Pavement Design Factors

Pavement Design Factors

Objectives of Structural Design of Pavements

- to determine total thickness of pavement structure as well as
- to determine the individual layer thickness

Performance (life cycle) of pavement depends upon

- Traffic forecasting
- Weather forecasting
- Pavement design
- Construction control
- Maintenance practices
- Overweight vehicle control

As such pavement design involves more than choosing thicknesses.

Pavement Design

Design Life

- Pavements are typically designed for a specified "design life".
- Design life (or "design period") is the time from original construction to a terminal condition for a pavement structure.
- Structural design is carried out so that the pavement structure is sufficient to withstand the traffic loading encountered over the pavement's design life.
- It is recognized that intermittent maintenance and rehabilitation efforts may be needed to preserve a pavement's surface quality and ensure that the structure lasts through the design life.

Analysis Period. This refers to the period of time for which the analysis is to be conducted, i.e., the length of time that any design strategy must cover. The analysis period is analogous to the term "design life" used by designers in the past. Because of the consideration of the maximum performance period, it may be necessary to consider and plan for stage construction (i.e., an initial pavement structure followed by one or more rehabilitation operations) to achieve the desired analysis period.

Highway Conditions	Analysis Period (years)
High-volume urban	30–50
High-volume rural	20–50
Low-volume paved	15–25
Low-volume aggregate surface	10–20

Pavement Design Factors

Design factors

Design factors can be divided into four broad categories:

- Traffic and Loading
- Environment
- Materials
- Failure criteria

The traffic and loading to be considered include:

- Axle Loads
- Number of Repetitions
- Contact Area
- Vehicle Speed

Traffic and Loading

Axle Loads Figure 1.12 shows the wheel spacing for a typical semitrailer consisting of single axle with single tires, single axle with dual tires, and tandem axles with dual tires. For special heavy-duty haul trucks, tridem axles consisting of a set of three axles, each spaced at 48 to 54 in. (1.22 to 1.37 m) apart, also exist.

