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# EVALUATION OF CLIMATIC FACTORS BASED ON THE MECHANISTIC-EMPIRICAL PAVEMENT DESIGN GUIDE

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**Abstract.** In this paper procedure for evaluating the effects of climate on pavement performance in Italy is proposed. To characterize the Italian territory nine different simulated scenarios have been used. These scenarios were obtained by combining three different situations of latitude (North, Central and South) with three conditions of altitude (high, medium, low altitude). For each of these scenarios, some configurations, proposed by the Italian CNR road pavement design catalogue with medium and high traffic flow, were verified using the Mechanistic-Empirical Pavement Design Guide. The results obtained showed that the Italian CNR road pavement design catalogue has a limited reliability.

**Keywords:** Mechanistic-Empirical Pavement Design Guide, pavement design, weather, climate model calibration.

## 1. Introduction and literature reviews

Pavements are an example of a complex engineering system requiring probabilistic modelling due to the uncertain nature of most of the pavement performance model parameters. Due to the large number of parameters involved, such as the thickness of layers, material properties and climatic conditions affecting pavement performance, it is usually not feasible to determine optimal design using a trial and error approach (Gaurav *et al.* 2011). The deterministic pavement performance models vary from simplistic empirical relationships to complex mechanistic-empirical computational algorithms (Wojtkiewicz *et al.* 2011). In this context, the overall objective of the Mechanistic-Empirical Pavement Design Guide (MEPDG) is to provide the highway community with a state-of-the-practice tool for the design of pavement structures, based on mechanistic-empirical principles according to the *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures* of 2004. The Mechanistic-Empirical format of the Design Guide provides a framework for future continuous improvement to keep up with changes in trucking, materials, construction, design concepts, computers, and particularly in climate modelling. As a support for implementing the new MEPDG, a sensitivity study was undertaken to assess the comparative effect of design input parameters pertaining to material properties, traffic and climate on the performance of two existing flexible pavements in Iowa with relatively thick asphalt concrete (AC) layers (Kim *et al.* 2007). Some of the required data either are not available or are stored in locations not familiar to designers. A recent study examined the adequacy of using conventional traffic data and national default values in the absence of weigh-in-motion (WIM) data for pavement design. A comparative study was conducted on 14 unique sections in Arizona, where WIM data are available through the Long-Term Pavement Performance Program (Ahn *et al.* 2011). The study consists of two parts: 1) comparisons of input traffic data and 2) comparisons of pavement distresses predicted by the MEPDG. The MEPDG distress prediction equations were used to predict the mixture performance as a function of density (Mogawer *et al.* 2011). The testing analysis and MEPDG predictions indicated that higher density specimens yielded improved fatigue and rutting performance. Moreover, tests were performed on asphalt rubber binder and asphalt rubber asphalt concrete (ARAC) mix in order to verify whether the new MEPDG can be used effectively for asphalt rubber (AR) materials (Pasquini *et al.* 2011).

## 2. The Italian CNR road pavement design catalogue

The Italian CNR road pavement design catalogue *Catalogo delle pavimentazioni stradali C.N.R.-B.U.-178, 1995* provides a set of solutions for the design and testing of pavements. The following types of pavement are considered: flexible, semi-rigid and rigid. For each pavement, the catalogue provides a series of solutions in relation to the bearing capacity

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of the substrate and the traffic conditions. In the catalogue there are 32 cards for each type of road (as prescribed under Italian law). Details regarding the assumptions on traffic, subgrade, material characteristics and climatic conditions are presented in to the *C.N.R.-B.U.-178, 1995.*

### 3. Mechanistic-Empirical Pavement Design Guide

The testing procedure and design guidance contained in the MEPDG is divided into three phases as follows. During the first phase, a characterization of the parameters constituting the pavement materials and those of the traffic is established. Moreover, a climate model is used to study changes in temperature and humidity within each layer of the pavement. The model takes into account climate data from weather stations (temperature, precipitation, solar radiation, cloud cover, wind speed) allocated in the area where the road is developed. The predictions of temperature and humidity for the layers of the pavement are calculated from the model each hour for the entire life of the pavement. The model uses this information to determine the modulus of the different materials used at different depths. The second phase of the process refers to the structural design and the analysis of the performance. The approach consists of an iterative process: starting from an initial design hypothesis conceived by the designer (or obtained from a catalogue) that describes the thickness of the pavement layers and material properties. The analysis is carried out using fatigue models (which provide the output deformation), the combined damage, and the evolution of pavement surface characteristics over time. If the hypothesis does not meet the criteria of efficiency, changes are made and new analyses are carried out via a feedback process until the reach of satisfactory result. In the third phase of the process, through a series of procedures, the design alternatives are compared from the point of view of technical terms and cost.

