Design of Flexible Pavement

Pavement Design

- Pavement Thickness design is the **determination of thickness of various pavement layers** (of various pavement materials) for a **given soil condition and the predicted design traffic** (in terms of equivalent standard axle load) that will **provide the desired structural and functional performance** over the selected **pavement design life.**

Flexible Pavement Design

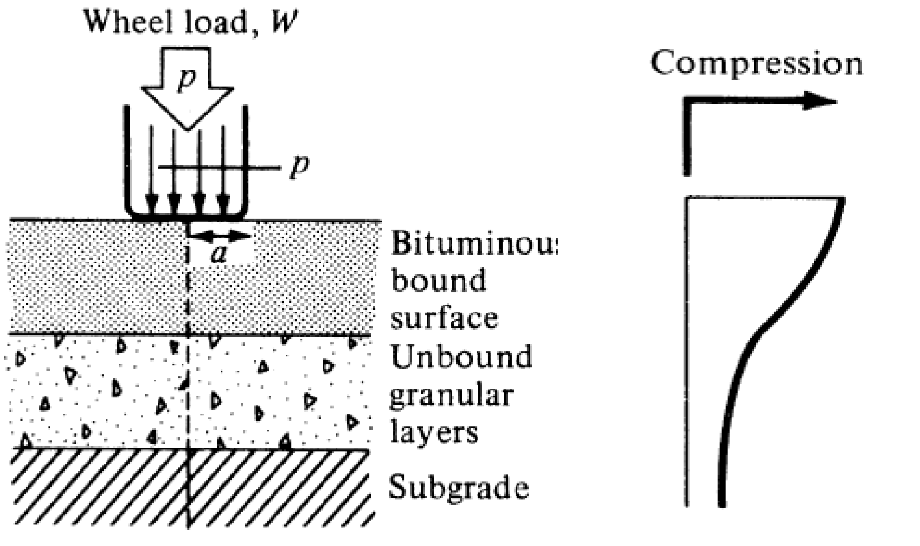
- In the design of **flexible pavements,** the pavement structure usually is considered as a **multilayered elastic system.**

- The material in **each layer characterized by certain physical properties** that may include the modulus of elasticity, the resilient modulus, and the Poisson ratio.

- The application of a **wheel load causes stress in each layer** of the flexible pavement.

Stresses in Flexible Pavement

- The **maximum vertical stresses are compressive** and occur directly under the wheel load.
- These decrease with an increase in depth from the surface.

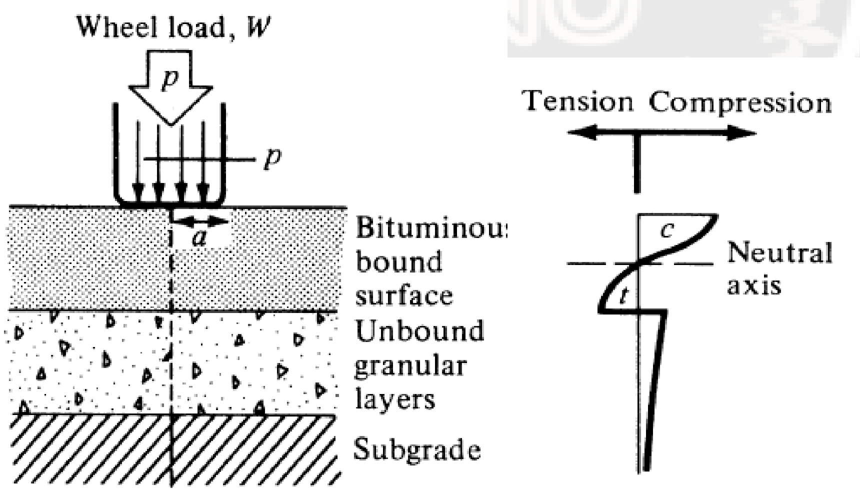


(a) Pavement layers

(b) Distribution of vertical stress under centerline of wheel load

Stresses in Flexible Pavement

- The maximum **horizontal stresses** also occur directly under the wheel load but can be **either tensile or compressive**.
- When the load and pavement thickness are within certain ranges, horizontal **compressive stresses** will occur **above the neutral axis** whereas horizontal **tensile stresses** will occur **below the neutral axis**.

