Effect of axle load on Chilean concrete pavements

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ABSTRACT

It the present study, it is analyzed the effects on chilean concrete pavements of discrete variations in the maximum dual axle load. These variations are between 10 and 13 ton, for seven sections, each one with its own design, considering construction and maintenance costs.
The changes of the pavement condition were evaluated with the AASHTO model, considering a final serviceability index of 2.5, value below which reconstruction is needed.
In the paper is introduced the concept of Truckload Habit. With this concept it was possible to quantify the influence of the constraints limits variations on the destructive factors of commercial vehicles.
Finally, it was possible to obtain the benefits from savings in substructure costs for the different dual axle loads considered, as well as, an evaluation of the cycle life of pavements with a social interest rate of 12%.

INTRODUCTION

The objective of this study is to analyze the effects of dual axle load variations on concrete pavements.
If we increase the maximum weights allowed there will occur an increase of the construction and maintenance costs.
On other hand, with an increase of the maximum weights, the operational costs will decrease.
The idea of the global study, is to determine the optimal maximum weight which minimize the global cost of transportation.
The objective of the present study is only one part of a global study. It will only considered the variations of one component of the global cost of transportation: the cost resulting of the pavement design.

2. Methodology of the Study

The method applied in the study is a simulation of a real transportation system, considering discrete variations of one ton of the maximum dual axle load, between the limits of 10 and 13 ton.
In the Figure 1 is presented the flow of the methodology of the study.
We understand as Truckload Habit, the set of characteristics of commercial vehicle which influences the principal costs involved. They are: the present total weights distribution (GWT), the distribution of the GWT on axles, the effective limits of axle load and the forecast of the traffic behavior in the horizon of the study.
The destructive factors of vehicles quantify the destructive capacity of one type of truck with an specific distribution of axle load obtained from the weight control stations.
The ASSTHO Model is used to evaluate the deterioration rate of pavements, to design them and to determine the destructive factors of trucks.
The estimation of the destructive factors of commercial vehicles, will permit to determine the variation of the life of slabs and also, the variations of the thickness of new pavements.

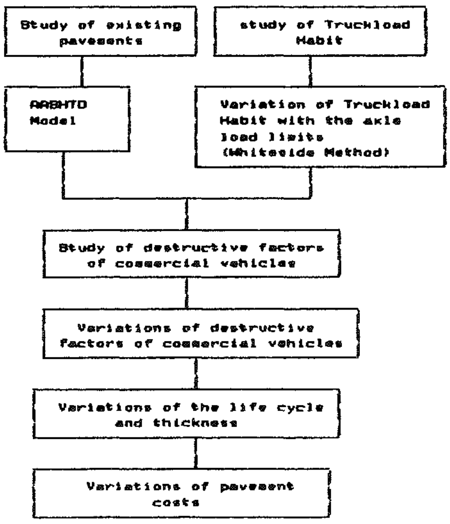


Figure Nº 1 Methodology of the Study

The thickness of slabs will be the most important parameter for the study.
In Table 1, are presented the different representative pavements of each one of the corridors.

Table Nº 1 Representative Concrete Pavement Corridors

Corridors	Thickness (cm) (no dowels)	Design ESAL
Santiago - Las Chilcas	24	68.610.000
Santiago - Valparaíso	24	18.255.000
Rancagua - Curicó	22	61.796.000
Curicó - Linares	22	14.994.000
Cabrero - Concepción	20	32.003.000
Linares - Los Angeles	22	14.994.000
Los Angeles - Osorno	22	14.994.000

4. Study of the Truckload Habit

All the set of characteristics involved by the truckload habit and named at point 2, must be studied to determine its possible variation caused by the different maximum dual axle loads.