### 4. Proposals to adapt the Italian CNR road pavement design catalogue through the Mechanistic-Empirical Pavement Design Guide

Both the catalogue that the MEPDG guide for the design and the road pavement tests are based on the concept of reliability. Moreover, to identify the performance of the pavement, the catalogue only refers to the Pavement Serviceability Index (*PSI*), and the MEPDG refers to International Roughness Index (*IRI*, in/mi). The MEPDG also makes it possible to estimate the following parameters: bottom-up cracking (%), total permanent deformation, permanent deformation AC (in), surface cracking down (ft/mi) and thermal fracture (ft) for flexible pavements, transverse cracking (%) and mean joint fault (in) for rigid pavements. For a comparison of the results it was necessary to standardize the results by referring to a single parameter. In this regard, reference was made to the report (Paterson 1986):

$$IRI = (5 - PSI)100, \quad (1)$$

where *IRI* – International Roughness Index, m/km; *PSI* – Pavement Serviceability Index, in particular is a concept derived during the AASHO Road Test. This concept is related to the primary function of a pavement structure: to provide the travelling public with a smooth, comfortable, and safe ride. A scale ranging from 0 to 5 is used to evaluate *PSI*; pavement with a rating of 0 is impossible and with a rating of 5.0 would be perfectly smooth.

To apply the MEPDG to the Italian reality the information contained in *C.N.R.-B.U.-178, 1995* was taken into account. Using the MEPDG, the solutions proposed in the catalogue were tested for the freeways (about 100 km) and highways (about 100 km). In particular, before starting the simulation, it was necessary to organize the data in the form required by the MEPDG.

The data included in the MEPDG support software were organized into the following three groups: characteristics of the materials, traffic characteristics and climatic conditions.

#### 4.1. Characteristics of materials

For the material properties and thickness of the layers, reference was made to the variables (and their values for the upper limit) given in *C.N.R.-B.U.-178, 1995*. In particular for the dynamic modulus, reference is made to a maximum value of 150 N/mm$^2$.

#### 4.2. Traffic characteristics

For traffic, reference was made to the following variables:

- average annual daily traffic (*AADT*, vpd) – provided by the administrators of the road analyzed on a five-years basis;
- percent of heavy vehicles ($P_t$, %) – provided by the management of the roads analyzed on a five-years basis;
- operating speed, estimated using predictive models for the operating speed.

It was also necessary to refer to the following calibration factors regarding traffic volume:

- factors of monthly adjustment ($MFA_i$);
- distributions of the classes of vehicles;
- distribution of vehicles per hour;
- factors of increase of traffic.

For $MAF_i$, it was assumed that during summer the movement of heavy vehicles is less. In this regard the distribution was as follows: $MAF_{1-6,10-12} = 1.08$ and $MAF_{7-9} = 0.76$.

For the distribution of vehicle classes, given the difference between USA vehicles and Italian vehicles, it was necessary to make adjustments in "terms of equivalence" (Table 1). For the hourly distribution factor (HDF), i.e. the percentage of the average daily traffic at all hours of the day, it is referred to the standard distribution prescribed by the MEPDG also taking into account particular kind of traffic surveys carried out on particular roads in the Italian territory.

#### 4.3. Factors of increased traffic

The MEPDG provides options for three different laws regarding an increase in traffic, and in this study, the one

**Table 1.** Equivalent classes in USA and Italy

| USA | | Italy | |
|---|---|---|---|
| According to the MEPDG Guide of the Federal Highway Administration | | According to the C.N.R.-B.U. 178, 1995 of the Italian National Research Council | |
| Class | Characteristic | Class | Characteristic |
| 4 | Buses 3 axis | 14 | Buses 2 axis |
| | | 15 | Buses 2 axis |
| | | 16 | Buses 2 axis |
| 5 | Truck 2 axis | 1 | Van 2 axis |
| | | 2 | Truck 2 axis |
| | | 3 | Truck 2 axis |
| | | 4 | Truck 2 axis |
| 6 | Truck 3 axis | 5 | Truck 3 axis |
| | | 6 | Truck 3 axis |
| 9 | Truck 5 axis | 9 | Truck 4 axis |
| | | 10 | Truck 4 axis |
| 10 | Truck 6 axis | 11 | Truck 5 axis |
| | | 12 | Truck 5 axis |
| | | 13 | Truck 5 axis |
| 11 | Trailer Truck 5 axis | 7 | Trailer truck 4 axis |
| | | 8 | Trailer Truck 5 axis |


**Fig. 1.** Map of the survey stations

providing the most serious condition was assumed. In particular, in the simulations, reference was made to the maximum value indicated in the catalogue.

### 4.4. Climate data

To take into account the climatic conditions, a series of data collected through the surveys conducted in the survey stations indicated in Table 2 and Fig. 1 were used. It was necessary to resort to other sources for some specified variables. The data was collected using the instrumentation of weather stations indicated in Table 2. These stations are constituted by a series of sensors connected to a data logger.

