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Long-Term Monitored Road Degradation Functions as a Tool to Increase Quality of Pavement Design

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Abstract: Ensuring the sustainability of road infrastructure cannot be achieved without the continuous application of new knowledge and approaches within individual management steps. A particularly risky stage in the life cycle of existing roads is the operation phase. High attention is paid to the environmental, financial and social impacts and benefits of individual processes applied by road managers. These processes meet in pavement management systems (PMS), which, however, cannot work reliably without the necessary input data. Information on the development of the technical condition of the road can also be included among the most important data. The paper brings the first outputs from several years of research of measurements on the Slovak 1st class road. Its aim is to gradually determine the degradation functions for the needs of Slovak geographical, climatic and transport conditions. The secondary objective is to verify the reliability of non-destructive measurement procedures of the technical condition of the road. Emphasis is placed on the application of such mathematical procedures that can not only reliably bring about the determination of past developments in the roadway, but can also present the expected picture of future developments.

Keywords: pavement condition; long-term monitored road; degradation functions; rut; iri; design

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1. Introduction

The sustainability of the road network is under ever-increasing economic, environmental and social pressures. Road infrastructure users are demanding higher and higher benefits from road administrators for their private as well as public financial resources. This represents, in particular, a combination of ensuring higher road safety level, acceptable time availability of destinations, but also economic efficiency in the processes of road infrastructure management by administrators. At the same time, new regulations related to environmental protection and efforts to actively implement finance in terms of value for money are constantly emerging. These, as well as other regulations and restrictions, challenge the whole sector to find new or improve existing solutions that have innovative features. Their goal is to move the whole society forward and at the same time in terms of sustainability rules, they will not generate adverse effects for future generations.

The general concept of road infrastructure sustainability is well defined and its basic characteristics are recognized worldwide. Nevertheless, there is scope for its partial parts to be modified, while the aim is to ensure a higher quality of the whole model. Among the most important processes within the sustainability model include pavement management systems (PMS). Their task is to optimize the performance of roads during their expected service life and, thus, especially to ensure the time optimization of construction interventions in the road [1,2]. Achieving this state cannot only bring significant financial benefits, but also reduce the demands on the environment and satisfy the user demand for quality road infrastructure.

The starting point for the successful applicability of PMS is the use of pavement performance forecasting model (PPFM) functions. It determines the planned performance of new roads and the residual life of existing roads, during their life cycle. For these two components of the sustainability model, a mutually complementary relationship applies, where PPFM directly evaluates and expresses the pavement condition in a presentable form. At the same time, all tasks associated with monitoring the condition of roads contribute to the improvement of PPFM.

As can be seen from Figure 1, due to its great importance, the pavement performance forecasting model must be able to work efficiently with a large group and several types of data.