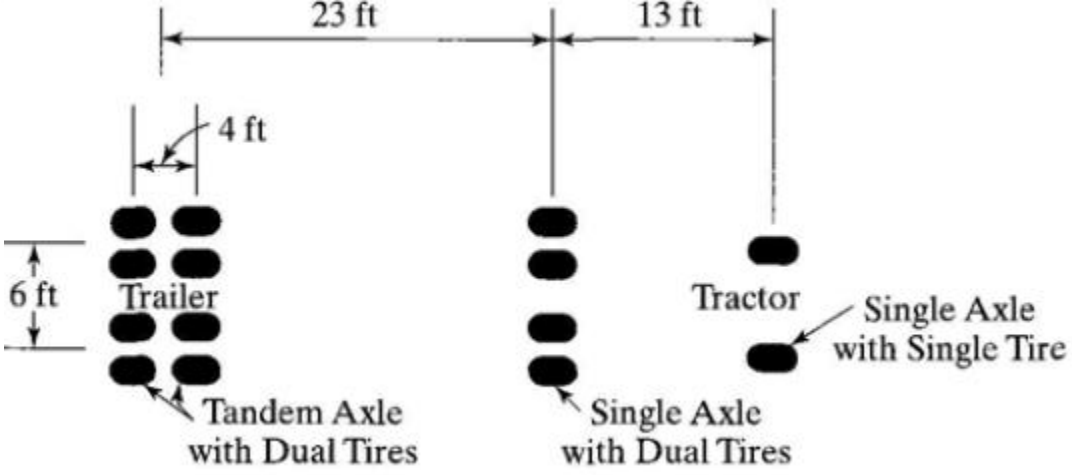


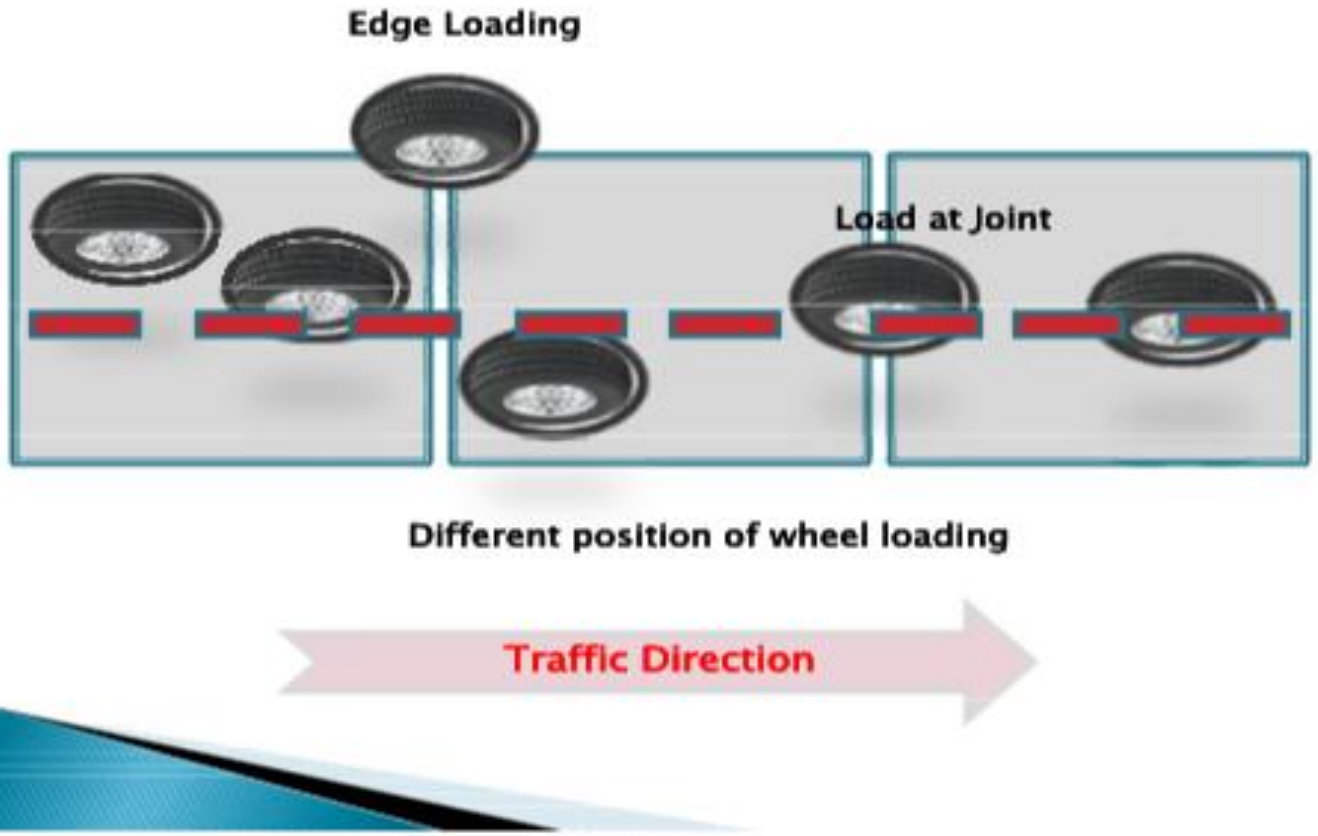
FIGURE 1.12

Wheel configurations for typical semitrailer units (1 ft = 0.305 m)

The spacings of 23 and 13 ft (7 and 4 m) shown in Figure 1.12 should have no effect on pavement design because the wheels are so far apart that their effect on stresses and strains should be considered independently. Unless an equivalent single-axle load is used, the consideration of multiple axles is not a simple matter. The design may be unsafe if the tandem and tridem axles are treated as a group and considered as one repetition. The design is too conservative if each axle is treated independently and considered as one repetition. A method for analyzing multiple-axle loads is presented

In the design of flexible pavements by layered theory, only the wheels on one side, say at the outer wheelpath, need be considered; in the design of rigid pavements by plate theory, the wheels on both sides, even at a distance of more than 6 ft (1.8 m) apart, are usually considered.

