

# General Axle Load Equivalency Factors

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The cumulative pavement damage effects of all highway vehicles are usually quantified using axle load equivalency factors. The existing axle load equivalency factors depend on, among other variables, pavement type and thickness. This means that the axle factors and consequently the number of equivalent axle loads change along a highway corridor as the construction of the pavement changes, even when the traffic loads do not change. General axle load equivalency factors that are independent of pavement-related variables and axle configurations and have a magnitude similar to the AASHTO axle factors are proposed. The general axle factors can simplify the management of pavement traffic load data and are suitable for routine pavement design purposes. Analysis of errors in prediction of cumulative equivalent axle load applications also suggests that the largest uncertainty is due not to the errors associated with axle load equivalency factors but to other variables, such as traffic volume estimates and axle weights.

The effect of heavy loads on pavement damage, such as fatigue cracking and rutting of asphaltic concrete pavements, has traditionally been expressed using the concept of axle load equivalency factors. Other terms used are wheel load equivalency factors, pavement load equivalency factors, pavement damage factors, and truck factors (1). For simplicity, the axle load equivalency factors are herein called axle factors (AFs).

AFs attempt to capture the combined influence of the entire traffic mix on pavement damage by converting the pavement damage caused by different axle loads and axle groups to that caused by a standard axle load. For convenience, AFs have been related to a standard axle load of 80 kN (18,000 lb) carried by a single axle with dual tires called the equivalent single-axle load (ESAL). A summation of all AFs for a given truck is called a truck factor (TF). Thus, a TF is equal to the number of ESALs per truck. In this way, all loads of a highway traffic mix can be converted, using AFs and TFs, into a total number of ESALs that is used for pavement management and pavement design purposes. The AFs provide the basic information needed.

Many different AFs have been proposed in the past. The most recognized AFs are those developed by AASHTO (2). AASHTO AFs, and other similar axle factors, have been developed for specific pavement types, pavement distresses, axle configurations, and other variables. Consequently, these AFs are not directly transferable or are not general in the way, for example, traffic volumes are. AFs, and consequently the number of equivalent single-axle loads, can change along a transportation corridor several times even when traffic loads and volumes do not change. To obtain a universal summary measure of traffic loads, the use of general axle load equivalency factors, which are independent of pavement-related variables and axle configurations, is proposed. In this paper, the general axle load equivalency factors are called general axle factors and are abbreviated GAFs.

The objectives of this paper are to

- Explore the need for the development and use of GAFs and to work to obtain a consensus on their usefulness and eventual definition. The GAFs proposed herein represent only one possible version for their definition.
- Stimulate discussion about calculation and use of AFs.
- Provide a better understanding of concepts used for summarizing the damaging effect of pavement traffic loads and, in particular, AFs.

A proposal of GAFs is intended to simplify the management of traffic load data for pavement design and maintenance.

## DETERMINATION OF AFs

AFs can be obtained in two basic ways: field experiments or evaluation of pavement responses to individual axle loads.

### AF From Field Experiments

A number of axle loads,  $N$ , of a given magnitude and type, required to cause a certain level of pavement deterioration, is determined in the field and is compared to the number of standard axle loads,  $N_{ESAL}$ , required to cause the same amount of pavement deterioration on an identical pavement structure. The resulting AF depends on the type and strength of the pavement structure used in the experiment and on the definition of pavement damage and its level.

$$AF = \frac{N_{ESAL}}{N} \quad (1)$$

The best known example of the full-scale pavement experiment is the AASHTO Road Test of the early 1960s (2). The AASHTO AFs were related mainly to pavement roughness and were defined for two pavement types (flexible and rigid), two axle configurations (single and tandem), and different levels of pavement serviceability (i.e., initial serviceability and terminal serviceability). They are based on relationships derived from the AASHTO Road Test data and not on direct observations of load equivalency ratios as suggested by Equation 1. AFs for triple axles were developed later using analytical procedures.

### AF From Evaluation of Pavement Responses to Individual Loads

Measured or calculated pavement responses to traffic loads are used to calculate AF by assuming the following general relationship:

$$AF_{ri} = \left( \frac{R_{ri}}{R_r} \right)^n \quad (2)$$

where

- $AF_{ri}$  = axle factor based on pavement response  $r$  for axle type  $i$ ,
- $R_{ri}$  = amount of pavement response  $r$  to the axle load of defined magnitude and type designated as  $i$ ,
- $R_r$  = amount of pavement response  $r$  to the standard 80-kN single-axle load, and
- $n$  = exponent that ensures similarity between Equations 1 and 2, usually set to about 4.

Again, as with AFs obtained by field experiments, AFs obtained by this method depend on pavement type and strength and on the pavement response type. The pavement response type serves as a surrogate for the pavement distress type. Of course, this method is easier to use than the previous method, which relies on extensive field experiments.

There are two significant complications facing the user. First, this method assumes that the changes in pavement responses (such as strains or stresses) can be related to the severity and type of pavement distresses and, consequently, to pavement damage. Second, according to Equation 2, it is assumed that the pavement response to an axle group load can be characterized and summarized by one quantity, or by one number,  $R_{ri}$ . However, pavement response to an axle group loading is complex. For example, the surface deflection of a flexible pavement caused by a triple axle exhibits three distinct and different deflection bowls (from the individual axles) superimposed on a total deflection bowl.

### Need for General Axle Load Equivalency Factors

The foregoing discussion indicates that the current definition of axle load equivalency factors is too specific. In general, AFs vary depending on the following factors:

- Pavement type,
- Pavement thickness (for a given pavement type),
- Pavement distress mode (e.g., roughness, rutting, fatigue cracking),
- Severity or level of distress, and
- Axle configuration.

Consequently, traffic loads summarized using existing AFs (e.g., total number of ESALs per year) can change when the pavement is rehabilitated, although the actual traffic loads may not. Also, the AASHTO AFs are available for two pavement types only (asphaltic concrete pavements and rigid pavements). There are other pavement types for which AFs are not available:

- Surface-treated pavements,
- Gravel roads,
- Semi-rigid pavements [portland cement concrete (PCC) pavements with thick asphalt concrete (AC) overlays, or asphalt concrete pavements with thick PCC-treated bases].

This means that either the damaging effect of traffic loads on these pavements cannot be summarized or the wrong factors are being used to do it.

There is a need for a traffic load statistic (such as an ESAL) that is independent of pavement variables in the same way annual average daily traffic (AADT) volumes are. Such a statistic would be useful for pavement management purposes, for example, for evalu-

ating and comparing pavement loading trends on a network consisting of a variety of pavement types. The proposed general axle load equivalency factors can be used to obtain such statistics in the form of general ESALs.

