

Economic Impacts Of Axle Load Limits And Heavy Vehicle Configurations On The Performance Of Pavements In Brazil

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ABSTRACT

The economic impacts of operating scenarios of truck configurations, axle loads, tire types and tire inflation pressures are evaluated by the Highway Design and Maintenance Standards Model (HDM-III). The effects of alternative loading conditions on the performance of Brazilian pavements are quantified by empirical-mechanistic models used to calculate Load Equivalency Factors (LEF).

It is concluded that, depending on cost parameters used in the HDM-III model, higher axle loads result in smaller total costs, although maintenance and construction costs are higher, a result that conflicts with the budget restrictions for road construction and maintenance in developing nations. It is shown that the operation of Long Combination Vehicles (LCVs) results in lower operational and maintenance costs than the operation of conventional heavy trucks carrying the same payload. It is also shown that higher maintenance and construction costs result from the operation of vehicles with super single tires and higher tire inflation pressures.

INTRODUCTION

As in many other countries, there has been a strong pressure in the last years in Brazil, towards increasing legal limits for GCW and axle loads. Simultaneously, there has been an evolution of the truck technology, represented by new truck configurations (e.g., Long Combination Vehicles, LCVs, with 7 to 9 axles), new suspension types (e.g., air bag instead of leaf spring), and new tire types (e.g., radial and super single tires, to support higher loads and inflation pressures).

AXLE LOADS

The present legal limits in Brazil [1] establish a maximum GCW of 45 m-tons and axle loads of 6, 10, 17 and 25.5 m-tons respectively for steering axles, single axles with dual wheels, tandem axles and tridem axles. Due to several challenges about scale accuracy in courts, the weight limits were revised in 1985 to include an allowance of 5% to compensate for inaccuracies of scale readings.

This actually implied in a systematic increase in the practically adopted limits.

As weight limits are not strictly enforced, heavy trucks normally operate with overweight in the range of 10 to 30%, as shown by recent data collection [2] and also by the Research on the Interrelationship of Highway Construction, Maintenance and Utilization Costs (PICR) [3], developed from 1976 to 1981 in Brazil and sponsored by the Brazilian government and the World Bank.

TRUCK CONFIGURATIONS

Using the same axle load limits, LCVs can be operated under special permits from Brazilian State Departments of Transportation (DOTs) with legal GCWs ranging from 63 to 74 m-tons. Figures 1 and 2 present the cargo vehicles considered in this study.

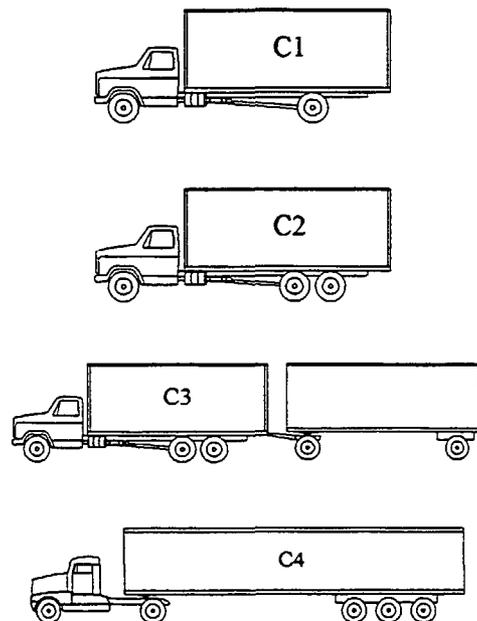


Figure 1. Conventional cargo vehicles: unrestricted traffic rights.

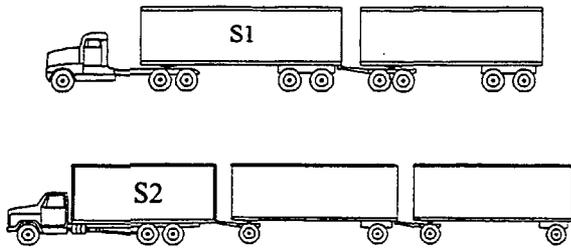


Figure 2. Special cargo vehicles: operation under special permit from Brazilian DOTs.