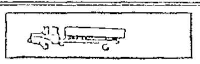
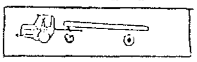
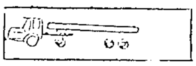
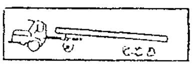
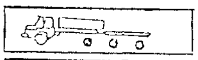
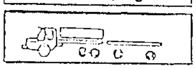
4.1 Information Sources

All the characteristics named at point 2 were studied from the information obtained from the weighing control station values of the National Road Direction from 1985 until 1988. For the concrete pavement corridors it was totalized 40000 weighings of vehicles.

4.2 Types of trucks with variation in the maximum gross weight (GWT)

The study of the mayor relative participation of the different types of trucks show that the 95% of all trucks in circulation and whose GWT do not exceed the legal maximum GWT, are included in Table 2.

Table Nº 2 Types of Trucks with Possible Variations in the Truckload Characteristics

code	Shape
200	
300	
410	
570	
400	
520/523	

4.3 Study of the Axle Load Effective Limits

The axle load effective limit, is a value exceeded by the 5% of the axle loads measured Table 3 show the effective limits for single, tandem and tridem axles.

Table Nº 3 Effectives Limits on the Concrete Pavement Corridors

Corridors	Effective Limits (ton)		
	Simple	Tandem	Tridem
Las Chilcas - Santiago	11,77	18,44	23,93
Santiago - Valparaíso	11,17	18,53	24,64
Rancagua - Curicó	11,42	18,55	24,61
Curicó - Linares	12,47	18,56	24,17
Cabrero - Concepción	11,73	18,28	24,92
Linares - Los Angeles	12,22	18,48	24,53
Los Angeles - Osorno	11,58	17,74	24,54

Table Nº 4 Typical Regression Relations

Station	Truck	Relation
Curacaví	510	$GWT=4,012 + 3,346*P_2$ (r^2 = 0,8855) $P_3=0,085 + 0,813*P_2$ (r^2 = 0,7410) $P_4=0,025 + 1,314*P_2$ (r^2 = 0,7077)
	410	$GWT=3,01 + 2,619*P_2$ (r^2 = 0,9046) $P_3=0,2764 + 1,493*P_2$ (r^2 = 0,7402)
	200	$GWT=1,217 + 1,4179*P_2$ (r^2 = 0,8974) $P_1=1,217 + 0,4179*P_2$ (r^2 = 0,4319)
Concepción	200	$GWT=1,1755 + 1,2266*P_2$ (r^2 = 0,4525) $P_1=1,873 + 0,317*P_2$ (r^2 = 0,4254)
	300	$GWT=5,177 + 1,254*P_2$ (r^2 = o,1537) P_1 = 2,616 + 0,169*P_2 (r^2 = 0,1685) $P_3=0,866 + 1,068*P_2$ (r^2 = 0,8181)
	400	$GWT=1,376 + 2,509*P_2$ (r^2 = 0,2764) P_1=2,772 + 0,284 (r^2 = 0,5505) $P_3=1,824 + 1,063*P_2$ (r^2 = 0,8072) $P_4=1,894 + 1,074*P_2$ (r^2 = 0,8107)

4.4 Study of the Distribution of the GWT on Axles

To study the variation of the GWT distribution produced by the changes of dual axle load, it

was used a method developed by Whiteside et alt (1973) (Ref.3). It is necessary to establish relations between the different axle loads and an axle of reference, in this case the second axleload, considering as the first one, the front axle.
This relations have the following forms:

a) $P_i = A^i + B_i*P_2$
b) $GWT = A + B*P_2$

Where Pi is axle load in the axle i and A_i and Bi are constants of regression.
In table 4 are showed the different regressions.

4.5 Traffic Forecasts
To forecast the ADT were used the counters of the National Road Direction considering also the regional gross products.

5. Variations of the Truckload Habit with the Different Dual Axle Load Limits.
(Whiteside Method Application)
An increase of the legal axle load limits produce a displacement of the distribution of the GWT in the sens of greater truckloads.
The procedure to displace the GWT distributions was developed by Whiteside et alt, (1973). With this method it is possible to obtain new distributions corresponding to a new effective limit of axle load.

