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COST 334 – EFFECTS OF WIDE TYRES AND DUAL TYRES

Task Group 3 – Pavement wear effects

Mechanistic approach for rutting – Stage 2

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COST 334 – EFFECTS OF WIDE TYRES AND DUAL TYRES
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COST 334 – ESTUDO COMPARATIVO DO EFEITO DE RODADOS SIMPLES DE BASE LARGA E DE RODADOS DUPLOS
Grupo de Trabalho 3 – Efeito no consumo do pavimento

Previsão de cavados de rodeira – Fase 2

COST 334 – EFFETS DE ROUES SIMPLES LARGES ET DE JUMELAGES
Groupe de Travail 3 – Effets dans la consommation des chaussées

Prévision d'ornières – Phase 2

COST 334 – EFFECTS OF WIDE TYRES AND DUAL TYRES
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Mechanistic approach for rutting – Stage 2

TABLE OF CONTENTS

INDEX OF FIGURES

COST 334 – EFFECTS OF WIDE TYRES AND DUAL TYRES
Task Group 3 – Pavement wear effects

Mechanistic approach for rutting – Stage 2

INDEX OF TABLES

COST 334 – EFFECTS OF WIDE TYRES AND DUAL TYRES
Task Group 3 – Pavement wear effects

Mechanistic approach for rutting – Stage 2

1 - INTRODUCTION

Action COST 334 (*Effects of wide single tyres and dual tyres*) aims at a better understanding of the overall effects of the widespread, and increasing use, of wide single tyres for heavy goods vehicles in Europe.

Within Task 3 (*Pavement wear effects*) a programme of research has been set up to evaluate the relative wear effects on pavements of wide base single and dual tyres.

The National Laboratory for Civil Engineering (LNEC) was engaged in a contribution for this research program for the evaluation of rutting using a mechanistic approach. The computational code used to perform the viscoelastic calculations was CREEPN developed at LNEC.

CREEPN is a 3D finite element program that allows to model the material in a linear viscoelastic behaviour expressed by the Burgers' model.

The contribution of LNEC has been programmed in four stages:

Stage 1 – Predicting, by CREEPN, of rutting measured in laboratory wheel tracking tests of a bituminous mixture. The viscoelastic characteristics of this bituminous mixture were evaluated in repeated uniaxial loading tests;

– Comparing the results from CREEPN with the results from VEROAD. Some additional calculations were performed with the widespread code DIANA that uses an approach similar to CREEPN;

Stage 2 – Validating the CREEPN approach with existent results of tests performed at TRL (UK) and LCPC (F);

Stage 3 – Validating the CREEPN approach with tests to be performed at TRL (UK) and LINTRACK (NL) in the context of Task Group 3;

Stage 4 – Performing additional calculations to allow a comparison of the relative potential for permanent deformation concerning:

- Dual Tyres versus Wide Single Tyre
- Magnitude of the inflation pressure
- Size of the contact area
- Unequal load sharing

The research carried out under Stage 1 was reported previously (Quaresma et al., 2000).

An important difference between Stage 2 and Stage 3 is the available data to perform the calculations concerning the full-scale pavement tests.

As Stage 2 is concerned with tests previously performed, data on material properties are bound to existing information. For Stage 3, the viscoelastic properties of asphalt layers used for calculation are supported on creep tests performed on samples from these layers.

This report presents the research for the Stage 2.

2 - METHOD OF ANALYSIS

2.1 - Rheological model for the bituminous layers

The rheological model used to simulate the stress-strain-time relation of bituminous layers was the Burgers model. This model is shown in Figure 1(a) where a Maxwell and a Kelvin model are connected in series.

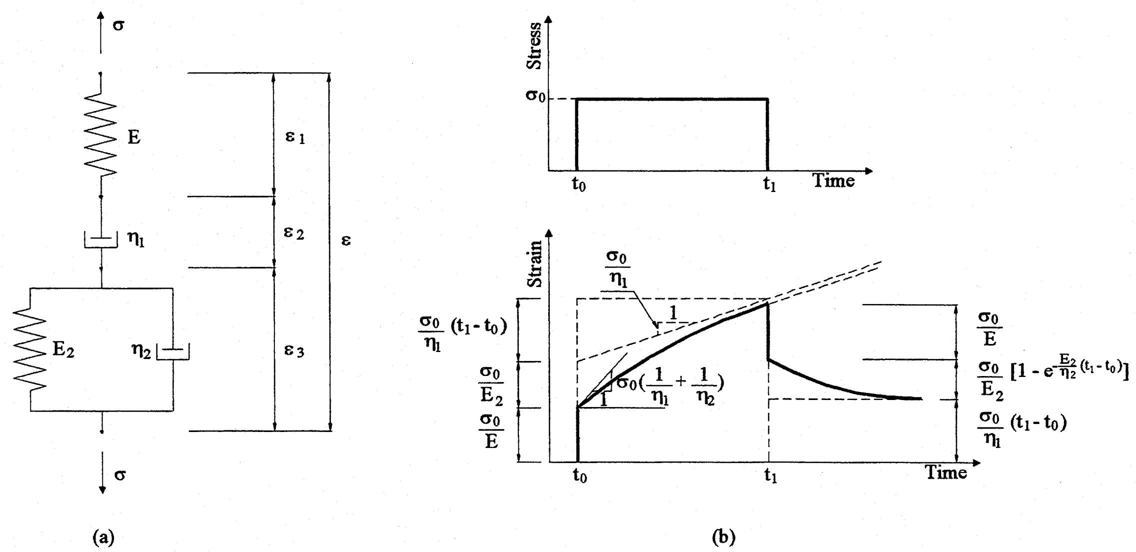

Figure 1 – Behaviour of a Burgers model

The differential equation for the Burgers model is

$$\eta_2 \ddot{\varepsilon} + E_2 \dot{\varepsilon} = \frac{\eta_2}{E}\ddot{\sigma} + \left(1 + \frac{\eta_2}{\eta_1} + \frac{E_2}{E}\right)\dot{\sigma} + \frac{E_2}{\eta_1}\sigma . \qquad (1)$$