SUPER SINGLE TIRES

The Brazilian Association of Manufacturers of Truck Equipment (ANFIR), influenced by industries that make products of German technology, has tried, for years, to introduce the super single tires in substitution of the conventional dual wheels. The utilization of super single tires in West Europe was the result of the lobby of itinerant transportation companies during and immediately after the first international petroleum crisis in 1973. There were no previous studies and the countries that allowed the substitution of dual wheels by super single tires have had many problems related to higher pavement deterioration rates. Theoretical studies, developed after the practical evidences, have confirmed that the super single tires cause more damage to pavements [4]. But, as a function of the legal structure in those countries, it has been crescent the utilization of super single tires by European truck operators has become the normal practice.

TIRE INFLATION PRESSURE

During the AASHO Road Test the tire inflation pressures varied from 75 to 80 psi. When the radial tires came into service, there was a great increase in tire pressures. At present, the mean tire inflation pressure in the U.S.A. [5] ranges from 100 to 105 psi. In Europe, the super single tires use an inflation pressure of about 140 psi. In Brazil, although little has been published about the subject, 120 psi is a good guess as the mean value [6]. Observations of tire inflation pressures above 100 psi have caused, in many countries, worries about its effects on pavement performance, since there is an increase in structural responses, particularly at the asphalt layer.

METHODOLOGY

The HDM III [7] is used to evaluate the economic impacts of alternative operating scenarios. The analysis extends over a period of 20 years and a highway network with characteristics that are representative of an average condition of the Brazilian highway system is used [8]. The highway costs (maintenance, construction, and vehicle operation) are calculated as a function of pavement performance. The trend of pavement condition is simulated under different maintenance strategies, traffic volumes, and traffic loading factors.

LOADING CONDITIONS

The traffic loading factors considered in this study are the following:

1. Axle Load - Conventional Cargo Vehicles:
 - 01 - Brazilian legal limits
 - 02 - *Turner Proposal*
 - 03 - Overload of 20%
2. Axle Load - Special Cargo Vehicles:
 - 04 - Brazilian legal limits
 - 05 - *Turner Proposal*
 - 06 - Overload of 20%
3. Tire Inflation Pressure:
 - 07 - 80 psi
 - 08 - 120 psi
4. Wheel Type:
 - 09 - Super single tires, conventional cargo vehicles
 - 10 - Super single tires, special cargo vehicles.

The loading condition 01 is taken as a reference for the comparative analysis. In alternatives 09 and 10 the super single tires are used instead of dual wheels, except for steering and tractor axles. The tire inflation pressure for super single tires is assumed equal to 140 psi. The axle loads for the simulated loading conditions are presented in Table 1.

	SINGLE AXLE, SINGLE WHEEL (m-ton)	SINGLE AXLE, DUAL WHEELS (m-ton)	TANDEM AXLE (m-ton)	TRIDEM AXLE (m-ton)
01	6.0	10.0	17.0	25.5
02	4.0	6.3	12.7	18.1
03	7.2	12.0	20.4	30.6
04	6.0	10.0	17.0	25.5
05	4.0	6.3	12.7	18.1
06	7.2	12.0	20.4	30.6
07	6.0	10.0	17.0	25.5
08	6.0	10.0	17.0	25.5
09	6.0	10.0	17.0	25.5
10	6.0	10.0	17.0	25.5

Each link of the highway network is assumed to have an extension of 1000 km, resulting a total of 36000 km (the combination of 3 highway conditions, 4 maintenance strategies and 3 traffic volume conditions).

The classes of highway condition are:

- highways in good condition: IRI = 2 (no cracks, no potholes and no rutting), where IRI is the International Roughness Index;
- highways in regular condition: IRI = 4 (area of classes 2 and 3 cracks equal to 30%, width of cracked area equal to 20%, area of potholes equal to 0.1%, and rutting of 5 mm);

- **highways in bad condition:** IRI = 7 (area of classes 2 and 3 cracks equal to 90%, width of cracked area equal to 60%, area of potholes equal to 1%, and rutting of 12 mm).

The maintenance and construction strategies are:

- **Strategy 0 - "do nothing":** reconstruction (5 cm of asphalt concrete and granular base) when the roughness exceed 9 IRI. The value of roughness after the reconstruction is 2 IRI. The basic routine maintenance (clean the ditches, hoe the right of way etc) is common to all of the alternatives;
- **Strategy 1 - "fill 100% of potholes":**
- **Strategy 2 - "fill potholes and seal cracks":** surface treatment (1.2 cm) when the cracked area exceed 30%;
- **Strategy 3 - "fill potholes and build overlay":** asphalt concrete (4 cm) when roughness exceeds IRI = 4.