5.1 Hypothesis of the Whiteside Method
1. The lower GWT detected represent the lower tare. This GWT value do not change with an eventual change of the axle load limits.
2. The vehicles which transit with a GWT corresponding to the effective axle load limit, will use the new effective limit, increasing his GWT and maintaining the same accumulative relative participation in the traffic distribution.
3. In the interval between the first GWT detected and the superior limit of the interval which contain the GWT, the displacement of the distribution is lineal.
4. After the interval which contain the effective limit, the displacement is obtained using a constant factor.

5.2 Whiteside Method Algorithm
This method was applied using a Lotus 1-2-3 computer form. The sequence of this application is the following.
1. To compute the GWT corresponding to the effective axle load limit, for each type of truck. This value will be obtained using the relation GWT = f(P_2) of the corresponding vehicle.
2. To compute the GWT* corresponding to the new value of the axle load limit in study, using the same previous relation.
3. To compute the ratio k = GWT*/GWT.
4. To divide (k-1) by the number of intervals between the lower value of GWT registered and the superior limit of the interval which contain the present effective GWT. This ration is named m.
5. To multiply the superior limit of each interval of order i by (1 + m*i) until to get the superior limit of the interval which contain the present effective GWT. From this point the multiplicator in constant.
6. To obtain by interpolation the new values of accumulated percentages corresponding to the superior limits of the intervals of weight of the original distribution of the GWT.
In Figures 2 and 3, are showed the distributions of GWT obtained with this method.

6. Actual Destructive Factors of the Trucks
6.1 The destructive factor of a trucks in the sum of the equivalent axle load (ESAL) of each one of the axle load defined by the AASTHO Method.
To determine ESAL corresponding to an axle load, were used the equivalent factors of AASHTO Method, 1986 (Ref.1).
The average destructive factor of one axle k is:

$$EE_k = \sum f_i*E_i$$

Where:
The subindex represent one load interval
E_i represent the equivalence factor of the axle load i.
f_i represent the relative frequency observed of the axle load of the interval load i.
Then, the destructive factor of a truck is the sum of the average destructive factors of each one of this axles load.

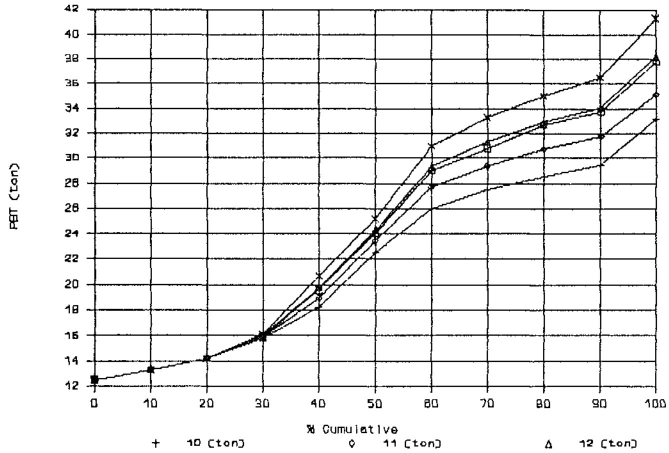


Figure Nº 2 Variation of the GWT Distribution of San Francisco Mostazal Control weight Station - Truck 410

