APPENDIX D

CUMULATIVE AXLE LOAD DISTRIBUTION AS A FUNCTION OF TIRE FOOTPRINT LENGTH

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CUMULATIVE AXLE LOAD DISTRIBUTION ON TIRE LENGTH

In order to analyze traffic load effect for reflection cracking, the length of tire patch was used to evaluate bending or shearing stress in asphalt overlay. Also, cumulative axle load distribution on tire length for each category should be determined based on collected traffic data such as WIM or AADTT.

Tire Patch Length

Existing practice for the evaluation of tire load effects on pavements assumes that the shape of the contact tire patch is a circle with an area which is equal to the ratio of the tire load over the tire pressure. However, a rectangular shape of tire contact area is close to real shape of tire applied to pavement surface (26). Therefore, the model tire load using the rectangular tire contact area, as shown in Figure D-1, was used to evaluate the effect of tire load on reflection cracking since the assumption can provide reasonable analysis of pavement response to tire loads.

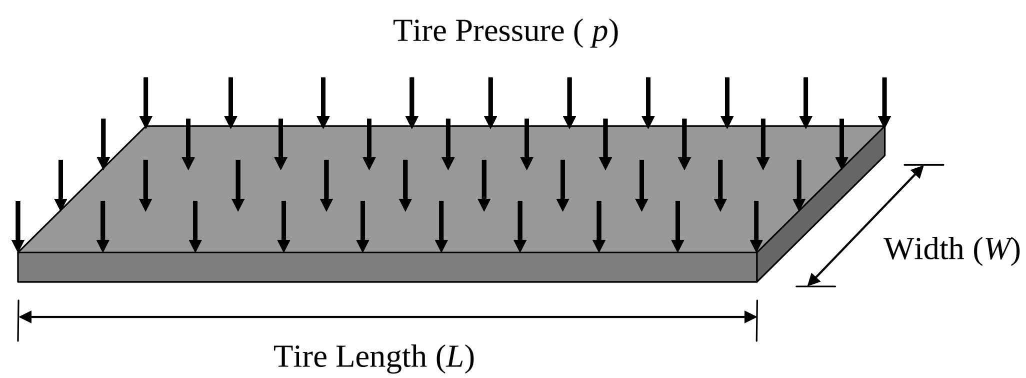


Figure D-1. Tire load applied to pavement surface.

Tire patch length would be variable for each traffic category (vehicle class and axle type) and under different tire pressure while tire width is constant. Thus, the tire length should be calculated based on the tire pressure and width and the axle load of each vehicle class as follows:

$$\text{Tire Length (in)} = \frac{\text{tire load (lb)}}{\text{tire pressure (lb/in}^2) \times \text{tire width (in)}}$$

$$= \frac{\text{axle load (lb)} \big/ \text{No. of tires}}{\text{tire pressure (lb/in}^2) \times \text{tire width (in)}} \qquad \text{(D-1)}$$

Determination of Cumulative Axle Load Distribution on Tire Length

It may be difficult to employ each tire length for axle load intervals to evaluate traffic load effects on propagation of reflection cracking. Therefore, the axle load distribution on tire patch length for each category was used for the evaluation of traffic load, instead of the axle load distribution on axle load mentioned previously. To convert the axle load distribution on load interval into on tire length, tire length for each load interval should be determined based on the characteristics of each axle type as presented in Table D-1.

The tire patch lengths on corresponding axle load intervals for each category could be calculated using Equation 1 and the characteristics of axle types. Table D-1 lists the calculated tire lengths on axle load intervals for all traffic categories. The tire patch length increment in Table D-2 should be used for the *x*-axis on the axle load distribution of the tire patch length.

Table D-1. Typical characteristics for each axle type.

Category	Axle Type	Tires	Tire width (in.)	Tire Pressure (PSI)	Axle Load Interval (lb.)
1	Single	Single	7.874	40 (< 6,000 lb) 120 (> 6,000 lb)	3,000 ~ 40,000 lb. at 1,000 lb intervals
2		Dual	8.740		
3	Tandem	Single	7.874	120	6,000 ~ 80,000 lb. at 2,000 lb intervals
4		Dual	8.740	120	
5	Tridem	Single	7.874	120	12,000 ~ 102,000 lb at 3,000 lb intervals
6		Dual	8.740	120	
7	Quad	Single	7.874	120	12,000 ~ 102,000 lb at 3,000 lb intervals
8		Dual	8.740	120	

Using the tire patch length and collected traffic data, cumulative axle load distribution can be determined for each category. Figure D-2 is the diagram illustrating the procedure for determining tire length and the cumulative axle load distribution of each category. The cumulative axle load distribution on tire length should be produced for all 8-categories to account for all types of vehicle and axles.