Pavement Design Factors



Pavement Design Factors

Axle Configurations and Loads



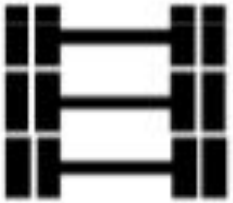
Single Axle With Single Wheel
(Legal Axle Load = 6t)



Single Axle With Dual Wheel
(Legal Axle Load = 10t)



Tandem Axle
(Legal Axle Load = 18t)

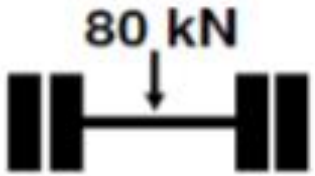


Tridem Axle
(Legal Axle Load = 24t)

Pavement Design Factors

Standard Axle

Single axle with dual wheels carrying a load of 80 kN (8 tonnes) is defined as standard axle



Standard Axle


Tandem axle
dual tires
Single axle
dual tires
Single axle
single tires


Trident Axle

Number of Repetitions With the use of a high-speed computer, it is no problem to consider the number of load repetitions for each axle load and evaluate its damage. The method of dividing axle loads into a number of groups has been used frequently for the design of rigid pavements, as illustrated by the PCA method in Section 12.2. However, its application to flexible pavements is not widespread, because of the empirical nature of the design and of the large amount of computer time required.

Instead of analyzing the stresses and strains due to each axle-load group, a simplified and widely accepted procedure is to develop equivalent factors and convert each load group into an equivalent 18-kip (80-kN) single-axle load, as illustrated by the Asphalt Institute method in Section 11.2 and the AASHTO method in Sections 11.3 and 12.3. It should be noted that the equivalency between two different loads depends on the failure criterion employed. Equivalent factors based on fatigue cracking could be different from those based on permanent deformation. Therefore, the use of a single equivalent factor for analyzing different types of distress is empirical and should be considered as approximate only.

No of Repitition



2000 Repetitions < 1 Repetition

Equivalent axle load factor (EALF)

- **An equivalent axle load factor (EALF)** defines the damage per pass to a pavement by the axle in question relative to the damage per pass of a standard axle load, usually the 18-kip (80-kN) single-axle load.
- EALF **depends** on the type of pavements, thickness or structural capacity and the terminal conditions at which pavement failed
- Most of the EALFs in use today are based on experience.
- One of the most widely used methods is based on the empirical equations developed from the AASHO Road Test (AASHTO ,1972).
- EALF also be determined theoretically based on the critical stresses & strains in the pavement and the failure criteria
- EALF for flexible and rigid pavements are different

EALF_ESAL

- If the axle load is not 18 kip (80 kN) or consists of tandem or tridem axles, it must be converted to an 18-kip single-axle load by an equivalent axle load factor **(EALF**) .
- The number of repetitions under each single- or multiple-axle load must be multiplied by its EALF to obtain the equivalent effect based on an 18-kip (80-kN) single-axle load.

ESAL

- A **summation** of the **equivalent effects of all axle loads** during the design period results in an **equivalent single-axle load (ESAL),** which is the single traffic parameter for design purposes.
- The great varieties of axle loads and traffic volumes and their intractable effects on pavement performance require that most of the design methods in use today.

ESAL

- The design is based on the **total number of passes** of the standard axle load during the design period, defined as the equivalent single-axle load (ESAL) and computed by

$$\text{ESAL} = \sum_{i=1}^{m} F_i \, n_i$$

- m is the number of axle load groups, *Fi* is the EALF for the ith-axle load group, and *ni* is the number of passes of the ith-axle load group during the design period.