The fleet considered in the traffic volume calculations is composed by the following vehicle types: small and medium cars, two axle trucks, three axle trucks, semi-trailers, trucks+full trailer and two LCVs, Figures 1 and 2. The traffic volumes, quantified in terms of average daily traffic (ADT), are 500 for low volume highways, 1500 for medium volume highways, and 2500 for high volume highways. The percentage of truck traffic is assumed to be in the order of 30% of the total traffic on a link. The effective truck traffic volume, however, is calculated as a function of the payload carried by each truck, which depends on the type of cargo vehicle and the adopted axle loads for each loading condition (Table 2), keeping the total payload constant in all simulated cases. So, the higher the payload of a given vehicle the lower is the number of trips of that vehicle.

Loading Condition	TRUCK CONFIGURATION					
	C1	C2	C3	C4	S1	S2
01	77	98	161	114	-	-
02	232	174	347	242	-	-
03	56	75	120	89		
04	-	-	-	-	114	93
05	-	-	-	-	241	152
06	-	-	-	-	87	72
07	77	98	161	114	-	-
08	77	98	161	114	-	-
09	77	98	157	114	-	-
10	-	-	-	-	112	91

LOAD EQUIVALENCY FACTORS

The relative effects of traffic loading factors on pavement performance are determined by the concept of load equivalence.

LEFs used by Brazilian DOTs however, are based on AASHTO, CBR and CDH pavement design methods, which

were developed under special conditions of climate, subgrade soils, and traffic loading, not being, in principle, a good representation of the Brazilian operational conditions.

Therefore, empirical-mechanistic Load Equivalency Factors [9] are used as the input for the HDM III. The LEFs were determined through a factorial experiment of deterministic simulations that included 8 Brazilian typical pavement sections, 2 structural models (linear elastic and non-linear elastic), and 5 empirical performance models, one for each of the following structural responses: *horizontal tensile strain at the bottom of the asphalt layer*, $\epsilon_{ht,1}$ and *vertical compressive strain at the top of subgrade*, $\epsilon_{vc,m}$, related, respectively, to fatigue cracking and rutting, *deflection at the surface*, δ_1 , *vertical compressive strain at the bottom of the asphalt layer*, $\epsilon_{vc,1}$ and *horizontal tensile stress at the bottom of cement-treated layer*, $\sigma_{ht,2/3}$, the last one related to cracking in cement-treated layers.

The LEF equations that resulted from the factorial experiment are presented below:

$$FEC(\epsilon_{ht,1}) = 3,56 + 1,04 A + 1,17 B + 1,18 C_1 + 0,85 D_1 + 0,76 AB + 0,30 AD_1 + 0,45 BC_1 \quad EQ (1)$$

$$FEC(\epsilon_{vc,m}) = 3,65 + 0,11 A + 1,04 B + 0,14 C_1 + 2,43 D_1 + 0,25 D_q + 0,08 AB + 0,09 AD_1 + 0,09 BC_1 + 0,66 BD_1 + 0,06 BD_q + 0,11 C_1 D_1 \quad EQ (2)$$

$$FEC(\delta_1) = 4,08 + 0,38 A + 1,38 B + 0,41 C_1 + 2,46 D_1 + 0,23 D_q + 0,29 AB + 0,23 AD_1 + 0,20 BC_1 + 0,78 BD_1 \quad EQ (3)$$

$$FEC(\epsilon_{vc,1}) = 7,41 + 2,73 A + 4,46 B + 2,89 C_1 + 2,21 D_1 + 2,27 AB + 1,03 AD_1 + 1,68 BC_1 + 1,35 BD_1 + 0,77 C_1 D_1 \quad EQ (4)$$

$$FEC(\sigma_{ht,2/3}) = 4,30 + 0,34 A + 1,69 B + 0,43 C_1 + 2,66 D_1 + 0,24 D_q + 0,31 AB + 0,33 BC_1 + 0,93 BD_1 \quad EQ (5)$$

where:

$A = +1$: non-uniform pressure distribution at the contact tire-pavement

$A = -1$: uniform pressure distribution

$B = +1$: super single tires

$B = -1$: dual wheels

$C_1 = (X_c - 100) / 20$

$D_1 = (X_d - 10) / 2$

$D_q = 3 (X_d - 10) / 2^2 - (2 / 3)$

and X_c is the value of factor C (tire inflation pressure, psi) and X_d is the value of factor D (axle load, m-ton).

