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Modeling of an asphalt pavement through the use of rational methodology and axle load spectra

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Abstract:

The traffic corresponds to one of the most important variables for the design of a pavement structure, for this reason, it must be evaluated and characterized in such a way that the effects generated on the modeled structure for a particular design, represent the real state of stresses to which the structure will be subjected during the service life. In order to fulfill this task, in this work the modeling of an asphalt pavement structure has been carried out, through the implementation of design by rational methodology and characterization of vehicular traffic through the axle load spectra, determined from a fixed gauging station and a mobile weighing operation, carried out in the Calamar-Barranquilla road sector, located in northern Colombia. For the determination of the stress and deformation state in the pavement structure, the Shell's BISAR software and the TRRL fatigue laws were used. In accordance with the results obtained, it could be established that the characterization of the traffic through the axle load spectra constitutes an effective way of representing the effect generated by vehicular traffic on an asphalt pavement structure.

Keywords - Asphalt pavement, Axle load spectra, rational design.

1. INTRODUCTION

In order to obtain the traffic variable for pavement design purposes, information related to the traffic volumes of the expected commercial vehicles must be available, as well as the distribution of the axle loads characteristic of the vehicles that make use of the road corridor under study [1]. For this purpose, traffic volumes can be estimated from historical series based on vehicle measurements made previously, over several years [2], or from specific vehicle counts carried out over several days, generally for a week in duration, in where all vehicles passing through the road section under study must be continuously classified and counted [3].

Regarding the effects generated by traffic loads, these can be characterized through the number of equivalent 80 KN standard axles expected in the design lane [2], or through the axle load spectra expected during the design period [4]. In both cases, information is required related to the characteristic loads of commercial vehicles that make use of the road corridor, and in particular, the axle loads transmitted by the heaviest vehicles (buses and trucks), this information being It achieves in Colombia from the weighing of the axles of the vehicles through mobile weighing operations, which are carried out in some strategically located sites within the different road sectors of the country [5].

In the case of asphalt pavements, most of the methods used for the design of this type of structure, such as the method of the Asphalt Institute, Shell and AASHTO-93, among others, characterize the traffic in terms the number of equivalent single axle load (ESAL) [6]; In contrast to this, in the case of rigid pavements, some methods, such as the PCA, characterize the traffic in terms of the axle load spectra, for which they determine the number of repetitions expected at each load step, for each of the axis configurations considered as representative [2], which correspond to the simple, tandem and tridem axles.

Although as noted above, the most widely used methods for the design of flexible pavement structures have traditionally characterized the traffic variable in terms of the number of equivalent standard axles [7], there is an increasingly pronounced trend to characterize the traffic to through the expected axle load spectra [8], [9], with which an estimate of the grouped effects of traffic loads can be obtained, through the determination of the number and type of vehicles that will circulate through the route, as well as the intensity of the weight and the configuration of the axis that applies it [10].

With regard to the design of the pavement in a flexible type structure, this work can be carried out, either by using empirical methods, such as the AASHTO-93 [2], or by implementing rational design, through the use of computational tools for the dimensioning of structures and of fatigue laws of materials [11].

The essential objective of this work has been to project the required thicknesses of an asphalt pavement through a rational design methodology, through the use of computational tools and characterization of the traffic in terms of the effects generated by the axle load spectra, based on the information obtained from a mobile weighing operation and vehicle gauging carried out along the Calamar - Barranquilla road corridor, located in northern Colombia.

2. MATERIALS AND METHODS

2.1 Vehicle volumes

The information related to the vehicular volume of the road section under study has been obtained from the periodic vehicular gauges carried out by the Instituto Nacional de Vías (INVIAS) throughout the different sectors that said entity is in charge of. In particular, the information recorded on the measurements carried out during 2018 was compared with the volumes registered at the existing Toll Station within the Calamar - Barranquilla sector, making it possible to determine the design traffic for the project, discriminated in its different types of vehicles.

For the determination of the total volume of heavy vehicles expected in the design lane during the design period, the following expression [2], [12] is used:

$$V_{HV} = ADT_i \cdot \frac{A}{100} \cdot \frac{B}{100} \cdot 365 \cdot \frac{(1+r)^n - 1}{\ln(1+r)} \qquad (1)$$

Where:

V_{HV}: Total number of heavy vehicles in the design lane

*ADT*i: initial average daily traffic

A: percentage of commercial vehicles of the capacity

B: factor per lane

r: annual growth rate of transit

n: design period (in years)

2.2 Information on vehicle weighing and axle load spectra

For the determination of the spectra of load per axles representative of the road corridor under study, the information provided by the Instituto Nacional de Vías, in relation to a mobile weighing operation carried out along the Calamar - Barranquilla section, where a sample made up of 2665 heavy trucks was taken into consideration.