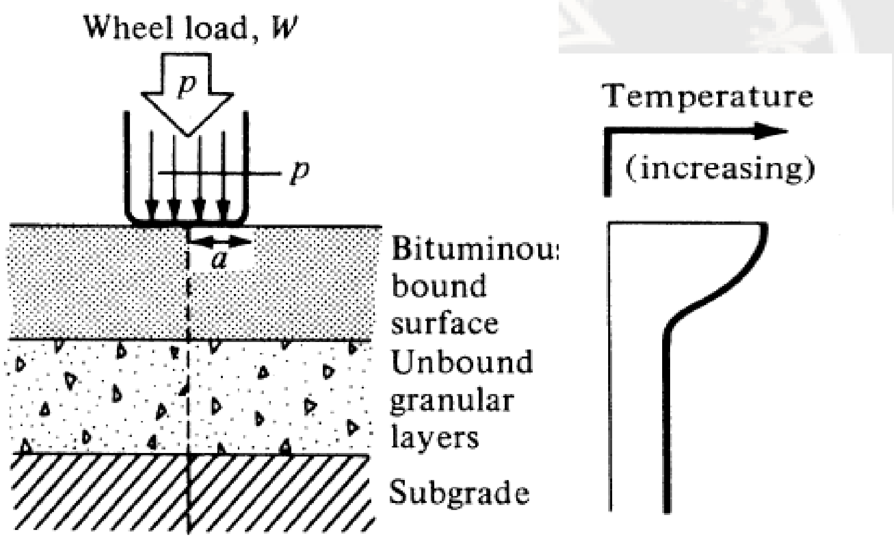


(a) Pavement layers

(c) Distribution of horizontal stress under centerline of wheel load

Stresses in Flexible Pavement

- Temperature stresses also exists in the pavements layer with the distribution as maximum stresses in the top layer and reduces at the bottom layers



(a) Pavement layers

(d) Temperature distribution

Flexible Pavement Design Methods

- **AASHTO Design Method**
- **Asphalt Institute Design Method**

AASHTO Design Method

- The AASHTO method for design of highway pavements is based primarily on the results of the AASHTO road test that was conducted in Ottawa, Illinois USA
- Conducted different tests under various pavement layer thicknesses and traffic conditions.
- These data were analyzed thoroughly, and the results formed the basis for the AASHTO method of pavement design.

AASHTO Design Method

- AASHTO initially published an interim guide for the design of pavement structures in 1961, which was revised in 1972. A further revision was published in 1986.
- Another edition was subsequently published in 1993 which included the overlay design procedure.
- Latest version released in 2010 (documented 2002)

Design Considerations

- The factors considered in the AASHTO procedure for the design of flexible pavement as presented in the 1993 guide are:

1. Pavement performance
2. Traffic
3. Roadbed soils (subgrade material)
4. Materials of construction
5. Environment
6. Drainage
7. Reliability

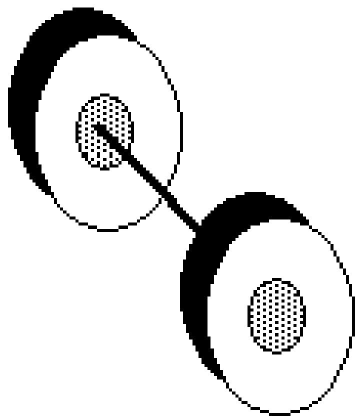
Pavement Performance

- The primary factors considered under pavement performance are the structural and functional performance of the pavement.
- ***Structural performance*** is related to the physical condition of the pavement such as the **capability** of the pavement to **carry the traffic load.**
- Factors which reduces the structural performance of the pavement includes **cracking, faulting, raveling**, and so forth.

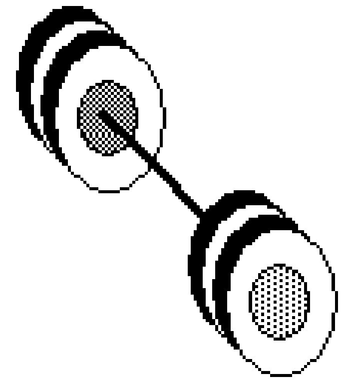
Pavement Performance

- ***Functional performance*** is an indication of how effectively the pavement serves the user. The main factor considered under functional performance is **riding comfort.**
- To quantify pavement performance, a concept known as the *serviceability performance* was developed and is measured using **Pavement Serviceability Index (PSI)**
- The scale ranges from 0 to 5, where 0 is the lowest PSI and 5 is the highest.