### DEFINITION OF GENERAL AXLE LOAD EQUIVALENCY FACTORS

The general axle load equivalency factors, GAFs, proposed here have a similar meaning and roughly the same magnitude as the AASHTO axle load equivalency factors. In fact, the GAFs, defined by Equation 3, are identical to AASHTO AFs for single-axle loads on flexible pavements with the structural number (a number related to the pavement strength) equal to 5, and the terminal serviceability index equal to 2.5.

$$GAF = (0.01169 L + 0.064) \left( 4 + \frac{8.9}{L} \right) \quad (3a)$$

where  $L$  is the axle load (of any type or spacing) in kN. In kips, Equation 3(a) becomes

$$GAF = (0.052 L + 0.064) \left( 4 + \frac{2}{L} \right) \quad (3b)$$

where  $L$  is the axle load (of any type or spacing) in 1,000 lb.

Equation 3 was originally proposed elsewhere (3), and its functional form was obtained by curve fitting to resemble typical AASHTO AF. It should be noted that the GAFs are not only independent of pavement-related variables, they are also independent of axle configuration and spacing—a significant simplification from the AASHTO approach. Any changes in the GAFs can be directly attributed to changes in traffic loads.

GAFs defined by Equations 3a and 3b provide one possible formulation. The present objective is not to establish definitive GAFs but to demonstrate need for their existence.

### COMPARISON OF GENERAL AXLE LOAD EQUIVALENCY FACTORS WITH OTHER FACTORS

Figure 1 compares GAFs with those developed by AASHTO (2) and works by Monismith (4), Painter (5), and Claessen (6) for single and tandem axles, respectively. The AASHTO AFs in Figure 1 are for SN = 5 and  $p_t$  = 2.5 psi. The GAFs are for all pavement types; the other factors used in Figure 1 are for asphalt concrete pavements only. Overall, the figures suggest that, for a typical range of axle loads, the proposed GAFs are similar to those calculated by the other four methods, including the AASHTO method. AASHTO AFs have been compared with AFs that have been derived in 10 other studies over the past 12 years (7).

It should be noted that analyses of the AASHO Road Test data do not produce unique values for AFs; AFs depend not only upon pavement distress types and levels but also upon the regression models and methods that are used to quantify them (7).

The following sections describe consequences of simplifying assumptions involved in the formulation of the GAF and the influence of major variables on the accuracy of traffic load estimates. The purpose of the discussion is to quantify, at least in relative terms, the influence of major factors on AF and on the ESAL calculations. Although many of the variables involved interact, for clarity the discussion addresses variables one by one under three main headings.

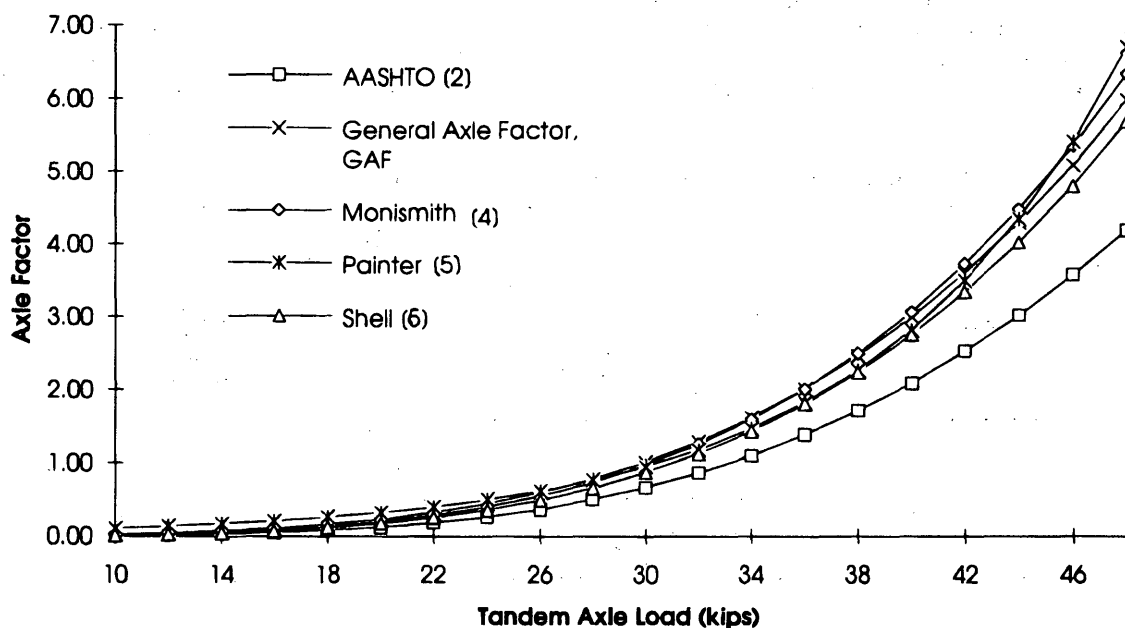
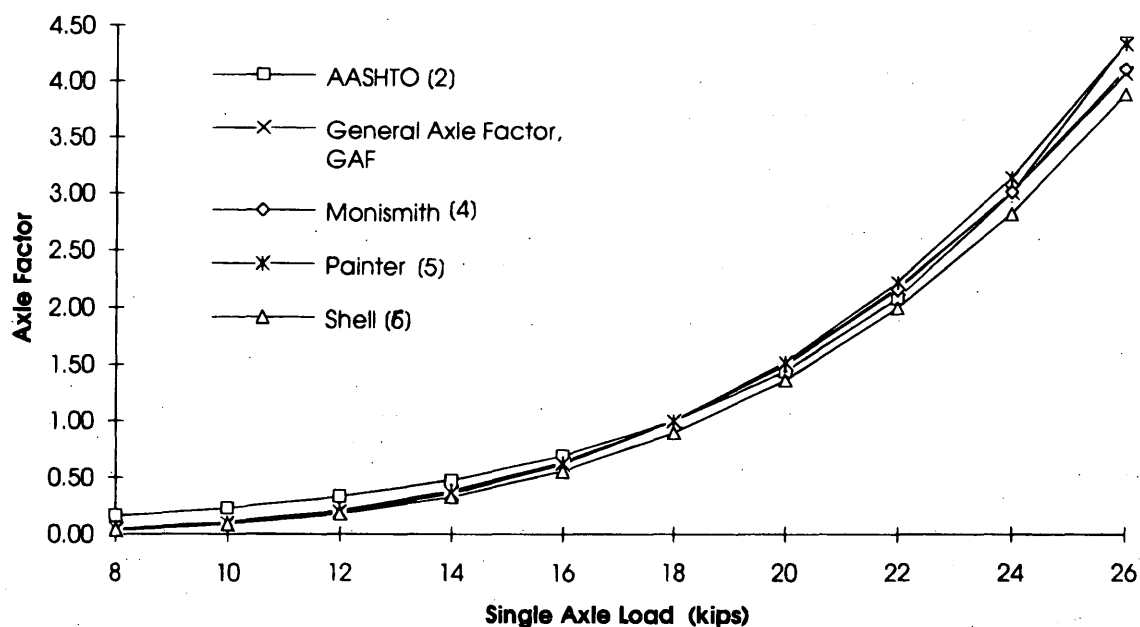


FIGURE 1 Comparison of axle factor values for single axes (*top*) and tandem axes (*bottom*).