To obtain the axle load spectrum of each class of truck, these were grouped by configuration, and for each axle, the weights obtained were ordered in ascending order, in order to obtain the frequency corresponding to each considered load interval. For this purpose, in the case of directional and non-directional simple axles, an interval width of one ton was taken; while in the case of the tandem and tridem axles, a width of two tons was used. For all cases, the corresponding average load was taken as the representative load for each interval.

2.3 Modeling the pavement structure

For the modeling of the pavement structure, a preliminary dimensioning was initially carried out, using the AASHTO-93 method, and from this, the trial thickness was established, to finally propose a structure that would check by rational design method with the two failure criteria considered: by tensile deformation in the lower fiber of the asphalt layers and by vertical deformation on the subgrade. To obtain the stress state, the BISAR software was used, determining through this tool the deformation values generated for each load step and from the fatigue laws of the TRRL (Transport and Road Research Laboratory), it was possible to establish the admissible repetitions for each load step, considering the four types of axles characteristic of the vehicles that most frequently transit through Colombian roads: directional single axles, non-directional single axles, tandem axles and tridem axles.

3. RESULTS AND DISCUSSION

3.1 Obtaining the transit for design

The vehicle volumes discriminated in the different typologies are shown in Table 1, in the case of the average daily monthly traffic; and in Table 2, in the case of the annual average daily traffic, for the year 2018, respectively. For the determination of the total volume of commercial vehicles from Equation 1, it was taken into consideration that the road under study is made up of a road with two lanes, with traffic in both directions of movement. Based on the information shown in Table 2, considering a 10 year design period and an estimated annual traffic growth rate of 3.0%, a total volume of expected commercial vehicles in the design lane of 2,773,386 was obtained.

Table - 1 Average daily monthly traffic during the year 2018. "Calamar" Toll Station.

AVERAGE DAILY MONTHLY TRANSIT – CALAMAR TOLL STATION - YEAR 2018									
MONTHS	**Light Cars**	**Buses**	**C2P**	**C2G**	**C3**	**C2-S2**	**C3-S2**	**C3-S3**	**TOTAL**
January	1656	220	54	630	52	14	87	262	2975
February	1090	223	53	624	50	13	100	273	2426
March	1380	218	55	636	47	12	84	256	2688
April	1174	227	55	640	55	14	96	277	2538
May	1054	206	53	621	49	13	77	218	2291
June	1221	190	53	622	38	10	55	172	2361
July	1291	207	52	611	46	12	76	236	2531
August	1127	219	54	629	57	15	86	254	2441
September	1052	217	53	618	59	16	90	250	2355
October	1172	221	55	636	66	18	90	239	2497
November	1173	227	55	639	68	18	97	260	2537
December	1547	236	58	674	86	23	93	248	2965

Source: Traffic and Collection Monthly Historical Rate Series From 2014 to July 2019 – Agencia Nacional de Infraestructura (ANI).

Table - 2 Average daily daily traffic during 2018. "Calamar" Toll Station.

ANNUAL DAILY AVERAGE TRANSIT - CALAMAR TOLL STATION - YEAR 2018									
	Light Cars	**Buses**	**C2P**	**C2G**	**C3**	**C2-S2**	**C3-S2**	**C3-S3**	**TOTAL**
TPDA	1247	218	54	632	56	15	86	245	2553

Source: Traffic and Collection Monthly Historical Rate Series From 2014 to July 2019 - Agencia Nacional de Infraestructura (ANI).

The spectra shown have been obtained by comparing the information recorded in the mobile weighing operation with the information on the vehicle volumes taken from Table 2. In the generated graphics, the number of axles expected within a given load range is represented for each type of axle, for every 100 heavy vehicles that pass through a section of the road.

Figure 1 shows the axle load spectra representative of the road sector under study, for the four types of axles characteristic of heavy vehicles passing through said road corridor.