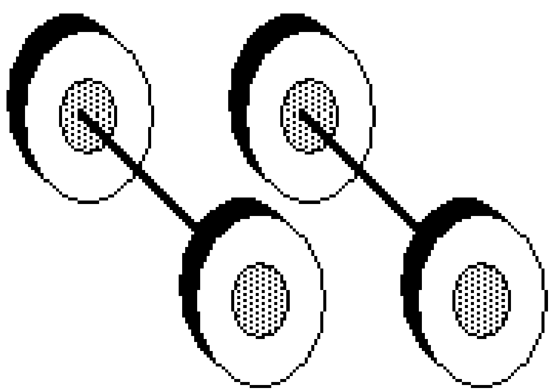
Traffic Load



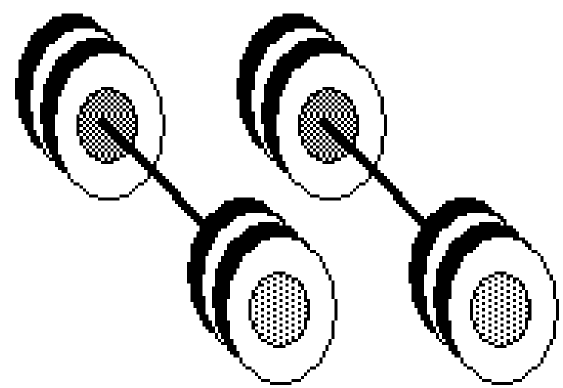
Single Axle with Single Tires



Single Axle with Dual Tires



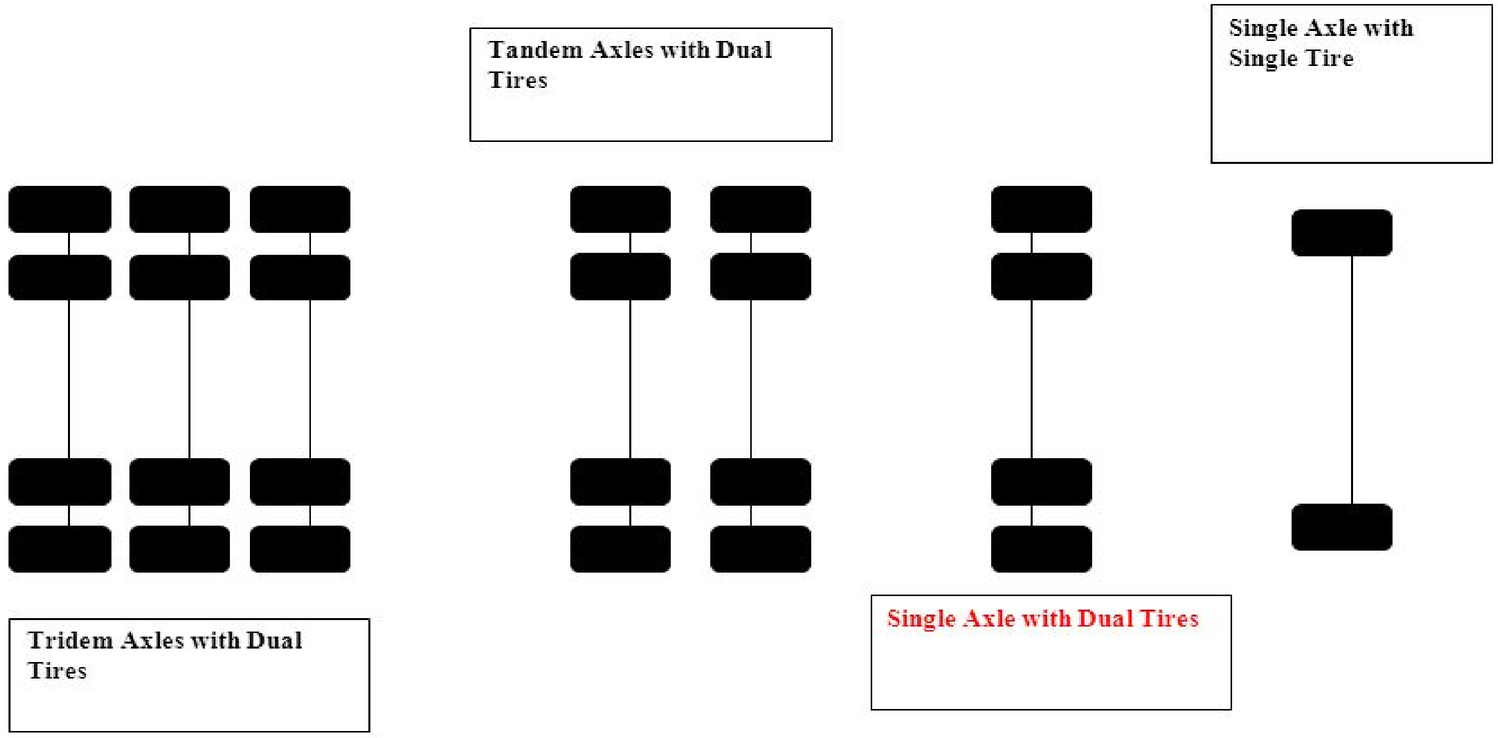
Tandem Axles with Single Tires



Tandem Axles with Dual Tires

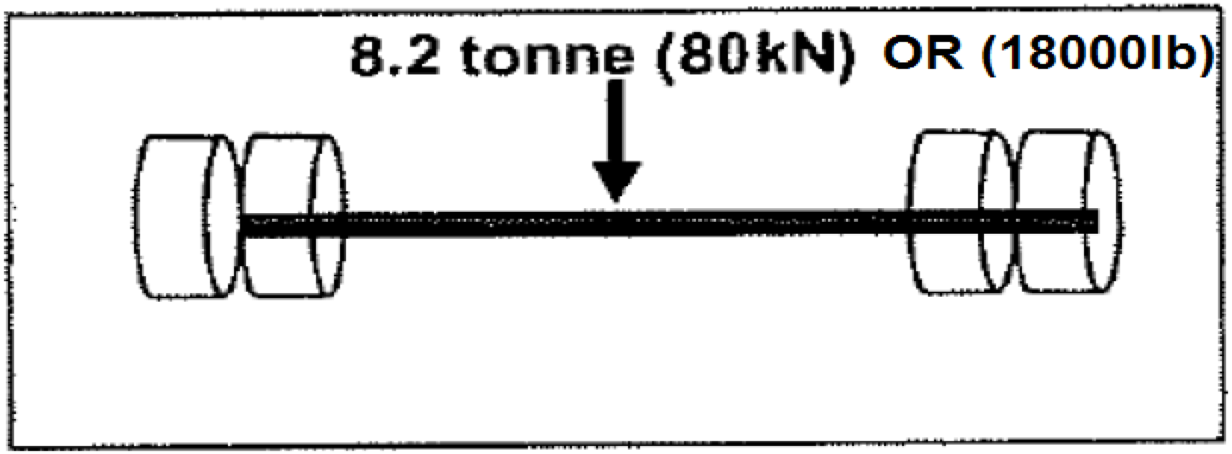
Traffic Load

Axle & Wheel Configurations



Traffic Load

- **The Standard Axle loading is defined as an axle with dual tyres loaded to 80kN (8.2 tonne)(18000lb).**
- In the AASHTO design method, the traffic load is determined in terms of the number of repetitions of an 18,000-lb (80 kilonewtons (kN)) single-axle load applied to the pavement on two sets of dual tires.
- This is usually referred to as the *equivalent single-axle load* (ESAL).