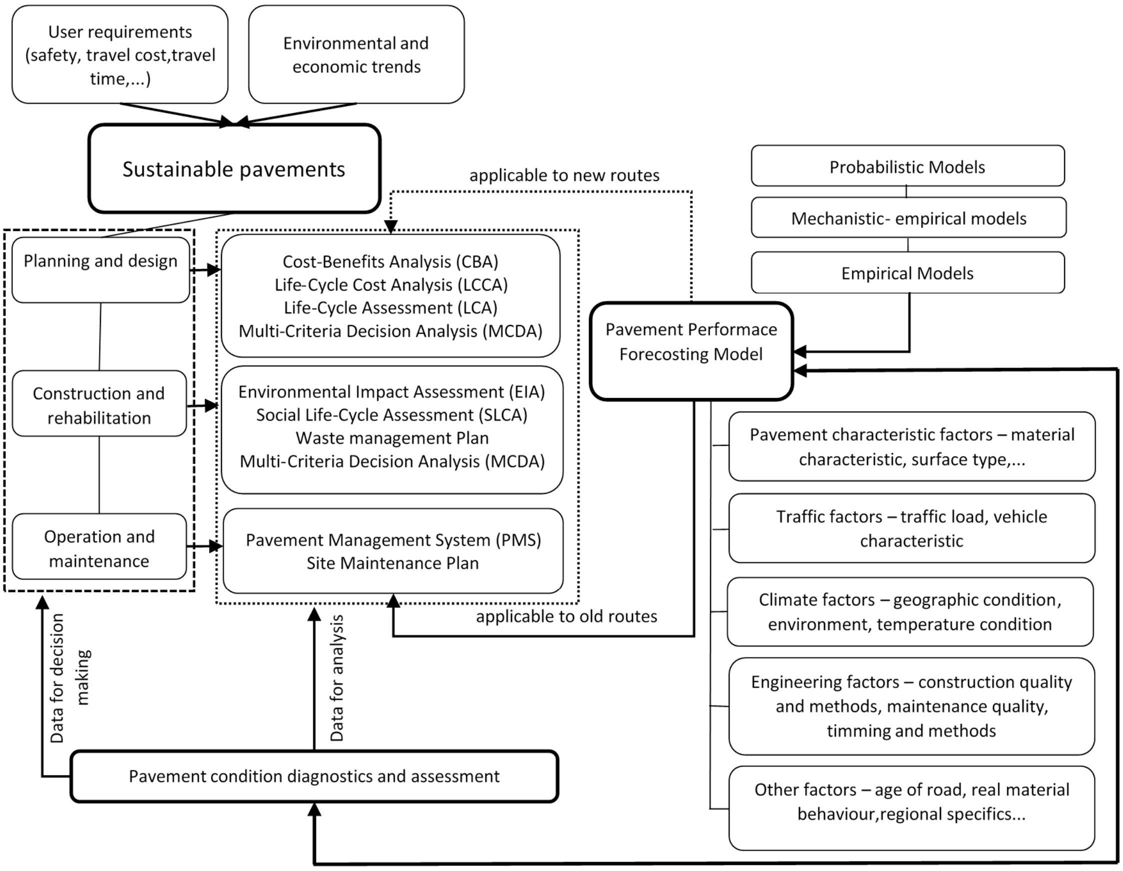


Figure 1. The position of the pavement management system in the general philosophy of the pavement sustainability [3,4].

Due to the different transport, climatic and construction characteristics of the managed road network, these data require their own approaches for collection, processing and, of course, their interpretation. This also applies to their basic part, which they are degradation models of residual road performance. They represent the so-called indicator of road quality [5] presented as a combined mathematical-graphical expression of the decline in road performance over time. The absence or poor quality of these functions greatly weakens the whole meaning of the pavement management system.

Administrators, without information about the exact development of the road condition in the future, applied maintenance and repair work solely on the basis of the current quality of the road, or made their own estimates of future development based on an expert estimate. This procedure, of course, often led to bad managerial decisions, which were accompanied by low financial efficiency. From this reason degradation models have already become an essential part of the road management system and their regular application can achieve the sustainability of the entire process of repairs, maintenance and reconstruction of the road network [6–8].

Figure 2 illustrates the general concept of application of corrective pavement treatment as a function of pavement condition.

