Predictive method for evaluation of pavement rutting

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Abstract

Pavement rutting not only decreases the road service life but also creates a danger for the security of road users. In recent years, pavement rutting rate has increased significantly due to constant traffic intensity increment. It is well known that the increase in heavy vehicles flow, transported load, tyre pressure and the use of single tyres instead of dual tyres induce considerable pressure within bituminous layers. Due to these solicitations, bituminous layers can quickly attain their permanent deformation limit resistance and this phenomenon can lead to a pavement depression, located in the tyre-road contact surface.

The purpose of this paper is to present a methodology to estimate the rutting of bituminous pavements and to be able to predict the rutting risk considering the results obtained with the LPC traffic simulator and taking into account the traffic and environmental characteristics. The traffic characteristics are represented by the total heavy traffic expressed in equivalent single axle loads (ESAL) passed on the pavement during the service period and the speed adopted by these heavy vehicles on the considered section. The environmental characteristic is represented by the pavement temperature at 2 cm depth.

The developed model gives rut depths values after having determined material and site characteristics and presents a very good correlation coefficient giving very satisfactory results in its verification phase with additional materials.

Keywords

Rutting – bituminous mixes – pavement – model

1. Objectives of the study

The main objective of this study is to develop a method that predicts the rutting risk for a pavement based on material characteristics, traffic load, mean speed of heavy vehicles and site climatic conditions. The material is taken into account by the experimental rutting resistance parameters obtained with LPC traffic simulator. The traffic is constituted of the heavy traffic load, in terms of equivalent single axle loads (ESAL), which solicited the pavement during its service period and the mean speed of heavy vehicles gives information about the solicitation loading time.

The study began with the selection of eleven road sections representing the traffic and climatic conditions met in Switzerland. The pavements should be younger than ten years. The localisation of the chosen materials should cover the whole Swiss territory and should be representative of the diverse possible climatic conditions (Plateau, Jura, Alps, South Alps). The inventory takes into account the following criteria:

- material (type of bituminous mix)
- age of the surface layer (<10 years)
- load and traffic type
- climatic conditions (Plateau, Jura, Alps, South Alps)
- rut depth

After the pavements selection, their rut depths were measured and bituminous material slabs were extracted from the selected pavements. The slabs have been fully analysed for the purpose of knowing their composition and their compacting degree and then tested in the LPC traffic simulator at different temperatures. In parallel, climatic conditions and traffic characteristics of the coring sites were also collected.

The next step consisted in creating a model able to represent the relation between the in situ rut depth, measured on the pavement, and the rate of rutting measured in laboratory with the slabs submitted to the LPC traffic simulator.

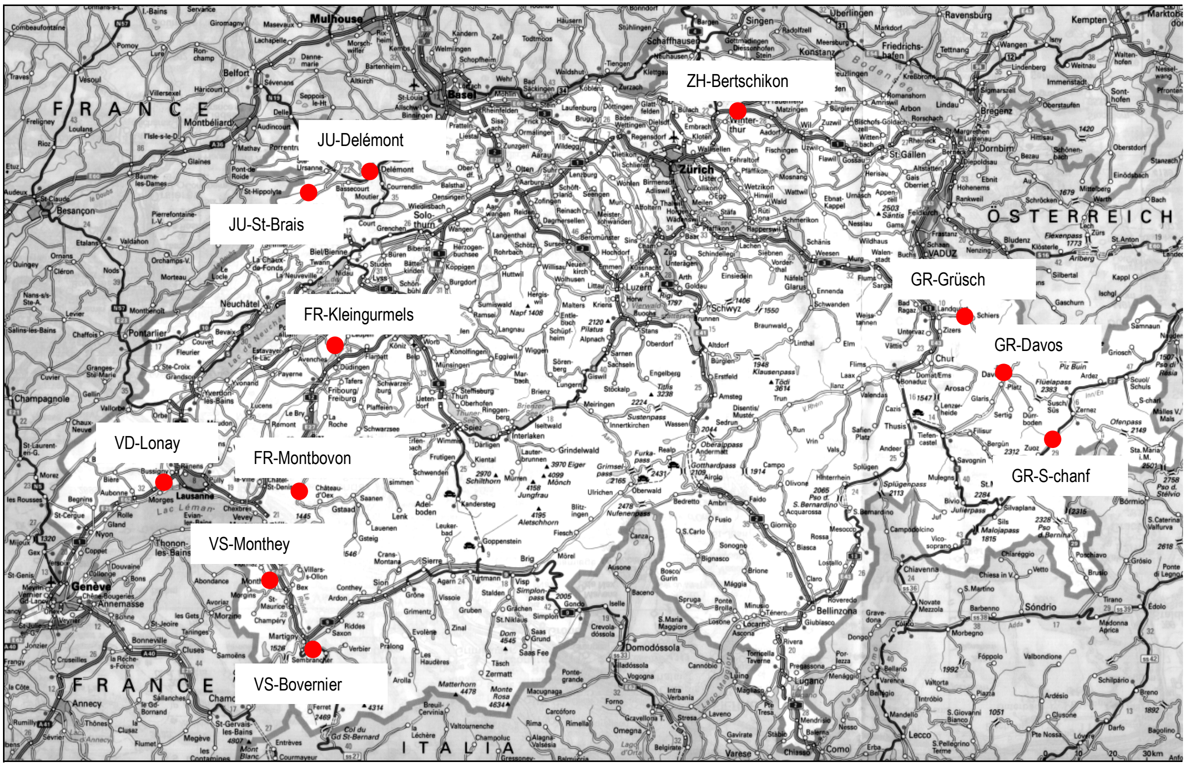
The developed model was then verified by introducing additional data from other materials not considered in the model development phase.