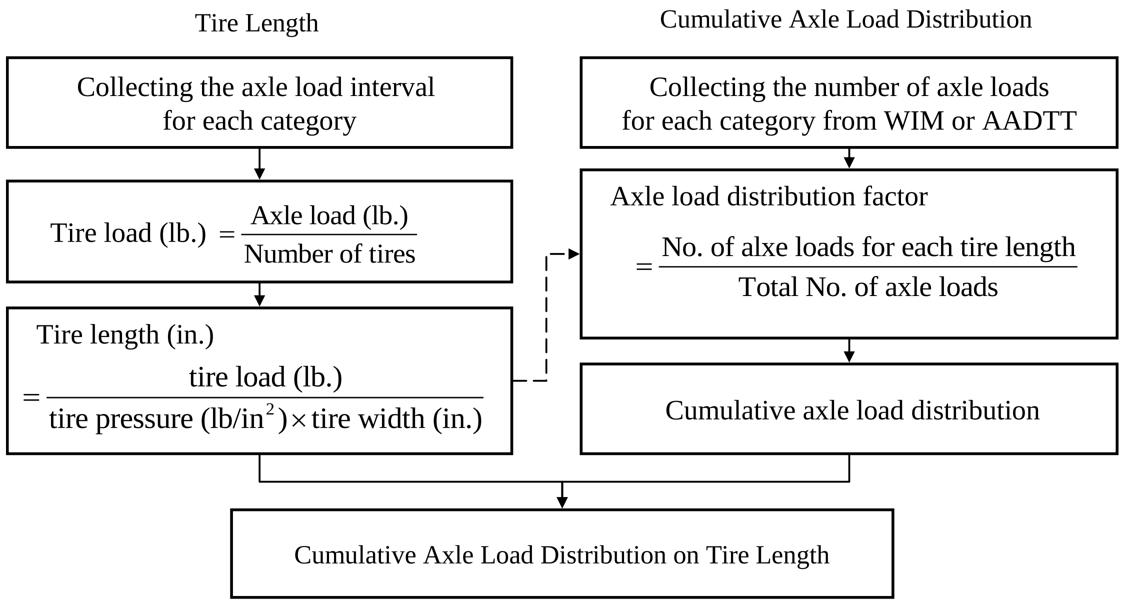


Figure D-2. Procedure for determination of cumulative axle load distribution on tire patch length.

Table D-2. Tire patch length increment for each load category.

No.	Category							
	1	2	3	4	5	6	7	8
1	3.704	1.669	1.588	0.715	2.117	0.953	1.588	0.715
2	4.233	1.907	2.117	0.953	2.646	1.192	1.984	0.894
3	4.763	2.145	2.646	1.192	3.175	1.430	2.381	1.073
4	5.292	2.384	3.175	1.430	3.704	1.669	2.778	1.251
5	5.821	2.622	3.704	1.669	4.233	1.907	3.175	1.430
6	6.350	2.860	4.233	1.907	4.763	2.145	3.572	1.609
7	6.879	3.099	4.763	2.145	5.292	2.384	3.969	1.788
8	7.408	3.337	5.292	2.384	5.821	2.622	4.366	1.967
9	7.938	3.576	5.821	2.622	6.350	2.860	4.763	2.145
10	8.467	3.814	6.350	2.860	6.879	3.099	5.159	2.324
11	8.996	4.052	6.879	3.099	7.408	3.337	5.556	2.503
12	9.525	4.291	7.408	3.337	7.938	3.576	5.953	2.682
13	10.054	4.529	7.938	3.576	8.467	3.814	6.350	2.860
14	10.583	4.767	8.467	3.814	8.996	4.052	6.747	3.039
15	11.113	5.006	8.996	4.052	9.525	4.291	7.144	3.218
16	11.642	5.244	9.525	4.291	10.054	4.529	7.541	3.397
17	12.171	5.482	10.054	4.529	10.583	4.767	7.938	3.576
18	12.700	5.721	10.583	4.767	11.113	5.006	8.334	3.754
19	13.229	5.959	11.113	5.006	11.642	5.244	8.731	3.933
20	13.758	6.198	11.642	5.244	12.171	5.482	9.128	4.112
21	14.288	6.436	12.171	5.482	12.700	5.721	9.525	4.291

Table D-2. Tire patch length increment for each load category (continued).

No.	Category							
	1	2	3	4	5	6	7	8
22	14.817	6.674	12.700	5.721	13.229	5.959	9.922	4.469
23	15.346	6.913	13.229	5.959	13.758	6.198	10.319	4.648
24	15.875	7.151	13.758	6.198	14.288	6.436	10.716	4.827
25	16.404	7.389	14.288	6.436	14.817	6.674	11.113	5.006
26	16.933	7.628	14.817	6.674	15.346	6.913	11.509	5.184
27	17.463	7.866	15.346	6.913	15.875	7.151	11.906	5.363
28	17.992	8.105	15.875	7.151	16.404	7.389	12.303	5.542
29	18.521	8.343	16.404	7.389	16.933	7.628	12.700	5.721
30	19.050	8.581	16.933	7.628	17.463	7.866	13.097	5.900
31	19.579	8.820	17.463	7.866	17.992	8.105	13.494	6.078
32	20.108	9.058	17.992	8.105	18.521	8.343	13.891	6.257
33	20.638	9.296	18.521	8.343	19.050	8.581	14.288	6.436
34	21.167	9.535	19.050	8.581	19.579	8.820	14.684	6.615
35	-	-	19.579	8.820	20.108	9.058	15.081	6.793
36	-	-	20.108	9.058	20.638	9.296	15.478	6.972
37	-	-	20.638	9.296	21.167	9.535	15.875	7.151
38	-	-	21.167	9.535	-	-	-	-

Figure D-3 shows the cumulative axle load distribution on tire load for Category 1 of LTPP section 180901 in 2004, which was determined using the data in Table D-2.