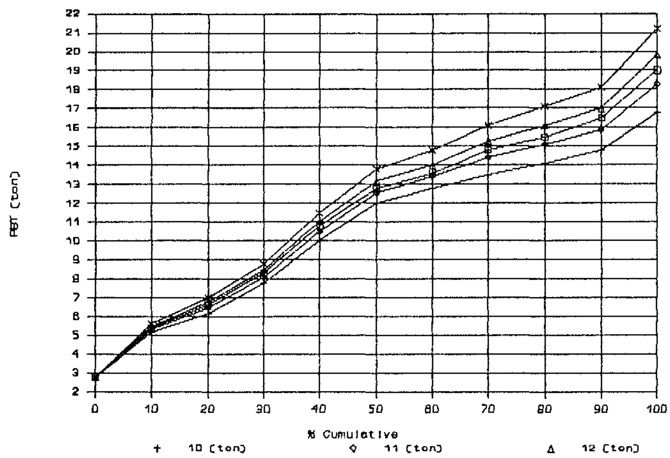


Figure Nº 3 Variation of the GWT Distribution San Francisco Mostazal Control weight Station - Truck 200

6.2 The Actual Destructive Factors

From the data obtained from the control weight station, it was possible to compute the actual destructive factors. In the table 5 are showed the destructive factors of the most important type of trucks.

Table Nº 5 Actual Destructive Factors of the Trucks of Mayor Presence

Type of truck	Control weight Station			
	Lampa	Curacaví	Concepción	Gorbea
200	2,10	1,87	2,66	1,88
310	2,09	1,90	2,46	3,37
454	2,54	1,66	2,33	2,96
300	4,70	2,36	2,40	4,76
400	9,21	5,17	7,26	7,74
520	8,77	6,54	6,86	8,51
410	4,58	3,19	3,44	4,94
530	3,62	3,03	3,73	3,70
570	6,89	4,86	6,17	4,76
690	4,16	4,16	4,80	6,21
buses	2,22	2,22	2,65	1,52

7. Variation of the Destructive Factors with the Different Limits in Study.

Through the regression relations between the GWT and the axle load it was possible to obtain the new GWT distribution and then the new value of axles load, and consequently, the new destructive factors of the different types of trucks.

In Figures 4, 5 and 6 are showed this variations.

8. Deterioration of Pavements with Different Dual Axle Load Limits.

A change of the maximum GWT produce variations in the average destructive factors of trucks or, equivalently variations in the ESAL by truck and consequently, a variation of the total of ESAL wich loads the pavement by unit of time: the pavement performance curve will change.

In tables 6, 7 and 8 it is possible to observe the variation in the total ESAL year by year, for different corridors