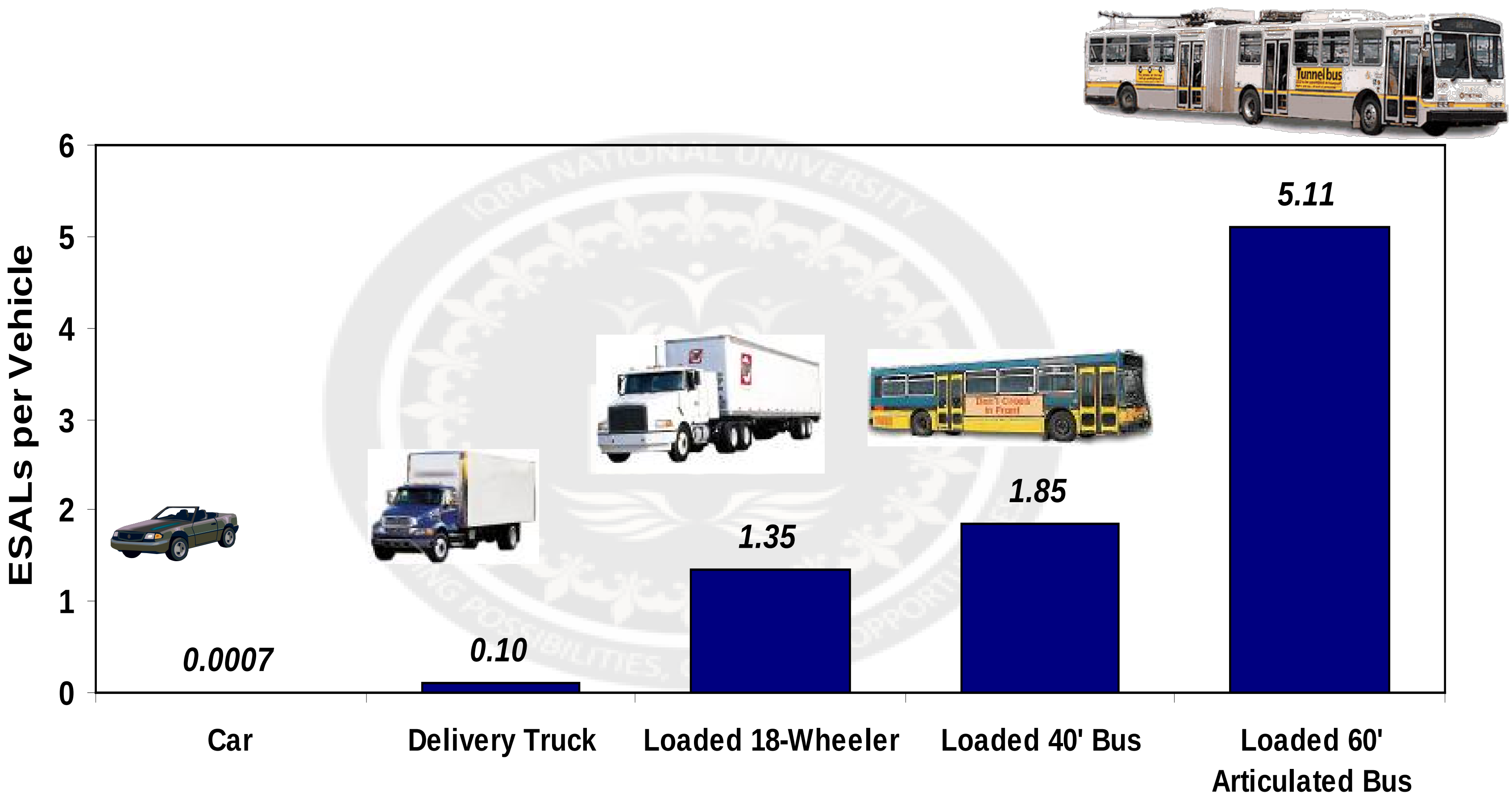


Traffic Load

Table 19.3a Axle Load Equivalency Factors for Flexible Pavements, Single Axles, and p_t of 2.5

Axle Load (kips)	Pavement Structural Number (SN) 1	2	3	4	5	6
2	.0004	.0004	.0003	.0002	.0002	.0002
4	.003	.004	.004	.003	.002	.002
6	.011	.017	.017	.013	.010	.009
8	.032	.047	.051	.041	.034	.031
10	.078	.102	.118	.102	.088	.080
12	.168	.198	.229	.213	.189	.176
14	.328	.358	.399	.388	.360	.342
16	.591	.613	.646	.645	.623	.606
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.3	9.5	7.9	6.8	7.0	7.8
32	13.9	12.8	10.5	8.8	8.9	10.0
34	18.4	16.9	13.7	11.3	11.2	12.5
36	24.0	22.0	17.7	14.4	13.9	15.5
38	30.9	28.3	22.6	18.1	17.2	19.0
40	39.3	35.9	28.5	22.5	21.1	23.0
42	49.3	45.0	35.6	27.8	25.6	27.7
44	61.3	55.9	44.0	34.0	31.0	33.1
46	75.5	68.8	54.0	41.4	37.2	39.3
48	92.2	83.9	65.7	50.1	44.5	46.5
50	112.0	102.0	79.0	60.0	53.0	55.0

Traffic Load



Notice that cars are insignificant and thus usually ignored in pavement design.

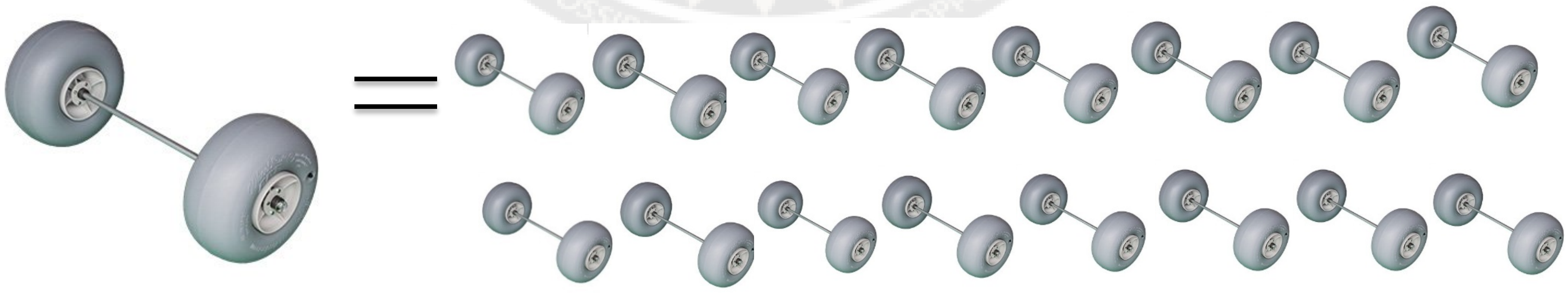
Traffic Load

$$\left(\frac{\text{load}}{18{,}000\ \text{lb.}}\right)^4 = \text{relative damage factor}$$

$$\left(\frac{\text{load(tons)}}{8.2\ \text{tons}}\right)^4 = \text{relative damage factor}$$

