also, Kentucky has associated 8,000,000 repetitions of 18-kip (80-kN) single axleloads as a reference pavement. Thus, a 34-kip (151-kN) tandem axleload must be associated with 8,000,000 repetitions on the same pavement.
Figure 7. Relationship between Repetitions of a 34-kip (151-kN) Tandem Axleload and Structural Number for Terminal Serviceability of 1.5; AASHO Road Test, Seasonally Weighted Data (Reference 7, Appendix A).

Figure 8. Relationship between Repetitions of a 34-kip (151-kN) Tandem Axleload and Structural Number for Terminal Serviceability of 2.0; AASHO Road Test, Seasonally Weighted Data (Reference 7, Appendix A).
Figure 9. Relationship between Repetitions of a 34-kip (151-kN) Tandem Axleload and Structural Number for Terminal Serviceability of 2.5; AASHO Road Test, Seasonally Weighted Data (Reference 7, Appendix A).

Figure 10. Relationship between Repetitions of a 34-kip (151-kN) Tandem Axleload and Structural Number for Terminal Serviceability of 3.0; AASHO Road Test, Seasonally Weighted Data (Reference 7, Appendix A).
Figure 11. Relationship between Repetitions of a 34-kip (151-kN) Tandem Axleload and Structural Number for Terminal Serviceability of 3.5; AASHO Road Test, Seasonally Weighted Data (Reference 7, Appendix A).
Figure 12. Relationship between AASHTO Structural Number and Tandem Axleload.
Equation 4 was used to express the single axleload-vs-repetitions relationship labeled as the 1973 Kentucky line in Figure 1:

\[ \text{EAL} = N(1.2504)(P - 18). \]  

Setting EAL equal to 8,000,000, N equal to one, and (P - 18) equal to \( "x_2" "x_1" \) was determined to be 71.2 kips (317 kN). This represents a line passing through 8,000,000 repetitions at an axleload of zero and through one repetition at an axleload of 71.2 kips (317 kN). Multiplying the 71.2 kips (317 kN) by the ratio of 34/18 (1.8888...) gives 134.5 kips (598 kN). Defining \( "x_1" "x_2" \) as \( P - 34 \) for tandem axleloads makes the tandem axleload for one repetition equal to 168.5 kips (750 kN). As shown in Figure 13, a straight line was connected from an axleload of 168.5 kips (750 kN) at one repetition and through 8,000,000 repetitions at an axleload of 34 kips (151 kN); this is the tandem axleload-vs-repetitions relationship as expressed by Equation 5:

\[ \text{EAL} = N(1.1254)(P - 34). \]  

The tandem axleload equivalency factors shown in Figure 14 were derived from Equation 6:

\[ \text{Traffic Equivalency Factor} = \frac{N_{34}}{N_p} \]  

where \( N_{34} \) = number of repetitions for 34-kip (151-kN) axleload and \( N_p \) = number of repetitions for any other given tandem axleload.

The traffic equivalency factor relationships for the 1973 Kentucky single axleload and the 1972 AASHO Interim Guide tandem axleload at a SN = 5.0 and level of serviceability of 2.5 are included in Figure 14.

AASHTO Serviceability Ratings

Figure 5 is the result of combining data for five pairs of axleload and serviceability levels and is shown in Figure 15 as the line labeled as single axleload. The one exception was that the data for 22.4 kips (100 kN) axleload should have been associated with a serviceability level of 2.87 instead of 3.0. Figure 16 is a corrected plot of Figure 5 and the Kentucky 480-ksi (3.31-GPa) and Equation 1 lines are superimposed.

The tandem-axleload serviceability-level relationship shown in Figure 15 was used to determine the serviceability level for the four levels of axleloads used at the AASHO Road Test. Road Test data /7/ were plotted for each axleload and the repetitions at the respective serviceability levels were interpolated and plotted in a manner similar to Figures 7-11. Using the 1975 Kentucky traffic equivalency factors for tandem axleloads shown in Figure 14, the interpolated data were equated to equivalent 34-kip (151-kN) repetitions as shown in Figure 17. Approximately 89 percent of the AASHO Road Test data were beneath the Kentucky 480-ksi (3.31-GPa) envelope while only 47 percent was beneath the line obtained for tandem axleload solutions of Equation 1.

