PAVEMENT DAMAGE – BRAZILIAN ROAD DETERIORATION TEST USING WIM





G.G. OTTO
UFSC
Brazil

K.J. SHINOHARA
UFSC
Brazil

A.J. ALMEIDA
UFSC
Brazil

L.MOMM
UFSC
Brazil

A.M.Valente
UFSC
Brazil

Abstract
This work aims to study the pavement deterioration in real conditions by doing pavement assessment, using both information from pavement instrumentation and multiple sensors weigh in motion to define a pavement deterioration model. The analysis model principle uses the accumulated damage caused by the traffic load. It considers the traffic load spectra, speed and pavement temperature, as the influence in pavement stiffness modulus and fatigue law. In the field, a data acquisition system provides strain and stress information of the pavement structure. WIM systems provides information about the heavyweight vehicles on the experimental track. The sensors are install in groups of sixteen rows spaced in one meter between each line. The study found that for any increase on the load above the legal limit diminish pavement life.

Keywords: Pavement, Pavement Damage, Pavement Deterioration, Heavy Vehicles, Weigh-in-Motion, WIM.

Resumo
Este trabalho tem como objetivo o estudo da deterioração de pavimento em condições reis por meio da avaliação do pavimento, usando ambas informações de instrumentação de pavimento e sistema de pesagem em movimento usando múltiplos sensores para definir uma modelo de deterioração de pavimento. O princípio do modelo de analise utiliza o dano acumulado causado pelo carregamento do tráfego. Considera a espectro de carregamento, velocidade e temperatura do pavimento, como fator de influência no módulo de rigidez e na lei de fadiga do pavimento. Em campo, um sistema de aquisição de dados provém as informações de tensão e deformação da estrutura do pavimento. Um sistema WIM provém as informações dos veículos de carga na pista experimental. Os sensores são instalados em grupos de dezesseis linhas com espaçamento de um metro entre cada linha. O estudo apresenta como resultado que o aumento acima do limite legal contribui para a redução da vida útil dos pavimentos.

Palavra-chave: Pavimento, Dano em pavimento, Deterioração de pavimento, Veículos pesados, Pesagem em movimento, WIM.

1. Introduction

The high-speed multiple sensors weigh in motion has been under research by several international organisms and countries. For Brazil, as for most of the nations, the weigh in motions systems are an important tool to perform weight enforcement directly on the highway. This project is inserted in a broader study called the High-speed Multiple Sensors Weigh in Motion Systems and Pavement Mechanical Analysis. This project was born due to DNIT (National Department of Infrastructure and Transportation) needs to perform weight control in the National Weighing Plan. Then, an agreement between DNIT and UFSC (Federal University of Santa Catarina) was done to elaborate and define MS/WIM procedures. In Brazil, these new technologies have potential to perform statistics data collection, overload pre-selection and, in the future, for direct enforcement. One of the most important contribution for WIM development and used as reference for this research is the COST 323 research (COST 323, 1998).

A pavement structure is design to resist a certain number of cycles of loading. The life span of this structure will depend only in the amount of loading of each vehicle. On the roads, pavement is constant submitted to distribution of loadings. The pavement life duration reduces as the number of vehicles overloaded increase.

The Weigh-in-Motion systems allow us to estimate the resultant force on each vehicle axle. Additionally, it has great potential to increase the efficiency and effectiveness of control overloading practices, which is in charge of the authorities responsible for road operations. This work aims to study the pavement deterioration in real conditions by doing pavement assessment, using both information from pavement instrumentation and multiple sensors weigh in motion to define a pavement deterioration model.

2. Damage analysis model

The analysis model is based on the accumulated damage caused by the traffic load. This model considers the traffic load spectra (load per axle or axle group), speed and pavement temperature, as the influence in pavement stiffness modulus and fatigue law. A numerical viscoelastic pavement software, such as ViscoRoute (Chabot et al., 2009), calculates the equivalent strains and stress for each load, which is dependent on the load speed and pavement temperature. The strains calculated to each load is than associated whit the frequency that appears at the load spectra. The strain frequency spectrum shows the distribution of deformation applied on the pavement due to passing traffic combined to pavement characteristics (a composition of load and speed). The pavement fatigue curve allows to access the strain ε value that represent the pavement lifetime N. The value N represent the number of cycles of loading on pavement structure. The fatigue curve can connect the pavement lifetime, in this analysis in years, with the amount of load applied.