The strain at time t under a constant stress $\sigma(t_0,t_1)=\sigma_0$ in a Burgers model can be obtained from (1) with two initial conditions, that are

$$\varepsilon(t = t_0) = \varepsilon_1 = \frac{\sigma_0}{E}$$

$$\dot{\varepsilon}(t = t_0) = \frac{\sigma_0}{\eta_1} + \frac{\sigma_0}{\eta_2} .$$

Thus the strain at time t is

$$\varepsilon(t) = \frac{\sigma_0}{E} + \frac{\sigma_0}{\eta_1}(t - t_0) + \frac{\sigma_0}{E_2}\left[1 - e^{-\frac{E_2}{\eta_2}(t-t_0)}\right] \quad \text{to} \quad t \le t_1 \qquad (2)$$

and by the Boltzmann's superposition principle

$$\varepsilon(t)=\frac{\sigma_0}{\eta_1}(t_1-t_0)+\frac{\sigma_0}{E_2}e^{-\frac{E_2}{\eta_2}t}\left(e^{\frac{E_2}{\eta_2}t_1}-e^{\frac{E_2}{\eta_2}t_0}\right) \quad \text{to} \quad t>t_1 \tag{3}$$

as shown in Figure 1b.

The first two terms in (2) represent instantaneous elastic strain and viscous flow (Maxwell model), and the last term represents delayed elasticity of the Kelvin model.

Differentiating (2) yields the strain rate as follows:

$$\dot{\varepsilon}(t)=\frac{\sigma_0}{\eta_1}+\frac{\sigma_0}{\eta_2}e^{-\frac{E_2}{\eta_2}(t-t_0)} \quad \text{to} \quad t\le t_1. \tag{4}$$

Thus the strain rate ($t \le t_1$) when t tends to infinity approaches asymptotically to the value (see Figure 1(b))

$$\dot{\varepsilon}(t=\infty)=\frac{\sigma_0}{\eta_1}$$

The recovery strain $\varepsilon(t>t_1)$, that was obtained according to the Boltzmann's superposition principle, has an instantaneous elastic recovery followed by creep recovery at a decreasing rate, as shown in (3) and in Figure 1b. The second term of (3) decreases toward zero for large time, while the first term represents a permanent strain due to the coefficient of viscosity of the dashpot in the Maxwell model (η_1). Thus the recovery approaches asymptotically to

$$\varepsilon(t=\infty)=\frac{\sigma_0}{\eta_1}(t_1-t_0)$$

when t tends to infinity.

The creep compliance for a Burgers model is given by

$$J(t)=\frac{1}{E}+\frac{t}{\eta_1}+\frac{1}{E_2}\left(1-e^{-\frac{E_2}{\eta_2}t}\right). \tag{5}$$

2.2 - Computational code

The computational code used to perform the numerical calculations for this research work was developed in LNEC. This computational code uses a three-dimensional finite element method (FEM) that allows to model the material with time dependent behaviour and viscoelastic properties (Batista, 1998).

The CREEPN uses volume elements with sixteen nodes. The boundary conditions can be of two types: rigid supports in any direction and surface elastic supports defined by means of the well known Vogt's coefficients (Batista, 1998).

The time dependent model used in CREEPN to simulate the stress-strain-time relation of materials is a Hooke model connected in series with a chain of Kelvin models connected in series as shown in Figure 2.

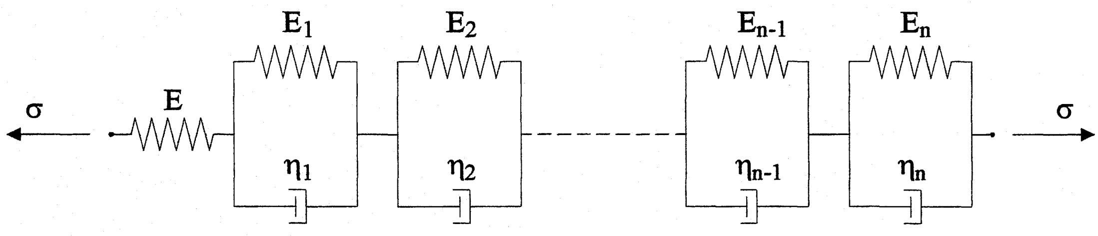

Figure 2 – Model used in CREEPN to simulate the material time dependent behaviour

The creep compliance associated to this model is approached, in CREEPN, by a Dirichlet series, with the form (Batista, 1998)

$$J(t,t_0)=\frac{1}{E(t_0)}+\sum_{i=1}^{n}\frac{1}{E_i(t_0)}\left(1-e^{-\frac{(t-t_0)}{t_i}}\right) \tag{6}$$

where the first term in (6) represents the deformation per unit stress of a Hooke model and the second term represents the deformation per unit stress of a chain of Kelvin models connected in series, in which $E_i(t_0)$ is the time dependent Young's modulus (to take into account the compaction, if necessary), $t_i=\eta_i/E_i(t_0)$ is the retardation time of the Kelvin unit and the η_i is the coefficient of viscosity of the dashpot of the Kelvin unit.

This technique allows the analysis to be performed step by step without the need of storing the whole load history.

By imposing values for E and η, one model may be converted to another model type. For example, a Maxwell model with infinite spring constant or a Kelvin model with zero spring constant becomes a dashpot. Similarly, a Maxwell model with infinite coefficient of viscosity or a Kelvin model with zero coefficient of viscosity is converted to a spring. Consequently, this model can simulate several rheological models. For the bituminous layers it was assumed that their time dependent behaviour can be represented by a Burgers model (see §2.1). To simulate the behaviour of the Burgers model in CREEPN, it is sufficient to consider two units in the Kelvin models chain (n=2 in Figure 2) and a value of E_1 near zero.