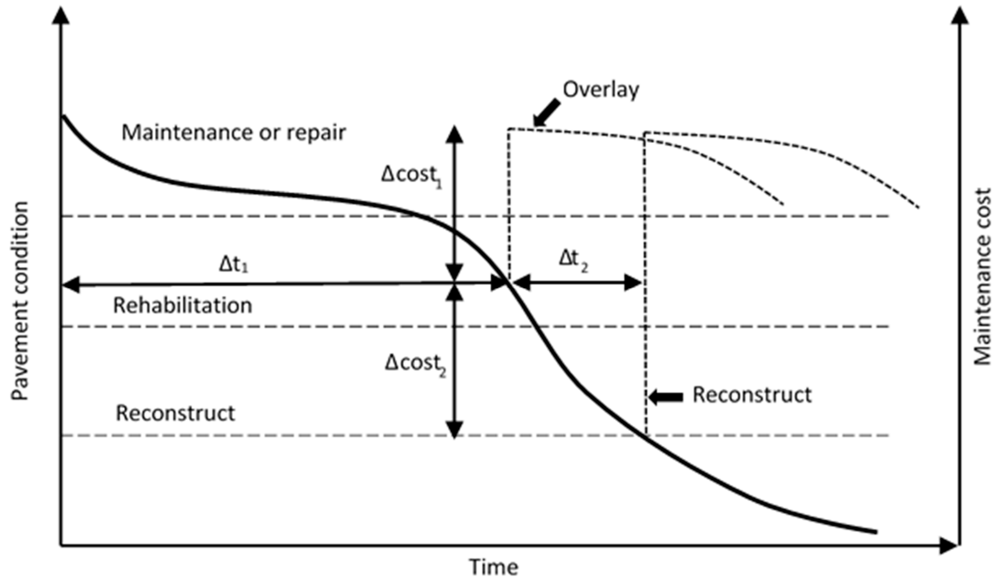


Figure 2. General concept of degradation function of pavement [9].

One of the basic problems is the fact that the course and shape of this function differs due to various factors that occur within the life cycle of the pavement. For this reason, it is appropriate to generate your own degradation function for certain regional characteristics.

This paper contains partial results of a long-term research project, one of the partial parts of which was the task of determining relevant degradation functions on the basis of a long-term monitored Slovak first class road. The results described in this paper build on further knowledge of the author team in the areas of road management systems, non-destructive road measurements and in the field of progressive materials used for roads, which are described mainly in the works [10–12].

Related Research

In the process of compiling degradation models, it is necessary to take into account factors such as the possibility of measuring input parameters (including the possibility of objectively evaluating them), verifiability of the model empirically based on physical properties and also local conditions. From this also follows the procedure whether we will proceed using the knowledge of the laws of aging of materials or from the analysis of experimental measurements. Procedures for determining degradation models can be defined as follows through three basic approach groups:

- based on the physical laws of failure mechanics and these models must be calibrated and verified using the results of laboratory tests and field measurements,
- on the basis of repeated laboratory tests of materials under load and conditions that are very close to the real one,
- on the basis of long-term measurement and evaluation of real roads under the same boundary conditions [13].

Road degradation can be monitored, evaluated and forecasted by changes in one parameter or also by changes in several parameters in the aggregated assessment. It is the availability of parameters and the possibilities for obtaining them, that are one of the conditions for selecting one of the above-mentioned methods for determining degradation models.

Within international standards, approaches to the creation of degradation models are divided into those that are created on the basis of experimental measurements in real conditions and on the basis of measurements in laboratory conditions [14]. Among the significant works that arose on the basis of real conditions, it is possible to include example results of the long-term pavement performance study [15]. The program and the results are focused on the collection of road performance data, containing more than 2500 test sections at more than 900 locations. The results serve as a very useful basis for follow-up work, such as the study [16], which instead of who developed a transformed linear regression model between the pavement condition index and IRI indices, or the study [17] where on data from the long-term pavement performance program analyzed various options for road maintenance and rehabilitation.

In general, activities related to the acquisition of degradation models are not implemented primarily to replace or substantially improve other predictive functions, with universal applicability. For certain regions and specific traffic conditions, it is necessary to develop individual degradation models and constantly work on their improvement. Among the parameters, which are in the set are condition of the road surface in terms of cracks, the course of transverse tracks, skid resistance and load-bearing capacity of road layers, traffic load, climatic conditions, humidity parameters of the internal structure of the road [18,19]. At the same time, it is necessary to observe in the background time factors and other serious external influences that may occur.

Subsequently, it is at the discretion of the creators and users of pavement management systems which collected, derived or estimated data prefer as inputs, or which parameters they consider crucial for determining the road quality. The studies contained in [20,21] emphasize the use for the pavement performance International Roughness Index (IRI) parameter. This is despite the fact that they collect various other data with different collect frequency (e.g., pavement crack, road roughness) that can provide more comprehensive assessments. While, for example, the studies described in [22] are based on more complicated approaches including road age, traffic load, cracks, temperature and rut depth. The model below states that IRI increases with an increase in age, rut depth, freezing index and plasticity index, while thicker overlay and base layers result in less IRI. As further stated in the study [22], when age and rut depth are considered as zero and average values of 5286, 1.416 °C-day, 243 mm and 263 mm are used for AADT, FI, overlay and base thickness, respectively, IRI_0 of 0.92 m/km is obtained using next Eq. This observation implies that although no milling is performed prior to overlay, a low IRI_0 of 0.92 m/km is still attained for the overlaid sections.