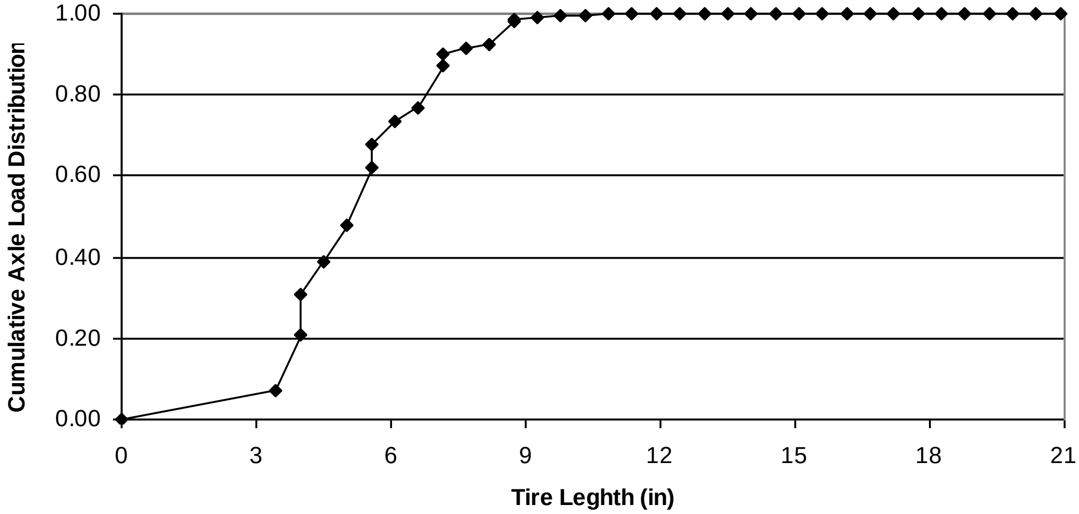


Figure D-3. Cumulative annual axle load distribution on tire length (category 1 of LTPP section 180901 in 2004)

Modeling of Cumulative Axle Load Distribution

Since the frequency distribution of each tire length of a category is used to evaluate load effects for reflection cracking propagation in this study, the cumulative axle load distribution of any pavement sections and categories should be developed along with the tire length. It is well known fact that the cumulative axle load distribution on traffic loads or tire length follows a sigmoidal curve having a lower asymptote of zero and a finite upper asymptote as shown in Figure D-4.

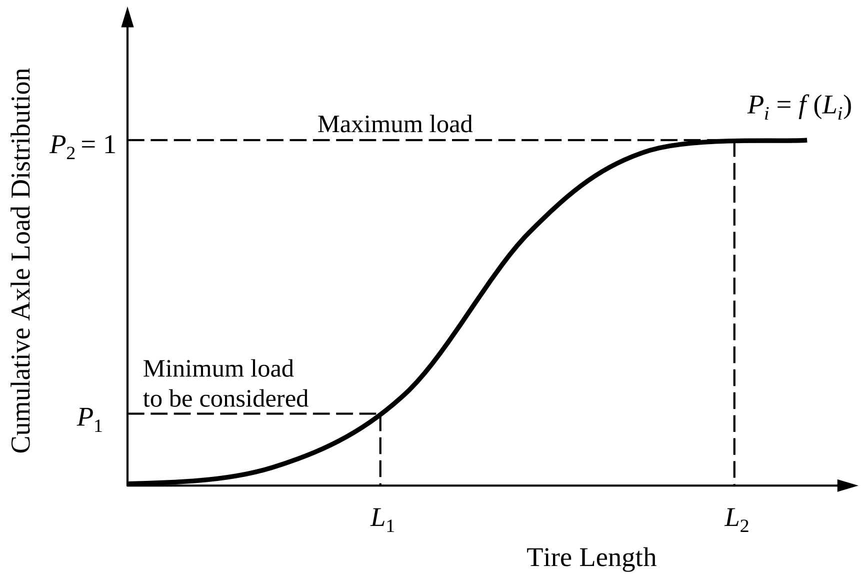


Figure D-4. Typical cumulative axle load distribution curve.

After searching useful models which can describe the statistical properties of cumulative axle load distribution on tire length, the Gompertz model was chosen follows as;

$$y = \alpha \exp\left[-\exp\left(\beta - \gamma x\right)\right] \quad \text{(D-2)}$$

where

α, β, and γ = model parameters

The Gompertz model can describe cumulative axle load distribution curve successfully since it has clear physical boundary condition which shows asymptotes at $y = 0$ and $y = \alpha$ and is asymmetric about its inflection point which occurs at β / γ (27). The parameter α in the model indicates the upper asymptote which is equal to 1.00 (100 percent) for cumulative axle load distribution curve. The parameter β describes how wide the rising portion of the curve is. In addition, the parameter γ indicates the slope of the cumulative axle load distribution curve. Figure D-5 illustrates a typical curve of Gompertz model with the explanation of each parameter.