- Variables affecting AASHTO axle factors,
- Other variables affecting axle factors, and
- Variables affecting overall traffic load estimates.

#### VARIABLES AFFECTING AASHTO AXLE FACTORS

Because the AASHTO AFs are widely used, all variables included in the determination of the AASHTO factors are described. The discussion is centered on the comparison of GAFs with the AASHTO factors.

#### Pavement Structure

AASHTO AFs are significantly influenced by the two pavement types, flexible and rigid, considered by the AASHTO Pavement Design Guide. However, the influence of pavement type is only significant for tandem and triple axes. For example, according to Table 1, the AF for a 160-kN (36,000-lb) tandem axle is 1.36 for a flexible pavement but 2.48 for a rigid pavement—an 82 percent increase. In comparison, a single axle of 80 kN (18,000 lb) has an AF of 1 for either pavement type. A single axle of 107 kN

(24,000 lb) has an AF of 3.03 for a flexible pavement and 3.36 for a rigid pavement—an increase of only about 11 percent.

A possible explanation of the differences in AF for the two pavement types is illustrated in Figure 2 (*top*) using the example of a tandem axle. For AC pavements, the tensile strain on the bottom of the asphalt concrete layer is considered one of the critical design parameters. The response curves for this strain in Figure 2 (*top*) show that the strain on the bottom of the asphalt concrete layer changes—from tensile to compressive—with the distance from the center of the load. The tensile strain is denoted in Figure 2 (*top*) by a negative sign (–), and the compressive strain by a positive sign (+). For closely spaced individual axles, some of the compressive strain from one axle may reduce the critical tensile strain from the other axle, and vice versa. The contributions of individual axles (of the tandem axle) to the peak tensile strain are to some degree counterproductive. This may help to explain why the AF for a tandem axle consisting of two standard axles is 1.38 on a flexible pavement, much less than the 2 that would result if the two standard axles were far apart and could be considered to be two single axles (see Table 1).

For rigid pavements, one of the critical design parameters is the slab deflection at transverse joints. According to Figure 2 (*middle*), the two individual axles of the tandem axle are in synergy: both contribute positively to the total critical deflection at the transverse joint. This may explain why the AASHTO AF for a tandem axle consisting of two standard axles is 2.4, more than 2, which would result if the two axles were far apart (single), and much more than 1.38 as was the case for a flexible pavement (see Table 1).

A similar case can also be advanced for triple axles. However, it should be noted that triple axles were not evaluated by the Road Test.

The AASHTO AFs for triple axles were developed by analytical means.

The significant influence of pavement type on the AASHTO AFs is attenuated by the following considerations:

- The tensile strain on the bottom of the AC layer, the parameter related to the AASHTO AF, is a good predictor of fatigue cracking. However, fatigue cracking is not a predominant failure mode of AC pavements, which are part of structurally adequate, mature pavement networks. Systematic analyses of pavement distresses in Ontario showed that the predominant failure modes of AC pavements are deteriorating transverse cracks and wheel track rutting (8). These two failure modes, unlike fatigue cracking, are virtually independent of axle configurations and thus also of pavement type.

- Over the years, the slab lengths of jointed PCC pavements have become considerably shorter, and the axle group spacing (of tandem, triple, and quadruple axles) has increased. For example, joint spacing on newly constructed PCC pavements in Ontario is about 4 m. The trailing axles of multiple axle groups on short slabs may no longer synergistically (or significantly) contribute to the total slab deflection at the joint (as in Figure 2 (*middle*)) but, on the other hand, may mitigate it [as in Figure 2 (*bottom*) where a trailing axle is at a midslab when a leading axle is at the joint].

- The Road Test distinction between flexible and rigid pavements is often blurred by the existence of semirigid pavements and full-depth (AC) pavements.

Those considerations indicate that the influence of pavement type may not be as significant as the AASHTO AFs suggest. However, it should be stressed that the purpose of the GAF is not to question

TABLE 1 AASHTO Axle Load Equivalency Factors for 80 kN (18000 lb) Loads (2)

Pavement Type	Axle Type	Axle Spacing		
		Zero Spacing (single axle only)	Typical <sup>3</sup> Spacing	Large <sup>3</sup> Spacing (independent axles)
Flexible <sup>1</sup>	Tandem (2 x 80 kN)	13.9	1.38	2.00
	Triple (3 x 80 kN)	above 50	1.66	3.00
Rigid <sup>2</sup>	Tandem (2 x 80 kN)	18.3	2.48	2.00
	Triple (3 x 80 kN)	above 50	4.16	3.00