Figure 18 is a combination of data from Figures 16 and 17. The Kentucky 480-ksi (3.31-GPa) line is an envelope for 93 percent of the AASHO Road Test data while the Equation 1 solution is an envelope for approximately 50 percent of the data.

Net Effect of Kentucky Traffic Equivalency Factors

To determine the net effect of the new, Kentucky single and tandem axleload traffic equivalency factors, data in W-4 tables for 1959 through 1973 were analyzed. The number of axleloads of various magnitude groupings of loaded and empty trucks and truck combinations of each type weighed were summed by axleload groups within the single and tandem axleload divisions. These sums were multiplied by the corresponding traffic equivalency factors for the 1959 Kentucky, 1973-75 Kentucky design systems, and the 1974 AASHTO Interim Guide factors for SN of 5.0 and serviceability level of 2.5. The accumulated EAL's are shown in Figures 19-21 for the single, tandem, and total accumulated EAL's, respectively. Figure 21 indicates that the AASHTO (3) factors would produce a 20-year design level which would be reached within 17.5 years using the 1959 Kentucky factors and 16.2 years using the 1973-75 Kentucky factors.

Until this current analysis, there has not been a set of tandem axleload equivalency factors for application in Kentucky. The practice has been to weigh the individual axles of the tandem arrangement and use the single axleload equivalency factor for each axleload. Thus, the calculated total accumulated EAL's have been higher than the 1974 AASHTO (3) but less than the 1973-75 Kentucky values.
Figure 13. Repetitions versus Single-Axleload Equivalencies.
Figure 14. Damage Factor versus Tandem Axleload.
Figure 15. Level of Serviceability versus Axleload.
Figure 16. Structural Number versus Repetitions of 18-kip (80-kN) EAL's.
Figure 17. Structural Number versus Repetitions of 34-kip (151-kN) Tandem Axleload.
Figure 18. Structural Number versus Repetitions of 18-kip (80-kN) Single Axleload or Repetitions of 34-kip (80-kN) Tandem Axleload.
Figure 19. Repetitions of 18-kip (80-kN) Single Axleload versus Years Since 1958.
Figure 20. Repetitions of 34-kip (151-kN) Tandem Axleload versus Years Since 1958.
Figure 21. Accumulated, Total EAL's versus Years Since 1958.
SUMMARY

The AASHO Road Test tandem axleload data were analyzed using the same procedure reported previously (8) for a single axleload analysis. The following are the major points in this report:

1. All other factors being equal, one tandem axleload of 34 kips (151 kN) was determined to produce the same fatigue damage as one 18-kip (80-kN) single, rear axleload.
2. The logarithm of repetitions-vs-axleload relationship used by Kentucky (5, 6) appears to be equally as valid for tandem axleloads as for single axleloads.
3. A correlation of serviceability index with axleload was developed relating single and tandem axleloads.
4. The combination of a variable terminal serviceability with axleloads and the equation of single and tandem axleloads permitted combining the AASHO Road Test single and tandem axleload-vs-repetitions data (Figure 18).
5. The superpositioned Kentucky design curve encompasses 89 percent of the combined single and tandem axleload data.
6. Pavements designed by the 1974 AASHTO thickness design nomographs have been shown to reach the design fatigue level in approximately 80 percent of the expected life when adjusted for increased volume. This discrepancy is explainable by the 1973-75 Kentucky axleload damage factors.

RECOMMENDATIONS

The AASHTO damage factors used in the Kentucky W-4 tables should be replaced with the following factors:

for Single Axleloads:

\[
\text{Damage Factor} = (1.2504)(P - 18)
\]

for Tandem Axleloads:

\[
\text{Damage Factor} = (1.1254)(P - 34)
\]

ADDITIONAL RESEARCH IN PROGRESS

Current efforts beyond the scope of this report utilizes superposition principles, elastic theory, and strain energy equations to analyze the AASHO Road Test loads and configurations of wheel loads applied to various pavement thicknesses in order to separate the fatigue effects due to front axles from that caused by rear axles. Increased use of wide tires on the front axle and trailers having three or four axles in one group requires additional analyses to determine the appropriate equivalent loads and associated damage factors.

REFERENCES

2. Drake, W. B. and Havens, J. H., Kentucky Flexible Pavement Design Studies, Bulletin No. 52, Engineering Experiment Station, University of Kentucky, 1959.