2. Experimental study

2.1 Sites and materials selection

By means of a questionnaire, eleven road sections satisfying the initially determined criteria were selected based on information obtained from several cantonal administrations. Figure 1 represents the situation of the eleven studied pavements.

Figure 1 Situation of the studied pavements



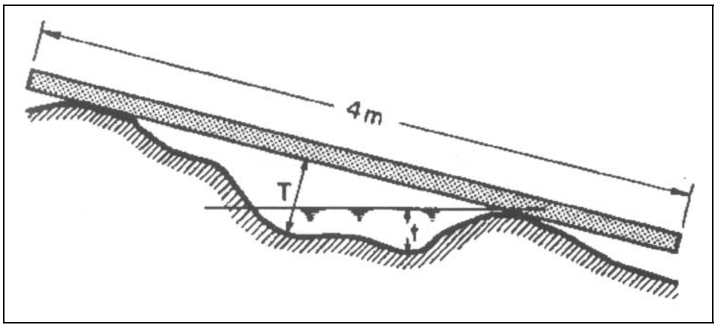
2.2 Transversal evenness measurement and sampling

Before the extraction of the samples, the in situ rut depths were measured according to the Swiss standard SN 640 520a [9]. The measure consists in placing a 4 m beam perpendicularly to the traffic flow and in measuring the following two values for the appreciation of the transversal evenness (see figure 2):

- T-value: represents the rut depth with regard to the straight line connecting the two highest points under the 4 m length beam.

- t-value: represents the rut depth with regard to a horizontal line and consequently the theoretical water height that can accumulate on the pavement surface.

Figure 2 Determination of T-values and t-values [9].

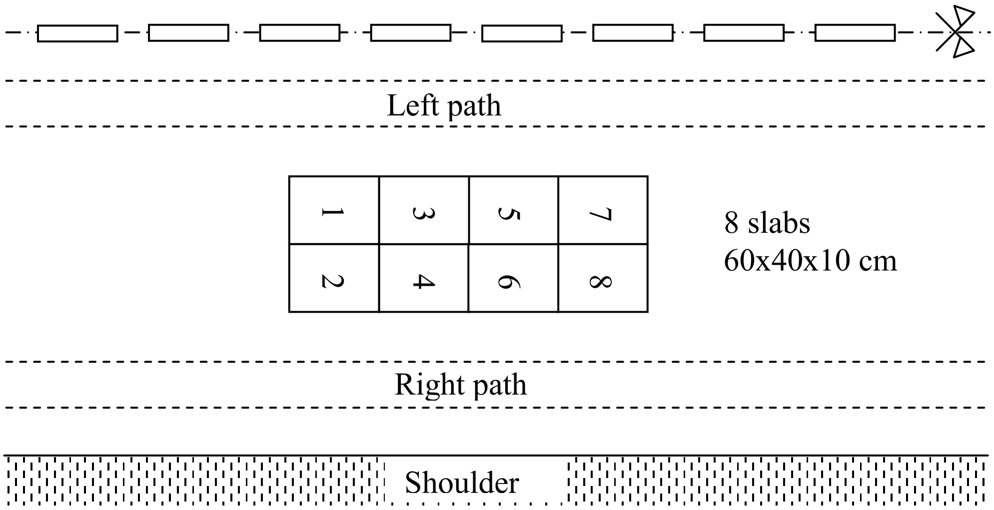


After the transversal evenness measurement (see table 1), the samples were cut and extracted from the pavement. To avoid errors and dispersion in the laboratory test results, it was necessary to dispose of least solicited material (not much damaged by traffic loads). Therefore, the eight samples for the rutting test were extracted from the road part situated between each rut (figure 3).

Table 1 In situ measured rut depths

Site	Left rut depth [mm]	Right rut depth [mm]	Mean rut depth [mm]
FR - Kleingurmels	11.0	11.0	11.0
FR - Montbovon	4.0	6.3	5.2
GR - Davos	16.7	7.0	11.8
GR - Grüsch	7.7	4.0	5.8
GR - S-chanf	7.7	7.0	7.3
JU - Delémont	34.0	27.7	30.8
JU - St-Brais	4.7	17.3	11.0
VD - Lonay	4.0	7.0	5.5
VS - Bovernier	8.0	17.0	12.5
VS - Monthey	17.5	32.5	25.0
ZH - Bertschikon	10.0	10.7	10.3

Figure 3 Pavement sampling scheme



2.3 Rutting test

The laboratory rutting test used in this study is defined in the French standard NF P 98-253-1 [6] and has been realised by means of the LPC-traffic simulator. The test shows the evolution of the bituminous mix permanent deformation. It consists in submitting a bituminous mix slab to a vertical rolling load induced by a tyre that induces a relative diminution of the slab thickness (rut).

The standard [6] defines the rutting evolution as a function of the number of cycles (bi-logarithmic axis):

$$Y = A \cdot \left(\frac{N}{1000} \right)^{b} \qquad (1)$$

where Y is the rut depth, A the rut depth at 1000 load cycles, N the number of load cycles and b the straight line slope (bi-logarithmic axis).