Figures 3 to 5 present examples of comparisons of the effects of wheel type (dual wheels versus super single tires) and tire inflation pressure based on the empirical-mechanistics LEF used in the research.

Load Equivalency Factors

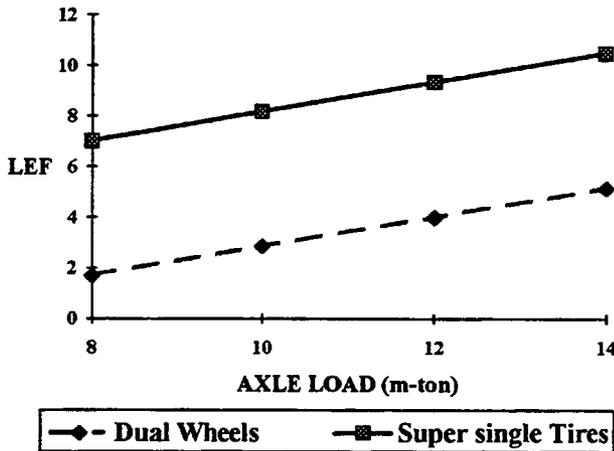


Figure 3. Dual wheels vs. super single tires - LEF($\epsilon_{ht,1}$).

Load Equivalency Factors

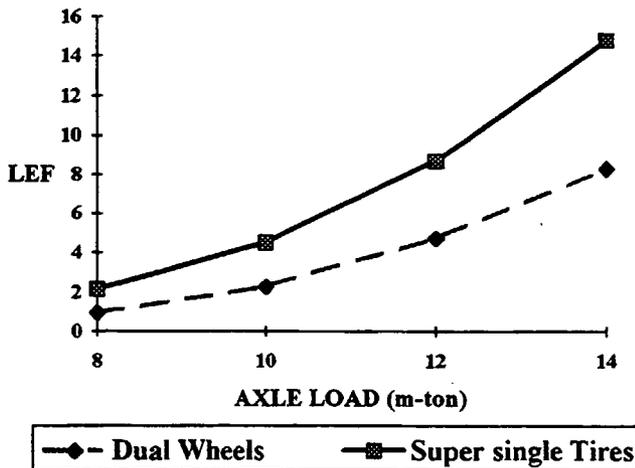


Figure 4. Dual wheels vs. super single tires - LEF($\epsilon_{vc,m}$).

Load Equivalency Factors

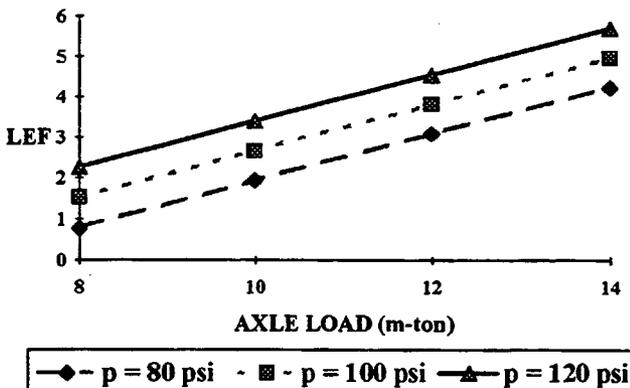


Figure 5. Tire Inflation Pressure - LEF ($\epsilon_{ht,1}$).

RESULTS

The results obtained from the HDM-III simulations are presented below:

TRUCK CONFIGURATIONS

Long Combination Vehicles (LCVs) result more economic than the conventional cargo vehicles in terms of maintenance and construction costs (Figure 6), as well as total costs (Figure 7).

AXLE LOADS

For the conventional heavy vehicles there is an increase in maintenance and construction costs for both lower axle loads (loading condition 02, *Turner Proposal*) and higher axle loads (loading condition 03, overload of 20%) indicating that there is an axle load that corresponds to minimum costs. Otherwise, for the LCVs a systematic increase in maintenance and construction costs with axle load increases was observed (Figure 6). The total cost, which is almost entirely (more than 95%) due to vehicle operation costs, presents a reduction with the increase in axle loads (Figure 7) for both special and conventional cargo vehicles.