Notes

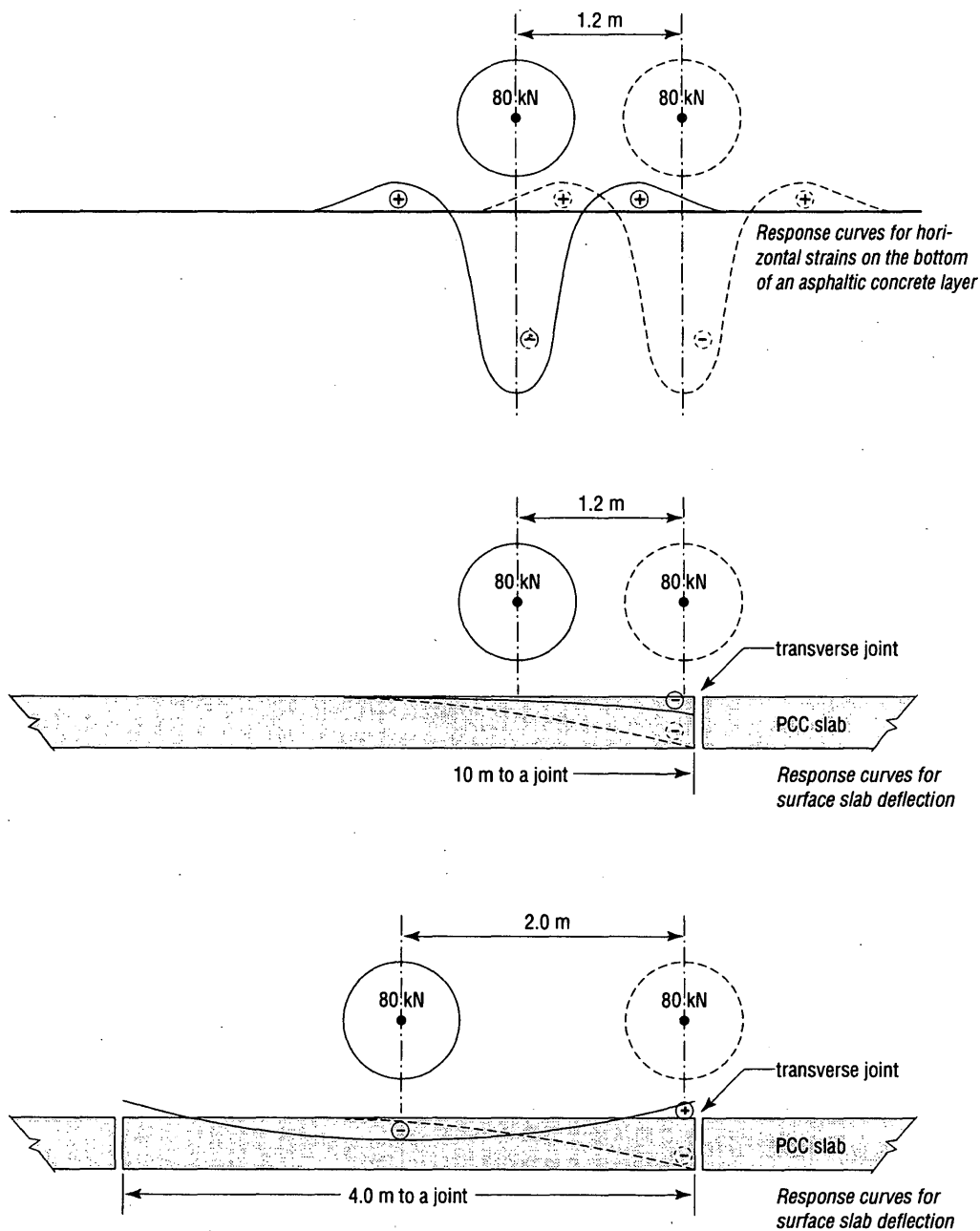
1) SN = 5

2) D = 10

3) Spacing (typical or large) is not defined by AASHTO.

- $P_t = 2.5$

- The load on each individual axle is always 80 kN (18,000 lb). A tandem axle consists of two axles each carrying 80 kN, and a triple axle consists of three axles each carrying 80 kN.



**FIGURE 2** Response of asphaltic concrete pavement: short axle spacing (*top*); response of rigid pavement: short axle spacing, long slab length (*middle*) and large axle spacing, short slab length (*bottom*).

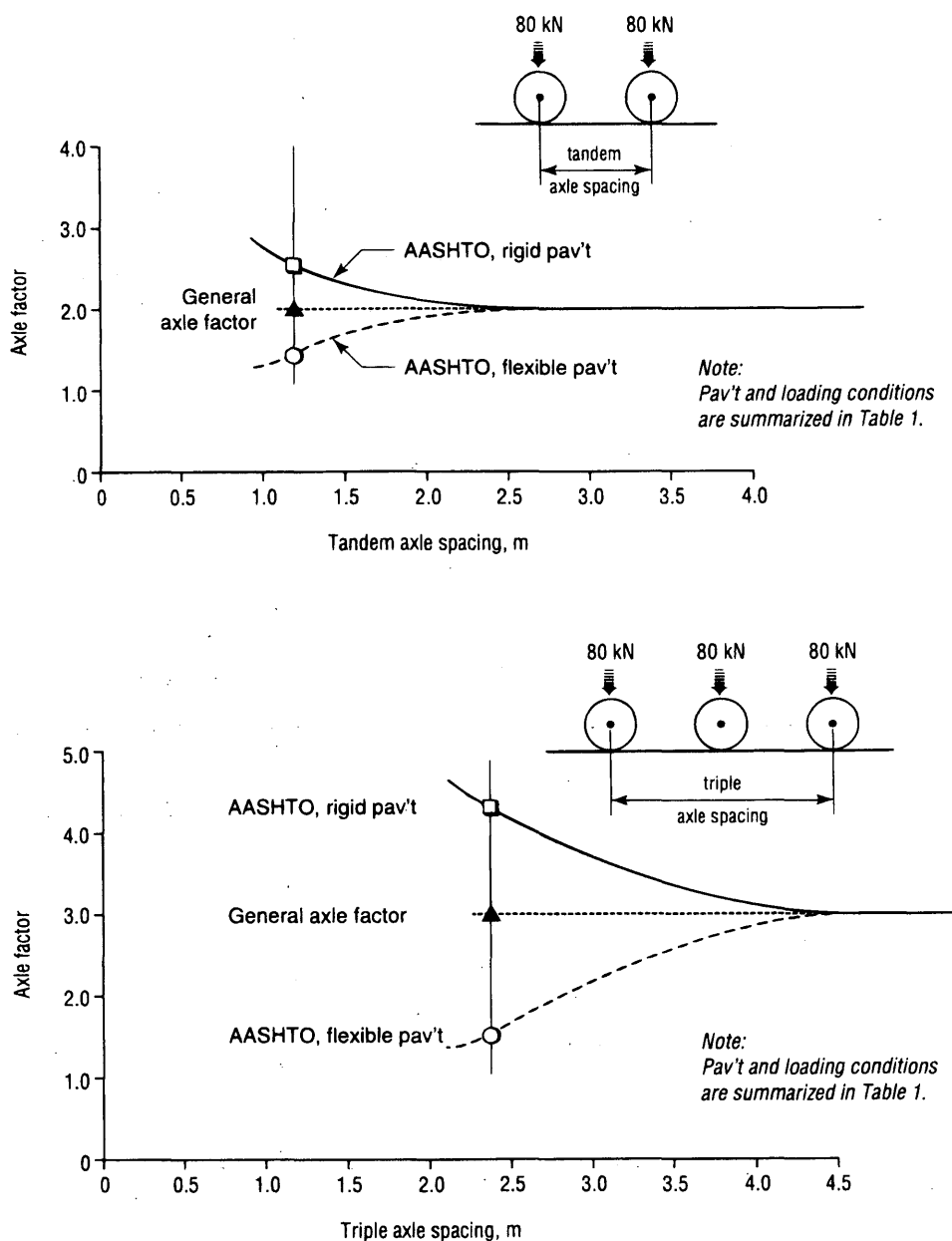
the accuracy of AASHTO's AFs or to improve the accuracy of AFs for specific pavement structures, but to provide a simple general set of axle factors for all pavement types.