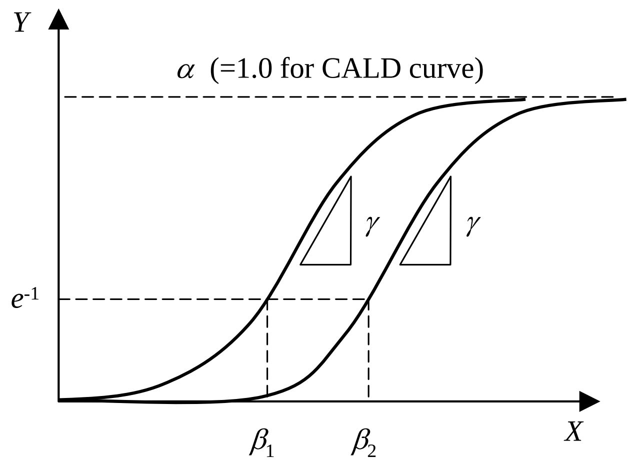


Figure D-5. Gompertz model curve.

The parameter α should be equal to 1.00 since the cumulative axle load distribution curve has physical boundary condition ranging 0 to 1.00 or 0 to 100 percent. Therefore, the modified model for cumulative axle load distribution can be defined as:

$$C(L_i)_j = \exp\left[-\exp\left(\beta - \gamma L_{ij}\right)\right] \quad \text{(D-3)}$$

where

L_{ij}	=	i^{th} tire length in tire patch length increment at category j
$C(L_i)_j$	=	cumulative axle load distribution factor at L_i within category j
β, γ	=	model parameters describing curve width and slope, respectively

The typical characteristics for each category as resented in Table C-3 and the collected traffic data from WIM or AADTT in a given section were used to develop the model parameters β and γ in the modified Gompertz model of Equation D-3. The results presented good data fitting along with relatively high significance. As an example, Table D-3 presents the developed model parameters β and γ for the category 1 of LPTT section 180901.

Table D-3. Model parameters and CALD on tire length (category 1 of LTPP section 180901 in 2004).

Parameter	Values	CALD Value		Tire Length (in.)	
β	4.301	C_1	0.071	L_1	3.704
γ	0.967	C_2	1.000	L_2	16.933
R^2	0.982				

Figure D-6 illustrates the plots of calibrated model corresponding measured traffic data for the LTPP section. The distribution factor of C_1 represents the minimum axle load (tire length) to be considered for load related distress. The lower limits of axle load and tire length are presented in Table D-4. C_2 is the factor at which the cumulative distribution reaches 100 percent first. L_1 and L_2 are corresponding tire lengths to C_1 and $C_{2,}$ respectively. The model parameters and plots of calibrated cumulative axle load distribution on tire lengths for all categories of the section 180901 can be found in subsequently in this appendix.

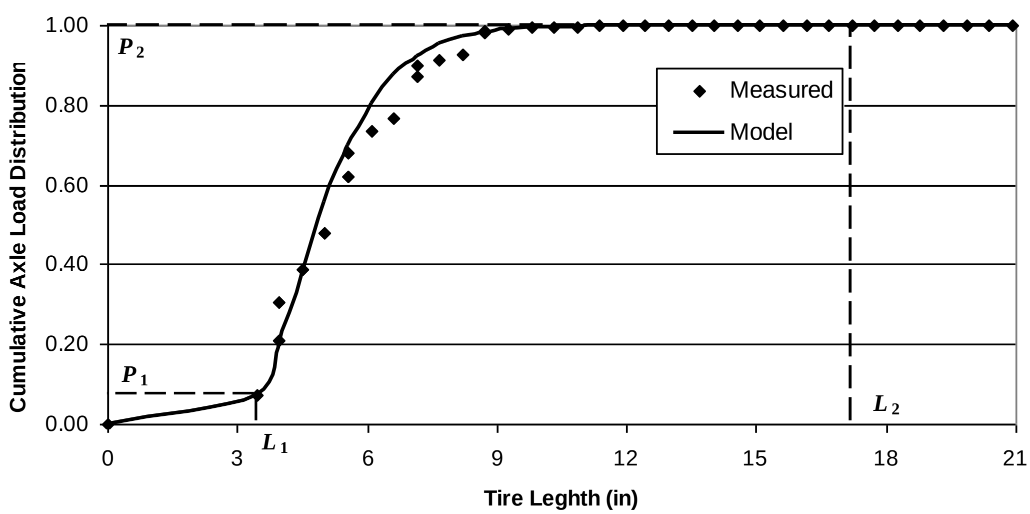


Figure D-6. Cumulative axle load distribution on tire length (category 1 of LTPP section 180901 in 2004.)

Table D-4. Minimum values to be considered for load related distress.