The instrumentation present in each station is:
- anemometer for measuring wind speed;
- thermometer to measure temperature;
- hygrometer to measure humidity;
- pyranometer to measure solar radiation;
- rain gauge for the determination of the intensity of rain.

These data, recorded by the logger, were organized in accordance with the procedures indicated by the MEPDG. Two different files were generated to insert the information contained in Fig. 2 into the MEPDG. The first file (*.hcd) contained information on the survey station and the second file (*.icm) contained the information/instructions needed to setup the Enhanced Integrated Climatic Model (EICM). In particular the data introduced into the EICM were organized into four groups.

Group I contains the time interval for which the meteorological data are available – data for 24 months were taken into consideration.

Group II contains the following information:
- geographical coordinates – latitude and longitude;
- elevation above sea level (ft);
- depth of water table (ft);
- annual average temperature in (° F);
- freezing degree days (° F) – an index of freezing *FDD*:

$$FDD = 32 - T_a, \tag{2}$$

where *FDD* – an index of freezing; $T_a$ – function of the average daily temperature.
- height of average annual rainfall (in);
- average monthly relative humidity (%).

Group III contains:
- date as month/day/year;
- time of sunrise and sunset, derived from the geographical coordinates of the survey station;
- daily maximum value of solar radiation. This data is taken directly from the instruments present in the different stations that provide it in W/m$^2$. However given that for this variable the EICM does not provide the units, reference was made to the "potential maximum daily radiation". This variable to which the MEPDG refers was obtained according to the following procedure.

The daytime period (time between sunrise and sunset) is:

$$N_i = \cos^{-1}(-tg\phi\ tg\delta), \tag{3}$$

where $N_i$ – the period between the point where the sun rises and the highest point of the sun, *t*; φ – the latitude, rad. φ and δ take a conventionally positive value with respect to the North.

The declination of the sun, i.e. the apparent distance of the orbit of the sun daily from the earth's equator:

**Table 2.** Survey stations

| Station | Height Survey Station | Area/Town | Scenarios |
|---|---|---|---|
| Mezzoldo (BG) | 1682 m | Bergamo | High Altitude - North |
| Edolo (BS) | 720 m | Brescia | Middle Altitude - North |
| Lambrate (MI) | 120 m | Milano | Lower Altitude - North |
| Pizzotrevescovi (MC) | 1670 m | Macerata | High Altitude - Centre |
| Camerino (MC) | 780 m | Macerata | Middle Altitude - Centre |
| Cerbara (PG) | 288 m | Perugia | Lower Altitude - Centre |
| Montescuro (CS) | 1671 m | Cosenza | High Altitude - South |
| Acri (CS) 750m | 750 m | Cosenza | Middle Altitude - South |
| Martirano (CZ) | 281 m | Catanzaro | Lower Altitude - South |

**ICM Files (*.icm)**

*StartDate (YYYYMMDD) – EndDate (YYYMMDD): The period for which this file contains data for.*
19960701-20011231

*Longitude, Latitude, ELEVATION, Annual Water Table Depth (-1 if using seasonal), spring water table depth, summer water table, fall water table, winter water table, MEAN ANNUAL TEMPERATURE, FREEZING DEGREE DAYS, ANNUAL RAINFALL, monthly average humidity (12 total-start January)*
-86.23,32.18,227,-
1,10,20,19,10,64.8035,12.8717,44.1237,72.3031,69.6847,65.7183,70.4444,70.5253,75.7314,75.2074,74.7333,74.5993,72.8259,74.0491,75.2558

*Month, Day, Year, Sunrise time (decimal-24 hour), sunset, daily solar radiation maximum. Sunrise/Sunset calculated from Lat/Long. Solar radiation data from rad.dat file, correct for Lat/Long.*
7 1 1996 4.95899 19.041 3730.48

*Hour, temperature, precipitation, wind speed, percent sunshine, hourly ground water depth.*
0 72 0 0 100 20
1 71.1 0 0 100 20
2 70 0 3 100 20
3 70 0 0 100 20

**Fig. 2.** Layout of data entered into the MEPDG

$$\delta = arcsen\left\{0.39785sen\left[4.869 + 0.0172i + 0.03345sen\left(6.224 + 0.0172i\right)\right]\right\}, \quad (4)$$

where δ – declination of the sun, rad, $i$ – days of the year, number of day.

Height of the sun, defined as the angle between the position of the sun and the horizon:

$$h = 90° - |\phi - \delta|, \quad (5)$$

where $h$ – height of the sun, rad.

Max height of the sun, measured at the passage on the upper meridian:

$$senh = sen\phi sen\delta + \cos\phi\cos\delta\cos P. \quad (6)$$

A factor of earth-sun distance correction that allows us to evaluate the potential radiation:

$$E_0 = 1 + 0.0334\cos(0.0172i - 0.0552), \quad (7)$$

where $E_0$ – factor of earth-sun distance, (MJ m$^{-2}$).