The damage calculus is a function of the load (C), velocity (V) and temperature (T) as shown in equation (1). The damage is cumulative sum of damages over the life of the pavement that breaks when the value D is equal to one. In the equation n is the cumulative traffic load summary over pavement lifetime and N is the number of loading accumulated that leads to the end of pavement life, accordingly to a certain amount of deformations.

$$D = \sum_k^C \sum_i^V \sum_j^T \frac{n_{ijk}}{N_{ijk}} * 100 \qquad (1)$$

3. Field analysis

In the field, a data acquisition system provides strain and stress information of the pavement structure. The recorded data correspond to the pavement structural layer behaviors as well as the dynamic force from the free flow traffic. In laboratory, material form the tests site allow to determine mechanical characteristics of material, mainly by the fatigue test and complex modulus determination, both performed in the Pavement Laboratory at Federal University of Santa Catarina, UFSC.

For this project, a 700-meter-long experimental track was built, located in BR-101 highway, km 418, near Araranguá city, Santa Catarina state, Brazil. The cross section is composed of a semi-infinite sand subgrade, 20 cm Macadam layer, 18 cm graded gravel layer and 17 cm of Hot Mix Asphalt layer. It was designed to be the Weigh Station main entrance, presented in Figure 1.

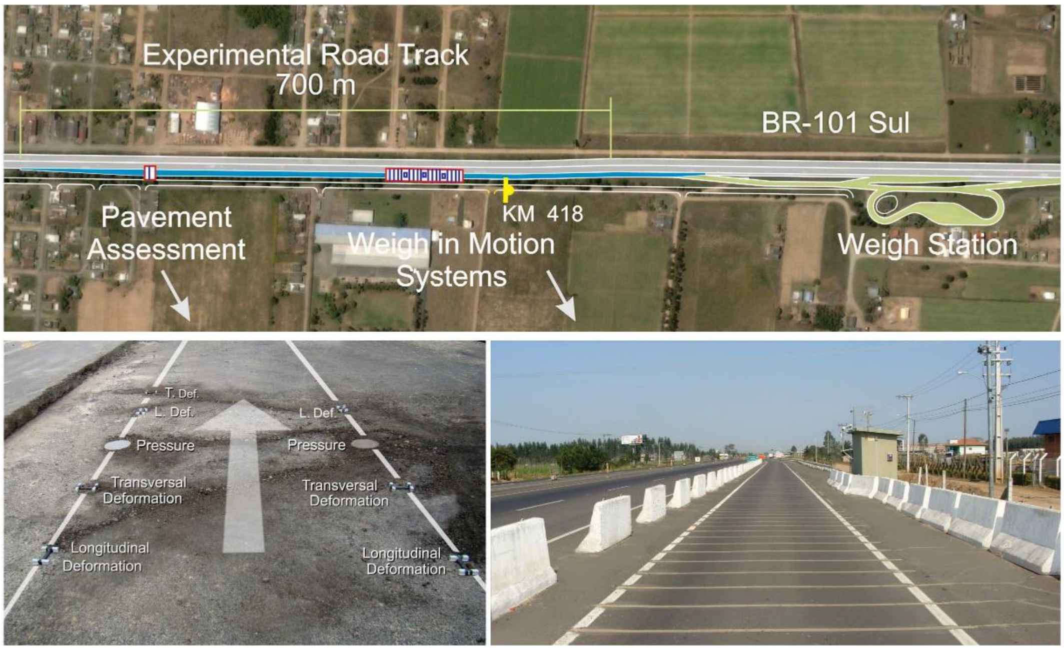

Figure 1 – This is a sample figure caption

4. Pavement deterioration analysis

The pavement structure fatigue process has origin in the repeated interactions between the tire and the pavement. The pavement material behavior, allied with external factors as solicitation and physic conditions, allow understanding of deterioration mechanical process of the pavement. The pavement strain and stress assessment shows the intensity of the efforts applied. It can be used to evaluate the pavement support parameters. Pavement design aims to obtain an appropriate behavior during lifetime, besides, to ensure safety and comfort to the road users. This process considers the load applied over time, the deformation found in the bottom of surface course and the stress found in the top of subgrade.