$$IRI = 0.786 + 0.099 \cdot e^{\frac{Age}{25}} \times AADT + 0.2 - \left(\frac{FI}{1000}\right) - 1.55 \times Base\ (m) - 1.5 \times AC\ (m) + 0.074 \times Rutting + 0.01 \times PI \quad (1)$$

where *AGE* is the last rehabilitation or construction activity life in years, *AADT* is average annual daily traffic, *FI* is freezing index, *base* (*m*) is base layer thickness in mm, *AC* is the layer or AC overlay thickness in mm, *rutting* is the 80th percentile rut depth and *PI* is plasticity index.

However, the general aim is to create the simplest possible predictive functions so that they are not greatly affected by the high number of input parameters. At the same time, emphasis must be placed not only on tests in laboratories, but also on additional measurements in the field, e.g., using non-destructive forms of diagnostics [23]. It is quite interesting to observe what is the decisive period on the basis of which individual prediction models and functions arise. Examples of models are available based on data collected over a period of 4 years [24], which result in a road condition index based on a change in the road construction and characteristics and traffic load of the road. Study [25] describes degradation relationships through an index based on a combination of roughness and macrotexture, with the experimental section being monitored for 7 years. It is quite interesting to observe that this period is not unified, but is chosen individually at the discretion of those skilled in the art. Below is a brief overview of how the quality of the road as a whole is determined or using values of the monitored parameters. As can be seen in Table 1, the approaches used by the authorities responsible for assessing the quality of road conditions are fundamentally different. Each state proceeds individually, especially taking into account the traffic, climate, road construction specifics that are present on a given road network. Changes in this direction are not expected in the future.

Table 1. Overview of approaches for evaluating the quality of roads and their parameters [24,26].

Country	Evaluation Function	Explanation of Function
Overview of Approaches for Rut Calculation		
Austria	$t = a\sqrt{N}$	T is rut depth, N is the number of loads equivalent to a standard axle (10 t), a is an empirically determined factor depending on the road structure.
Finland	$RD_p = RD_m + \left(\frac{RD_m - 2.0}{AGE_{orm}}\right) \times AGE_{mp}$	RD_p is predicted rut depth, RD_m is measured rut depth, AGE_{orm} is the number of years from the last road reinforcement to the year of measurement, AGE_{mp} is number of years from measurement to year of wheel path depth forecast
Hungary	$RUT = e^{a+b\times AGE}$ $RUT = e^{a+b\times FORG}$	AGE is age of the road abrasive layer, $FORG$ is number of repeated crossings of equivalent passenger cars a, b are constants
Ireland	$IRI_t = IRI_{t-1} + (a + b \times ESAL_t \times 0.41 \times 10)$	$ESAL_t$ is number of passes of uniaxial design axles (80 kN), IRI_t is value IRI in year t, a, b are calibration parameters
HDM 4	$\Delta RDM = RDO + \Delta RDPD + \Delta RDW,\ for\ AGE4 \leq 1$ $\Delta RDM = \Delta RDST + \Delta RDPD + \Delta RDW,\ for\ AGE4 > 1$	ΔRDM is the annual increment in the total average wheel path depth in both wheel paths RDO is depth of inequalities due to initial compaction, $\Delta RDST$ is the annual increment due to structural deformations, $\Delta RDPD$ is an annual increase due to plastic deformations, ΔRDW is the annual increase due to wear and tear, $AGE4$ is the number of years since the last road reconstruction or construction
Overview of Approaches for IRI Calculation		
Finland	$IRI_{t+1} = a + b \times IRI_t$	IRI_{t+1} is IRI prediction for year $t + 1$, IRI_t is IRI prediction for year, a, b are the parameters of the model according to the type of road construction
Hungary	$IRI = e^{a+b\times AGE}$ $IRI = e^{a+b\times FORG}$	AGE is age of the road abrasive layer, $FORG$ is number of repeated crossings of equivalent passenger cars a, b are constants
Ireland	$RD_t = a \times (0.41 \times cumESAL_t)^b$	RD is transverse evenness in mm $cumESAL_t$ is cumulative number of passes of uniaxial design axles (80 kN) per year t, a, b are calibration parameters
HDM 4	$\Delta RI = K_{gr}(\Delta RI_s + \Delta RI_c + \Delta RI_r + \Delta RI_t) + \Delta RI_e$	ΔRI is incremental change of IRI K_{gr} is calibration factor for the development of longitudinal roughness, ΔRI_s is contribution of the structural component of roughness, ΔRI_c is the contribution of cracks to inequalities, ΔRI_r is the contribution of variations in transverse inequalities to longitudinal inequalities, ΔRI_t is contribution of pressures to inequalities, ΔRI_e is the contribution of the environment to inequalities
Poland	$IRI = IRI_0 \cdot e^{0.033(t-t_0)}$	IRI is predicted value IRI in year t, IRI_0 is measured IRI in year t_0