The potential maximum daily radiation ($R_a$, MJ m$^{-2}$) for each location indicated in the Table 1 was obtained as:

$$R_a = 117.5E_0\left(\frac{N_i sen\phi\ sen\delta + \cos\phi\cos\delta\ senN_i}{\pi}\right). \quad (8)$$

Group IV containing information:
- time (0–24 format);
- temperature, ° F;
- rainfall intensity, in/h;
- wind speed, mph;
- cloud cover, %, – this information was derived from Meteorological Aerodrome Report bulletins. In particular, using this information it was possible to determine cloud cover according to the following classification: CLR (clear), FEW (few clouds 1/8–2/8), SCT (scattered clouds 3/8–4/8), BKN (broken 5/8–7/8), OVC (overcast 8/8).

## 5. Numerical simulations with MEPDG

Nine different scenarios were simulated. They are obtained from the combination of 3 different latitude values (North, Central, South) with 3 altitude conditions (high, medium, low). Through these simulations it was possible to study in 9 different configurations the performance offered by 6 different solutions proposed by the *C.N.R.-B.U.-178, 1995*. Figs 3–11 report the results obtained for the 54 combinations simulated. In particular, by analyzing the results concerning the flexible pavement, the tests

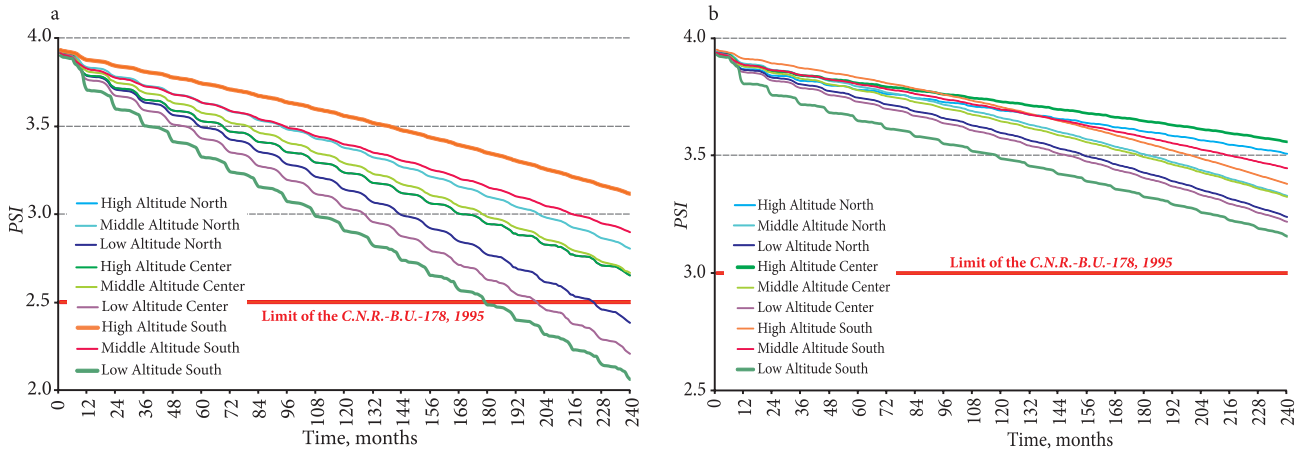


**Fig. 3.** Simulation *PSI* decay:
a – *PSI* decay highway one carriageways – flexible pavement; b – *PSI* decay – freeway two carriageways – fexible pavement