SUPERSINGLE TIRES

The results of this study reinforce the conclusions of previous researches that the super single tires result in maintenance and construction costs that are higher than the costs associated to conventional dual wheels, for both conventional cargo vehicles and LCVs (Figure 9). Considering the vehicle operation costs, there is no significant variation in the total cost. There is a small reduction in the total cost for the conventional cargo vehicles and a small increase in the total cost for the LCVs (Figure 10).

TIRE INFLATION PRESSURE

The maintenance and construction costs related to the lower tire inflation pressure (80 psi) are significantly lower than the costs related to the higher tire inflation pressure (120 psi). The total cost presents a small increase for a change from 80 psi to 120 psi (Figure 8).

ANALYSIS OF THE RESULTS

AXLE LOADS

The results of this study show that there is an apparent economic advantage in operating with higher axle loads.

However, in developing countries the lack of resources for additional activities of maintenance and restoration of pavements may result in a very high pavement deterioration rate, which causes an increase in vehicle operation costs and loss of safety and riding comfort.

Operators apparently do not assess this additional operating costs on deteriorated highways in a proper form, considering only the economic advantage of higher payloads.

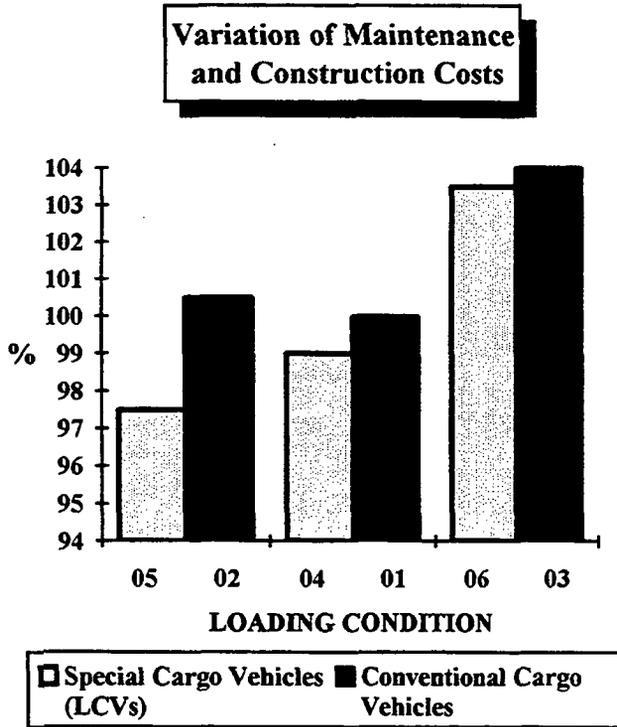


Figure 6. Variation of maintenance and construction costs as a function of truck type and loading condition.

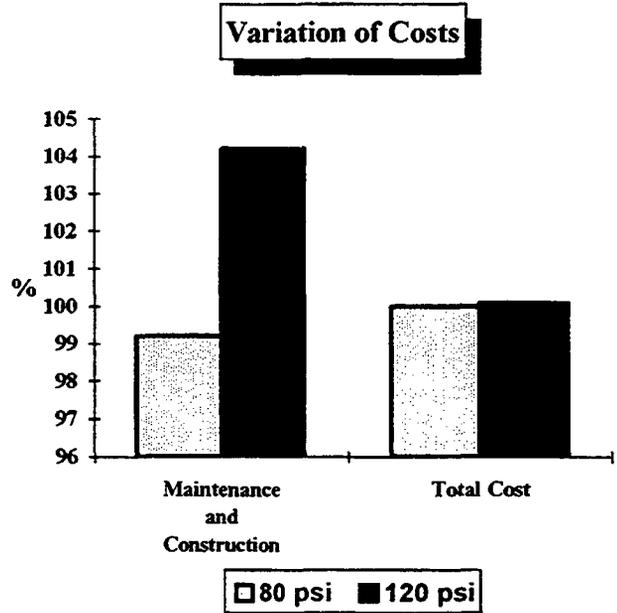


Figure 8. Variation of maintenance, construction and total costs as a function of tire inflation pressure.