The pavement assessment system uses devices under and over pavement surface, which allow the acquisition of information for the identification and quantification of pavement behavior under certain conditions of temperature and humidity. A set of sensors are installed in a way that allow identify the deformation under asphalt layer, base layer and sub-base, in longitudinal and transverse alignments. Likewise, pressure on top of the base layer, sub-base and subgrade. Moisture of granular layers and temperature at three depths in the asphalt concrete are measure at same time as the others measures. The longitudinal transversal strains, in the bottom of the layers, are monitored by strain gauge specially designed for this function.

The vehicle weighing data derives from the weigh-in-motion system. The weigh-in motion sensors are installed in rows in transversal aliment to the direction of the traffic. The technologies used are piezoelectric quartz, piezoelectric ceramic, piezoelectric polymer and fiber-optic sensors.

WIM systems provides information about the heavyweight vehicles on the experimental track. The sensors are install in groups of sixteen rows spaced in one meter between each line. The data of the weighing system are organized by date and time, which is recorded when a vehicle met the first sensor. Each event contains information of the vehicle class, axle numbers and space between them, axle weight, gross weight and speed.

The deterioration of pavements analysis uses both measurements of pavement assessment system and weigh-in-motion system together with material characteristics defined in laboratory. The sensors installed in the pavement structure informs the pavement behavior in the moment that one vehicle passes by. As vehicle pass over the experimental track, the WIM system identifies and measures the axle weight.

Viscoelastic software input parameters, resented by Chabot et al. (2009), are the pavement material characteristics determined in the laboratory and field. The material characteristics defined in laboratory are complex modulus and fatigue curve. These two characteristics, mainly fatigue, governs the structural behavior of the pavement during the lifetime span. The pavement structure is assessed applying both traffic information from WIM system data collection and data traffic from the weigh station.

The alternated bending test machine accesses asphalt mechanical characteristics. This equipment allows determining the complex modulus and the fatigue characteristics in different conditions of temperature and load frequency. The results of complex modulus determination give a linear viscoelastic characteristics of the asphalt material, because they are measured in the field of small deformations.

All viscoelastic materials responds relatively to the tension applied by a with a delay. In the field of small deformations, the small sinusoidal force results also in a sinusoidal response. Thus, the deformation presents a phase shift in relation to the force, which reflects the material behavior. When the phase shift is equal to 0º, it means that the material is purely elastic. When phase shift is equal to 90º, it means that the material is purely viscous. The modulus of the complex |E*| can be express by equation (2):

$$|E^*| = (E_1^2 + E_2^2)^{\frac{1}{2}} \tag{2}$$

The different components of the complex modulus vary with temperature and frequency. The experimental results |E*|, φ, E1 and E2 are expressed by graphical representation called: Isotherme, equivalent frequency, Isochrone, Cole-Cole and Black space. E1 represents the real part, or elastic part, and E2 the imaginary part, or viscoelastic part. The specimen is a block with dimensions h_{layer}(17cm) x 60cm x 40cm removed from de asphalt course. From it, trapezoidal specimens are made to perform complex modulus and fatigue tests in the two point bending machine.

The Cole-Cole representation provides the parameters for the Huet-Sayegh model (Huet, 1963), which provides parameter for pavement design, Table 1, calculated with aid of Viscoanalyse (Chailleux, 2009). The model is obtained by a spring of stiffness E_0, which represents the elastic modulus. The model is given by Equation (3):

$$E^*(i\omega\tau) = \frac{(E_0+(E_\infty-E_0))}{1+\delta\,(i\omega\tau)^{-k} + (i\omega\tau)^{-h}} \tag{3}$$

Table 1 – The Huet-Sayegh parameters

E_0	E_{inf}	δ	k	H	τ	$A0$	$A1$	$A2$
53	13304	0.573	0.132	0.518	0.065	1.405	-0.295	0.0013

Figure 2 shows the comparative of complex modulus between two different years representation the asphalt mixture from the experimental road track.