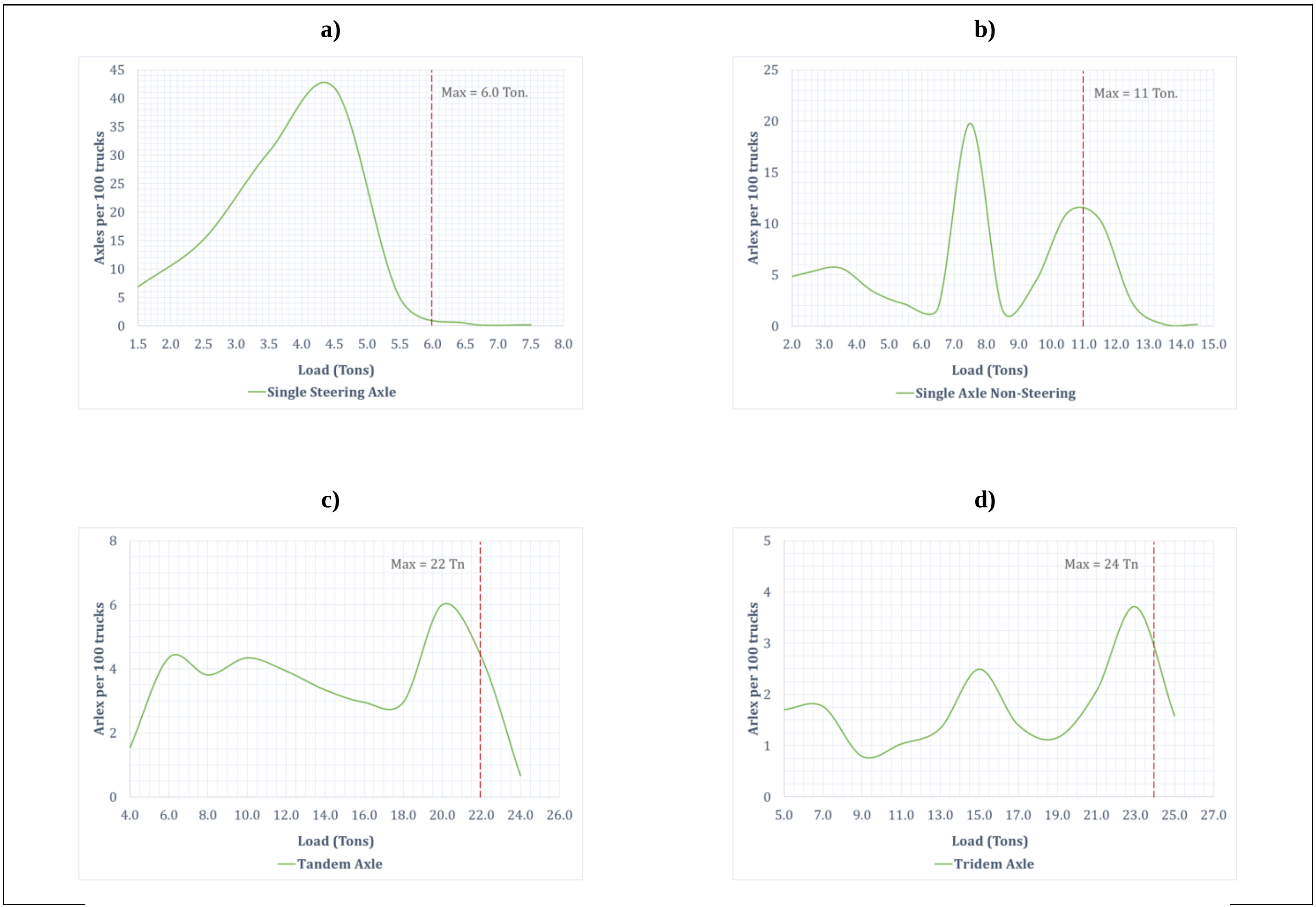

Figure 1. Load spectrum for: a) single steering axle, b) single axle non-steering, c) Tandem Axle and d) Tridem axle

Table 3 shows the relationship and number of trucks analyzed, which were weighed in a mobile operation carried out within the Calamar - Barranquilla Highway Sector, which corresponds to the road corridor analyzed in this work.

Table - 3 List of heavy trucks within the Calamar - Barranquilla road sector

TYPE OF TRUCK	NUMBER
C2-P	160
C2-G	1866
C3	125
C2-S2	33
C3-S2	165
C3-S3	316
TOTAL	2665

Source: Technical Secretariat of the Instituto Nacional de Vías of Colombia

Table 4 shows the expected number of repetitions for each load range and for each type of axle.