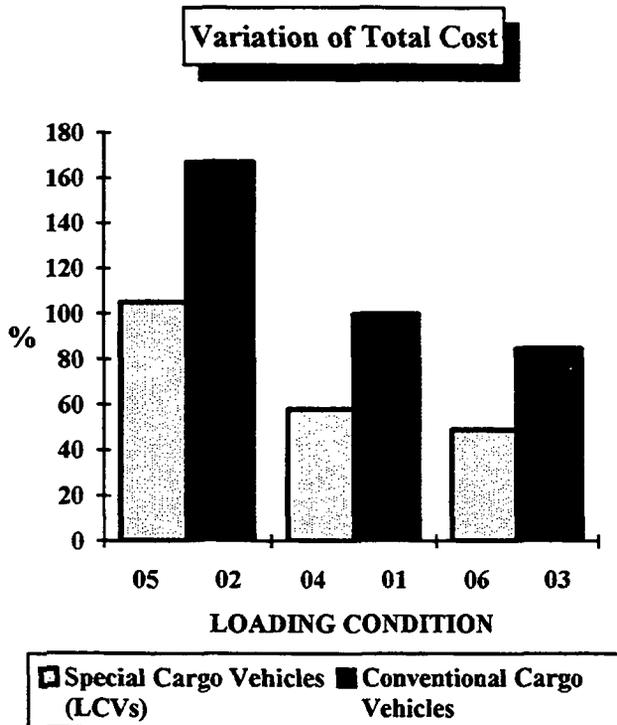


Figure 7. Variation of total cost as a function of truck type and loading condition.

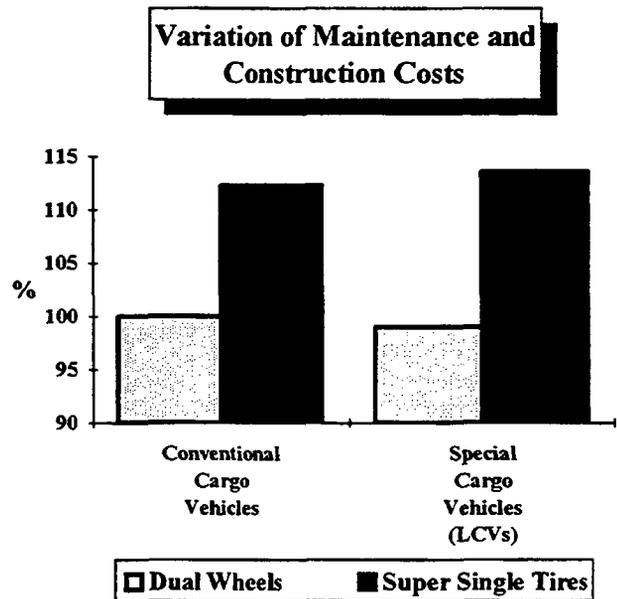


Figure 9. Variation of maintenance and construction costs as a function of wheel type.

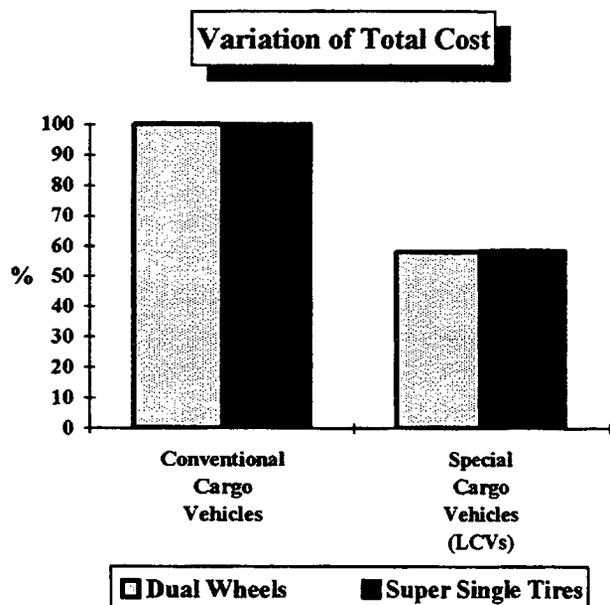


Figure 10. Variation of total cost as a function of wheel type.