Figure 4 and figure 5 present some rutting curves obtained from LPC traffic simulator. For each slab, the test has been first realised at a temperature of 50°C and then, based on the material behaviour and its temperature susceptibility more tests were done at different temperatures:

- 55°C and 60°C if 60'000 cycles were attained at 50°C
- 40°C and 45°C if the material attained the 15% rutting limit at 50°C

Figure 4 Evolution of rutting curves

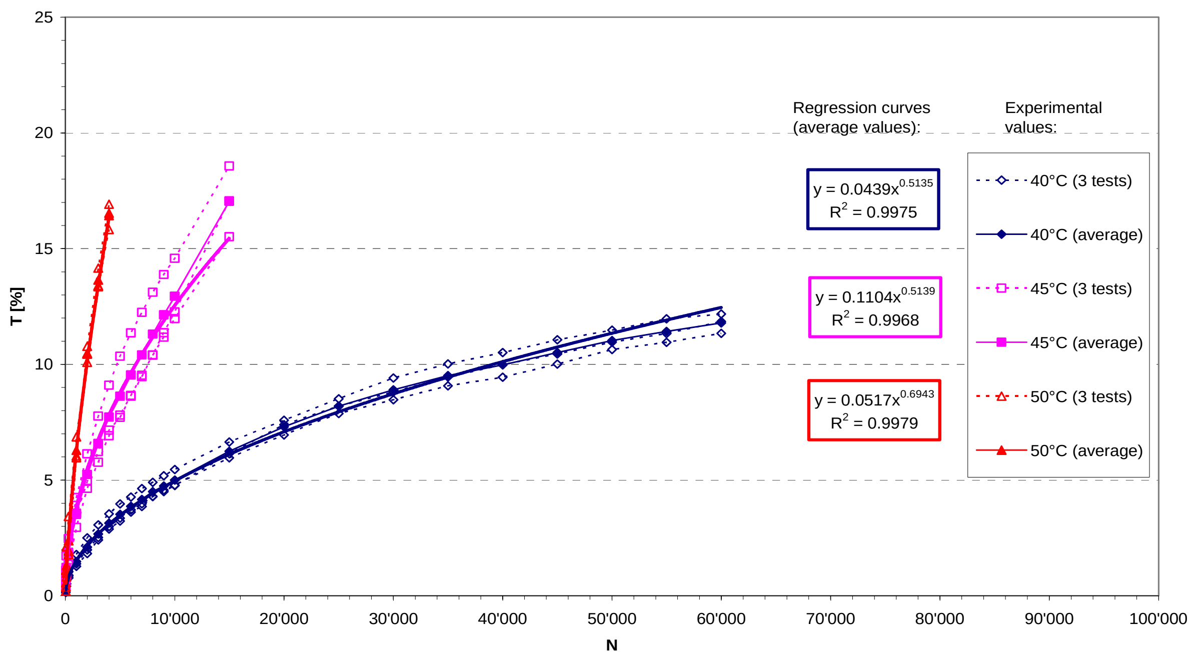
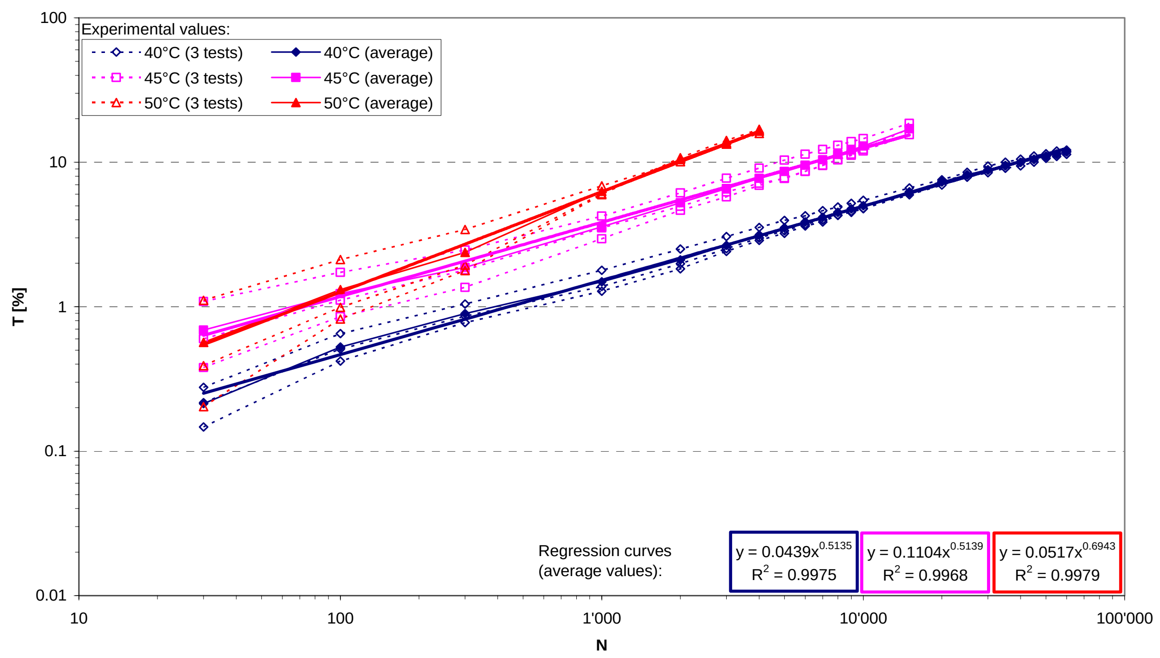


Figure 5 Evolution of rutting curves (bi-logarithmic axis)



3. Development of the predictive method

The prediction of the in situ rutting evolution is based on the most widely used empirical rutting equation for bituminous mixes [2] [3] [5] [6]:

$$T = \alpha \cdot N^{\beta} \tag{2}$$

where T is the rut depth, N is the number of load cycles, α and β are experimentally determined parameters (function of material properties).

It is experimentally observed that the curve represented by the equation (2) becomes more regular from 1000 load applications. According to this, the empirical equation (2) has been changed in the French standard [6] as follows:

$$T = \alpha \cdot \left(\frac{N}{1000} \right)^{\beta} \tag{3}$$

where α represents the rut depth at 1000 load cycles and β is the slope of the rutting straight line plotted in bi-logarithmic axis. The last mentioned coefficients α and β have been used for this study.