For the calculations it was assumed that the granular layers and the foundation have a linear elastic behaviour characterised by the Young's modulus (E) and the Poisson's ratio (ν). With these assumptions for the calculations only the bituminous layers contribute to the permanent deformation.

3 - SIMULATION OF TESTS AT LCPC

3.1 - Introduction

During the summer of 1997 the "Laboratoire Central des Ponts et Chaussées" (LCPC), the "Manufacture Française des Pneumatiques Michelin" and the "Société des Pétroles Shell" carried out together an experiment at the LCPC full-scale test facility, at Nantes.

One of the objectives of this experiment was to compare the pavement rutting of a new wide base single tyre (495/45R22.5) and current twinned single tyres (10R22.5).

The pavement used in the tests form a ring with four separate wheel tracks. These wheel tracks have radius of 16.5, 17.5, 18.5 and 19.5 m. The angular speed is 6.5 cycles/minute.

The pavement structure comprises a 8 cm asphalt concrete surface layer (0/14 mm), a 20 cm "grave-bitume" intermediate layer, a 20 cm "grave-ciment" road-base and a 20 cm granular layer. The pavement was built on a 3m thick sand-clay soil (Gramsammer et al., 1998).

3.2 - Burgers' serial damper parameter for the asphalt layers

The Burgers' serial damper parameter for the asphalt layers was obtained by VEROAD (DEBUROAD.EXE). This program estimates the Burgers' parameters from data concerning frequencies (Hz), stiffness (MNm^{-2}) and phase angle (degree).

As LCPC conducted another experiment in 1996, with similar materials for the pavement layers, the input data from LCPC tests of the asphalt layers were sent by LCPC to LNEC.

Table 1 – Input data from LCPC (Odeon, 1999)

Temperature (°C)	Frequencies (Hz)	Surface layer		Intermediate layer	
		Stiffness (MNm^{-2})	Phase angle (degree)	Stiffness (MNm^{-2})	Phase angle (degree)
20	40	9332	22.0		
	30	8689	23.4	13191	13.0
	25	8287	24.2	12932	13.0
	10	6432	28.7	11198	15.0
	3	4239	35.3	8960	18.0
	1	2690	41.4	7055	21.0
30	40	4068	37.8		
	30	3594	39.6	7851	21.0
	25	3330	40.7	7545	21.0
	10	2182	45.9	6017	24.0
	3	1161	51.2	4211	29.0
	1	623	53.4	2877	32.0
40	40	1226	55.4		
	30	1033	55.6	3576	33.0
	25	930	55.8	3312	34.0
	10	541	55.9	2291	37.0
	3	270	52.9	1349	41.0
	1	160	45.8	840	43.0

Table 1 shows the input data from LCPC tests conducted in 1996 (Odeon, 1999). Table 2 shows, for different temperatures, the Burgers' serial damper parameter for the asphalt layers obtained by DEBUROAD (VEROAD).

Table 2 – Burgers' serial damper parameter for the asphalt layers of LCPC test pavement

T (ºC)	Serial damper - η_1 ($MNm^{-2}s$)	
	Surface layer	Intermediate layer
20	637-744	2264-3328
30	132-135	758-1005
40	39-43	203-230

The stiffness and phase angle were obtained from flexural tests. Since the Burgers' serial damper parameter is dependent on the volume composition of the bituminous mixtures and there is a compaction during the first phase of the wheel passes, the values in Table 2 can only be used as an estimate for the beginning of the experience at the Nantes facility.

The pavement test facility is located outdoors, and during the experiment the pavement temperature was not kept constant. From the report of the LCPC test the mean measured temperature at 1 cm below the surface, during the test, was slightly higher than 35ºC (Gramsammer et al, 1998).

3.3 - Data for CREEPN

Table 3 shows the load characteristics (tyre contact area and contact pressure) that was used in CREEPN, according to data from Michelin (Penant, 1999).

Table 3 – Load characteristics for LCPC test simulation (Penant, 1999)

Tyre code	Load per tyre (kN)	Inflation pressure (kNm^{-2})	Width (mm)	Length (mm)	Contact pressure (kNm^{-2})	Ratio Contact/Inflation (%)
10R22.5	26.5	800	183	226	640.7	80.1
495/45R22.5	53.0	800	428	190	651.7	81.5

Figure 3 shows the finite element mesh to simulate the test at LCPC (only asphalt layers). All nodes in the base are fixed and the lateral nodes are fixed only in the perpendicular direction. This computer simulation was done for one cycle (1 pass).

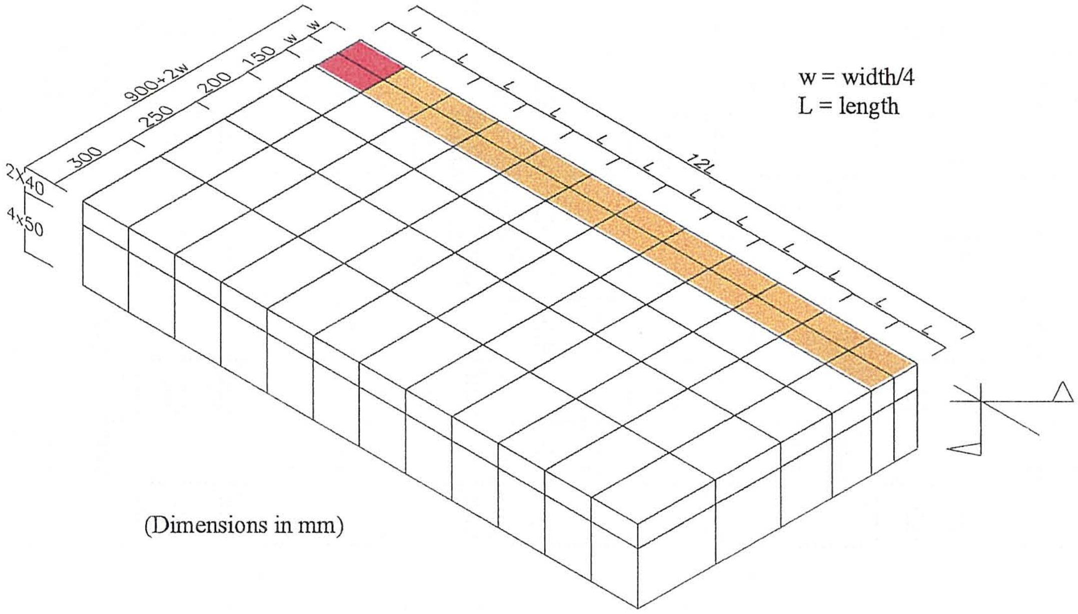

Figure 3 – Finite element mesh to simulation the test at LCPC

For the simulation of the test in 1997 it was assumed that the materials are similar to those of the test in 1996. Taking into account the data of Table 2 and the mean pavement temperature this case was calculated on the basis of the following data:

Surface layer (asphalt layer 1):

thickness	h=80 mm
serial damper	η_1=90 MNm^{-2}s
Poisson's ratio	ν=0.40

Intermediate layer (asphalt layer 2):

thickness	h=200 mm
serial damper	η_1=550 MNm^{-2}s
Poisson's ratio	ν=0.40

Table 4 shows the different speeds that were used in CREEPN simulation for the four tracks.

Table 4 – Linear speed for the different tracks

Track (radius)	16.5 m	17.5 m	18.5 m	19.5 m
Speed (ms^{-1})	11.23	11.91	12.59	13.27

Figure 4 shows the lateral distribution during the tests at LCPC (Gramsammer et al., 1998).

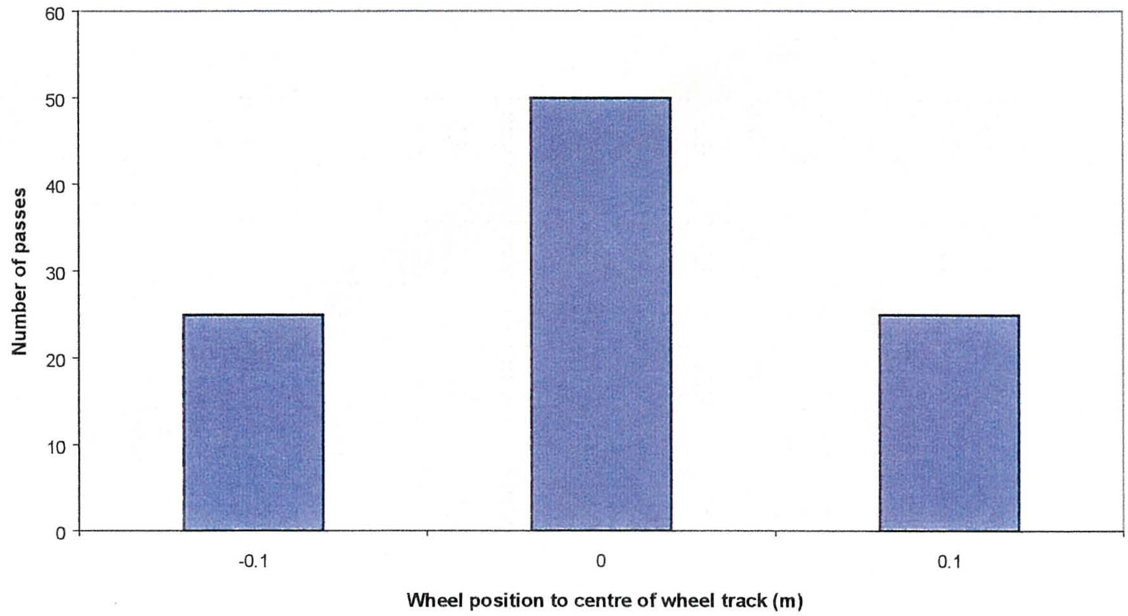

Figure 4 – Lateral distribution for test at LCPC (Gramsammer et al., 1998)

3.4 - Results from CREEPN

Figure 5 shows the permanent deformation parameters that were calculated by CREEPN program and Table 5 shows the results for these parameters.

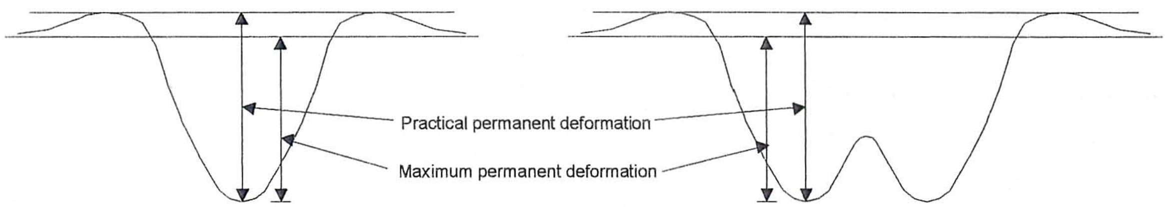

Figure 5 – Parameters that were analysed in CREEPN

Table 5 – Permanent deformation by cycle (mm/cycle) with lateral wandering

Tyre		Tracks (radius)			
		16.5 m	17.5 m	18.5 m	19.5 m
10R22.5	Maximum	0.00642		0.00573	
	Practical	0.00654		0.00583	
495/45R22.5	Maximum		0.00694		0.00623
	Practical		0.00716		0.00643

Figure 6 shows the rate of practical permanent deformation at surface for the different test tracks.