Flexible pavement : EALF
4th Power Rule

$$\text{EALF} = \left(\frac{L_x}{18}\right)^4 \tag{6.23}$$

in which L_x is the load in kip on a single axle. Equation 6.23 is valid only when L_x is on a single axle. For tandem or tridem axles, a more general equation is

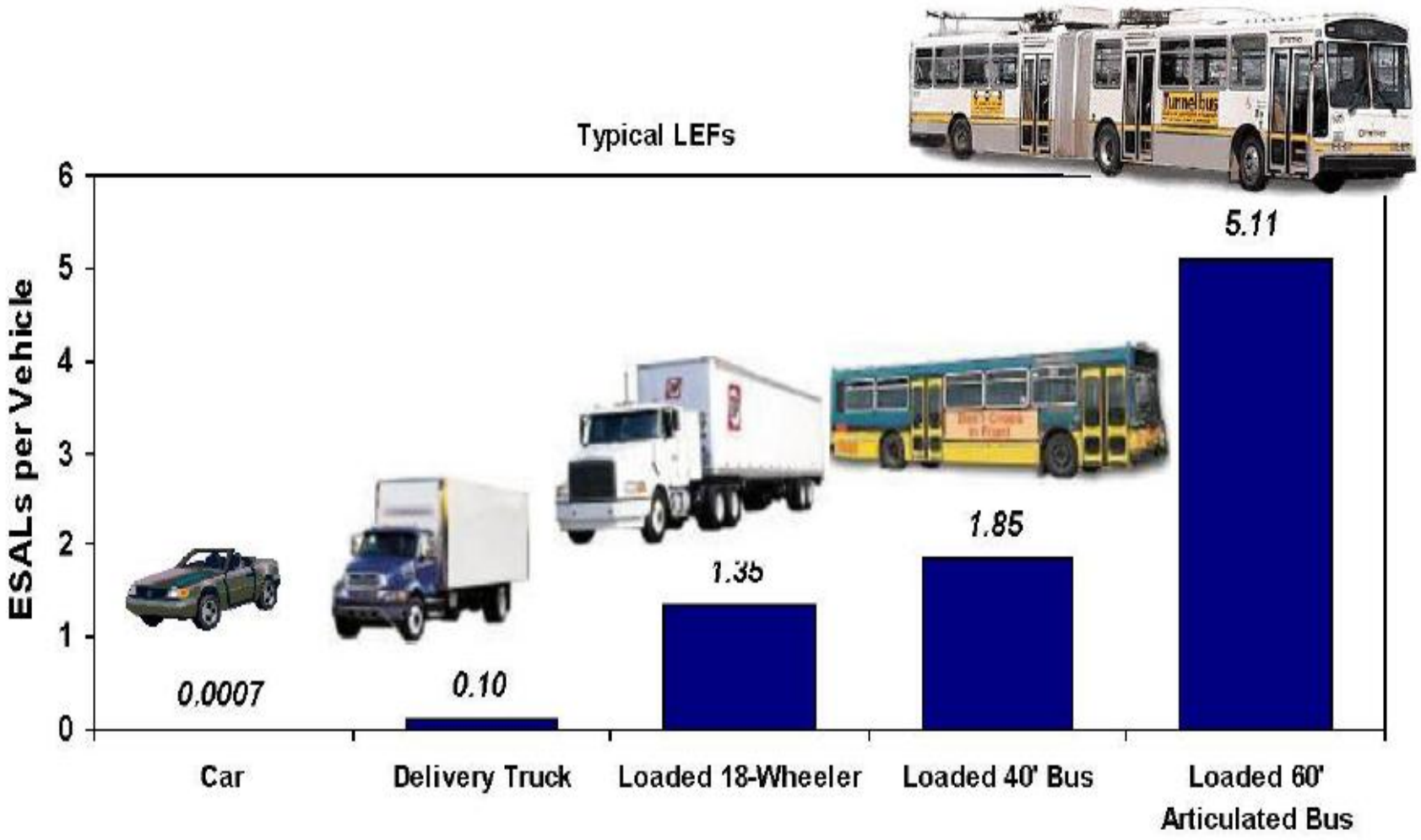
$$\text{EALF} = \left(\frac{L_x}{L_s}\right)^4 \tag{6.24}$$

in which L_s is the load in kip on standard axles which have the same number of axles as L_x. If the EALF for one set of tandem or tridem axles is known, that for other axles can be determined by Eq. 6.24.