In the equations (2) and (3) the number of load cycles corresponds to a certain amount of loads and a certain loading speed imposed by the standardised test procedure described in [6]. However, in real pavements, applied loads and loading speeds are specific to each road section, that is why it was necessary to introduce some adjustment coefficients to take this reality into account.

The general concept of the presented method consists in taking the general rutting equation (3) as starting point and applying it to the real rutting phenomenon. For this purpose, three hypotheses were introduced:

1. The real rutting phenomenon follows the same function as the one observed in laboratory

2. There is no structural rutting, i. e. only appears in the bituminous layers and not in the soil

3. There is no temperature gradient in the bituminous layer, i. e. temperature is constant in the whole material

In equation (3) the number of laboratory cycles N is replaced by a number of "equivalent cycles" N_{eq} that are supposed to be applied in real pavements:

$$T = \alpha \cdot \left(\frac{N_{eq}}{1000} \right)^{\beta} \tag{4}$$

In reality, the traffic solicitation depends on a certain traffic load at a certain speed. That is why the term N_{eq} includes the adjustment coefficients related to these two parameters, C_W for the traffic load and C_V for the speed, that permits to give a ratio between the accelerated laboratory test and the real traffic load:

$$N_{eq} = f(W, C_W, C_V) \tag{5}$$

where W is the number of equivalent single axle loads (ESAL)

The material temperature has a non negligible influence in the rutting phenomenon. Laboratory tests are conducted at a certain temperature and the adjustment coefficient for temperature C_θ was introduced to take into account the correspondence between laboratory tests and reality:

$$T = C_\theta \cdot \alpha \cdot \left(\frac{N_{eq}}{1000} \right)^{\beta} \tag{6}$$

Finally, a last adjustment coefficient δ was added for the purpose of fitting the developed model with the theoretical model y=x:

$$T = C_\theta \cdot \alpha \cdot \left(\frac{N_{eq}}{1000} \right)^{\beta} + \delta \tag{7}$$

3.1 Material related parameters

The parameters α and β represent the rut depth at 1000 load cycles and the slope of the rutting straight line plotted in bi-logarithmic axis, respectively.

To allow a comparison between all tested materials, the considered temperature for the determination of the material parameters α and β was the one common to all tests, i. e. 50°C.

For the eleven sites considered in this study, these experimentally determined coefficients are presented in table 2.

Table 2 Experimental parameters α and β for tests at 50°C

Site	Experimental parameter "α"	Experimental parameter "β"
FR - Kleingurmels	1.936	0.4051
FR - Montbovon	3.251	0.3796
GR - Davos	4.468	0.5580
GR - Grüsch	1.818	0.3870
GR - S-chanf	4.608	0.6353
JU - Delémont	6.292	0.6943
JU - St Brais	2.106	0.2027
VD - Lonay	2.111	0.2925
VS - Bovernier	2.226	0.3997
VS - Monthey	5.816	0.7507
ZH - Bertschikon	2.820	0.5458

3.2 Traffic related parameters

The rutting test gives a rut depth expressed as a function of the number of load cycles and the experimental parameters α and β. The effect of each load cycle on the sample depends on the applied load level and the imposed speed. The number of laboratory load cycles N is converted in "equivalent cycles" supposed to be observed in reality. For this conversion an estimation of the total traffic load W [ESAL] and an adjustment traffic coefficient C_w are needed.

$$T = \alpha \cdot \left(\frac{C_W \cdot W}{1000} \right)^{\beta} + \delta \quad (8)$$

The coefficients C_w and δ fit the model with a theoretical model where the calculated rut should equal the real rut. The determined values giving good correlations are:

$$C_W = 5{,}128 \cdot 10^{-3} \quad (9)$$

$$\delta = 4{,}9 \quad (10)$$

3.3 Speed related parameter

The vehicles speed influences the pavement rut evolution. Because of the viscous behaviour of pavements, the lower the speed is the higher the rut depth will be. To take into account the vehicles speed effect in the model, the general equation developed by Louis Francken [4] was used. This equation gives the permanent deformation ε_p as a function of the vertical and horizontal stresses σ_v and σ_h, the number of load cycles N, the speed V and the plastic deformation module E_p depending on the material characteristics.

$$\varepsilon_p = (\sigma_v - \sigma_h) \cdot \left(\frac{N}{450 \cdot V} \right)^{0,25} \cdot \frac{1}{2 \cdot E_p} \tag{11}$$

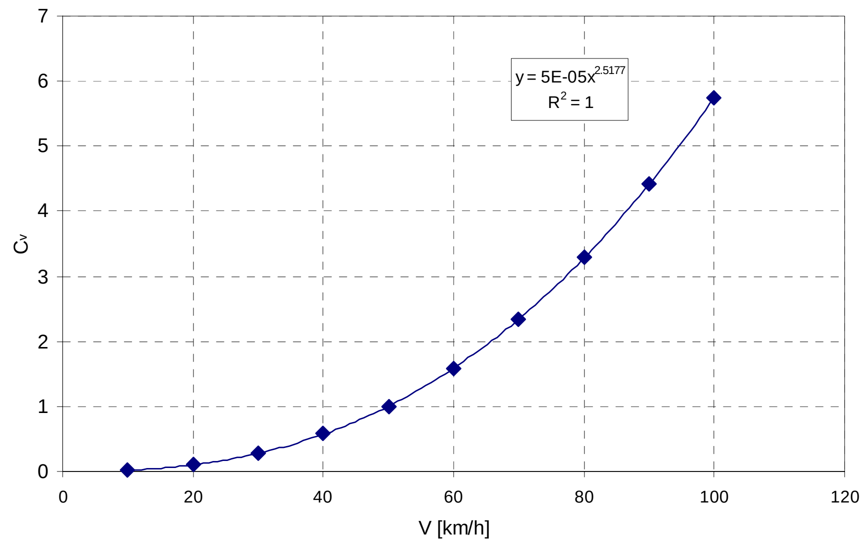
The characteristics of a standard mix were introduced to calculate the values of E_p for temperatures from -20°C to 40°C and speeds from 10 km/h to 100 km/h. The reference temperature was 50°C according to the one used in laboratory tests. For the determination of the speed adjustment coefficient C_V the reference speed was 50 km/h:

$$C_V = \frac{T(V)}{T(V_{ref})} = \frac{\varepsilon_{p(V)} \cdot h}{\varepsilon_{p(V_{ref})} \cdot h} = \left(\frac{V_{ref}}{V} \right)^{0,25} \cdot \frac{E_{p(V_{ref})}}{E_{p(V)}} \tag{12}$$