#### Axle Spacing

The influence of axle spacing on the AASHTO AF is illustrated in Figure 3 for tandem and triple axles, respectively. As in Table 1, both tandem and triple axles in Figure 3 are carrying 80-kN (18,000-lb) loads on each individual axle. For a rigid pavement, such a tandem axle has the AASHTO AF of 2.48 regardless of the actual

spacing between the two axles. If the spacing between the two axles exceeds an unspecified distance so that the two axles can be considered to be independent, the corresponding AASHTO AF is 2. Similarly, for a flexible pavement, two 80-kN axles far apart have AFs of 2; if they are close, their AF is 1.38; and if the spacing is zero, AF equals 13.9 (see Table 1). This suggests a reversal of curvature of the function relating AF to axle spacing.

Figure 3 (*bottom*) shows an equally significant influence of the axle spacing on the AASHTO AF for triple axles. Again, when the axle spacing between three consecutive axles exceeds an unspecified distance, the AF changes significantly.



**FIGURE 3** Influence of tandem axle spacing on axle factors (*top*) and influence of triple axle spacing on axle factors (*bottom*).

During the time of the Road Test (early 1960s), the tandem axle spacing was uniform (1.22 m) and triple axles (and quadruple axles) were not used. The trucks used in the Road Test reflected the truck fleet on the road. All tandem axles had 1.22-m (48-in.) spacing (and no triple axles were used). The exception was one truck type, used to carry extra heavy loads, which had tandem axle spacing on the tractor of 1.37 m (and again 1.22-m tandem spacing on the trailer) (9).

Truck design has changed considerably since the Road Test. The current axle group spacing in many jurisdictions, including Ontario, varies notably and is considerably larger, particularly on trucks with six axles or more, than the spacing 30 years ago. An example of truck axle spacing encountered in Ontario is presented in Figure 4. The figure is based on a 1988 random survey of 2,089 trucks

conducted at 16 locations and shows separately axle spacing distribution for trucks with four axles and trucks with seven and more axles. The axle spacing is shown regardless of axle group type.

According to Figure 4, the frequency distribution of axle spacing in the range of 1 to 4 m appears to be bimodal with the dividing line at about 2 to 2.5 m. The bimodal distribution is the result of truck operators using the vehicle weight regulations (10) to maximize the payload. Axle spacings up to 1.9 m include most tandem and triple axles. A single axle can always carry a larger load than any axle that is part of an axle group. To qualify as a single axle, the axle spacing from any other axles must exceed 2.4 to 3 m, depending upon jurisdiction. Thus, given a choice, truck designers place additional axles, such as liftable axles, at least 2.4 m from all other axles. This spacing is based on the load-carrying capacity of the bridge components

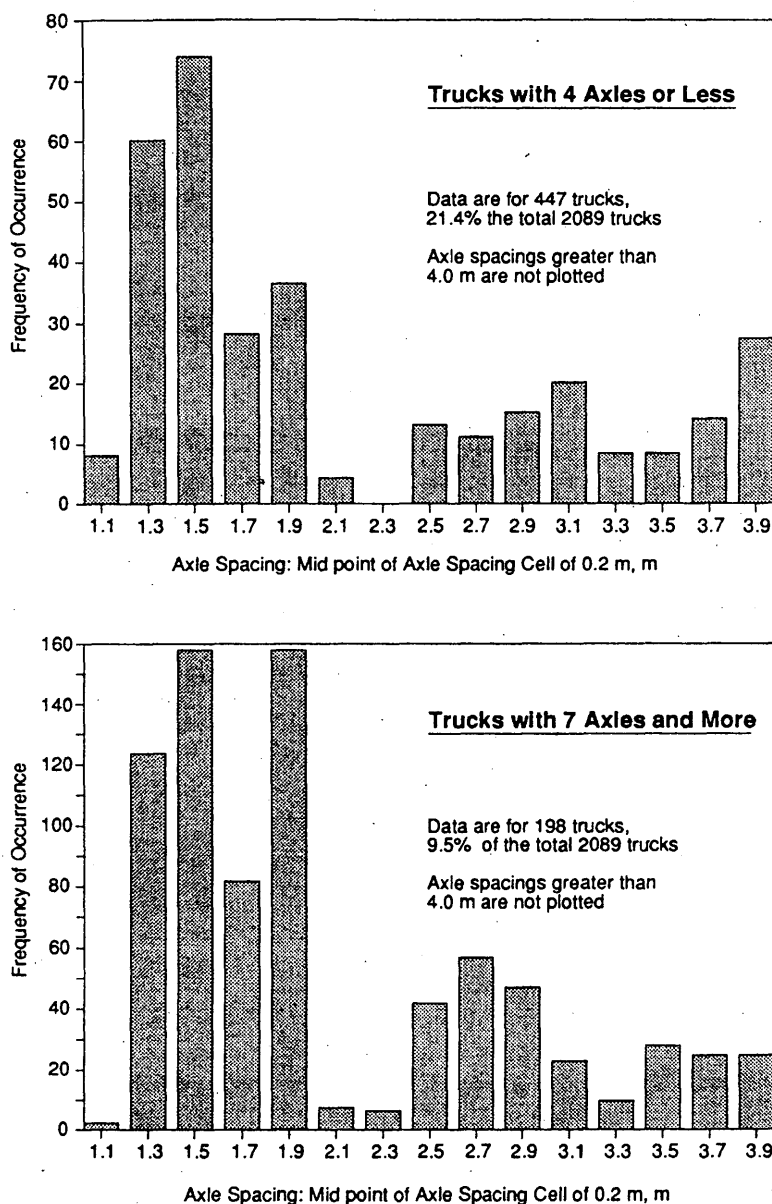


FIGURE 4 Frequency distribution of axle spacing for two truck types.

and not on pavement considerations. There is nothing special about the 2.4-m axle spacing to warrant the drastic change in AF.

GAFs are not influenced by axle configuration or spacing. Referring to Figure 3, the GAF for tandem and triple axles (comprising 80-kN single axles) are 2 and 3, respectively, basically in the midrange of AASHTO AFs for flexible and rigid pavements. This eliminates the need to define how AFs should change with axle spacing; for example, at which distance two single axles become a tandem axle (or two-axle group). Because GAFs are independent of axle spacing, they can also be used for summarizing the loads on quadruple axles.