Category	Axle Type	Minimum Values	
		Axle load (lb.)	Tire Length (in.)
1	Single	3,000	3.704
2			1.669
3	Tandem	6,000	1.588
4			0.715
5	Tridem	12,000	2.117
6			0.953
7	Quad	12,000	1.588
8			0.715

For Level 1 data inputs, the model parameters for cumulative axle load distribution can be computed using WIM data for each category, while the default values for Level 3 input are provided. The default model parameters, as shown in Table D-5, were prepared using traffic data from the LTPP database. Also, Table D-6 presents the default cumulative axle load distribution values which were determined based on the model parameters default values.

Table D-5. CALD model parameter default values determined based on LTPP data.

Category	Parameters		R^2
	β	γ	
1	3.44056	0.73836	0.980
2	3.58353	1.61999	0.999
3	1.62387	0.48959	0.972
4	2.03042	1.04234	0.990
5	1.72904	1.10906	0.906
6	1.92533	1.02297	0.982
7	1.47412	0.98443	0.969
8	2.70840	1.48446	0.956

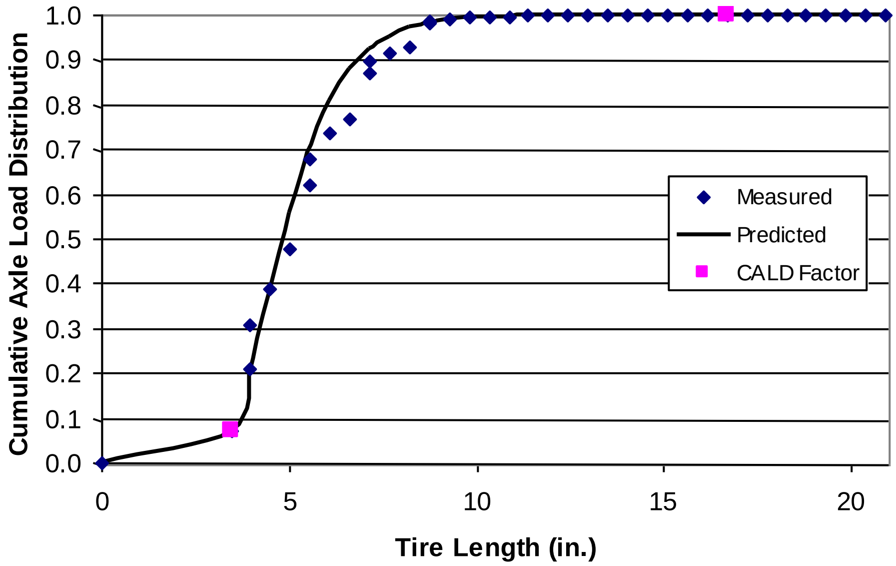
Table D-6. Default cumulative axle load distribution for each load category.

No.*	Category							
	1	2	3	4	5	6	7	8
1	0.1320	0.0896	0.0971	0.0269	0.5835	0.0754	0.4005	0.0056
2	0.2541	0.1941	0.1654	0.0596	0.7411	0.1318	0.5384	0.0187
3	0.3958	0.3282	0.2494	0.1109	0.8465	0.2044	0.6578	0.0472
4	0.5341	0.4689	0.3424	0.1799	0.9115	0.2882	0.7532	0.0962
5	0.6542	0.5977	0.4373	0.2624	0.9498	0.3772	0.8255	0.1660
6	0.7505	0.7048	0.5281	0.3522	0.9718	0.4658	0.8783	0.2523
7	0.8235	0.7884	0.6110	0.4431	0.9842	0.5496	0.9160	0.3478
8	0.8769	0.8508	0.6837	0.5300	0.9912	0.6256	0.9423	0.4449
9	0.9149	0.8960	0.7457	0.6094	0.9951	0.6924	0.9606	0.5373
10	0.9416	0.9281	0.7973	0.6796	0.9973	0.7497	0.9732	0.6210
11	0.9601	0.9505	0.8396	0.7398	0.9985	0.7979	0.9818	0.6940
12	0.9728	0.9661	0.8738	0.7905	0.9992	0.8379	0.9876	0.7557
13	0.9815	0.9768	0.9011	0.8325	0.9995	0.8706	0.9916	0.8067
14	0.9875	0.9842	0.9228	0.8668	0.9997	0.8971	0.9943	0.8481
15	0.9915	0.9892	0.9399	0.8945	0.9999	0.9184	0.9962	0.8813
16	0.9942	0.9927	0.9533	0.9167	0.9999	0.9355	0.9974	0.9076
17	0.9961	0.9950	0.9637	0.9344	1.0000	0.9491	0.9982	0.9284
18	0.9974	0.9966	0.9719	0.9484	1.0000	0.9599	0.9988	0.9446
19	0.9982	0.9977	0.9782	0.9596	1.0000	0.9684	0.9992	0.9572
20	0.9988	0.9984	0.9832	0.9683	1.0000	0.9752	0.9995	0.9670
21	0.9992	0.9989	0.9870	0.9752	1.0000	0.9805	0.9996	0.9746
22	0.9994	0.9993	0.9899	0.9806	1.0000	0.9847	0.9997	0.9805