Figure 6 shows the speed adjustment coefficient calculated for each speed from 10 km/h to 100 km/h. The coefficient C_V has the form of a power function depending on the speed (13).

$$C_V = 5 \cdot 10^{-5} \cdot V^{2,5177} \tag{13}$$

Figure 6 Speed adjustment coefficient C_V



To take into account the speed effect in the calculation of the rut depths, the equation (8) becomes:

$$T = \alpha \cdot \left(\frac{C_W \cdot W}{1000 \cdot C_V} \right)^{\beta} + \delta \qquad (14)$$

3.4 Temperature related parameter

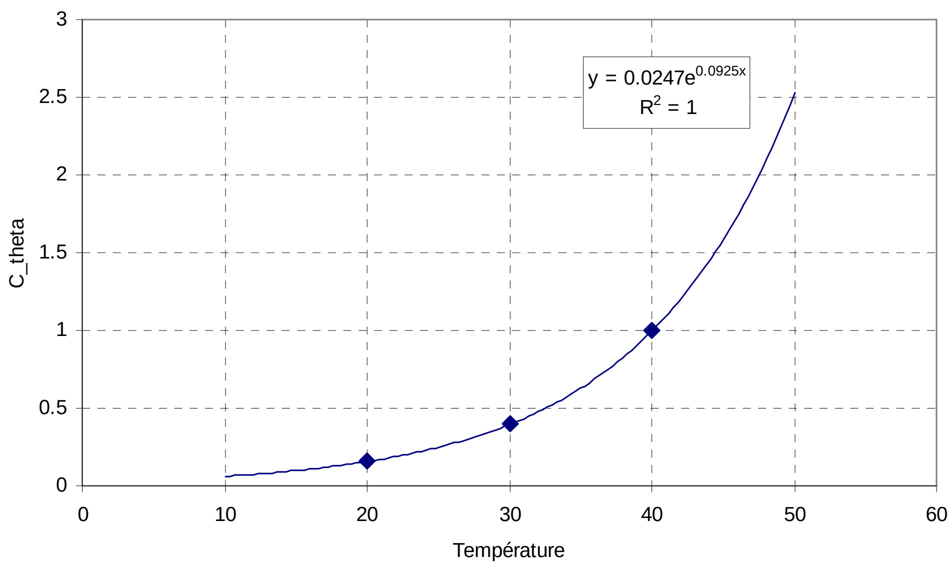
Similar to the determination of the speed adjustment coefficient, the temperature adjustment coefficient C_θ is obtained as the ratio of the rut value obtained at a certain temperature to the one obtained at the reference temperature θ_{ref}= 50°C:

$$C_\theta = \frac{T(\theta)}{T(\theta_{ref})} = \frac{\varepsilon_{p(\theta)} \cdot h}{\varepsilon_{p(\theta_{ref})} \cdot h} = \frac{E_{p(\theta_{ref})}}{E_{p(\theta)}} \qquad (15)$$

The temperature adjustment coefficient C_θ plotted for temperatures from 10°C to 50°C is exponential (see figure 7):

$$C_\theta = A \cdot e^{B \cdot (\theta - \theta_{ref})} \qquad (16)$$

Figure 7 Temperature adjustment coefficient C_θ



The final value of the temperature coefficient is:

$$C_\theta = e^{\frac{\theta - 50}{10,8}} \tag{17}$$

With the determination of this last adjustment coefficient, the final equation becomes:

$$\boxed{T = C_\theta \cdot \alpha \cdot \left(\frac{C_W \cdot W}{1000 \cdot C_V} \right)^\beta + \delta} \tag{18}$$

3.5 Predictive calculation of rut depths

With the previous developments and using the model final equation (18) it was possible to calculate all sites predicted rut depths and compare these values with the real measured rut depths (see table 3 and figure 8).

Table 3 Summary of the considered characteristics

Site	Material characteristics		Site characteristics			Rut depths	
	α	β	W [ESAL]	V [km/h]	Θ [°C]	Measured rut [mm]	Calculated rut [mm]
FR - Kleingurmels	1.936	0.4051	2'464'813	53	46.07	11.0	8.79
FR - Montbovon	3.251	0.3796	569'422	62	45.44	5.2	7.78
GR - Davos	4.468	0.5580	240'425	30	44.56	11.8	10.50
GR - Grüsch	1.818	0.3870	2'212'906	80	45.85	5.8	7.14
GR - S-chanf	4.608	0.6353	458'403	80	44.33	7.3	8.05
JU - Delémont	6.292	0.6943	2'051'390	51	46.39	30.8	30.04
JU - St-Brais	2.106	0.2027	894'259	41	45.22	11.0	7.14
VD - Lonay	2.111	0.2925	13'172'339	90	46.49	5.5	8.30
VS - Bovernier	2.226	0.3997	2'407'905	69	46.88	12.5	8.52
VS - Monthey	5.816	0.7507	765'121	35	45.72	25.0	29.32
ZH - Bertschikon	2.820	0.5458	9'808'574	90	46.22	10.3	12.13