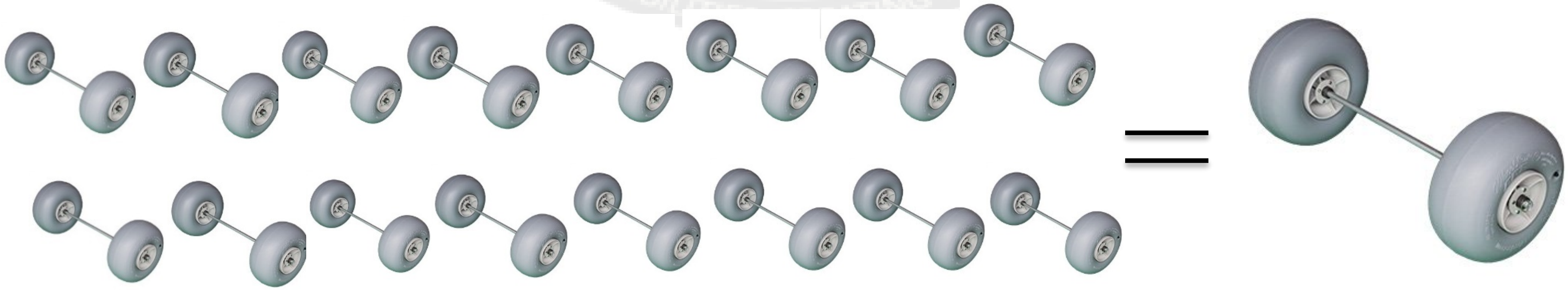
Traffic Load

- **Consider two <u>Axles A</u> and <u>B</u>**
- ***A-Axle = 16.4 tons***
- Damage caused per pass by A-Axle = $(16.4/8.2)^4 = 16$
- It means A-Axle causes same amount of damage per pass as caused by 16 passes of the standard 8.2 ton axle



Traffic Load

- ***B-Axle = 4.1 tons***
- Damage caused per pass by A-Axle = $(4.1/8.2)^4$ = 0.0625
- It means B-Axle causes only 0.0625 times damage per pass as caused by 1passes of the standard 8.2 ton axle.
- In another words 16 (1/0.0625) passes of B-Axle causes same amount of damage as caused by 1 pass of standard 8.2 ton axle.



Traffic Load

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?

Traffic Load

Empty

$$(13{,}000/18{,}000)^4 = 0.272$$

$$(15{,}000/18{,}000)^4 = 0.482$$

$$(9{,}000/18{,}000)^4 = 0.063$$

- Total = 0.817 ESALs

Full

$$(17{,}000/18{,}000)^4 = 0.795$$

$$(20{,}000/18{,}000)^4 = 1.524$$

$$(14{,}000/18{,}000)^4 = 0.366$$

- Total = 2.685 ESALs

➢ Increase in total weight = 14,000 lb. (about 80 people) or 39%

➢ Increase in ESALs is 1.868 (229%)

Traffic Load

Table 19.3b Axle Load Equivalency Factors for Flexible Pavements, Tandem Axles, and p_t of 2.5

	Pavement Structural Number (SN)					
Axle Load (kips)	*1*	*2*	*3*	*4*	*5*	*6*
2	.0001	.0001	.0001	.0000	.0000	.0000
4	.0005	.0005	.0004	.0003	.0003	.0002
6	.002	.002	.002	.001	.001	.001
8	.004	.006	.005	.004	.003	.003
10	.008	.013	.011	.009	.007	.006
12	.015	.024	.023	.018	.014	.013
14	.026	.041	.042	.033	.027	.024
16	.044	.065	.070	.057	.047	.043
18	.070	.097	.109	.092	.077	.070
20	.107	.141	.162	.141	.121	.110
22	.160	.198	.229	.207	.180	.166
24	.231	.273	.315	.292	.260	.242
26	.327	.370	.420	.401	.364	.342
28	.451	.493	.548	.534	.495	.470
30	.611	.648	.703	.695	.658	.633
32	.813	.843	.889	.887	.857	.834
34	1.06	1.08	1.11	1.11	1.09	1.08
36	1.38	1.38	1.38	1.38	1.38	1.38
38	1.75	1.73	1.69	1.68	1.70	1.73
40	2.21	2.16	2.06	2.03	2.08	2.14
42	2.76	2.67	2.49	2.43	2.51	2.61
44	3.41	3.27	2.99	2.88	3.00	3.16
46	4.18	3.98	3.58	3.40	3.55	3.79
48	5.08	4.80	4.25	3.98	4.17	4.49
50	6.12	5.76	5.03	4.64	4.86	5.28
52	7.33	6.87	5.93	5.38	5.63	6.17
54	8.72	8.14	6.95	6.22	6.47	7.15
56	10.3	9.6	8.1	7.2	7.4	8.2
58	12.1	11.3	9.4	8.2	8.4	9.4
60	14.2	13.1	10.9	9.4	9.6	10.7