Example 6.9:

Given $p_t = 2.5$ and SN = 5, determine the EALF for 5000-lb (22.3-kN) and 50,000-lb (223-kN) single axles by Eq. 6.23. If the EALF of a 32-kip (142-kN) tandem axle is 0.857, determine the EALF for 15,000-lb (66.8-kN) and 80,000-lb (356-kN) tandem axles by Eq. 6.24.

Solution: For a single axle with $L_x = 5$, from Eq. 6.23, EALF = $(5/18)^4 = 0.006$, which compares with 0.005 from Table 6.4. For a single axle with $L_x = 50$, EALF = $(50/18)^4 = 59.54$ compared with 52.88 from Table 6.4. For tandem axles with $L_x = 15$ and $L_s = 32$, from Eq. 6.24, the equivalent factor between 15-kip (66.8-kN) and 32-kip (142-kN) tandem axles is $(15/32)^4 = 0.0483$, which must be multiplied by 0.857 to obtain the equivalent factor between 15-kip (66.8-kN) tandem axles and an 18-kip (80-kN) single axle, so EALF = $0.0483 \times 0.857 = 0.041$ compared with 0.036 from Table 6.4. For tandem axles with $L_x = 80$, EALF = $0.857 \times (80/32)^4 = 33.48$ compared with 28.99 from Table 6.4. It can be seen that the equivalent factors based on tensile strains at the bottom of the asphalt layer check favorably with the AASHTO and Asphalt Institute's equivalent factors.


Typical LEFs
ESALs per Vehicle
0
1
2
3
4
5
6
0.0007
0.10
1.35
1.85
5.11
Car
Delivery Truck
Loaded 18-Wheeler
Loaded 40' Bus
Loaded 60' Articulated Bus

The standard axle weights for a standing-room-only loaded Metro articulated bus (60 ft. Flyer) are:

Axle	Empty	Full
Steering	13,000 lb.	17,000 lb.
Middle	15,000 lb.	20,000 lb.
Rear	9,000 lb.	14,000 lb.

Using the 4th power approximation, determine the total equivalent damage caused by this bus in terms of ESALs when it is empty. How about when it is full?



When empty:

$$\text{Total ESAL's} = \left(\frac{13000}{18000}\right)^4 + \left(\frac{15000}{18000}\right)^4 + \left(\frac{9000}{18000}\right)^4 = 0.817$$

When full:

$$\text{Total ESAL's} = \left(\frac{17000}{18000}\right)^4 + \left(\frac{20000}{18000}\right)^4 + \left(\frac{14000}{18000}\right)^4 = 2.686$$

Pavement Design Factors

Vehicle Speed Another factor related to traffic is the speed of traveling vehicles. If the viscoelastic theory is used, such as in VESYS and KENLAYER, speed is directly related to the duration of loading. If the elastic theory is used, the resilient modulus of each paving material should be properly selected to be commensurate with the vehicle speed. Generally, the greater the speed, the larger the modulus, and the smaller the strains in the pavement.

Moving loads (Speed): The damage to the pavement is much higher if the vehicle is moving at creep speed. Many studies show that when the speed is increased from 2 km/hr to 24 km/hr, the stresses and deflection reduced by 40 per cent.

Pavement Design Factors

Environment

The environmental factors that influence pavement design include temperature and precipitation. Both these factors affecting elastic modulus of various layers.