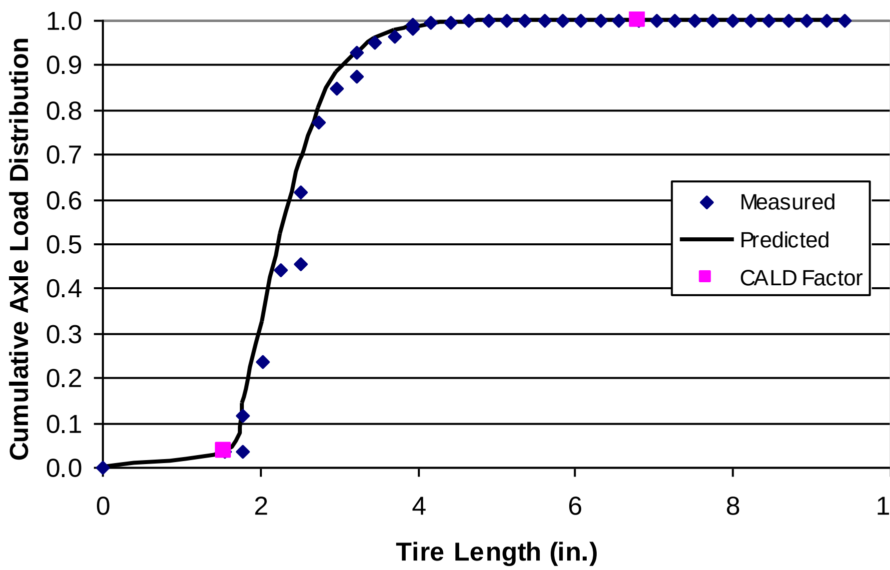
Table D-6. Default cumulative axle load distribution for each load category (continued).

No.*	Category							
	1	2	3	4	5	6	7	8
23	0.9996	0.9995	0.9922	0.9848	1.0000	0.9880	0.9998	0.9850
24	0.9997	0.9997	0.9940	0.9882	1.0000	0.9906	0.9999	0.9885
25	0.9998	0.9998	0.9954	0.9907	1.0000	0.9926	0.9999	0.9911
26	0.9999	0.9998	0.9964	0.9928	1.0000	0.9942	0.9999	0.9932
27	0.9999	0.9999	0.9972	0.9944	1.0000	0.9954	1.0000	0.9948
28	0.9999	0.9999	0.9979	0.9956	1.0000	0.9964	1.0000	0.9960
29	1.0000	1.0000	0.9984	0.9966	1.0000	0.9972	1.0000	0.9969
30	1.0000	1.0000	0.9987	0.9973	1.0000	0.9978	1.0000	0.9976
31	1.0000	1.0000	0.9990	0.9979	1.0000	0.9983	1.0000	0.9982
32	1.0000	1.0000	0.9992	0.9984	1.0000	0.9987	1.0000	0.9986
33	1.0000	1.0000	0.9994	0.9987	1.0000	0.9989	1.0000	0.9989
34	1.0000	1.0000	0.9995	0.9990	1.0000	0.9992	1.0000	0.9992
35	-	-	0.9997	0.9992	1.0000	0.9994	1.0000	0.9994
36	-	-	0.9997	0.9994	1.0000	0.9995	1.0000	0.9995
37	-	-	0.9998	0.9995	1.0000	1.0000	1.0000	1.0000
38	-	-	1.0000	1.0000	-	-	-	-

* Number represents the tire patch length increment listed in Table D-2.

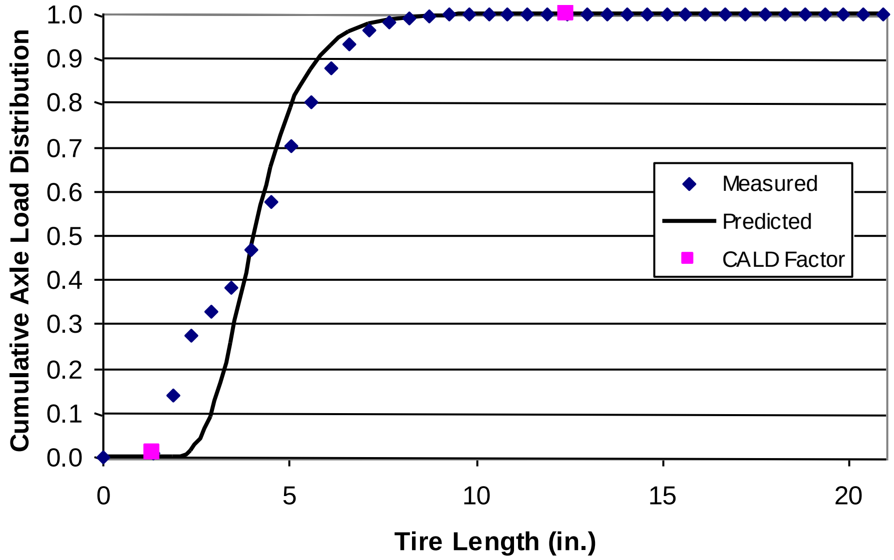


(a) Category 1 (Single axle/single tire)