#### Pavement Distress Type

By definition, AFs are defined for a specific type of pavement distress and its level (Equations 1 and 2). The AASHTO AFs were

developed for the present serviceability index (psi). The psi is dominated by pavement roughness. Cracking, patching, and rutting contribute only about 5 percent to the value of the psi. In general, AFs used by an agency should be based on the pavement distress or distresses that trigger the local need for pavement rehabilitation.

All AFs developed since the time of the Road Test have been based either on independent analyses of the Road Test data, with their often-stated limitations (e.g., accelerated test, only one subgrade, old pavement and truck technology) or on analytical methods. Analytical methods now predominate; AASHTO Road Test data have become obsolete [although they are frequently reanalyzed (7,11)], while the technology used to measure or calculate pavement responses to loads has improved.

The following pavement responses, linked previously to the formation of pavement distress, have been used for the development of AFs for AC pavements:

- *Pavement surface deflection.* The deflection has been linked to pavement deterioration, measured mainly in terms of roughness. Several pavement distresses, such as cracking, distortion, and rutting, can contribute to pavement roughness.

- *Interfacial strain.* Strain at the bottom of the asphalt concrete layer has been related to fatigue (alligator) cracking.

- *Vertical strain on top of subgrade.* This response has been related both to rutting in the pavement structure and to pavement deterioration.

- *Vertical strain in AC layer.* Vertical strain in the AC layer, about 50 to 75 mm from the pavement surface, has been linked to rutting in the AC layer only (so-called mix instability rutting).

The AFs based on analytical methods depend not only on the selection of pavement responses but also on analytical methods used. For illustration, the dependence of AFs on pavement responses and analytical methods is quantified by the following example.

The example assumes a triple axle and other conditions summarized at the bottom of Table 2. Typical pavement response curves for the first three pavement responses listed are shown in Figure 5. To obtain AF, it is necessary to modify Equation 2 to sum the responses of the individual axles within the triple axle using a summation method.

$$AF_{r,m} = \frac{\sum_{i=1}^p (R_i)^n}{R^n} \quad (4)$$

where

$AF_{r,m}$  = axle factor for pavement response  $r$  and summation method  $m$ .

$R_i$  = amount of discrete pavement response for load cycle  $i$  identified by method  $m$ .

$n$  = See Equation 2. There is no general or standard exponent. In this example, the exponent used was 3.8 (12).

$P$  = number of load cycles (axles).

$R$  = amount of pavement response  $r$  to the standard load (80-kN single-axle load).

In the absence of a universally accepted procedure, a number of methods have been proposed to sum pavement responses to individual axle loads. (The pavement responses are shown as  $D_1$ ,  $D_2$ ,  $D_3$  and  $S_1$ ,  $S_2$ ,  $S_3$  in Figure 5.) In this example, three summation methods have been used: the Roads and Transportation Association of Canada (RTAC) method (12), the University of Waterloo method (13), and the Peak method (14).

The three summation methods differ by the way in which the pavement responses ( $D_i$ ,  $S_i$ ) are defined. The reasons for different definitions are summarized elsewhere (14). For example, proponents of the Peak method argue that although the surface deflections between two subsequent axles do not reach a rest position (zero deflection), the asphaltic concrete layer at this location reverses its curvature (tensile strain changes to compressive strain, Figure 5). Consequently, they believe that the use of the total deflection best models the overall pavement response.

The results of the example are summarized in Table 2 and provide the basis for the following observations:

- Pavement response types (and consequently pavement distress types) influence AF significantly. This also applies when the same summation method is used.

TABLE 2 Influence of Pavement Response Type on Axle Load Equivalency Factors for Triple Axles

Pavement Response Type	Method of Response Summation		
	RTAC	Waterloo	Peak
Surface Deflection	2.2	3.5	8.2
Tensile strain on the bottom of the AC layer	2.8	3.0	N/A
Vertical strain on the subgrade	1.1	3.1	N/A

#### Conditions

- The triple axle has individual axle spacing of 1.25 m.
- Each axle has an 80 kN (18,000 lb) load, the total triple axle load is 240 kN.
- Flexible pavement with SN = 5.7 and asphaltic concrete thickness of 130 mm.
- Pavement responses were calculated using ELSYM5 [15].
- Exponent  $n$  (Equation 4) equals to 3.8
- According to Reference [14].

Note: The corresponding general equivalency factor is 3.



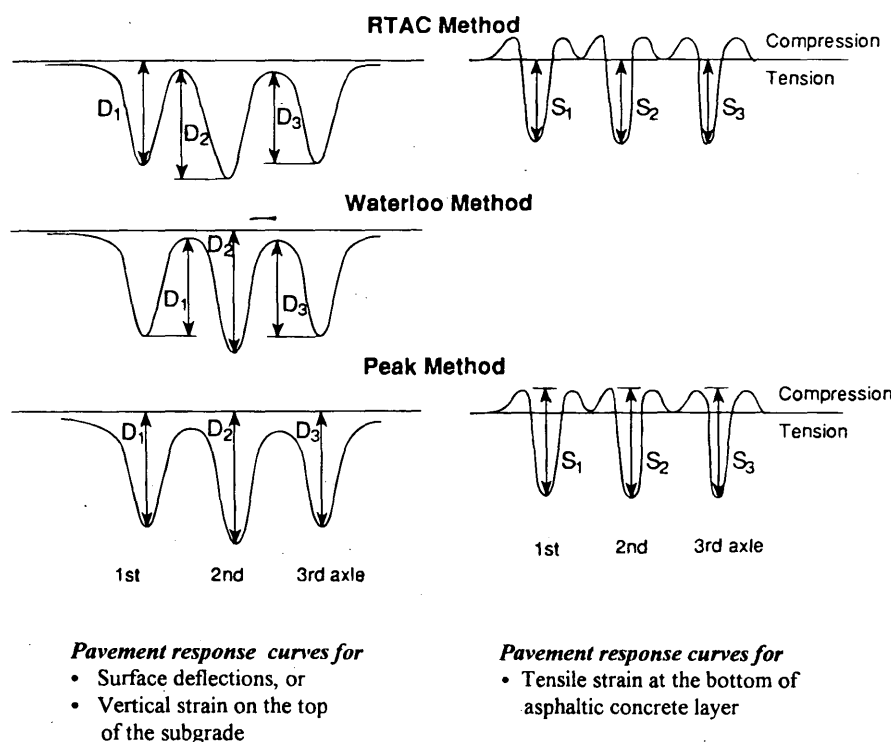


FIGURE 5 Pavement response curves for triple axles.