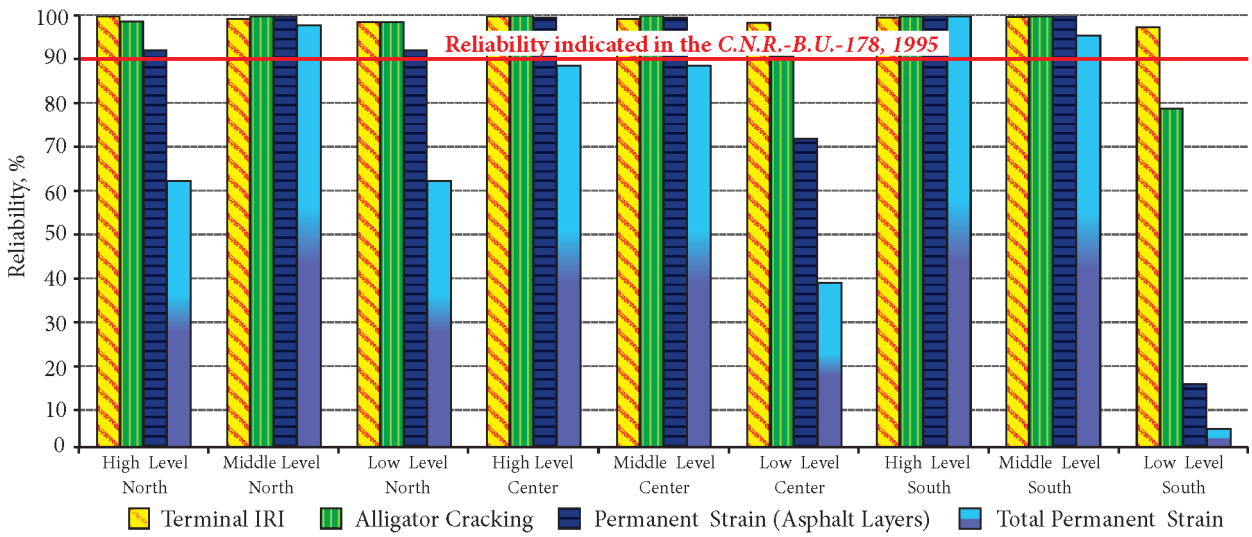


**Fig. 4**. Decay of the pavement – freeway/flexible pavement after 20 years

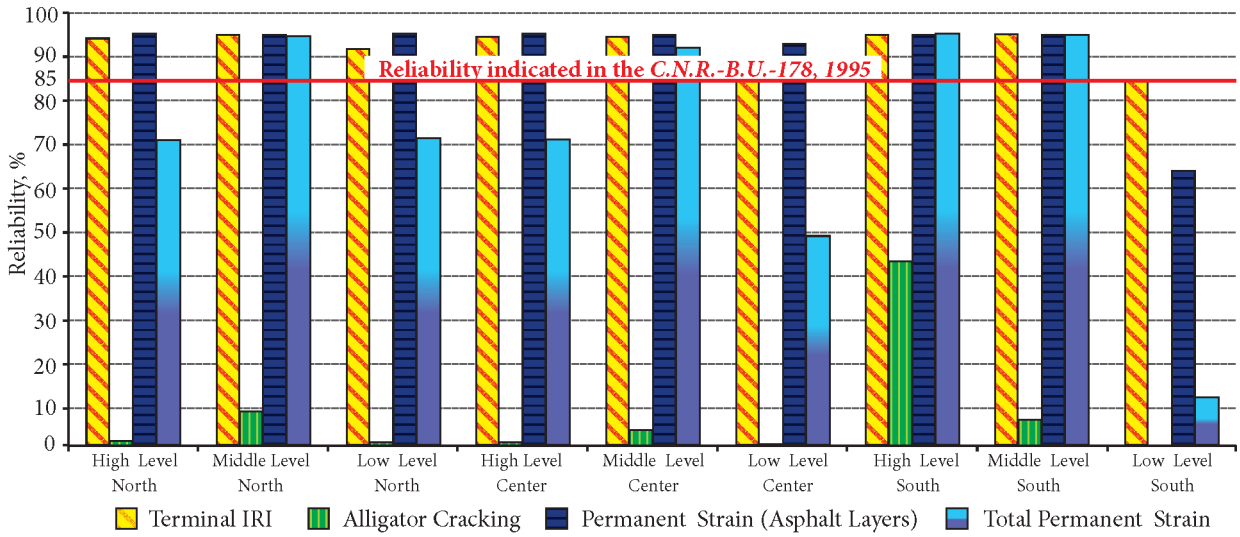


**Fig. 5.** Decay of the pavement – highway/flexible pavement after 20 years

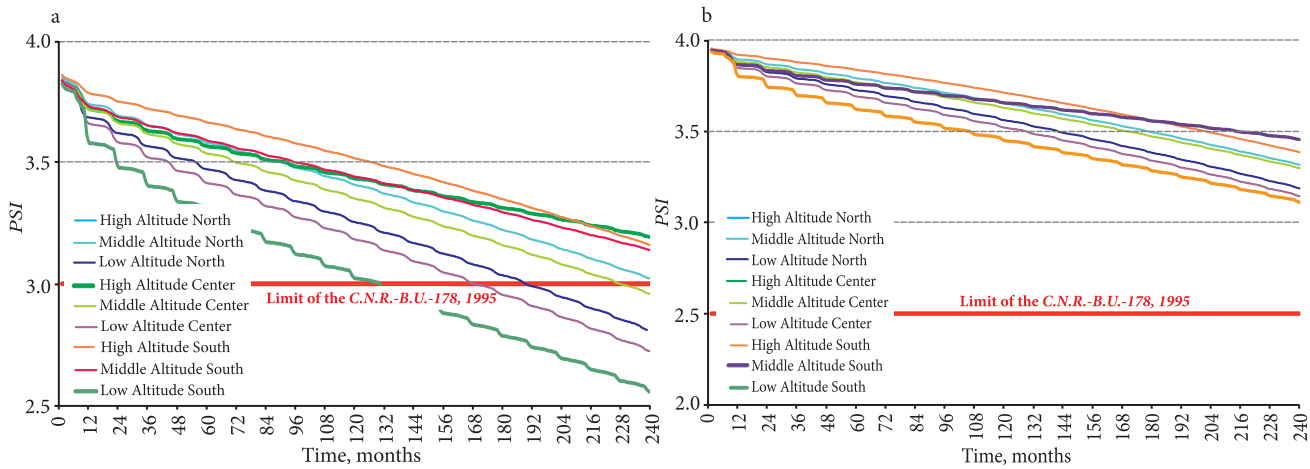


**Fig. 6.** Simulation PSI decay:
a – *PSI* decay freeway two carriageways – semi-rigid pavement; b – *PSI* decay highway one carriageways – semi-rigid pavement