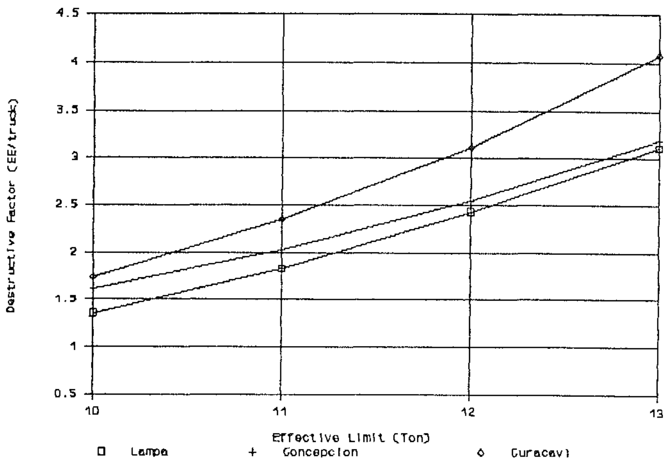


Figure Nº 4 Variation of the Destructive Factor Truck 410

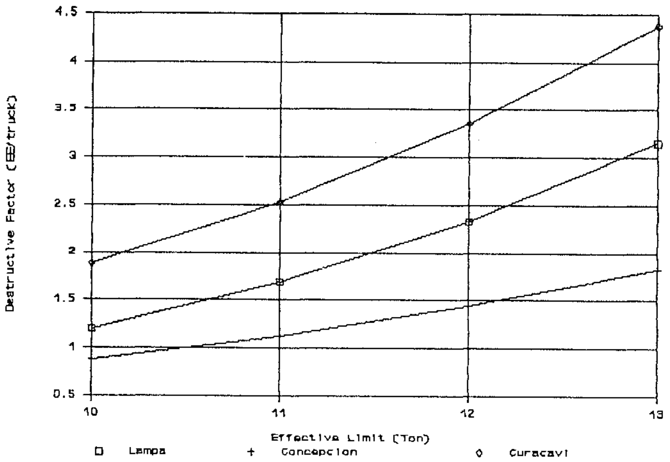


Figure Nº 5 Variation of the Destructive Factor Truck 300

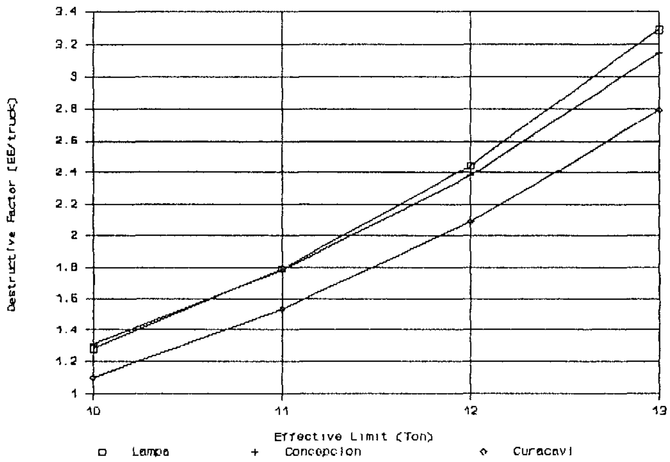


Figure Nº 6 Variation of the Destructive Factor Truck 200

Table Nº 6: EAL for Different Limits in Study Corridor Cabrero-Concepción

1987		1990	
ACTUALES	1.570.770	ACTUALES	6.800.915
10 (TON)	1.150.777	10 (TON)	4.798.151
11 (TON)	1.259.431	11 (TON)	5.449.342
12 (TON)	1.406.987	12 (TON)	6.089.383
13 (TON)	1.559.152	13 (TON)	6.748.956
1993		1996	
ACTUALES	12.642.262	ACTUALES	18.830.487
10 (TON)	9.253.809	10 (TON)	13.825.585
11 (TON)	10.129.809	11 (TON)	15.135.378
12 (TON)	11.320.006	12 (TON)	16.914.770
13 (TON)	12.546.068	13 (TON)	18.748.366
1999		2002	
ACTUALES	25.465.302	ACTUALES	32.262.503
10 (TON)	18.634.677	10 (TON)	23.606.213
11 (TON)	20.401.186	11 (TON)	25.845.048
12 (TON)	22.001.021	12 (TON)	28.886.418
13 (TON)	25.274.071	13 (TON)	32.020.963
2005		2006	
ACTUALES	39.277.440	ACTUALES	41.658.061
10 (TON)	28.735.357	10 (TON)	30.476.593
11 (TON)	31.462.007	11 (TON)	33.368.756
12 (TON)	35.166.007	12 (TON)	37.297.560
13 (TON)	38.963.633	13 (TON)	41.347.925

Table Nº 7: EAL for Different Limits in Study Corridor Santiago-Las Chilcas

1987		1990	
ACTUALES	7.109.434	ACTUALES	13.018.582
10 (TON)	5.101.500	10 (TON)	9.123.804
11 (TON)	5.676.764	11 (TON)	10.329.261
12 (TON)	6.609.290	12 (TON)	12.048.117
13 (TON)	7.637.136	13 (TON)	13.916.574
1993		1996	
ACTUALES	19.687.319	ACTUALES	26.938.319
10 (TON)	13.734.917	10 (TON)	18.632.917
11 (TON)	15.565.368	11 (TON)	21.158.487
12 (TON)	18.149.543	12 (TON)	24.734.176
13 (TON)	20.954.918	13 (TON)	28.594.877
1999		2002	
ACTUALES	35.319.381	ACTUALES	44.734.864
10 (TON)	24.340.679	10 (TON)	30.709.719
11 (TON)	27.648.941	11 (TON)	34.903.308
12 (TON)	32.344.327	12 (TON)	40.867.896
13 (TON)	37.391.458	13 (TON)	47.254.986
2005		2006	
ACTUALES	55.315.265	ACTUALES	59.126.751
10 (TON)	37.821.887	10 (TON)	40.374.797
11 (TON)	43.017.687	11 (TON)	45.933.192
12 (TON)	50.421.146	12 (TON)	53.857.714
13 (TON)	58.323.073	13 (TON)	62.307.270