- AFs, for a given pavement response, are significantly influenced by the summation method used—while there is no standard summation method available.

- It is difficult to obtain definitive AFs using analytical methods; there are too many assumptions involved, which significantly influence the results. The range of AFs given in Table 2 is from 1.1 to 8.2, making the use of analytical methods speculative. This certainly creates a role for the GAFs, which are not linked to any specific pavement distresses. However, by their link to the AASHTO AFs, the GAFs are still linked to the psi.

### Pavement Thickness

The influence of the pavement thickness (SN number for flexible pavements and slab thickness,  $D$  for PCC pavements) on the AASHTO AFs was evaluated elsewhere (1). It was concluded that, for typical pavement structures, the change in AASHTO AFs is limited to about 5 to 10 percent. The influence of pavement thickness on AFs is probably even smaller when considering the total pavement structure including subgrade. (Subgrade is not included in SN and  $D$ .) A very good subgrade may considerably reduce the need for a large SN and result in a thin pavement that, nevertheless, has a high overall strength. In other words, the total pavement strength does not vary as much as SN or  $D$  vary. Consequently, the influence of pavement thickness on the AF is reduced. At any rate, the influence of pavement thickness is relatively small and is not included in the GAF.

### Level of Pavement Distress

For the AASHTO AFs, the influence of the level of pavement distress is accounted for by the initial and terminal serviceability index

( $p_o$  and  $p_t$ , respectively). The influence of  $p_o$  and  $p_t$  has also been evaluated (1). It was concluded that the change in the AASHTO AFs because of changes in  $p_o$  is about  $\pm 4$  percent and because of changes in  $p_t$  about 4 to 20 percent. The influence of serviceability on AF is relatively small and is often disregarded (particularly the influence of  $p_o$ ), even for AASHTO AFs. It is also disregarded by the GAF.

### OTHER VARIABLES AFFECTING AFS

In addition to variables that have been included in the calculation of the AASHTO AFs, and in some other routinely used axle factors, there are other variables that are not included in the calculation or determination of AFs but, nevertheless, influence the value of these factors.

### Truck Suspension Type

Pavement response or damage is affected more by dynamic loads than by static loads. The dynamic loads depend, to a large extent, on a truck suspension type and condition. It is beyond the scope of this paper to discuss the influence of different truck suspension systems on pavement damage. However, it is generally recognized that an air suspension provides a better load equalization between axles, and about 10 percent lower dynamic loads than a leaf spring suspension (on moderately rough roads at highway speeds) (16,17). Air suspensions, which were not used in the Road Test, appear now on over 50 percent of all new tractors and on 20 percent of all new trailers. According to Equations 1 to 3, a 10 percent change in static load results in about a 45 percent change in AF.

## Tire Type and Pressure

The influence of truck tire type and tire pressure on dynamic axle loads is small, if tire pressures are not unusual and the number of tires remains the same (16). However, tire truck types (wide-base tires or single tires on steering axles) and tire pressures can significantly influence wheel track rutting and other distresses on AC pavements.

## Number of Tires

For the same load, single axles with single tires can be twice as damaging as single axles with *double tires* (12,18).

## Speed

Truck speed is a secondary variable that interacts with truck suspension systems and pavement roughness. Although axle loads applied at lower speeds can cause higher pavement damage than loads applied at higher speeds, particularly on AC pavements, higher speeds produce higher dynamic loads.

In summary, neither analyses of the AASHTO Road Test data nor analyses of pavement response parameters to loads produce unique or definitive values for AFs. In addition to physical characteristics, such as pavement type or truck suspension type, the resulting AFs also depend on analytical methods that are used to calculate them.

## VARIABLES AFFECTING OVERALL TRAFFIC LOAD ESTIMATES

The AFs are only one of the several variables necessary for estimating accumulated pavement traffic loads. For pavement design and management purposes, traffic loads are usually summarized using ESAL. A generic formula for the calculation of a total number of ESALs ( $\Sigma$ ESAL), for one lane in one direction of a multilane highway, is

$$\Sigma \text{ESAL} = \sum_{i=1}^n (\text{AADT} \cdot \text{DF} \cdot T_i \cdot \text{LDF} \cdot \text{TF}_i \cdot \text{days} \cdot \text{years} \cdot \text{growth}) \quad (5)$$

where

- $\Sigma$ ESAL = total number of ESALs during the design period,
- $i$  = truck class (type),
- $n$  = number of truck classes,
- AADT = average annual daily traffic (current),
- DF = directional factor (directional split),
- $T_i$  = proportion of AADT volume that belongs to truck class  $i$  (if  $n = 1$ ,  $T_i$  = truck proportion),
- LDF = lane distribution factor for trucks,
- $\text{TF}_i$  = truck factor for truck class  $i$  [ $\text{TF}_i$  = sum of AF for all axles (and axle groups) of truck type  $i$ ],
- days = days per year for truck traffic,
- years = design period in years, and
- growth = traffic growth rate (for traffic loads).

Virtually all variables in Equation 5 are subject to approximations, assumptions, and errors. The errors associated with the indi-

vidual variables used in Equation 5 are compounded and are reflected in the overall error associated with  $\Sigma$ ESAL estimates. Typical estimated differences between the actual and estimated values for the variables used in Equation 5 are summarized in Table 3. Considering the estimated error ranges given in Table 3, it appears that the errors associated with methods used to establish AFs are overshadowed by errors associated with other variables. A similar conclusion was reached in a work by Witczak (1), who found that the largest uncertainty associated with computing the total number of ESALs is due to errors not related to the method used for determining axle factors. The use of GAFs will not significantly change this situation.

## ROLE OF GAFS IN PAVEMENT DESIGN AND MANAGEMENT

The sum of GAFs for all axles of a truck equals a general truck factor (GTF). The use of GTF for the calculation of ESALs (using, for example, Equation 4) will yield general ESALs (GESALs). Like GAFs and GTFs, the GESALs are independent of pavement type and thickness, level of pavement damage, and axle configuration.

Pavement design thickness is not overly sensitive to changes in traffic loads. A doubling of traffic loads (e.g., ESAL) typically results in a 25-mm (1-in.) increase in the thickness of the asphaltic concrete layer or the PCC slab. This does not mean that traffic loads are unimportant and that approximate GAFs are sufficient. The objective of the GAF is to provide a simpler and easier way to handle pavement traffic loads that should lead to their better management and use in pavement design.