- Temperature: The effects of temperature on asphalt pavements is different from that on concrete pavements. Temperature affects the resilient modulus of asphalt layers, while it induces curling of concrete slab. In rigid pavements, due to difference in temperatures of top and bottom of slab, temperature stresses or frictional stresses are developed. While in flexible pavement, dynamic modulus of asphaltic concrete varies with temperature. Frost heave causes differential settlements and pavement roughness. Most detrimental effect of frost penetration occurs during the spring break up period when the ice melts and subgrade is a saturated condition.

- Precipitations: The precipitation from rain and snow affects the quantity of surface water infiltrating into the sub-grade and the location



Pavement Design Factors

Materials

In the mechanistic–empirical methods of design, the properties of materials must be specified, so that the responses of the pavement, such as stresses, strains, and displacements in the critical components, can be determined. These responses are then used with the failure criteria to predict whether failures will occur or the probability that failures will occur. Details of material characterization are presented in Chapter 7.

General Properties The following general material properties should be specified for both flexible and rigid pavements:

1. When pavements are considered as linear elastic, the elastic moduli and Poisson ratios of the subgrade and each component layer must be specified. The Poisson ratios have relatively small effects on pavement responses, so their values can be reasonably assumed.
2. If the elastic modulus of a material varies with the time of loading, the resilient modulus, which is the elastic modulus under repeated loads, must be selected in accordance with a load duration corresponding to the vehicle speed.
3. When a material is considered nonlinear elastic, the constitutive equation relating the resilient modulus to the state of stresses must be provided.

Failure Criteria

Failure Criteria

- Failure criteria for Flexible and Rigid pavements are different;
- It is generally agreed that Fatigue cracking, Rutting, Thermal cracking are the three principal types of failure criteria to be considered for Flexible pavement design.

- Fatigue cracking has long been considered the major or only criterion for Rigid pavement design. Only recently has pumping or erosion been considered.

TRAFFIC ANALYSIS

To design a highway pavement, it is necessary to predict the number of repetitions of each axle load group during the design period. Information on initial traffic can be obtained from field measurements or from the W-4 form of a loadometer station that has traffic characteristics similar to those of the project in question. The initial daily traffic is in two directions over all traffic lanes and must be multiplied by the directional and lane distribution factors to obtain the initial traffic on the design lane. The traffic to be used for design is the average traffic during the design period, so the initial traffic must be multiplied by a growth factor. If n_i is the total number of load repetitions to be used in design for the ith load group, then

$$n_i = (n_0)_i(G)(D)(L)(365)(Y) \tag{6.26}$$

in which $(n_0)_i$ is the initial number of repetitions per day for the ith load group, G is the growth factor, D is the directional distribution factor, which is usually assumed to be 0.5 unless the traffic in two directions is different, L is the lane distribution factor

which varies with the volume of traffic and the number of lanes, and Y is the design period in years. If the design is based on the equivalent 18-kip (80-kN) single-axle load, then the initial number of repetitions per day for the ith load group can be computed

$$\text{ESAL} = (\text{ADT})_0(T)(T_f)(G)(D)(L)(365)(Y) \tag{6.30}$$

Truck Factor

A single truck factor can be applied to all trucks, or separate truck factors can be used for different classes of trucks. The latter case should be considered if the growth factors for different types of trucks are not the same. Table 6.10 shows the distribution of truck factors for different classes of highways and vehicles in the United States. Table 6.11 shows the computation of truck factors for trucks with five or more

TABLE 6.10 Distribution of Truck Factors for Different Classes of Highways and Vehicles in the United States[a]