Table Nº 8: EAL for Different Limits in Study Corridor Santiago-Valparaiso

1987		1990	
ACTUALES	1.443.657	ACTUALES	4.179.569
10 (TON)	1.046.032	10 (TON)	2.972.600
11 (TON)	1.256.516	11 (TON)	3.589.479
12 (TON)	1.539.101	12 (TON)	4.420.374
13 (TON)	1.822.781	13 (TON)	5.234.971
1993		1996	
ACTUALES	7.369.812	ACTUALES	10.777.010
10 (TON)	5.185.252	10 (TON)	7.535.916
11 (TON)	6.280.407	11 (TON)	9.143.599
12 (TON)	7.758.223	12 (TON)	11.315.266
13 (TON)	9.187.515	13 (TON)	13.399.599
1999		2002	
ACTUALES	14.370.871	ACTUALES	18.567.050
10 (TON)	10.010.497	10 (TON)	12.823.375
11 (TON)	12.158.930	11 (TON)	15.617.978
12 (TON)	15.063.110	12 (TON)	19.393.943
13 (TON)	17.836.656	13 (TON)	23.017.123
2005		2006	
ACTUALES	22.541.993	ACTUALES	23.904.498
10 (TON)	15.552.951	10 (TON)	16.488.125
11 (TON)	18.946.060	11 (TON)	20.086.362
12 (TON)	23.533.003	12 (TON)	24.951.309
13 (TON)	27.916.598	13 (TON)	29.595.189

9. Effect of the Change of Axle Load Limits in the Single Axle on the Pavements Life Cyc

The periods of design of the pavements are between 10 and 20, years supporting the traffic and his growth. With the variation of the total ESAL, will change the life cycle of the pavements. In figure 9 is showed the variation of the life cycle of the representative pavements for the different axle load limits in study.

Table Nº 9 Variation o the Life Cycle for Different Limits in Study

Corridor	life cycle (years)					effective actual limit (ton)
	Limit in study (ton)					
	present	10	11	12	13	
Las Chilcas- - Santiago	25	33	31	27	25	11,77
Santiago- - Valparaiso	17	23	19	16	14	11,17
Rancagua- - Curicó	27	34	32	29	26	11,42
Curicó-Linares	8	11	10	8	7	12,47
Cabrero- - Concepción	16	21	20	18	16	11,37
Linares- - Los Angeles	9	13	11	9	8	12,22
Los Angeles- - Osorno	21	27	28	24	20	11,58

In table 10 are showed this variations more clearly.

Table Nº 10 Variations of the Life Cycle Related with the Life Cycle with Actual Conditions

Corridor	Variation (years)			
	10	11	12	13
Santiago - Las Chilcas	+8	+6	+1	-1
Santiago - Valparaiso	+6	+2	-1	-3
Rancagua - Curicó	+7	+5	+2	-1
Curicó-Linares	+3	+2	0	-1
Cabrero - Concepción	+5	+4	+2	0
Linares - Los Angeles	+4	+2	0	-1
Los Angeles - Osorno	+6	+5	+3	-1

+ = increase of the life cycle
- = decrease of the life cycle

From the table 10, it is possible to obtain the average life cycle for all the corridors with concrete pavement. This variations are showed in Table 11.