GAFs are not intended to replace all other AFs. It is suggested, however, that the GAFs and the associated GESALs are suitable and appropriate for summarizing the damaging effect of traffic loads for pavement management purposes and for routine pavement design work. It should be noted that the GAFs have (or can have) magnitudes similar to several other axle factors, including AASHTO factors. The use of GAFs, or similarly conceived factors, greatly simplifies the management of pavement traffic loads. Specialized axle factors may still be required for quantifying pavement damage for unusual traffic loads, specific pavement distresses, and research purposes.

## SUMMARY AND CONCLUSIONS

1. The AASHTO definition of axle load equivalency factors is too specific for pavement management purposes. Traffic loads summarized using existing axle load equivalency factors change with pavement type and pavement thickness even when traffic loads remain constant.

2. Considering the variety of pavement structures and truck configurations, there is a need for a summary universal pavement traffic load statistic that is independent of pavement-related variables and axle configurations.

3. The uncertainty associated with computing the accumulated number of ESALs is due primarily to errors in parameters other than those related to the determination of axle factors. These include, for example, traffic volume estimates and axle weights.

TABLE 3 Estimated Errors Associated with Variables Used for ESAL Predictions

Variable <sup>1)</sup>	Estimated Error Range <sup>2)</sup> , %	Comments
$T_i$ (truck class)	$\pm 10$ to $\pm 100$	$\pm 10$ for Automatic Vehicle Classifiers $\pm 100$ if truck percentage is estimated
AADT	$\pm 10$ to $\pm 100$	AADT estimates for highways built on a new alignment are often unreliable
LDF	$\pm 10$ to $\pm 40$	The distribution of heavy trucks on multilane facilities is different from that of passenger cars (which is often used instead)
Days	$\pm 20$	Usually 300 days are assumed in Ontario
Growth	$\pm 10$ to $\pm 100$	Difficult to predict for new facilities where historical data are missing
$TF_i$ <sup>3)</sup>		
Load measurements	$\pm 10$ to $\pm 100+$	$\pm 10$ for weigh-in-motion scales $\pm 100$ where loads are estimated
Truck suspension type	$\pm 40$	Air suspension compared to walking beam
Level of pavement distress	$\pm 2$ to $\pm 10$	$\pm 2$ for initial serviceability $\pm 10$ for terminal serviceability
Pavement thickness	$\pm 5$	for SN or D

1) Defined for Equation 5.

2) Typical range between the actual and estimated values, expressed as the percentage of the actual value.

3) Only a few contributing variables are listed.

4. The summation of pavement traffic loads can be greatly simplified using general axle factors. The general axle factors would be particularly useful for pavement management purposes, for example, for evaluating and comparing pavement loading trends on a network consisting of a variety of pavement types.

5. The proposed general axle factors are independent of pavement-related variables and axle configurations. Furthermore, the general axle factors can have similar magnitudes as the existing AASHTO axle load equivalency factors.

6. The proposed general axle factors and the associated general ESALs would be suitable and appropriate for pavement management and routine pavement design purposes.

## ACKNOWLEDGMENTS

I express my appreciation to John Billing, Ontario Ministry of Transportation, for his helpful and valuable comments and review of the manuscript.

## REFERENCES

1. Witczak, M. W. *Equivalent Wheel Load Factors*. Report prepared for Association of American Railroads. University of Maryland, Feb. 1981.
2. *AASHTO Guide for Design of Pavement Structures 1993*. American Association of State Highway and Transportation Officials, Washington, D.C. 1993.
3. Maghsoudi, A. *A Method for Estimating the Number of Equivalent Standard Axle Loads From Visual Classification Counts*. Internal Report PAV-78-02. Ontario Ministry of Transportation, Downsview, Ontario, Canada, 1978.
4. Monismith, C. L. *An Introduction to the Analytical Design of Asphalt Concrete Pavements*, University of California, Berkeley, 1981.
5. Painter, L. J. Analysis of AASHO Road Test Data by the Asphalt Institute. *Proc., International Conference on the Structural Design of Asphalt Pavements*, University of Michigan, Ann Arbor 1962.
6. Claessen, A. I. M. *Asphalt Pavement Design: The Shell Method, Manual on Asphalt Pavements and Overlays for Road Traffic*. Shell International Petroleum Company Ltd., London, England, 1978.
7. Irick, P. E., S. B. Seeds, and M. A. Diaz. *Characteristics of Load Equivalence Relationships Associated With Pavement Distress and Performance, Phase II Study*. Trucking Research Institute, Alexandria, Va., 1991.

8. Hajek, J. J., and W. A. Phang. Moving From Subjective to Objective Evaluation of Pavement Performance. *Proc. 1986 RTAC Conference*, Toronto, Ontario, Canada, 1986.
9. Special Report 61E: *The AASHO Road Test: Report 5—Pavement Research*. HRB, National Research Council, Washington, D.C., 1962.
10. *Vehicle Dimensions and Weight Limits in Ontario*. Compliance Branch, Ministry of Transportation, Downsview, Ontario, Canada, 1986.
11. Small, K. A., C. Winston, and C. A. Evans. *Road Work*. The Brookings Institution, Washington, D.C., 1989.
12. Christison, J. T. *Vehicle Weights and Dimension Study, Vol. 9: Pavement Response to Heavy Vehicle Test Program, Part 2—Load Equivalency Factors*. Roads and Transportation Association of Canada, Ottawa, Ontario, 1986.
13. Hutchison, B. G., R. C. G. Haas, P. Meyer, K. Hadipour, and T. Papa-  
giannakis. Equivalencies of Different Axle Load Groups. *Proc. 2nd North American Conference on Managing Pavements*, Toronto, Ontario, Canada, 1987.
14. Hajek, J. J., and A. C. Agarwal. Influence of Axle Group Spacing on Pavement Damage. In *Transportation Research Record 1216*, TRB, National Research Council, Washington, D.C., 1989, pp. 58–66.
15. *ELSYM5*. Report FHWA-RD-85. FHWA, U.S. Department of Transportation, 1985.
16. Mamlouk, M. S. A Rational Look at Truck Axle Weight. Presented at Annual Transportation Research Board Meeting, Washington, D.C., 1991.
17. Davidson, E. Dynamic Load Distribution of Axle Suspension Systems on Truck Tractors and Semi-Trailers. Report FHWA/CA/RO/83-19. California Department of Transportation, Sacramento, 1983.
18. Hallin, J. P., J. Sharma, and J. P. Mahoney. Development of Rigid and Flexible Pavement Load Equivalency Factors for Various Widths of Single Tires. In *Transportation Research Record 949*, TRB, National Research Council, Washington, D.C., 1983, pp. 4–13.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.