Table 1. *Cont.*

Country	Evaluation Function	Explanation of Function
Overview of Approaches for Pavement Bearing Capacity Calculation		
Hungary	$E = a - b \times AGE$ $E = a - b \times FORG$	AGE is age of the road abrasive layer, $FORG$ is number of repeated crossings of equivalent passanger cars a, b are constants
Other Approach—Structural Failure Index		
Spain	$ID = ND^a \times 10^b$	ID is structural failure index ND is the number of vehicle a, b are the constants determined from the tables according to the road construction
Other Approach—Surface Failure Index		
Finland	$DI_p = \frac{DI_m}{AGE_{om}^b} \times AGE_{ob}^b$	DI_p is predicted failure index DI_m is failure index-measured, AGE_{om} is time period in years from the last replacement of the cover to the year of measurement AGE_{ob} is time period in years from the last cover replacement to the year of prediction, b is constant based on type of pavement

2. Research Methods

2.1. Theoretical Approach

Experimental approaches for determining the course of road aging differ significantly, despite certain common principles. The baseline curve of the road degrading without intervention is expressed by a decreasing curve [27–29]. Over the last 20 years, a number of scientific approaches have been presented to predict road performance and residual life. They were based on the evaluation of long-term measured data in the statistical form [30], stochastic approaches using probabilistic trends from real measurements [31,32] or fuzzy logic and analytic hierarchy process [33], or the artificial neural network approach [34]. However, among the most reliable approaches, it is possible to include those based on a combination of long-term collected data, combined with high quality diagnostic and evaluation equipment [35]. This approach represents a backward regression in the form of an iteration between traffic conditions, the specific construction of the road and the condition of its surface [2,36,37].

The experimental approach presented in the article is based on monitoring the technical condition of a specific section of Slovak 1-st class road over a period of 20 years, while this monitoring continues. This is an important 1st class road (built in 1973) marked as I/64 connecting the transport hub of northern Slovakia (the city of Žilina) to another regional center (the city of Prievidza). Specifically, the monitored section is located between Poluvsie and Porúbka cities, in a zone where relatively regular and sudden fluctuations in temperature and changes in weather conditions occur during the year. The annual average temperature is about 7.5 °C, while the warmest month of July has an average temperature of 16.7 °C. The average number of days with a snow cover is about 50 days. The average height of the snow cover is 15 cm and during dry winters only 5 cm. The maximum height of the snow cover is 70 cm. The road construction consists of a mastic asphalt concrete, an asphalt concrete for the load-bearing layer, an asphalt concrete for the upper base layer, a cement-bonded mixture and an unbonded layer of gravel. Daily intensity is at the level of about 12,600 vehicles, while the share of heavy trucks is about 16%.