Table Nº 11 Average Variations of the Concrete Pavement Life Cycle

Limit in study (ton)	Variation of the life cycle (years)	Increase or Decrease
10	6	increase
11	4	increase
12	0	no thing
13	1	decrease

10. Analysis of the Variation of the Slab Thickness Necessary for New Pavement.
The variation of the total ESAL for the different limits in study, will determine also the variation of the slab thickness necessary to reconstruct in future the deteriorated pavements. Consequently, an increase of the total ESAL will obligate to greater thickness slab.

10.1 Slab Thickness Design Necessary for New Pavements.
To design the new thickness it was used a subgrade modules k = 1,8 (MPa/cm^3) and a 28 days modules of rupture = 40 (MPa/cm^2).
It was considered a life cycle of 20 years with the total ESAL accumulated from 1986 to 2006.
The new thickness are showed in Table 12

Table Nº 12 Variations of the Slab Thickness for Different Dual Axle Load Limit

Corridor	Thickness in Actual Conditions (cm)	Thickness (cm)			
		Limits in study (ton)			
		10	11	12	13
Las Chilcas - Santiago	27	25	26	26	27
Santiago - Valparaíso	23	22	23	24	24
Rancagua - Curicó	25	24	25	25	26
Curicó - Linares	26	25	25	26	26
Cabrero - Concepción	26	25	25	25	26
Linares - Los Angeles	26	24	25	26	26
Los Angeles - Osorno	21	20	20	21	22

From table 12 it was obtained the variations of the slab thickness related of the actual thickness for the actual conditions.

Table Nº 13 Variations of the Slab Thickness related Present Conditions

Corridor	Variation (cm)			
	Limits in study (ton)			
	10	11	12	13
Las Chilcas - Santiago	-2	-1	-1	0
Santiago - Valparaíso	-1	0	+1	+1
Rancagua - Curicó	-1	0	0	+1
Curicó - Linares	-1	-1	0	0
Cabrero - Concepción	-1	-1	-1	0
Linares - Los Angeles	-2	-1	0	0
Los Angeles - Osorno	-1	-1	0	+1

In Table 14, are showed the average variations of the slab thickness related the actual conditions

Table Nº 14 Average Variations of Slabs Thickness Related the Present Conditions, Independently of the Corridors

Limit in study (ton)	Average Variation (cm)	Increase Decrease
10	1	Decrease
11	1	Decrease
12	0	no Change
13	1	Increase

11. Study of Substructure Costs
The costs for different slab thickness, forcement treated subbase and granular subbase are showed in Table 15 for March, 1989.

Table Nº 15 Construction Cost of Concrete Slab

Thickness (cm)	Cost (U$/m^2)
20	9,19
22	9,77
23	10,11
24	10,50

Table Nº 16 Construction Cost of Cement Treated Subbase

Thickness (cm)	Cost (U$/m^2)
12	3,17
15	3,97
30	7,93

Table Nº 17 Construction Cost of Granular Subbase

Thickness (cm)	Cost (U$/m^2)
15	0,69
30	1,39

To evaluate the variation of the costs, it was used an structure composed by a cement treated base of 15 cm thickness and a granular subbase of 15 cm thickness.
The costs of 15 cm of thickness of this structural section are showed in Table 18

Table Nº 18 Cost Depending of the slab Thickness

Thickness (cm)	Cost (U\$/m²)
20	13,85
22	14,43
23	14,77
24	15,11

Additionally, it was considered a maintenance constant cost in the 20 years igual to 3,99 U\$/m².

12. Variation of the Structure Costs with Different Limits in Study

Considering like level of reference a slab thickness of 22 cm, it is possible to obtain the variations of the slab thickness with the different limits in study. In table 19 are showed this variations.

Table 19 Variations of the slab Thickness

Limits in study	Slab Thickens
10 (ton)	21 (cm)
11 (ton)	21 (cm)
12 (ton)	22 (cm)
13 (ton)	23 (cm)

For this thickness, in Table 20 are showed the variations of the pavement costs.