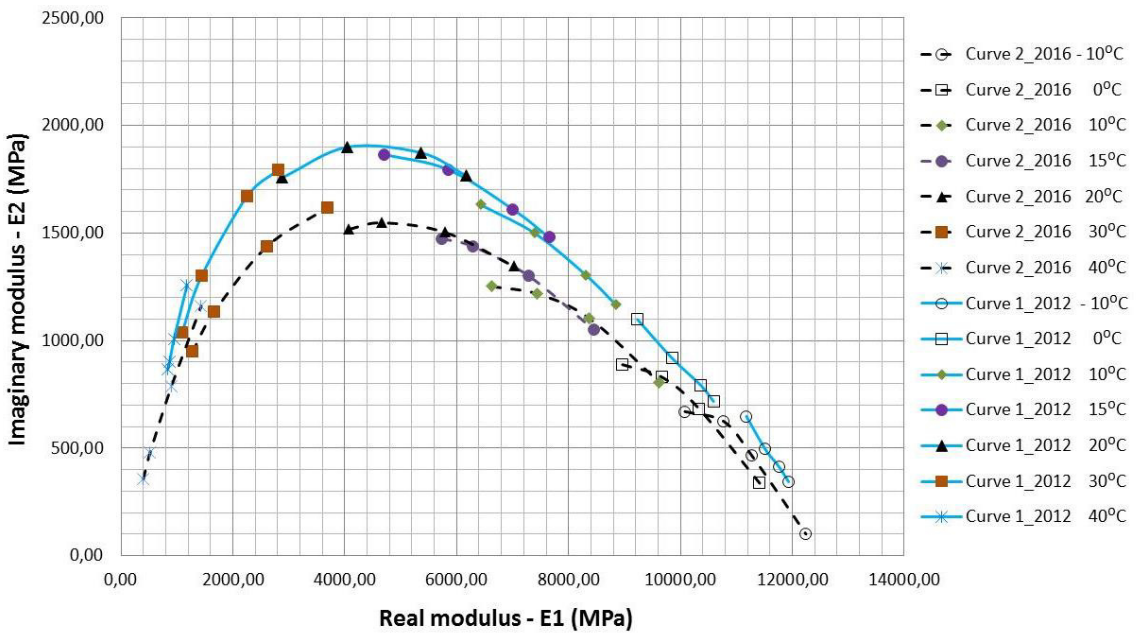

Figure 2 – Comparative Cole-Cole curve

The fatigue test is performed in continuous mode and controlled deformation, thus the stiffness of the specimen decreases as the number of deformations applied increases. The results must be around the 10^6 numbers of alternated deformations, in two point bending test. The test aims to found a deformation corresponded to one million cycles applied, called ε_6. The criteria adopted are the same as recommended by French fatigue test method, executed at 10ºC and 25 Hz.

The fatigue curve which accompanies deterioration of the pavement 2012 and 2016 are presented in the Figure 3. The curve represents the susceptibility of asphalt mixture to deformation effort, represented in scale log-log. The abscissa is the deformation, in 10^{-6} m, and the ordinate is the accumulate number of deformation cycles. The curve is a line represented by an exponential equation, which curve inclination is the exponent. The equations of the year fatigue curves 2012 and 2016 are:

$$\mathrm{N} = 1.22 * 10^{16} * \varepsilon^{-5.10} \qquad 2012 \tag{4}$$
$$\mathrm{N} = 1.17 * 10^{15} * \varepsilon^{-4.60} \qquad 2016 \tag{5}$$

The deformation specific result of fatigue test result is the deformation for 10^6 cycles. From equations (4) and (5) are determined to deformation for 10^6 cycles, for the year 2012 and 2016. The found values of deformation ε_6 are 95.024 µm and 94.998 µm respectively. N represents the number of axels accumulated on the pavement over the years, in other words, the sum of loads, which will pass by the road section during the pavement lifetime. Therefore, the equation enables comparing the deformation found in field with the fatigue curve to establish the deterioration degree.