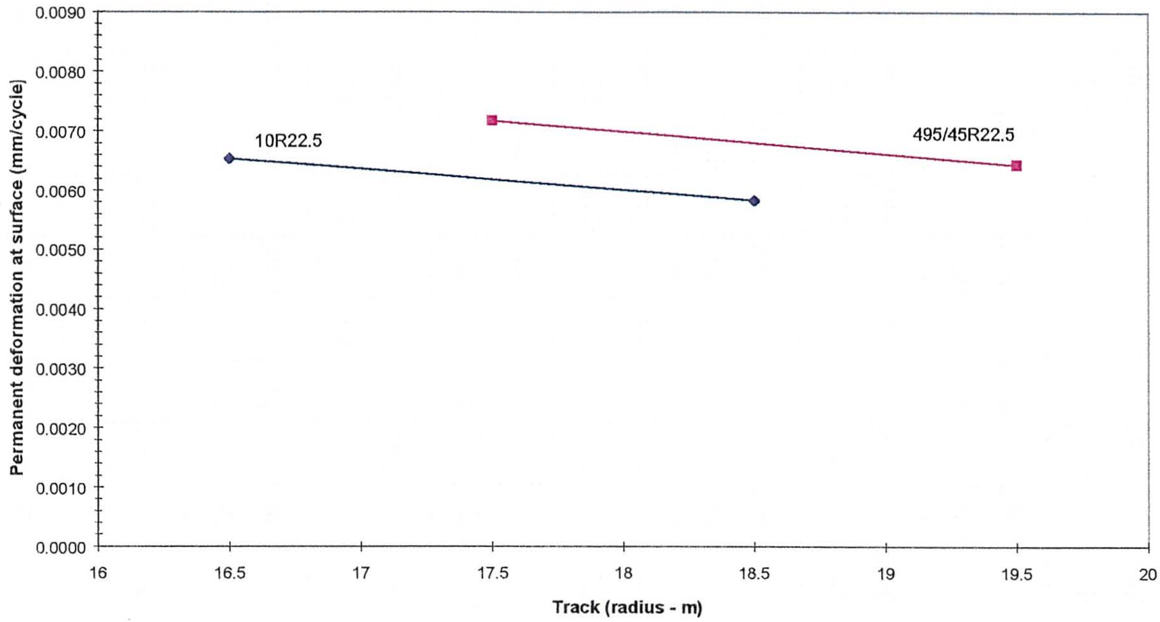

Figure 6 – Rate of practical permanent deformation for the different tracks

Figure 7 shows the permanent deformation, at surface, for a cross section for the different tracks.

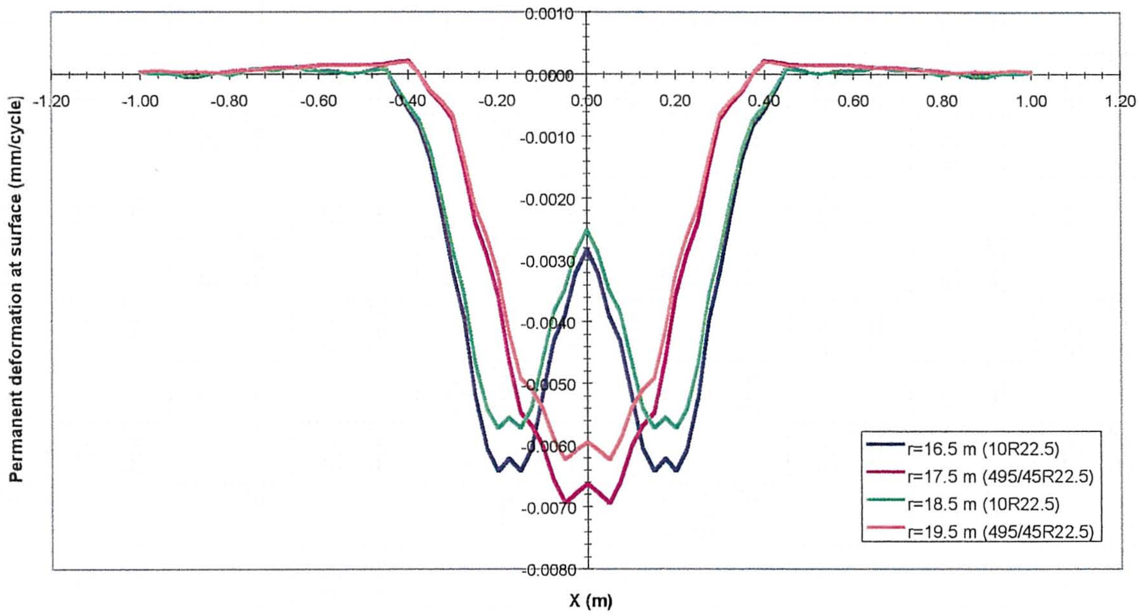

Figure 7 – Permanent deformation by cycle at surface for a cross section for the different tracks

3.5 - Measurements at LCPC test

From the report of the LCPC test there are different rates of deformation during the experiment (Gramsammer et al., 1998). Table 6 presents a general overview of the rate of practical permanent deformation during the test.

Table 6 – Rate of practical permanent deformation (mm/cycle) during the LCPC tests

Tyre code	Stage (cycles)	Track (radius)			
		16.5 m	17.5 m	18.5 m	19.5 m
10R22.5	1 – 20000	0.002 – 0.0002		0.002 – 0.00013	
	20000 – 60000	0.0002		0.00013	
	60000 - 100000	Close to zero		Close to zero	
495/45R22.5	1 – 20000		0.002 – 0.00013		0.002 – 0.0001
	20000 – 60000		0.00013		0.0001
	60000 - 100000		Close to zero		Close to zero

The initial rate of the measured deformation (Table 6) are close to 0.002 mm/cycle.

3.6 - Discussion of the results

From the results of the study, the following conclusions can be made:

- Both the field data and the results from CREEPN show that a higher track radius corresponds to a slightly lower rate of permanent deformation.

  This difference is likely to be due to an increase of the linear speed from the lower to the higher track radius.
- The permanent deformation at the pavement test track is similar for the dual and single tyres. The results of CREEPN show a slightly higher (≈15%) pavement deformation for the wide single tyre.
- The available data on asphalt layers, resulting from flexural tests, do not take into account the change in the volume composition of the materials during the test track experiment. So the calculations performed with CREEPN should simulate the initial phase of the experience at the Nantes facility, where the rate of permanent deformation is close to 0.002 mm/cycle.