Figure 8 Measured and calculated rut depths for all sites

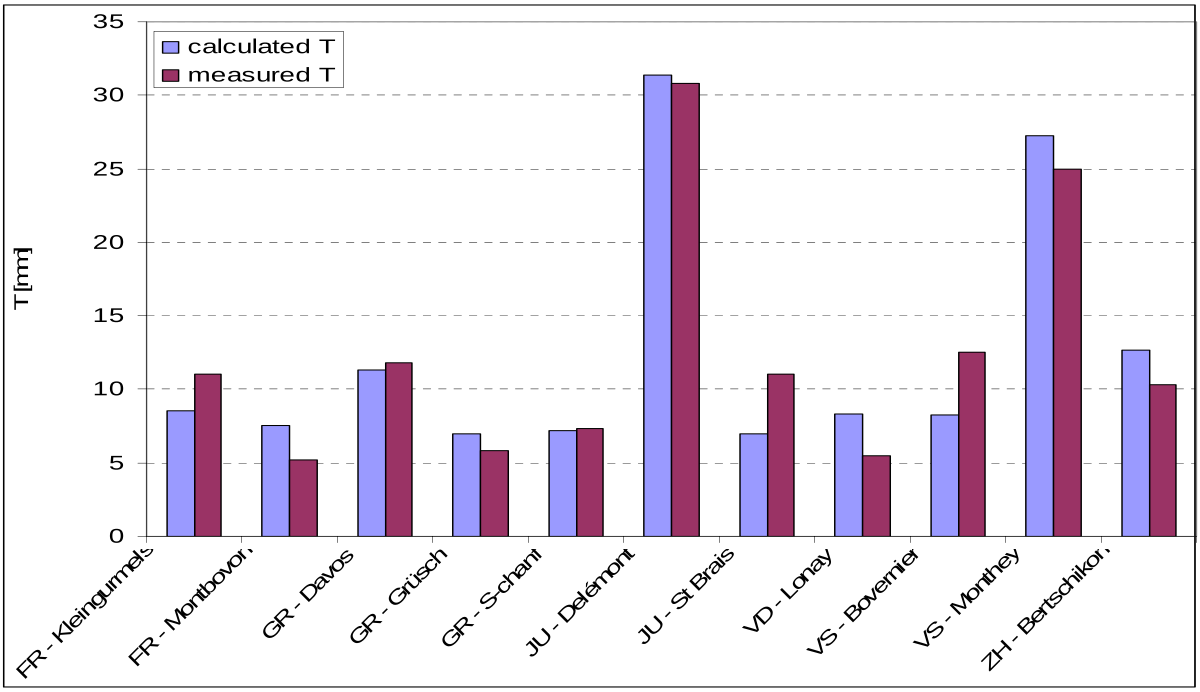


Figure 9 Modelled relation between measured and calculated rut depths

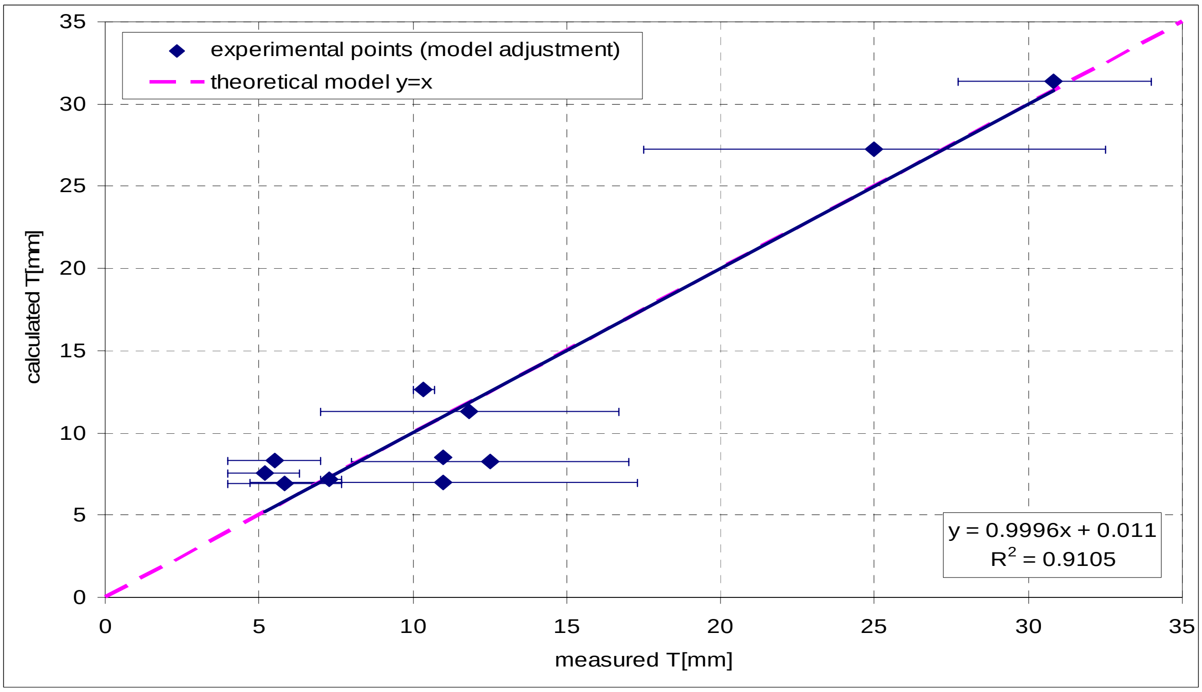


Figure 9 illustrates the relation between the calculated rut depths with the model equation and the in situ measured rut depths on the chosen eleven sites. The points represent mean values calculated with the left and right rut and the horizontal lines indicate the minimal and maximal rut depth for each site.