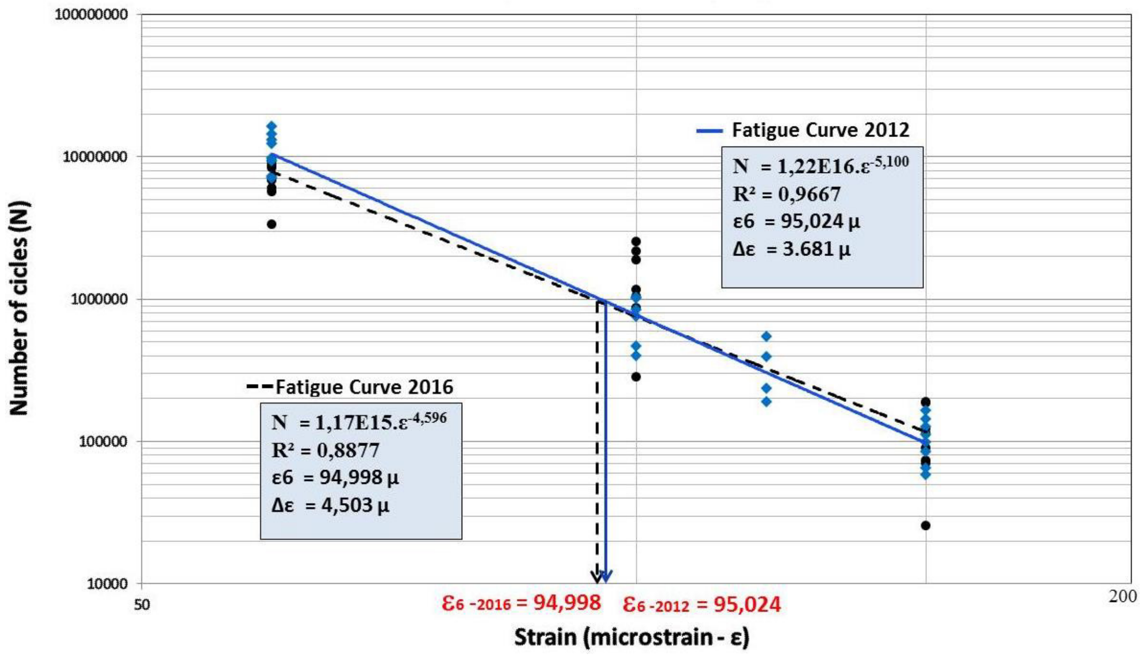

Figure 3 – Comparative curve of fatigue (temperature= 10ºC e frequency=25Hz)

5. Damage analysis

Mainly there are four types of axes: single axle single wheel, single axle dual tire, tandem axle, tridem axle. Vehicle fleet have its specific axle composition and, for each axle type, there is a respective load distribution. The loads in field obey a normal distribution, with the most common value near legal limit and other values below or above the expected value. Figure 4 shows the load spectra for the three most influent types of axles and their legal limits (describe in the Brazilian legislation).