Traffic Load

- To determine the ESAL, the number of different types of vehicles such as cars, buses, single-unit trucks, and multiple-unit trucks expected to use the facility during its lifetime must be known.
- The total ESAL applied on the highway during its design period can be determined only after the design period and traffic growth factors are known.
- The design period is the number of years the pavement will effectively continue to carry the traffic load without requiring an overlay. Flexible highway pavements are usually designed for a 20-year period

Traffic Load

- Since traffic volume does not remain constant over the design period of the pavement, it is essential that the rate of growth be determined and applied when calculating the total ESAL.
- The growth rate ranges between 3-6% and in some cases up to 10%
- The growth factors (*Grn*) for different growth rates and design periods can be obtained from Equation

$$G_{rn} = \frac{\left[(1+r)^n - 1\right]}{r}$$

n = number of years
r = growth rate in decimals

Traffic Load

Table 19.4 Growth Factors

Design Period, Years (n)	Annual Growth Rate, Percent (r)							
	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

Traffic Load

- The portion of the total ESAL acting on the **design lane (*f_d*)** is used in the determination of pavement thickness.
- Either lane of a two-lane highway can be considered as the design lane whereas for multilane highways, the outside lane is considered

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 6.15 Percentage of Total Truck Traffic in Design Lane

Number of traffic lanes in two directions	Percentage of trucks in design lane
2	50
4	45 (35–48)[a]
6 or more	40 (25–48)[a]

[a] Probable range.
Source. After AI (1981a).

The percentage in Table 6 .1 5 is based on total traffic, but the percentage in Table 6 .16 is based on the traffic in one direction .

Traffic Load

- A general equation for the accumulated ESAL for each category of axle load is obtained as

$$ESAL_i = f_d \times G_{rn} \times AADT_i \times 365 \times N_i \times F_{Ei} \quad (19.2)$$

where

$ESAL_i$ = equivalent accumulated 18,000-lb (80 kN) single-axle load for the axle category i
f_d = design lane factor
G_{rn} = growth factor for a given growth rate r and design period n
$AADT_i$ = first year annual average daily traffic for axle category i
N_i = number of axles on each vehicle in category i
F_{Ei} = load equivalency factor for axle category i

Traffic Load Example

Example 19.1 Computing Accumulated Equivalent Single-Axle Load for a Proposed Eight-Lane Highway Using Load Equivalency Factors

An eight-lane divided highway is to be constructed on a new alignment. Traffic volume forecasts indicate that the average annual daily traffic (AADT) in both directions during the first year of operation will be 12,000 with the following vehicle mix and axle loads.

Passenger cars (1000 lb/axle) = 50%
2-axle single-unit trucks (6000 lb/axle) = 33%
3-axle single-unit trucks (10,000 lb/axle) = 17%

The vehicle mix is expected to remain the same throughout the design life of the pavement. If the expected annual traffic growth rate is 4% for all vehicles, determine the design ESAL, given a design period of 20 years. The percent of traffic on the design lane is 45%, and the pavement has a terminal serviceability index (p_t) of 2.5 and SN of 5.

The following data apply:

Growth factor = 29.78 (from Table 19.4)
Percent truck volume on design lane = 45
Load equivalency factors (from Table 19.3)
Passenger cars (1000 lb/axle) = 0.00002 (negligible)
2-axle single-unit trucks (6000 lb/axle) = 0.010
3-axle single-unit trucks (10,000 lb/axle) = 0.088

Traffic Load

Table 19.4 Growth Factors

Design Period, Years (n)	No Growth	2	4	5	6	7	8	10
	Annual Growth Rate, Percent (r)							
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

Traffic Load

Table 19.3a Axle Load Equivalency Factors for Flexible Pavements, Single Axles, and p_t of 2.5