The predictive model represented by a straight line with a correlation coefficient R^2=0,91 seems to be a good method to estimate the rut depth on any type of bituminous material (see figure 9).

3.6 Procedure for the application of the predictive rutting method

Following are the four steps for the application of the new rutting prediction procedure (see figure 10):

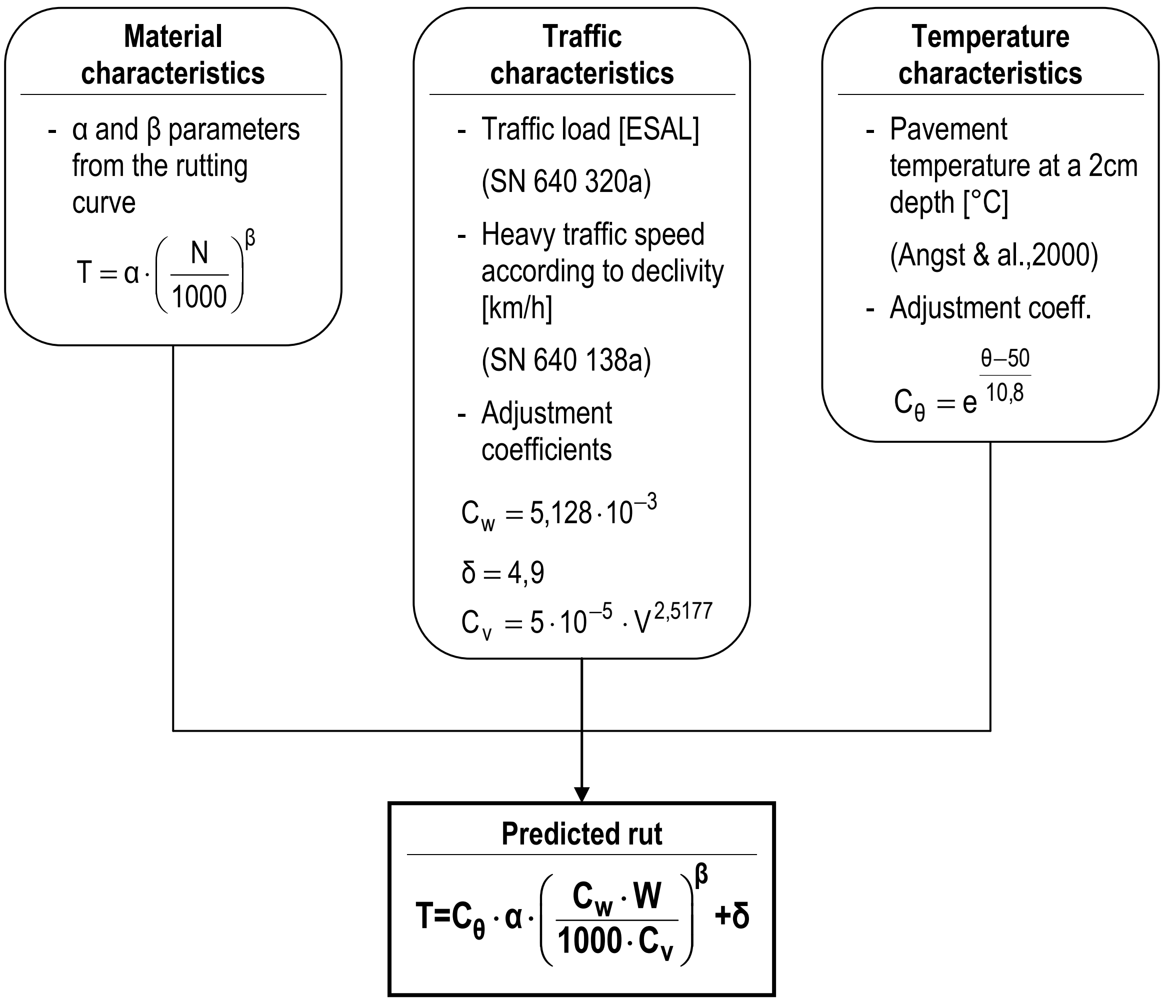
- **Step 1**: Determination of the experimental coefficients α and β from a laboratory rutting test (LPC traffic simulator [6]) or from an existing database.

- **Step 2**: Determination of the total equivalent traffic load W [ESAL] considered during the pavement service period using the Swiss standard SN 640 320a [8] and/or any available traffic data. Once W is calculated the constant value of the adjustment coefficient $C_W=5{,}128\cdot10^{-3}$ has to be introduced in the model equation (18).

- **Step 3**: Determination of the heavy vehicles (>3,5 t) mean speed on the considered pavement using the Swiss standard SN 640 138a [7] and/or in place speed measures if it is an existing pavement. The speed has to be linked to the model rutting equation (18) by the introduction of the speed adjustment coefficient $C_V=5\cdot10^{-5}\cdot V^{2,5177}$.

- **Step 4**: Determination of the maximal material temperature for a return period of 20 years with the method described by Angst & al. [1]. The temperature has to be linked to the model (18) by the introduction of the temperature adjustment coefficient $C_\theta=e^{(\theta-50)/10,8}$.

Figure 10 Procedure for the application of the rutting prediction method



3.7 Method verification

For the verification and the validation of the developed model, four additional bituminous mixes have been analysed. These mixes were independent of the initial materials used for the model development and were not taken into account for its calibration.

After applying the four steps of the method procedure described before (see figure 10) and determining all the values and adjustment coefficients needed for their introduction in the method equation, the four additional points have been calculated with the method equation (18) and were put in the graph model presented in figure 9.

The difference between the calculated and measured rut depths are presented in figure 11. It can be observed in figure 12 that the additional materials perfectly integrate the initial graph obtained from the method development phase.