  The rate of permanent deformation predicted by CREEPN, for the initial phase of the experience, is close to 0.006 mm/cycle. It is remembered that the pavement temperature was not constant during the experiment at Nantes, and data from repeated uniaxial loading tests was not available for the asphalt mixtures. Therefore there was a significant limitation in modelling the test track results.

4 - SIMULATION OF TRL TEST

4.1 - Introduction

Michelin Tyre PLC Ltd commissioned the Transport Research Laboratory in June 1996 to conduct tests in their Pavement Test Facility, at Crowthorne, in order to compare the pavement wear associated with twinned single tyres and a new wide base single tyre.

The objective of these tests was to make a comparison of the concepts of a new wide base single tyre (495/45R22.5) and a current twinned single tyres (10R22.5) by comparing the damage produced on the same flexible pavement.

The flexible test pavement used in the tests has an 8 m length and 10 m with two tracks (one track for each tyre). The speed used in the test was 5.56 ms^{-1} (20 km/h).

The pavement structure comprises a 4 cm hot rolled asphalt wearing course, a 6 cm dense bitumen macadam base course, a 15 cm dense bitumen macadam roadbase and a 37.5 cm granular sub-base (Halliday et al., 1997).

The pavement temperature, 20ºC, was kept constant during the tests. The measurements of rut depth made by TRL show an initial stage, until 80000 passes, where the rate of permanent deformation is strongly increasing. After 80000 cycles, the rate of permanent deformation tends to stabilise. The simulation of TRL test with CREEPN is intended for the stage of the test track experiment after 80000 cycles.

4.2 - Burgers' serial damper parameter for the asphalt layers

From repeated uniaxial loading tests the Burgers' serial damper parameter, η_1, can be calculated by

$$\eta_1 = \frac{\int_{t_0}^{t_1} \sigma(t)dt}{\Delta\varepsilon_{perm}(t_0, t_1)} \tag{7}$$

Where t_0 and t_1 in (7) are, respectively, the initial and final time of each loading cycle.

As TRL conducted another experiment in 1998/99, with similar materials for the pavement layers, some cores of the asphalt layers were sent by TRL to LNEC. Therefore, the data on the viscoelastic properties of these asphalt layers assumed for the simulation of the experiment conducted in 1996 are based on repeated uniaxial loading tests performed on samples of similar materials used in pavement built in 1998.

In order to apply to the sample a load history similar to the tests, a 0.05s loading period with a harversine shape and a 0.95s unloading time were applied.

Since the Burgers' serial damper parameter is dependent on the compaction of the bituminous mixtures and there is a change in the volume composition during the first stage of the test, it was decided to perform a previous conditioning of the test specimen. The conditioning phase consisted in inserting the sample into a mould in order to get a lateral confinement. For this phase the number of load cycles was 80000 at 20ºC.

In a second step it is performed an unconfined repeated uniaxial loading tests at 20ºC to obtain the Burgers' serial damper parameter for the linear stage of the test.

Table 7 presents the set of η_1 obtained from data of repeated uniaxial loading tests performed at LNEC on cores sent by TRL. This cores was drill from the TRL's Pavement Test Facility built in 1998.

Table 7 – Burgers' serial damper parameter from repeated uniaxial load tests at 20°C

Serial damper, η_1 ($GNm^{-2}s$)		
HRA	DBM_b	DBM_r
170 - 200	190 - 400	270 - 290

HRA – Hot Rolled Asphalt wearing course
DBM_b – Dense Bitumen Macadam base course
DBM_r – Dense Bitumen Macadam Roadbase

4.3 - Data for CREEPN

Table 8 shows the load characteristics (tyre contact area and contact pressure) that were used in CREEPN, according to data from Michelin (Penant, 1999).

Table 8 – Load characteristics for TRL simulation with CREEPN (Penant, 1999)

Tyre code	Load per tyre (kN)	Inflation pressure (kNm^{-2})	Width (mm)	Length (mm)	Contact pressure (kNm^{-2})	Ratio Contact/Inflation (%)
10R22.5	26.0	800	183	226	628.7	78.6
495/45R22.5	52.0	800	428	190	639.4	79.9

Figure 8 shows the finite element mesh to simulate the TRL test (only asphalt layers). All nodes in the base are fixed and the lateral nodes are fixed in the perpendicular direction. This computer simulation was done for one cycle (1 pass).

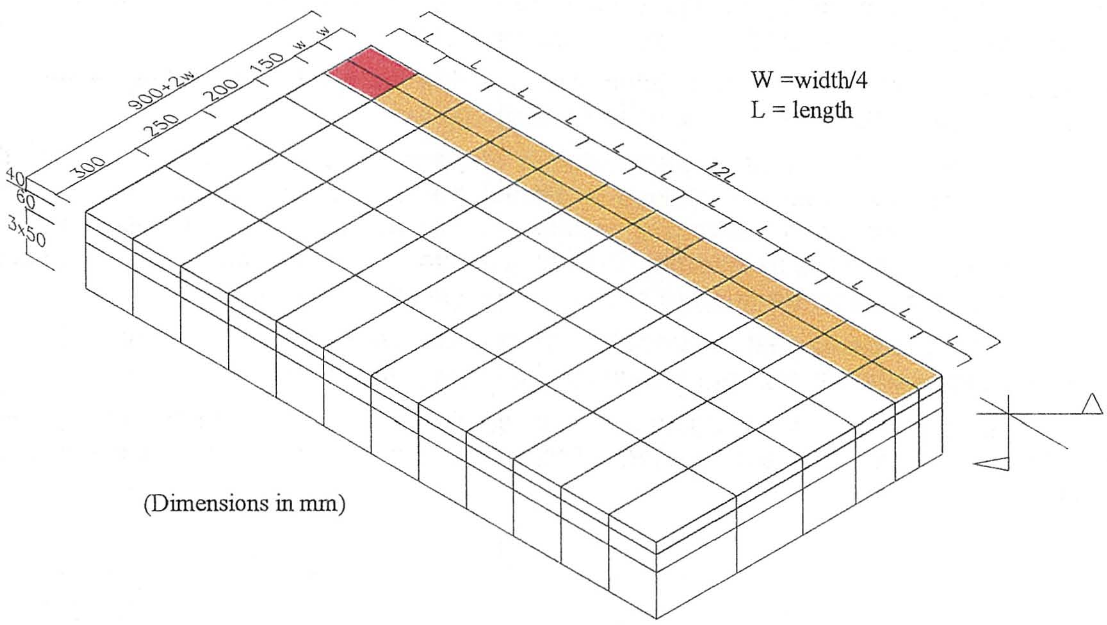

Figure 8 – Finite element mesh to simulation of TRL test

This case was calculated on the basis of the following data:

Hot Rolled Asphalt wearing course (HRA):

thickness h=40 mm

serial damper η_1=185 GNm^{-2}s

Poisson's ratio ν=0.40

Dense Bitumen Macadam base course (DBM$_b$):

thickness h=60 mm

serial damper η_1=290 GNm^{-2}s

Poisson's ratio ν=0.40

Dense Bitumen Macadam Roadbase (DBM$_r$):

thickness h=150 mm

serial damper η_1=280 GNm^{-2}s

Poisson's ratio ν=0.40

Figure 9 shows the lateral distributions during the TRL tests (Halliday et al., 1997).

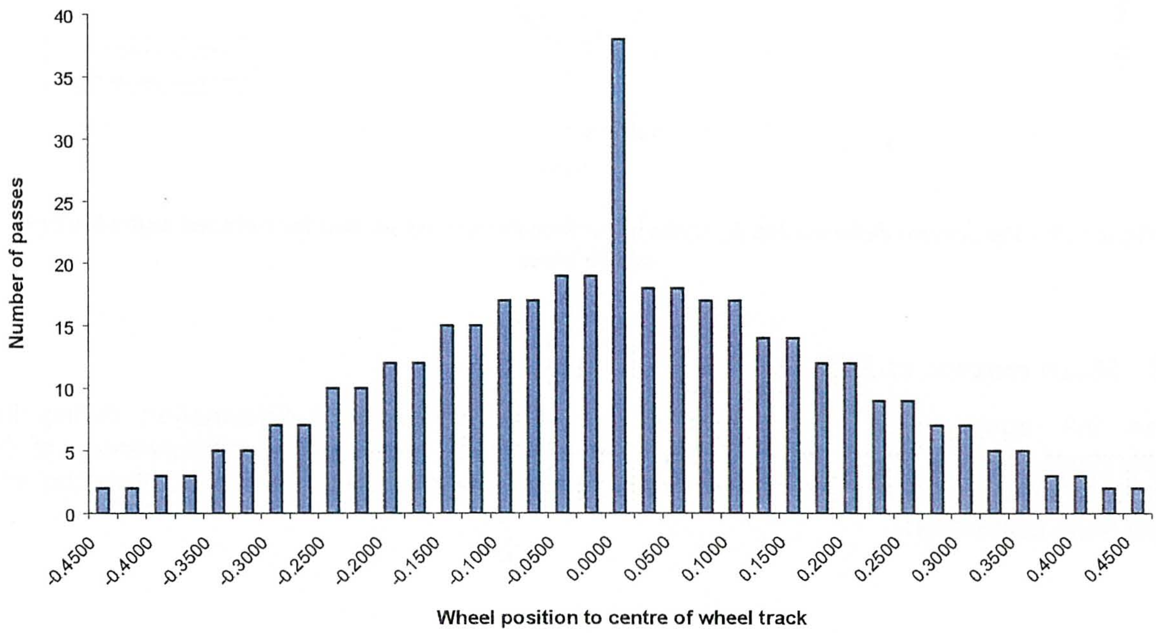

Figure 9 – Lateral distribution for TRL test (Halliday et al., 1997)

4.4 - Results from CREEPN

Since the permanent deformation during the TRL test is reported (Halliday et al., 1997) in terms of the practical permanent deformation (vd. Figure 5), the results from CREEPN are presented in Table 9 in terms of the rate of practical permanent deformation.

Table 9 – Rate of practical permanent deformation predicted for TRL test

Tyre code	(mm/cycle)
10R22.5	0.000005
495/45R22.5	0.000005

Figure 10 shows the permanent deformation by cycle at surface for a cross section, for both tyres.

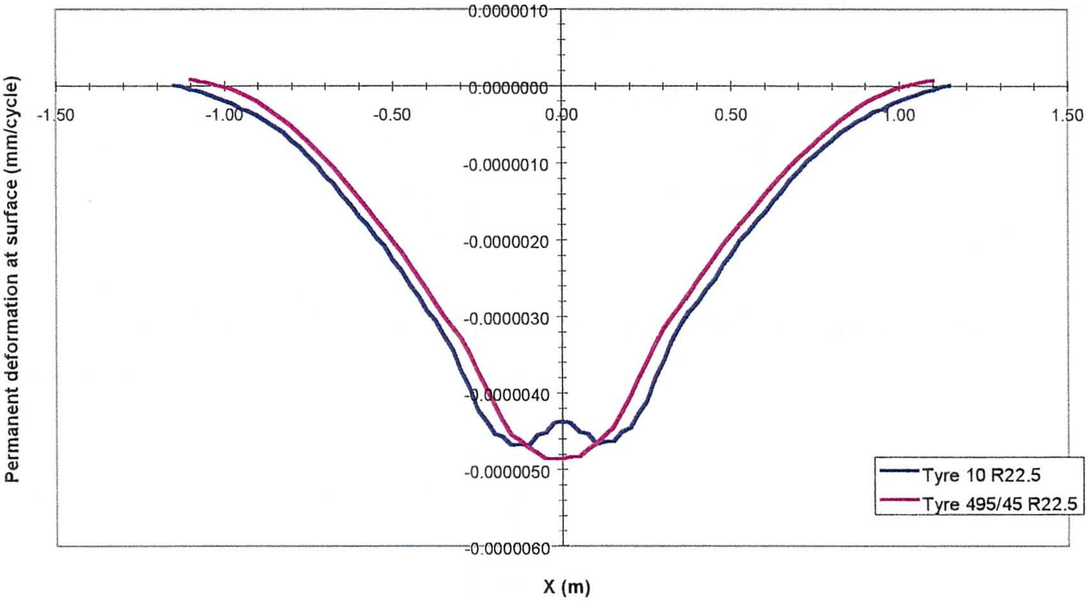

Figure 10 – Permanent deformation by cycle at surface for a cross section for twinned and wide base single tyres