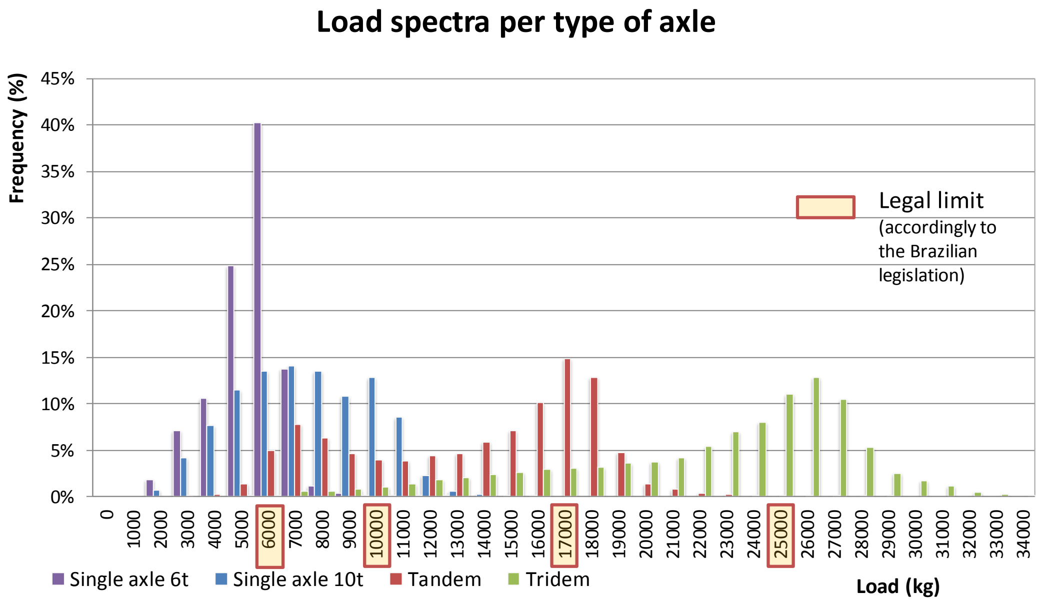

Figure 4 – This is a sample figure caption

All parameters are organized and loaded into the analysis software together with pavement structural characteristics. Among all results, the pavement longitudinal deformation is the behaviour observed. This value then can be linked directly to the deformation found in the fatigue curve. The design information used for simulation of the traffic and the behaviour of the pavement are:

- traffic open year 2011;
- project period of 15 years, 2026;
- characteristics of asphalt concrete (Model rheological Huet-Sayegh);
- characteristics of the base BG, sub-base and subgrade MS;
- axle types: single axle dual tire, tandem and tridem;
- actual average temperature of the pavement (z = 17cm): 22 ° C;
- Speed: 80km/h e 60km/h.

Table 2 - Pavement physical and statistical parameters

	Parameters	Value (2012)	Value (2016)
Complex modulus	|E*| (10°C; 10Hz) - Mpa	8418	8446
	|E*| (10°C; 25Hz) - Mpa	8801	9355
Fatigue	|E*| (15°C; 10Hz) - Mpa	7186	7404
	ε_6 (10^6)	95.024	94,998
Coefficient	Fatigue slope	-5.1	-4,6
	Kr	1.0	1.0
	Kc	1.1	1.1
	Ks	1.0	1.0

Axle interaction simulation Table 2 contains the physical and statistical parameters, used in the pavement numerical simulation. The coefficients kr, kc and ks corrects the deformation ε6 from the fatigue test and then becomes working strain at the base of the bituminous layer, define both in 2012 and 2016.

5.1

Two simulations can present how pavement life is related to load and velocity variations. The analysis uses the correspondent strain considering a fleet of hundred per cent of single axel, a hundred per cent of tandem axle and a hundred per cent of tridem axle. Table 3 presents the result from traffic and pavement life interaction, considering increasing the load, starting from legal limit, and vehicle velocity variation. On this simulation, the modulus and fatigue adopted are from the material extract in 2012, at the moment of construction.

Table 3 - Pavement end of life proportional to load increase and velocity variation

Axle	Load (t)	εt (obtained) (10^{-6}) Load speed 80km/h	εt (obtained) (10^{-6}) Load speed 60km/h	End of life in years after traffic opening 80 km/h	End of life in years after traffic opening 60 km/h
Single axle	8.2	49.9	51.0	15	12
	10	60.8	62.1	2	2
	10.5 (5 %)	63.8	65.2	-	-
	10.75 (7.5 %)	65.4	66.8	-	-
Tandem axle	17	49.7	50.9	15	12
	17.85 (5 %)	52.2	53.5	11	9
	19.19 (7.5 %)	56.1	57.5	6	5
Tridem axle	25	48.3	49.6	15	12
	26.25 (5 %)	50.8	52.0	12	12
	28.22 (7.5 %)	54.6	55.9	8	6

The study found that for any increase on the load above the legal limit diminish pavement life. In addition, velocity variation has an important effect on the damage caused on pavement structure, the lower velocities the bigger the damage. An analysis considering wide range of velocity and load shows how important load speed is to pavement life.

5.2 Real traffic composition interaction

Consider an entire fleet of vehicle composed by a hundred percent of traffic with a specific load is too radical, but indicates how important an overload of a specific axle is comparing to others. As we can see in the Figure 5, even when we consider a real traffic data and an increase of 5, 7.5, 10 and 20% of overload.