	Truck factors											
	Rural systems						Urban systems					
				Collectors								
Vehicle type	Interstate	Other Principal	Minor Arterial	Major	Minor	Range	Interstate	Other Freeways	Other Principal			Range
Single-unit trucks												
2-axle, 4-tire	0.003	0.003	0.003	0.017	0.003	0.003–0.017	0.002	0.015	0.002	0.006	—	0.006–0.015
2-axle, 6-tire	0.21	0.25	0.28	0.41	0.19	0.19–0.41	0.17	0.13	0.24	0.23	0.13	0.13–0.24
3-axle or more	0.61	0.86	1.06	1.26	0.45	0.45–1.26	0.61	0.74	1.02	0.76	0.72	0.61–1.02
All single units	0.06	0.08	0.08	0.12	0.03	0.03–0.12	0.05	0.06	0.09	0.04	0.16	0.04–0.16
Tractor semitrailers												
4-axle or less	0.62	0.92	0.62	0.37	0.91	0.37–0.91	0.98	0.48	0.71	0.46	0.40	0.40–0.98
5-axle[b]	1.09	1.25	1.05	1.67	1.11	1.05–1.67	1.07	1.17	0.97	0.77	0.63	0.63–1.17
6-axle or more[b]	1.23	1.54	1.04	2.21	1.35	1.04–2.21	1.05	1.19	0.90	0.64	—	0.64–1.19
All multiple units	1.04	1.21	0.97	1.52	1.08	0.97–1.52	1.05	0.96	0.91	0.67	0.53	0.53–1.05
All trucks	0.52	0.38	0.21	0.30	0.12	0.12–0.52	0.39	0.23	0.21	0.07	0.24	0.07–0.39

a Compiled from data supplied by the Highway Statistics Division, U.S. Federal Highway Administration.
b Including full-trailer combinations in some states.
Source. After AI (1991).

Growth Factor

One simple way to project the growth factor is to assume a yearly rate of traffic growth and use the average traffic at the start and end of the design period as the design traffic:

$$G = \tfrac{1}{2}[1 + (1 + r)^Y] \tag{6.31}$$

The Portland Cement Association (1984) applies the traffic at the middle of the design period as the design traffic:

$$G = (1 + r)^{0.5Y} \tag{6.32}$$

Table 6.12 shows the growth factors for 20- and 40-year design periods based on Eq. 6.32.

The Asphalt Institute (AI, 1981a) and the AASHTO design guide (AASHTO, 1986) recommend the use of traffic over the entire design period to determine the total growth factor, as indicated by

$$\text{Total growth factor} = (G)(Y) = \frac{(1 + r)^Y - 1}{r} \tag{6.33}$$

TABLE 6.12 Traffic Growth Factors

Annual growth rate (%)	20-Year design period	40-Year design period
1.0	1.1	1.2
1.5	1.2	1.3
2.0	1.2	1.5
2.5	1.3	1.6
3.0	1.3	1.8
3.5	1.4	2.0
4.0	1.5	2.2
4.5	1.6	2.4
5.0	1.6	2.7
5.5	1.7	2.9
6.0	1.8	3.2

Source. After PCA (1984).

TABLE 6.16 Lane Distribution Factor

No. of lanes in each direction	Percentage of 18-kip ESAL in design lane
1	100
2	80–100
3	60–80
4	50–75

Source. After AASHTO (1986).