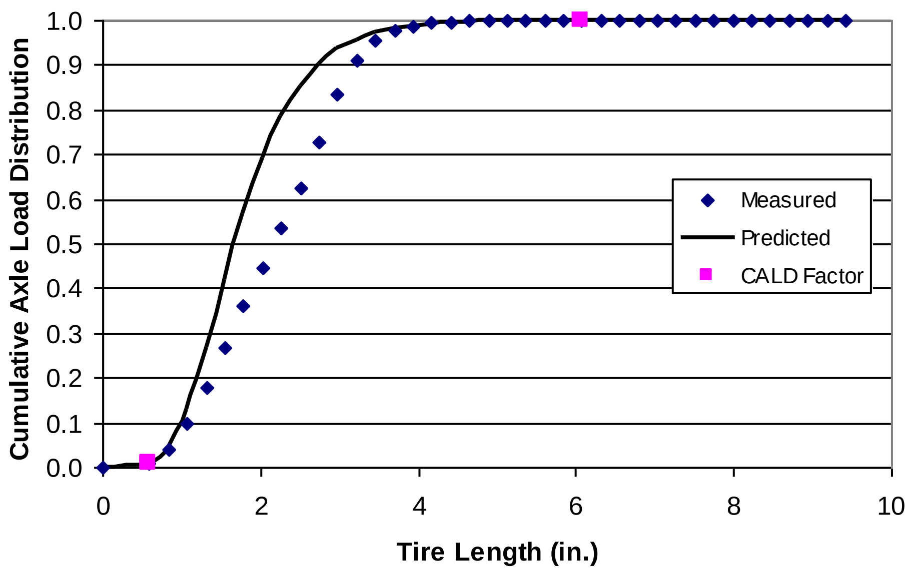


(b) Category 2 (Single axle/dual tires)

Figure D-7. Cumulative axle load distribution for LTPP section 180901 (2004).

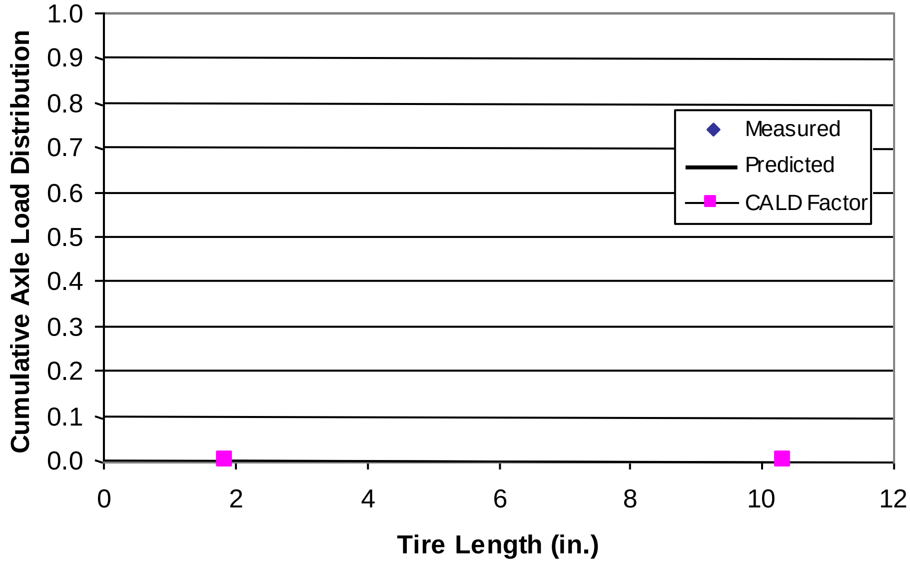


(c) Category 3 (tandem axle/single tire)

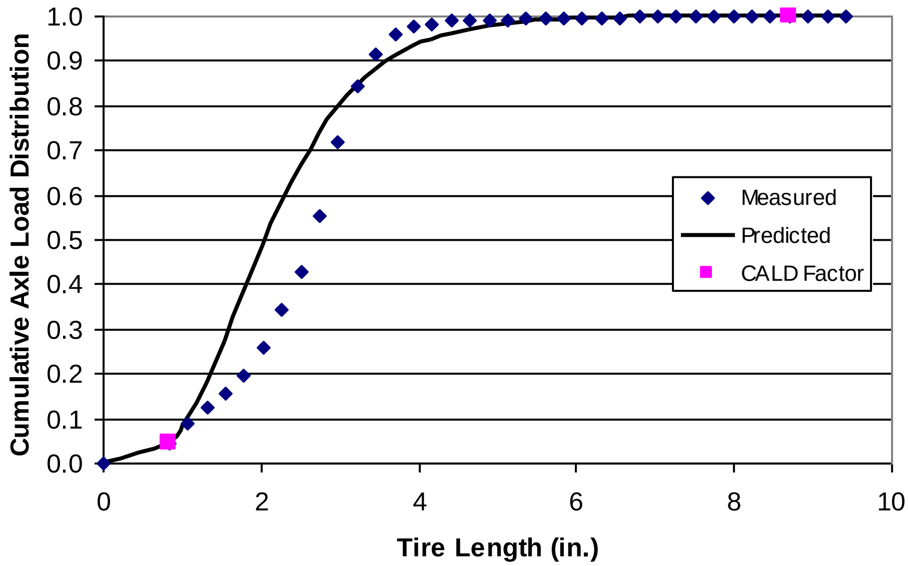


(d) Category 4 (Tandem axle/dual tires)

Figure D-7. Cumulative axle load distribution for LTPP section 180901 (2004) (continued).