The present situation is leading members of the Brazilian trucking industry to admit that they "have to" build structural reinforcements in the vehicles in order for them to support overweight even on a very badly maintained roadway network. According to the industrial director of an important trailer manufacturer [10], "who does not adopt this procedure, which can increase the final price of a trailer of up to 15%, loses market share".

If maintenance and construction costs are the dominant decision factors, then the control of axle weights is of vital importance for the pavement management. Scales and weigh-in-motion systems may result in benefits that more than compensate the costs for their installation, maintenance and operation. Unfortunately, according to data published by the Brazilian Ministry of Transportation [2] there are only 19 weigh-stations operating along the 50000 km of the interstate highway network, resulting in an average of one weigh-station for more than 2500 km of highways.

TRUCK CONFIGURATIONS

The results presented in this study show that LCVs reduce the maintenance and construction costs and, at the same time, they also reduce significantly the vehicle operation costs. Although the LCVs need extra care related to geometric design and stability and control, they should be considered as an alternative, and research has to be conducted in order to provide a technical support for imminent decisions to be made by the Brazilian DOTs with respect to traffic compatibility on the road network.

SUPER SINGLE TIRES

Although the super single tires are responsible for the highest increase in maintenance and construction costs when substituting dual wheels carrying the same loads, they may present a feasible solution to some axle load problems.

The results of previous research [9] show that the utilization of super single tires should be encouraged for short trucks that present problems of weight distribution and tend to overload the steering axle.

Based on the LEF equations used in this study, the steering axles with conventional tires can be responsible for a large amount of pavement deterioration since its legal limit in Brazil is very high (6 m-ton). The increase from 5 m-ton to 6 m-ton, approved a few years ago, should be revised. It is suggested that the 5 m-ton axle load should be used as the legal limit for steering axles with conventional tires and that steering axles carrying between 5 to 7 m-tons could be accepted if equipped with super single tires.

TIRE INFLATION PRESSURE

The tire inflation pressure is a factor that results in significant alteration in maintenance and construction costs. The results of this study show an increase of about 6% in maintenance and construction costs when the tire pressure increases from 80 psi to 120 psi. So, the tire inflation pressure should be considered by pavement and asphalt mixture design methods, by technical regulations, and by cost allocation criteria.

ACKNOWLEDGMENT

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REFERENCES

- LAZZARI, C.L. and WITTER, I.R.R. - *Brazilian Transit Regulation* (in Portuguese) - Ed. Sagra - Porto Alegre, RS, Brazil - 1991
- GEIPOT - Brazilian Company for Planning in Transportation - *Annual Report of Transportation Statistics* (in Portuguese) - Brasília, DF, Brazil - 1994
- GEIPOT - *Research on the Interrelationship of Highway Construction, Maintenance and Utilization Costs* - Reports 1 to 12 - Brasília, DF, Brazil - 1976 to 1981
- EISENMAN, J. - *Bewertung der Strassenbeanspruchung* - Strasse and Autobahn - Bonn - Germany - pp. 107-110 - 1979
- MIDDLETON, D.; ROBERTS, F.L. and CHIRACHAVALA, T. - *Measurement and Analysis of Truck Tire Pressures on Texas Highways* - TRR 1070 - Washington, DC - 1986
- REIS, N.G. and GELLI, A. - *Personal Communication* - Respectively, Chief Editor of the Journal *Transporte Moderno* and Responsible for Technical Courses on Tires promoted by *Transporte Moderno* - São Paulo, SP, Brazil - 1994

7. WATANATADA, T.; HARRAL, A.; PATERSON, W.D.O.; DHAR4ESHWAR, A.; BHANDARI, A. and TSUNOKAWA, T. - The Highway Design and Maintenance Standards Model - World Bank - Transportation Department - Washington, DC - 1987
8. STATE OF MINAS GERAIS DOT - *Maintenance of Roads - Annual Bulletin* (in Portuguese) - Belo Horizonte, MG, Brazil - 1993
9. FERNANDES, JR., J.L. - *Investigation of the Effects of Traffic Loading Factors on Pavement Performance* (in Portuguese) - Ph.D. Dissertation - Engineering School of São Carlos - University of São Paulo, Brazil - São Carlos, SP - 1995
10. GAZETA MERCANTIL - *Interview of Mr. Erino Tonon, industrial director of Randon Co., to the reporter Guilherme Arruda* - Caxias do Sul, RS, Brazil - 1991