Axle Load (kips)	Pavement Structural Number (SN) 1	2	3	4	5	6
2	.0004	.0004	.0003	.0002	.0002	.0002
4	.003	.004	.004	.003	.002	.002
6	.011	.017	.017	.013	.010	.009
8	.032	.047	.051	.041	.034	.031
10	.078	.102	.118	.102	.088	.080
12	.168	.198	.229	.213	.189	.176
14	.328	.358	.399	.388	.360	.342
16	.591	.613	.646	.645	.623	.606
18	1.00	1.00	1.00	1.00	1.00	1.00
20	1.61	1.57	1.49	1.47	1.51	1.55
22	2.48	2.38	2.17	2.09	2.18	2.30
24	3.69	3.49	3.09	2.89	3.03	3.27
26	5.33	4.99	4.31	3.91	4.09	4.48
28	7.49	6.98	5.90	5.21	5.39	5.98
30	10.3	9.5	7.9	6.8	7.0	7.8
32	13.9	12.8	10.5	8.8	8.9	10.0
34	18.4	16.9	13.7	11.3	11.2	12.5
36	24.0	22.0	17.7	14.4	13.9	15.5
38	30.9	28.3	22.6	18.1	17.2	19.0
40	39.3	35.9	28.5	22.5	21.1	23.0
42	49.3	45.0	35.6	27.8	25.6	27.7
44	61.3	55.9	44.0	34.0	31.0	33.1
46	75.5	68.8	54.0	41.4	37.2	39.3
48	92.2	83.9	65.7	50.1	44.5	46.5
50	112.0	102.0	79.0	60.0	53.0	55.0

Traffic Load Example

Solution: The ESAL for each class of vehicle is computed from Eq. 19.2.

$$\text{ESAL} = f_d \times G_{jt} \times \text{AADT} \times 365 \times N_i \times F_{Ei}$$

$$\text{2-axle single-unit trucks} = 0.45 \times 29.78 \times 12{,}000 \times 0.33 \times 365 \times 2 \times 0.010$$
$$= 0.3874 \times 10^6$$
$$\text{3-axle single-unit trucks} = 0.45 \times 29.78 \times 12{,}000 \times 0.17 \times 365 \times 3 \times 0.0877$$
$$= 2.6343 \times 10^6$$

Thus,

$$\text{Total ESAL} = 3.0217 \times 10^6$$

It can be seen that the contribution of passenger cars to the ESAL is negligible. Passenger cars are therefore omitted when computing ESAL values. This example illustrates the conversion of axle loads to ESAL using axle load equivalency factors.

Traffic Load Example (Using Truck Factor)

- 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 truck factors is as shown in 0.38, compute the ESAL for a design period of 20 years.

$$ESALs = P_i \times AADT \times G_{rn} \times f_{DL} \times 365 \times T_f$$

$$ESALs = 0.25 \times 4000 \times 29.78 \times 0.50 \times 365 \times 0.38$$

$$ESALs = 2065200$$

P_i = percentage of trucks

Grn = Growth rate factor

f_{DL} = Factor for design lane

T_f = Truck Factor

Traffic Load Example

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

	Truck Factors					
	Rural systems					
				Collectors		
Vehicle type	Interstate	Other Principal	Minor Arterial	Major	Minor	Range
Single-unit trucks						
2-axle, 4-tire	0.003	0.003	0.003	0.017	0.003	0.003–0.017
2-axle, 6-tire	0.21	0.25	0.28	0.41	0.19	0.19–0.41
3-axle or more	0.61	0.86	1.06	1.26	0.45	0.45–1.26
All single units	0.06	0.08	0.08	0.12	0.03	0.03–0.12
Tractor semitrailers						
4-axle or less	0.62	0.92	0.62	0.37	0.91	0.37–0.91
5-axle[b]	1.09	1.25	1.05	1.67	1.11	1.05–1.67
6-axle or more[b]	1.23	1.54	1.04	2.21	1.35	1.04–2.21
All multiple units	1.04	1.21	0.97	1.52	1.08	0.97–1.52
All trucks	0.52	0.38	0.21	0.30	0.12	0.12–0.52

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).

Traffic Load Example

	Truck Factor					
	Urban systems					
Vehicle type	Interstate	Other Freeways	Other Principal	Minor Arterial	Collectors	Range
Single-unit trucks						
2-axle, 4-tire	0.002	0.015	0.002	0.006	—	0.006–0.015
2-axle, 6-tire	0.17	0.13	0.24	0.23	0.13	0.13–0.24
3-axle or more	0.61	0.74	1.02	0.76	0.72	0.61–1.02
All single units	0.05	0.06	0.09	0.04	0.16	0.04–0.16
Tractor semitrailers						
4-axle or less	0.98	0.48	0.71	0.46	0.40	0.40–0.98
5-axle[b]	1.07	1.17	0.97	0.77	0.63	0.63–1.17
6-axle or more[b]	1.05	1.19	0.90	0.64	—	0.64–1.19
All multiple units	1.05	0.96	0.91	0.67	0.53	0.53–1.05
All trucks	0.39	0.23	0.21	0.07	0.24	0.07–0.39


Q
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Answer