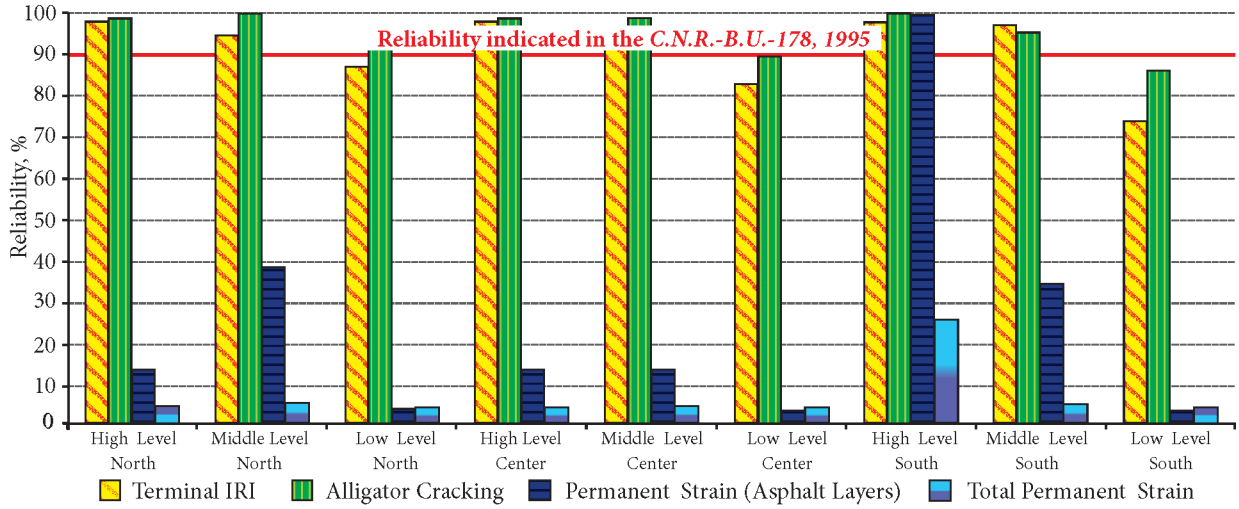


**Fig. 7.** Decay of the pavement – freeway/semi-rigid pavement after 20 years

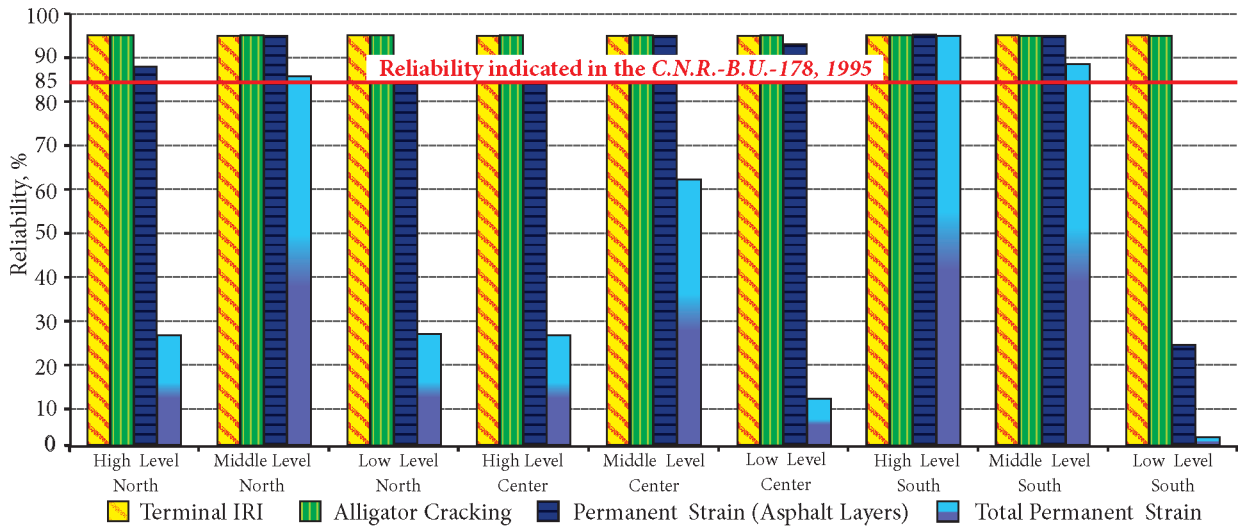


**Fig. 8.** Decay of the pavement – highway/semi-rigid pavement after 20 years

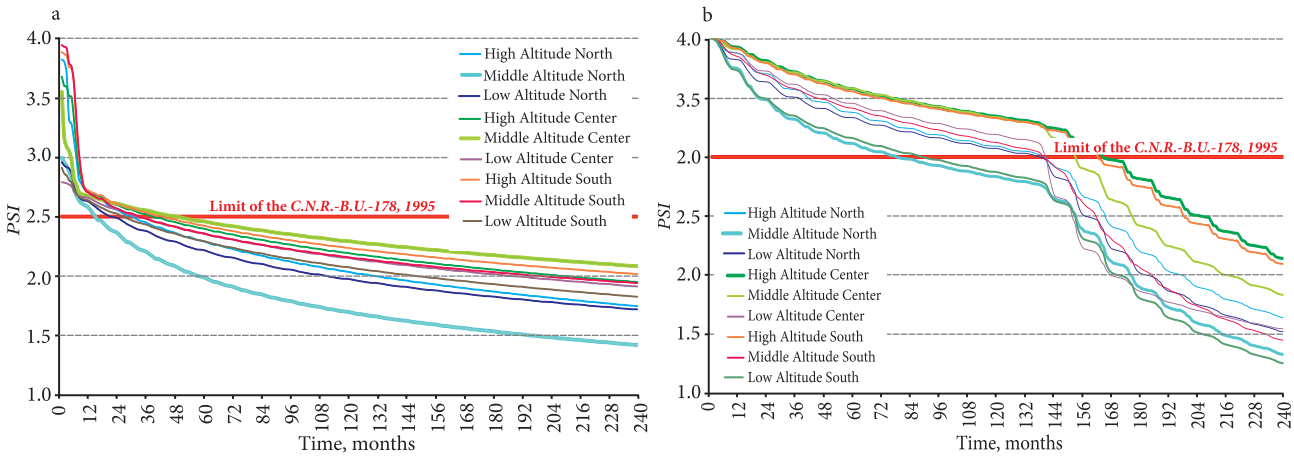


**Fig. 9.** Simulation *PSI* decay: a – highway rigid pavement; b – freeway rigid pavement

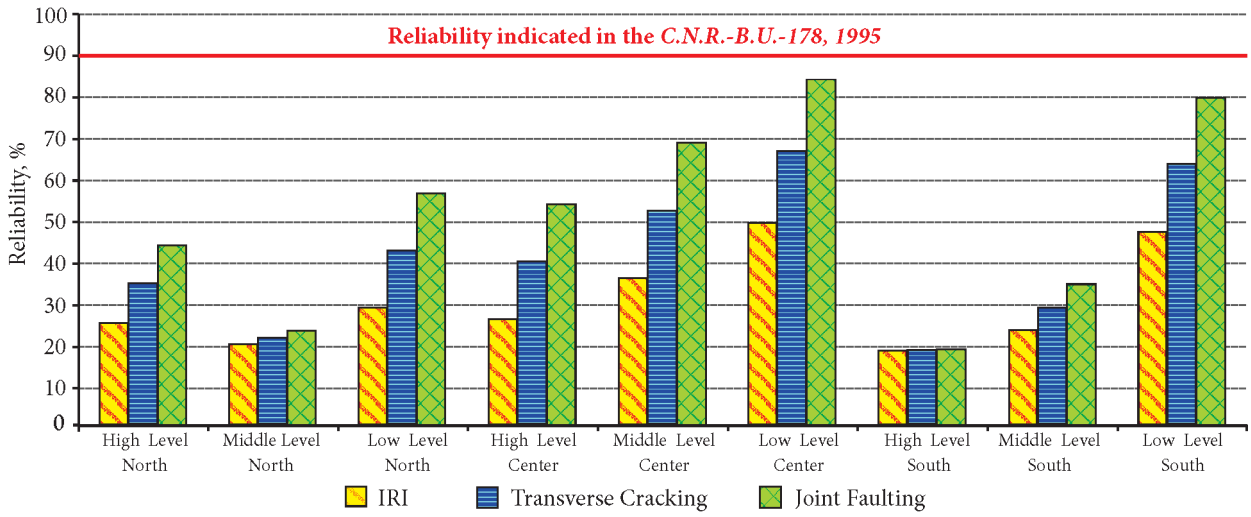


**Fig. 10.** Decay of the pavement – freeway/rigid pavement after 20 years

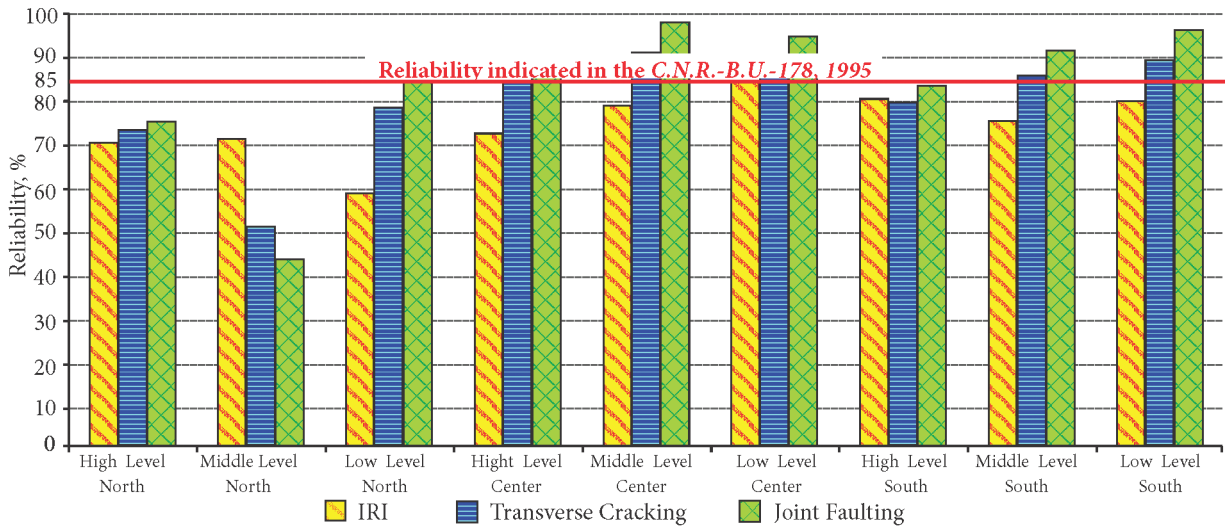


**Fig. 11.** Decay of the pavement – highway/rigid pavement after 20 years

carried out using the MEPDG on the solutions suggested by the catalogue, in reference to the IRI index, are positive (Dell'Acqua *et al.* 2011).

For alligator cracking on highways the tests are positive, while for the freeway the proposed solution is not acceptable. For the permanent strain (asphalt layer), it is observed that the checks are almost always satisfied for both (freeway and highway). For total permanent strain, for both freeway and highway, checks are satisfied for about half of the scenarios simulated. Finally, the *PSI* is always satisfied for the freeway, while for highways, it only fails to be satisfied in three scenarios.

For the semi-rigid pavement, the solutions suggested by the *C.N.R.-B.U.-178, 1995*, in reference to *IRI* and alligator cracking, are satisfied for both types of roads (freeway and highway).