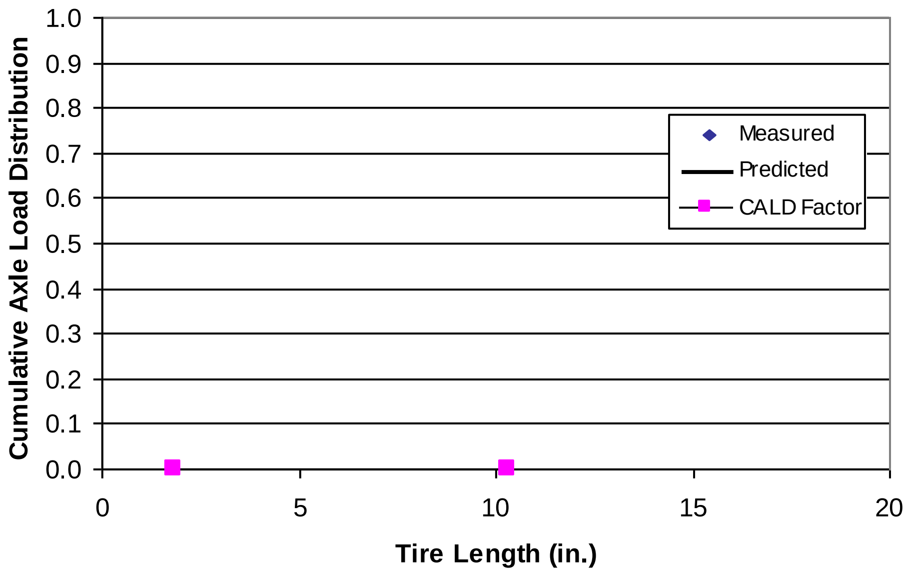


(e) Category 5 (Tridem axle/single tire)

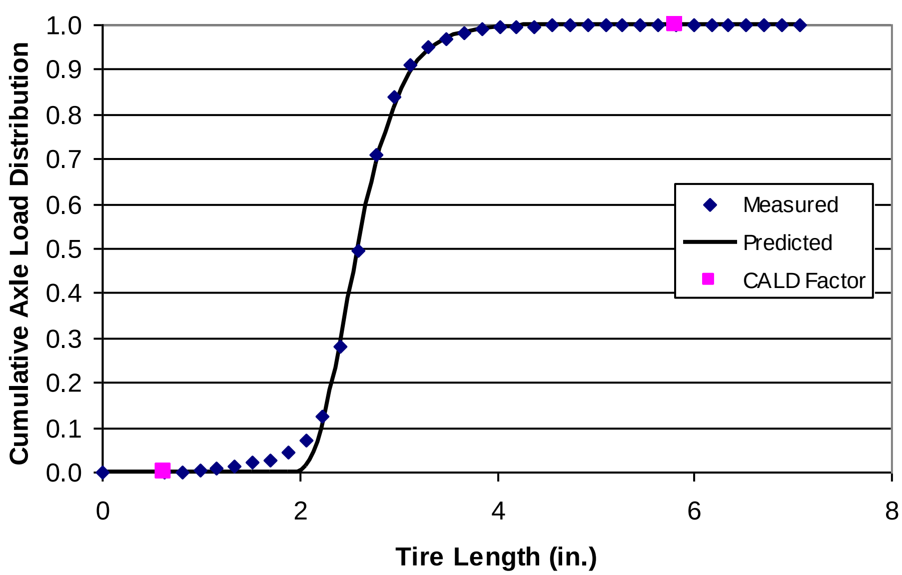


(f) Category 6 (Tridem axle/dual tires)

Figure D-7. Cumulative axle load distribution for LTPP section 180901 (2004) (continued).



(g) Category 7 (Quad axle/single tire)



(h) Category 8 (Quad axle/dual tires)

Figure D-7. Cumulative axle load distribution for LTPP section 180901 (2004) (continued).

The following figures and tables are presented as an example of a complete characterization of the cumulative axle load distribution for a specific pavement section, LTPP Section 180901.

These eight cumulative axle load distributions graphs have been generated with the β and γ model parameters that are found in Table D-7. Load categories 5 and 7 were missing and this fact is reflected in Table D-7 which is missing the β and γ values for those two categories of traffic load.

Table D-7. Model parameters and CALD on tire length of LTPP section 180901 (2004).

Category	Parameter			CALD Value		Tire Length (in.)	
	β	γ	R^2	C_1	C_3	L_1	L_3
1	4.301	0.967	0.982	0.071	1.000	3.440	16.669
2	4.781	2.302	0.977	0.034	1.000	1.549	6.793
3	4.075	1.096	0.948	0.010	1.000	1.323	12.435
4	2.627	1.789	0.934	0.008	1.000	0.596	6.078
5	-	-	-	-	-	-	-
6	2.140	1.215	0.943	0.046	1.000	0.834	8.700
7	-	-	-	-	-	-	-
8	8.384	3.377	0.999	0.001	1.000	0.626	5.810