Figure 11 Calculated and measured rut depths (additional points)

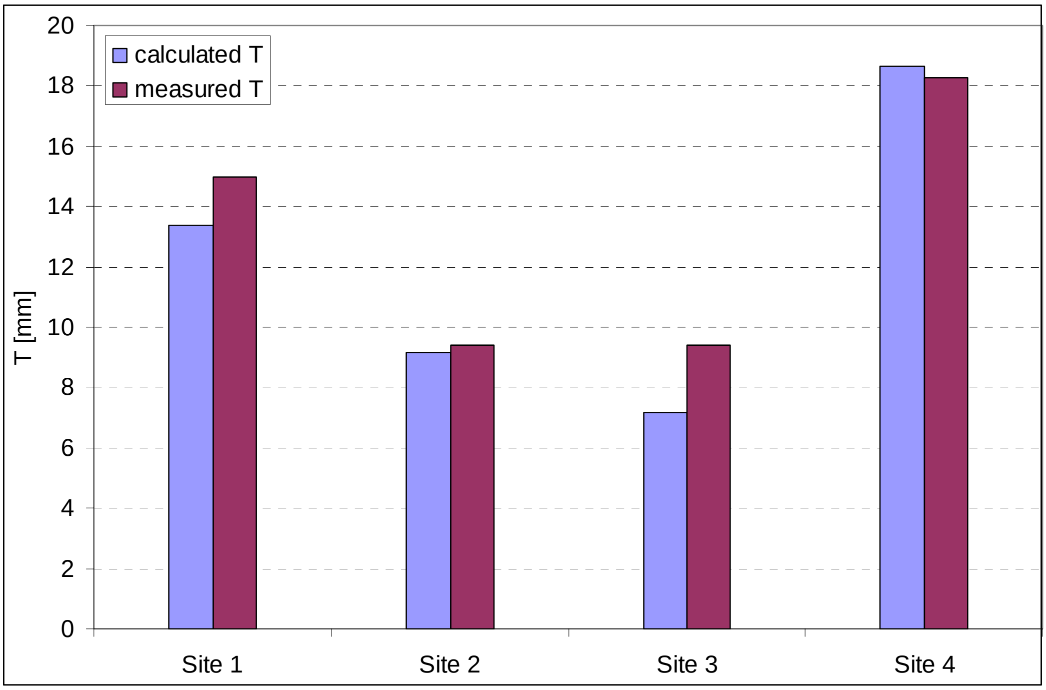
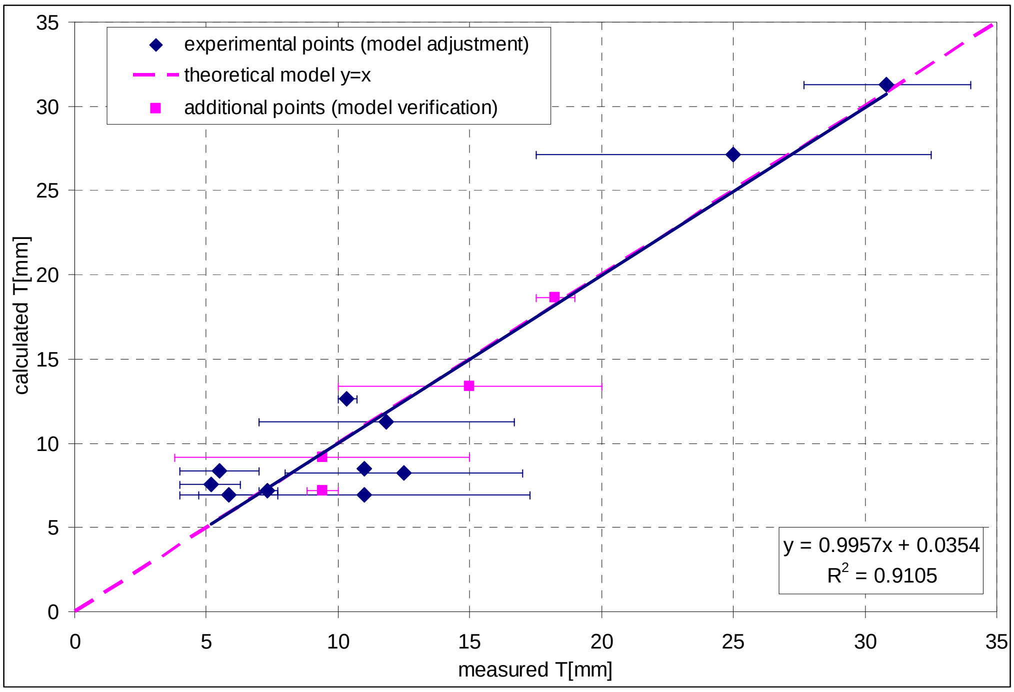


Figure 12 Initial mixes (blue points) and additional mixes (pink points)



4. Conclusions

This study presented the development of a predictive rutting model based on the most widely used empirical rutting equation. The general concept consists in taking as starting point the general rutting equation and apply it to the real rutting phenomenon introducing three fundamental equations:

- The real rutting phenomenon observed in a pavement has the same function as the one observed in laboratory

- There is no structural rutting i. e. rutting only occurs in the bituminous material and not in the soil

- There is no temperature gradient in the bituminous layer i. e. the temperature remains constant in the whole material

The use of the predictive model is linked to the knowledge of some parameters like material experimental parameters (α and β), traffic characteristics (traffic load, speed) and environmental characteristics (in situ bituminous mix temperature). Some adjustment coefficients were introduced for each material independent parameter.

The model has been adjusted analysing the properties of eleven sites supposed to be representative of the Swiss climatic conditions and independent from each other.

The final model equation gives rut depths values after having determined material and site characteristics and shows a very good correlation coefficient giving very satisfactory results in its verification phase with the additional materials.

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