Table - 4 Number of repetitions expected for each load range per axle type

SINGLE AXLE, SIMPLE WHEEL		SINGLE AXLE, DOUBLE WHEEL		TANDEM AXLE		TRIDEM AXLE	
LOAD (KN)	**EXPECTED REPETITIONS**	**LOAD (KN)**	**EXPECTED REPETITIONS**	**LOAD (KN)**	**EXPECTED REPETITIONS**	**LOAD (KN)**	**EXPECTED REPETITIONS**
15	251,442	15	118,497	40	41,653	50	46,101
25	410,853	25	141,538	60	117,804	70	47,747
35	828,711	35	153,411	80	103,004	90	21,403
45	1,131,533	45	91,337	100	117,535	110	27,990
55	131,717	55	57,548	120	106,424	130	36,222
65	13,242	65	47,237	140	90,383	150	67,504
75	4,448	75	535,163	160	79,924	170	37,869
		85	41,261	180	80,038	190	31,283
		95	115,797	200	162,488	210	55,979
		105	299,941	220	118,199	230	100,433
		115	280,048	240	17,902	250	42,807
		125	60,189				
		135	4,315				
		145	4,315				

Source: self-made

It should be noted that in the case of buses, taking into account that in Colombia these are not weighed during mobile weighing operations, a representative average load of 4.75 tons was estimated for the single directional axis and 7.50 tons for the single axis not directional.

3.2 Sizing of the pavement structure

For the determination of the effects of traffic loads, in terms of the damage generated on the pavement structure, the concept of damage defined by Miner, 1945, was taken as a reference, where for each type of axis, i, and each load level, j, the quotient between the number of corresponding repetitions expected during the design period, n, and the number of admissible repetitions, N, is obtained to limit the development of a certain type of deterioration. The total damage, for each type of deterioration, is calculated with equation 2 [13].

$$D = \sum_i \sum_j \frac{n_{ij}}{Nij} \quad (2)$$

Regarding the number of expected repetitions, n, for each type of axle, i, and each load level, j, these values have been obtained by contrasting the information related to the total volume of heavy vehicles expected during the design period and the axle load spectra shown in Figure 1.

In relation to the number of admissible repetitions, N, for each type of axle, i, and each load level, j, these values have been obtained, by associating the number of admissible repetitions with the maximum deformations that occur at certain points critics of the structural section of the pavement. For this purpose, the maximum stress unit deformation, ε_t, has been evaluated in the lower fiber of the asphalt layer and, for the permanent deformation of the lower layers, the maximum compression unit deformation, ε_c, in the upper part of the subgrade.

To associate the variables involved in the Nij estimation, the deterioration models for fatigue cracking in the asphalt layers and deterioration due to permanent deformation of the subgrade have been used, from the Transport and Road Research Laboratory (TRRL) of the Great Brittany.

For the case of fatigue cracking evaluation, equation 3 is available, while for permanent deformation on the subgrade, equation 4 is available.

$$N_f = f_1 \varepsilon_t^{-f_2} \quad (3)$$

Where:

N_f = Number of admissible repetitions, for the criterion of

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maximum strain deformation in the lower fiber of the asphalt layers.

f_1=1.66x10^{-10}

f_2= 4.32

$$N_d = f_4 \varepsilon_c^{-f_5} \tag{4}$$

Where:

N_d = Number of admissible repetitions, for the criterion of maximum compression deformation on the subgrade.

f_4 = 6.18x10^{-8}

f_5 = 3.97

3.3 Modeling the structural section

After carrying out a pre-dimensioning of the section of the pavement structure using the AASHTO-93 method and making some adjustments, the structural section shown below was found, which was modeled considering each load step established in the spectra of load, for each one of the configurations of axles characteristic of the traffic of heavy vehicles that make use of Colombian highways, namely: single directional axles, non-directional single axles, tandem axles and tridem axles.