4.5 - Measurements at TRL test

From the report of the TRL test, there are different rates of deformation during the experiment (Halliday et al., 1997). Table 10 and Figure 11 present a general overview of the practical deformation and the rate of practical deformation during the test for twinned and wide base single tyres.

Table 10 – Practical deformation and rate of practical deformation measured at TRL facility's

Cycle	Practical deformation (mm)		Rate (mm/cycle)	
	Twinned	Wide base	Twinned	Wide base
0	0.00	0.00		
1960	1.25	1.00	0.000638	0.000510
10584	2.05	2.00	0.000093	0.000116
21168	2.70	2.65	0.000061	0.000061
50569	3.50	3.40	0.000027	0.000026
79968	4.25	4.00	0.000026	0.000020
200312	5.25	5.00	0.000008	0.000008

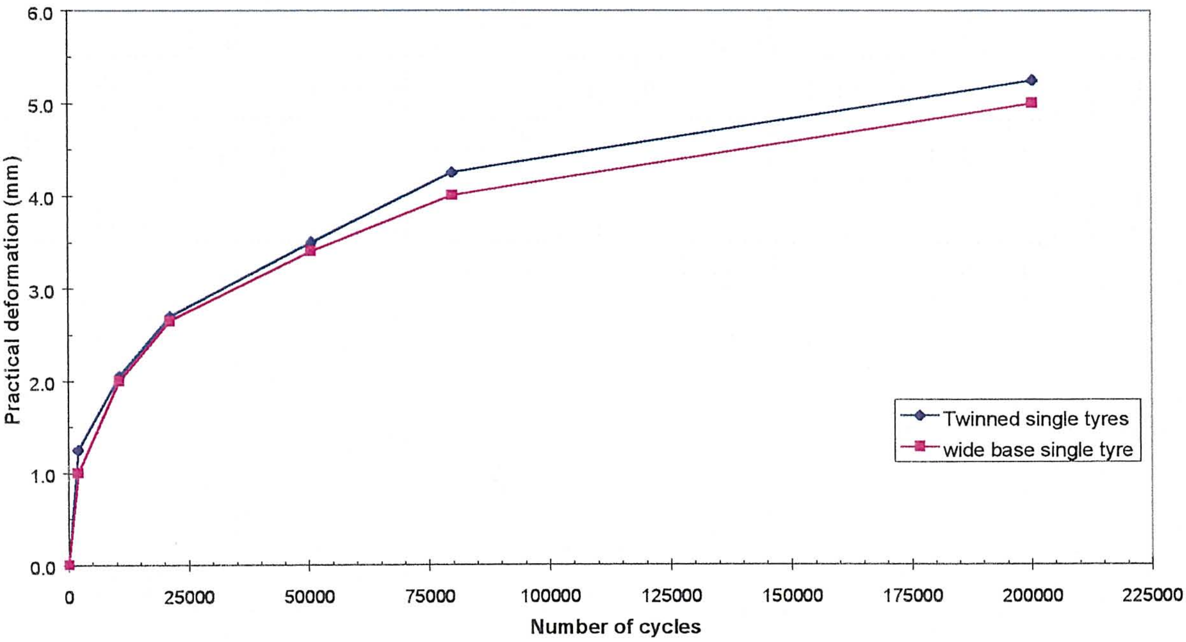

Figure 11 – Practical deformation during the TRL test for twinned and wide base single tyres

4.6 - Discussion of the results

From the results of the study, the following conclusions can be made:

- Both the measurements made by TRL during the experience and the results from CREEPN lead to a similar rate of practical permanent deformation for the wide base single tyre and twinned tyres.
- The simulation of the TRL test by CREEPN was intended for the stage after 80000 passes, where the rate of permanent deformation was approximately constant. From CREEPN it is predicted a rate of permanent deformation close to 0.000005 mm/cycle. The rut depth measurements, made by TRL, the permanent deformation increases at a rate of 0.000008 mm/cycle after 80000 passes. So the values predicted by CREEPN are 60% of the TRL measurements. This difference may be due, in part, to the lack of data from tests on samples of the bituminous layers used in this experiment and to the fact that CREEPN predicted only the permanent deformation for the bituminous layers and TRL measured the permanent deformation for all pavement layers.

5 - FINAL REMARKS

From the results of the research, the following conclusions, can be outlined:

- The tyres used in the experiments at LCPC and TRL were the same: a dual tyre (10R22.5) and a wide base single tyre (495/45R22.5).
- Both tests showed that the permanent deformation is similar for the two tyres. The CREEPN calculations show that the permanent deformation for the two tyres are similar but a slightly higher value for the new wide base single tyre (495/45R22.5) was obtained in the simulation of LCPC tests.
- The rate of permanent deformation obtained from CREEPN is 200% and 60% of the measured values, respectively for the test at LCPC and at TRL.

  These differences may be due, in part to the restrictions of the Stage 2, namely the lack of data from tests on samples of the asphalt layers to obtain their real viscoelastic properties and to the fact that CREEPN predicted only the permanent deformation for the bituminous layers and LCPC and TRL measured the permanent deformation for all pavement layers.
- It is considered that the results of Stage 1 and Stage 2 encourage the use of CREEPN to carry out the research of Stage 3 and Stage 4.

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