TABLE 6.13 Total Growth Factor

Design period (years)	Annual growth rate (%)							
	No growth	2	4	5	6	7	8	10
1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
2	2.0	2.02	2.04	2.05	2.06	2.07	2.08	2.10
3	3.0	3.06	3.12	3.15	3.18	3.21	3.25	3.31
4	4.0	4.12	4.25	4.31	4.37	4.44	4.51	4.64
5	5.0	5.20	5.42	5.53	5.64	5.75	5.87	6.11
6	6.0	6.31	6.63	6.80	6.98	7.15	7.34	7.72
7	7.0	7.43	7.90	8.14	8.39	8.65	8.92	9.49
8	8.0	8.58	9.21	9.55	9.90	10.26	10.64	11.44
9	9.0	9.75	10.58	11.03	11.49	11.98	12.49	13.58
10	10.0	10.95	12.01	12.58	13.18	13.82	14.49	15.94
11	11.0	12.17	13.49	14.21	14.97	15.78	16.65	18.53
12	12.0	13.41	15.03	15.92	16.87	17.89	18.98	21.38
13	13.0	14.68	16.63	17.71	18.88	20.14	21.50	24.52
14	14.0	15.97	18.29	19.16	21.01	22.55	24.21	27.97
15	15.0	17.29	20.02	21.58	23.28	25.13	27.15	31.77
16	16.0	18.64	21.82	23.66	25.67	27.89	30.32	35.95
17	17.0	20.01	23.70	25.84	28.21	30.84	33.75	40.55
18	18.0	21.41	25.65	28.13	30.91	34.00	37.45	45.60
19	19.0	22.84	27.67	30.54	33.76	37.38	41.45	51.16
20	20.0	24.30	29.78	33.06	36.79	41.00	45.76	57.28
25	25.0	32.03	41.65	47.73	54.86	63.25	73.11	98.35
30	30.0	40.57	56.08	66.44	79.06	94.46	113.28	164.49
35	35.0	49.99	73.65	90.32	111.43	138.24	172.32	271.02

Source. After AI (1981a).

Table 6.13 shows the total growth factor, which is the growth factor multiplied by the design period, as recommended by the Asphalt Institute. The same factor is used in the AASHTO design guide. If the growth rate is not uniform, different growth rates should be used for different load groups or types of vehicles.

To determine the annual growth rate, the following factors should be considered:

1. Attracted or diverted traffic due to the improvement of existing pavement
2. Normal traffic growth due to the increased number and usage of motor vehicles
3. Generated traffic due to motor vehicle trips that would not have been made if the new facility had not been constructed
4. Development traffic due to changes in land use as a result of the new facility

Example 6.11:

For an annual growth rate of 3.5% and a design period of 30 years, compute the growth factors by Eqs. 6.31, 6.32, and 6.33.

Solution: From Eq. 6.31, $G = 0.5[1 + (1 + 0.035)^{30}] = 1.90$; from Eq. 6.32, $G = (1 + 0.035)^{0.5\times30} = 1.68$; and from Eq. 6.33, $G = [(1 + 0.035)^{30} - 1]/(0.035 \times 30) = 1.72$. It can be seen that the use of Eq. 6.31 by averaging the traffic at the start and the end of a design period is most conservative and results in the greatest growth factor, while the growth factor based on Eq. 6.33 is only slightly greater than that based on Eq. 6.32.

Example 6.12:

A two-lane major rural highway has an AADT of 4000 during the first year of traffic, 25% trucks, 4% annual growth rate, and 50% on the design lane. If the distribution of trucks is the same as shown in Table 6.9 and the distribution of truck factors is as shown in Table 6.10, compute the ESAL for a design period of 20 years.

Solution: For a growth rate of 4% and a design period of 20 years, from Table 6.13, or Eq. 6.33, $(G)(Y) = 29.78$. The truck factor for all trucks, as shown in Table 6.10, is the weighted average of the distribution of trucks shown in Table 6.9. If the distribution of trucks is given in Table 6.9, it is not necessary to break down the trucks into different classes; the use of $T_f = 0.38$ for all trucks in the "other principal" column of the rural systems, as shown in Table 6.10, is sufficient. From Eq. 6.30, ESAL $= 4000 \times 0.25 \times 0.38 \times 29.78 \times 0.5 \times 365 = 2{,}065{,}200$.

Sum

6.6 Estimate the equivalent 18-kip single-axle load applications (ESAL) for a four-lane pavement (two lanes in each direction) of a rural interstate highway with a truck count of 1000 per day (including 2-axle, 4-tire panel, and pickup trucks), an annual growth rate of 5%, and a design life of 20 years. [Answer: 2.82×10^6]

Question/Discussion