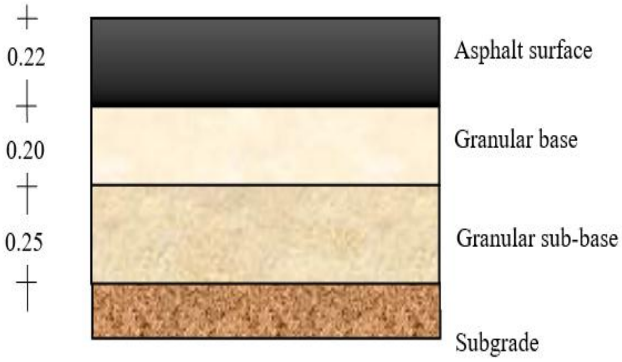

Figure 2. Structural model for design

In Table 5, the results of the analysis performed as a result of the modeling of the pavement structure illustrated in Figure 2 are presented. According to the obtained results, it is had that the accumulated fatigue damage is 94.69% and the accumulated damage associated with permanent deformation is 34.41%, which is indicative that the design obtained is optimal, fulfilling the two deterioration criteria considered in the analysis.

Table 5. Analysis of consumption of fatigue damage and permanent deformation

	AXLE LOAD (KN)	EXPECTED REPETITIONS	FATIGUE ANALYSIS		DEFORMATION ANALYSIS	
			ALLOWABLE REPETITIONS	Fatigue (%)	ALLOWABLE REPETITIONS	Damage (%)
SINGLE AXLE SIMPLE WHEEL	15	251,442	862,788,917	0.03	7,590,560,833	0.00
	25	410,853	120,309,829	0.34	1,017,862,971	0.04
	35	828,711	35,099,462	2.36	272,913,829	0.30
	45	1,131,533	14,598,539	7.75	102,390,797	1.11
	55	131,717	7,462,075	1.77	46,987,760	0.28
	65	13,242	4,372,425	0.30	24,647,784	0.05
	75	4,448	2,805,697	0.16	14,221,669	0.03
SINGLE AXLE DOUBLE WHEEL	15	118,497	4,384,991,541	0.00	11,290,752,280	0.00
	25	141,538	532,417,333	0.03	1,496,442,801	0.01
	35	153,411	136,797,278	0.11	396,642,978	0.04
	45	91,337	50,587,677	0.18	147,119,278	0.06
	55	57,548	23,143,206	0.25	66,901,110	0.09
	65	47,237	11,816,064	0.40	34,674,329	0.14
	75	535,163	6,705,548	7.98	19,803,593	2.70
	85	41,261	4,096,905	1.01	12,141,820	0.34
	95	115,797	2,664,933	4.35	7,855,167	1.47
	105	299,941	1,814,428	16.53	5,319,286	5.64
	115	280,048	1,285,329	21.79	3,734,304	7.50
	125	60,189	941,203	6.39	2,701,561	2.23
	135	4,315	705,080	0.61	2,004,756	0.22
	145	4,315	539,659	0.80	1,520,454	0.28

TANDEM AXLE	40	41,653	1,853,086,390	0.00	2,912,899,654	0.00
	60	117,804	368,665,275	0.03	586,107,034	0.02
	80	103,004	112,059,028	0.09	188,476,119	0.05
	100	117,535	46,777,757	0.25	78,210,823	0.15
	120	106,424	21,659,044	0.49	38,164,973	0.28
	140	90,383	11,391,077	0.79	20,827,552	0.43
	160	79,924	6,511,446	1.23	12,335,781	0.65
	180	80,038	3,968,813	2.02	7,777,714	1.03
	200	162,488	2,545,492	6.38	5,151,812	3.15
	220	118,199	1,701,681	6.95	3,551,410	3.33
	240	17,902	1,177,353	1.52	2,529,146	0.71
TRIDEM AXLE	50	46,101	5,601,995,403	0.00	4,861,460,474	0.00
	70	47,747	1,421,853,273	0.00	1,292,262,760	0.00
	90	21,403	516,788,872	0.00	477,080,285	0.00
	110	27,990	233,265,512	0.01	215,676,180	0.01
	130	36,222	122,096,209	0.03	111,760,009	0.03
	150	67,504	70,487,012	0.10	63,592,005	0.11
	170	37,869	43,926,688	0.09	38,734,077	0.10
	190	31,283	29,037,241	0.11	25,071,653	0.12
	210	55,979	20,151,752	0.28	16,912,019	0.33
	230	100,433	13,735,024	0.73	11,820,767	0.85
	250	42,807	9,658,788	0.44	8,510,897	0.50
			TOTAL:	94.69	TOTAL:	34.41

4. CONCLUSION

In accordance with the results obtained in this work, it can be established, in the case of the modeling of the structure of an asphalt pavement through rational methodology, that the characterization of the design traffic from the axle load spectra, is a very effective way of representing the effects generated by traffic loads on the performance of the structure.

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