Table 20 Variation of the Pavement Cost with the Different Limits in Study

Limits in Study (ton)	Slab Thickness (cm)	Cost (U\$/m²)
10	21	18,00
11	21	18,00
12	22	18,42
13	23	18,76

With the variations of the costs presented in Table 20, it was computed the benefit obtained with the variations of the limits in study. The benefits, showed in Table 21, are U\$/Km, considering a road of 3,5 m of width by way. Also, are showed the percentages of benefit considering an actual cost of U\$/m² = 18,42 then U\$/Km = 128.907.

Table 21 Benefits for the Different Axle Load Limit in Study

Limit in Study (ton)	BeneficitS (U\$/Km)	% Benefit
10	+ 2902,67	+ 2,3 %
11	+ 2902,67	+ 2,3 %
12	0	0
13	- 2394,00	- 1,9 %

13. Evaluation of the Life Cycle Variation Considering a Social Interest Rate = 12%

To consider the life cycle variations, it was supposed that the pavement cost analyzed in point 12 is payed in many years. It will be suppose that, if a pavement have a life cycle of n years, its total cost will be "payed" at the year n. The economic cost was obtained of its present value with the social interest ratio.
The economic cost to construct a pavement in the year n will be.

$$\text{Actualization Cost} = \frac{\text{Cost}}{(1 + r)^n}$$

where:

r = social actualization rate
n = years of life cycle

It was considered that the slab in study have, in actual conditions, a life of 23 years. It was supposed that this life cycle change with the average variations observed at point 12.
According with this, the life cycle for different limits in study will be.

Limit in Study (ton)	Life Cycle (years)
10 (ton)	29
11 (ton)	27
12 (ton)	23
13 (ton)	22

14. Variations of the Costs Due to the Changes of the Thickness of the New Pavement and to the Changes of the Life Cycle for Social Actualization rate = 12%

In table 22, are showed the variations of the substructure cost:

Table 22 Variations of the Economic Cost of a Representative Pavement for Different Limits in Study

Limit in Study (ton)	Slab Thickness (cm)	Life Cycle (year)	Cost of the Pavement (U\$/m²)	Economic Actualized Cost (U\$/m²)
10	21	29	18,00	0,67
11	21	27	18,00	0,84
12	22	23	18,46	1,36
13	22	22	18,76	1,55

According with the table 22, the economic benefits in U\$/Km and his percentages related to the actual cost, are showed in Table 23.
The cost for actual conditions is 1,36 U\$/m² = 9510,67 U\$/Km (actualized cost with rate - 12%).

Table 23: Economic Benefits by Cost of the Structure for the Different dual Axle Load Limits for Concrete Pavement

Limits of Study (ton)	Benefits (U$/Km)	% Benefits
10	4799,67	+ 50,5 %
11	3602,67	+ 37,9 %
12	0	0
13	1349,33	- 14,1 %

15. Conclusions

From the analysis and considering the legal single dual axle load of 11,0 ton, it is possible to conclude:

1.- The actual conditions of the traffic present average axle load greater than the legals permitted, specially in dual single axle, with values near of 12 ton.

2.- The life cycle of pavement increase, for limits inferior of the actuals, in 6 year. For limits of 3 ton, the life cycle decrease in 1 year.

3.- The slab thickness increase in 1 cm for a limit greater than the actual (11.0 ton), and decrease also in 1 cm for limits lower than 11.0 ton.

4.- The construction and maintenance cost decrease until a 12% for limits lower than the actuals and increase in the same percentage for a limit of 13 ton.

5.- Evaluating also the effect of the variation of the life cycle, it is possible to conclude that it generate benefit of until 50% for limits lower than the actuals and additional cost of 14%, for a limit of 13 ton.

6.- The methodology give a good approximation for the solution of the problem. It is important to note that we are verifying the results considering the E.E.M. Method to compute the stress considering the combined effect of thermal gradient and traffic.

13. REFERENCES

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