For the permanent strain (asphalt layer) checks are almost never satisfied on the highway. They are almost always satisfied on the freeway. For the total permanent strain, checks have never been satisfied on the highway and only in some cases are satisfied on the freeway. Finally, the verification of the *PSI* is satisfied on the highway. On the freeway, it is not satisfied for about half of the simulated scenarios. For the rigid pavement in almost all scenarios, the simulated checks are not satisfied. *IRI* testing is never satisfied on both types of roads analyzed.

On freeways no test concerning transverse carking and joint faulting is satisfied. Only in a few cases, (on highways) these two tests (transverse carking and joint faulting) are satisfied. Finally, the verification of the PSI is never satisfied for both types of roads analyzed (freeway and highway). For the permanent strain (asphalt layer) checks are almost never satisfied in the highway. They are almost always satisfied on the freeway. For the total permanent strain, checks have never been satisfied in the Highway and only in some cases are satisfied in the freeway. Finally, the verification of the *PSI* is satisfied on the highway. On the freeway, it is not satisfied for about half of the simulated scenarios.

For the rigid pavement in almost all scenarios, the simulated checks are not satisfied. *IRI* testing is never satisfied in both the types of roads analyzed. On freeways no test concerning transverse carking and joint faulting is satisfied. Only in a few cases, (on highways) these two tests (transverse carking and joint faulting) are satisfied. Finally, the verification of the *PSI* is never satisfied for both types of roads analyzed (freeway and highway).

## 6. Conclusions

The comparison between the proposed solutions from the catalogue and the results of simulations carried out using MEPDG showed that many proposed solutions from the catalogue are very approximate. As extensively discussed and illustrated for all types of pavements examined, in many cases the checks are not satisfied. It is clear that the assumptions introduced in the Italian CNR road pavement design catalogue and specifically the assumptions adopted for the characterization of climatic conditions should be modified. Therefore it is necessary to revise the tool design and verification of the pavement, through more sophisticated tools such as the MEPDG. The scenarios that have not passed the tests, compared with the total examined, are significant in number. It is believed on the basis of the information obtained in this study that this approach (i.e. to revise the proposed solutions of the catalogue with MEPDG) is a good strategy to revise and upgrade the Italian CNR road pavement design catalogue *Catalogo delle pavimentazioni stradali C.N.R.-B.U.-178, 1995*.

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