If all vehicle starts to carries more than 5% of overload, the pavement life reduces in 15%, if it carries more than 7.5% of overload, the pavement life reduces in 22%. If carries more than 10 and 20% of overload, the life is reducing in 28 and 50%, respectively.

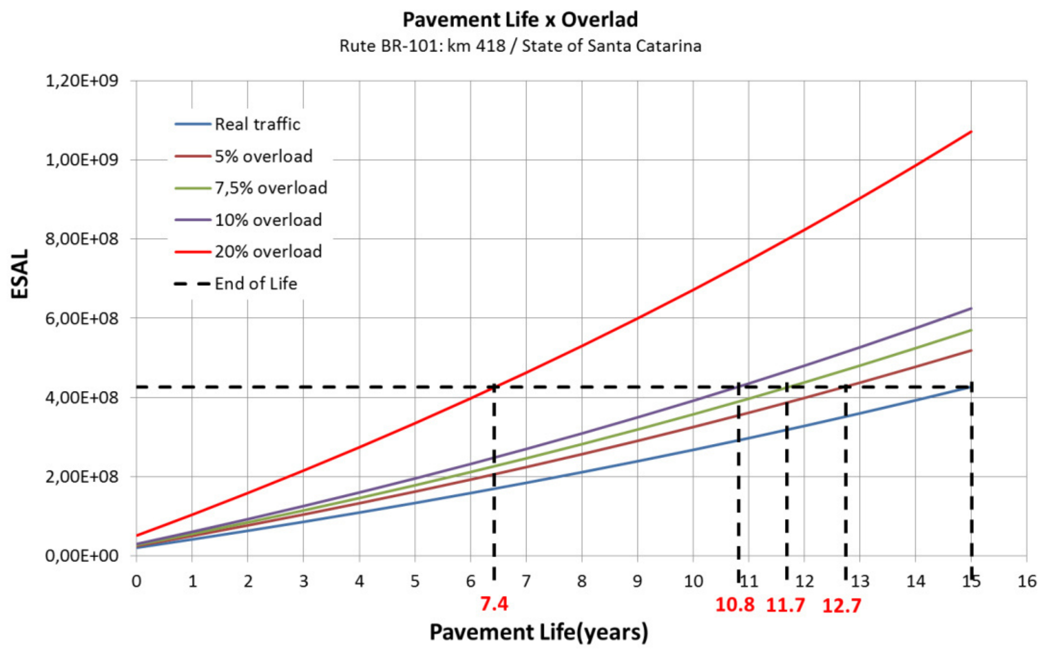

Figure 5 – This is a sample figure caption

6. Conclusion

It can be assuring that any increase on the load over the axles is the major problem for pavement performance and consequently contributes to reduce pavement life. These phenomena can be observed in the first analysis. The analysis of fatigue curve and complex modulus curve shows the deterioration of the pavement was increase along the time. Comparing the two fatigue curves, year 2012 and 2016, it shows reduction of the working strain of 10^6 cycles, also reduction of the complex modulus, presented at Cole-Cole curve. Mainly these two changes in the bituminous concrete are related to natural aging process. According to the material viscoelastic behaviour law, faster the load is applied harder the material behaves. As shown in the results, as lower de the vehicle speed shorter the pavement lifespan is. The real traffic composition shows the increase of overload and pavement life reduction, it is clear that 20% of overload can reduce pavement life in approximately 50%.

7. References

- Huet, C (1963), "Étude par une méthode d'impédance du comportement viscoélastique des materiaux hydrocarbonés". *Doctor These*. Faculté des Sciences de l'Université de Paris, 63.
- COST 323 (1998), "Weigh-in-Motion of Road Vehicles: Final Report". *Institut Francais des Sciences et Technologies des Transports*, *de l'Amenagement et des Reseaux* (IFSTTAR). Paris, France.
- Chabot, A., Chupin, O., Deloffre, L., Duhamel, D. (2009), "Viscoroute 2.0: a tool for the simulation of moving load effects on asphalt pavement", *Road Materials and Pavements Design*, Volume X
- Chailleux, E. (2009). "Note d'utilisation de l'application logicielle visco-analyse". *Institut Francais des Sciences et Technologies des Transports*, *de l'Amenagement et des Reseaux,* Paris, France.