The starting point for determining road degradation is based on the relationship between the independent variables and the modeled parameter based on a general deterministic model [38,39]:

$$PCS_t = f(P_0, ESAL_{st}, H_e, M_R, C, W, I) \tag{2}$$

where PCS_t is the road condition in t year, P_0 is the initial road condition in the first year, $ESAL_{st}$ is the equivalent load of one axle on the road in t age, H_e is the total equivalent structure thickness, M_R—is the modulus of elasticity of the subsoil, W—is the climatic or the environmental impacts, C—is the structural conditions of roads and I is interaction effects [40].

Most pavement management systems require degradation models designed from rut, IRI and pavement bearing capacity parameters [40–43]. The rut parameter is one of the most important parameters in terms of influencing operational capability. The development of rut in degradation models is mainly represented by an increase in the depth of the wheel path. When creating degradation functions/models, it is appropriate to monitor only one wheel path, whose prediction of development reaches the limit value earlier than the other [13].

The processing of functions was based on the initial degradation models described in [39] used in Slovakia, Austria, Netherlands, Ireland and also in the software HDM-4. Expressing the IRI parameter through degradation models is a more demanding process than with the rut parameter. This is mainly due to the need of ensuring the same boundary conditions for long-term repeated measurements. The course of IRI in degradation models is represented by its own parameter: IRI (International Roughness Index) [13]. The starting models were the findings presented in [14,44].

Due to the volume of measured data from long-term repeated measurements, deterministic (empirical) degradation models were created. In the creation of degradation functions, polynomial regression analysis was used, which prescribes a general regression relation in the form of a polynomial with an independent variable. Experience has shown that, for most of the modeled parameters, it is sufficient to consider polynomials of at most fourth degree.

$$D(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + a_4 x^4 \tag{3}$$

where $D(x)$ is a modeled degradation function, x is an independent variable (time or traffic load) and a_0, a_1, a_2, a_3 and a_4 are regression constants.

To mathematically model the degradation function, it was necessary to create a relationship between the relative values of the monitored parameters. When processing the amount of data, local extremes were eliminated, which could have occurred due to non-compliance with the wheel path of the measuring device, non-compliance with measurement procedures, extraordinary climatic impact, etc. The data prepared were thus further processed using statistical methods. Extrapolation methods were used to monitor further developments. The road condition can be expressed using the function as follows:

$$Q(t) = q \times f \tag{4}$$

where q are the transport conditions and climatic conditions and f is the time. After modification, this relationship can be defined as follows:

$$q = \frac{Q(t)}{f(t)} \tag{5}$$

The known time value T represents the limit value of the monitored parameter. Then, the mathematical ratio t/T determines the dimensionless monitoring of changes in the state of individual parameters, depending on the ratio between real time and time, which represents the end of life of a particular parameter. In the same way, it is possible to define the dependence on the traffic load n/N, which depends on the knowledge of the number of passes of the traffic load. Parameter N represents the total (limit) number of design axles for the whole life of the road and parameter n expresses the number of axles up to the moment of evaluation. The mathematical relationship t/T is called the time index and the relationship n/N is called the load index.

The $P_{(x)}$ function is the value of the deformation. At a time that can be considered as the beginning of the road life cycle, or at a time when it is fully operational, the value is equal to 1. This means that it shows absolutely no degradation effects. The parameter $P_{(x)}$ acquires the value 0, or it acquires a value close to 0 at the time when the road is degraded. The relative expression of the parameters of transverse roughness used in Slovak conditions is as follows:

$$P_{(x)} = 1 - \frac{h_{k,mer}}{h_{k,dov}} \tag{6}$$

where the parameter $h_{k,mer}$ is the measured wheel path depth (mm) for repeated measurements, $h_{k,dov}$ is the maximum permitted wheel path depth (mm) specified in the technical conditions for the Slovak road in general [45]. The relative expression of the parameters of longitudinal roughness used in Slovak conditions is as follows:

$$P_{(x)} = 1 - \frac{IRI_{mer}}{IRI_{dov}} \tag{7}$$

where IRI_{mer} is the measured IRI value (m/km) during repeated measurements, IRI_{dov} is the maximum allowed IRI value (m/km) stated in the technical conditions for the Slovak road in general [46]

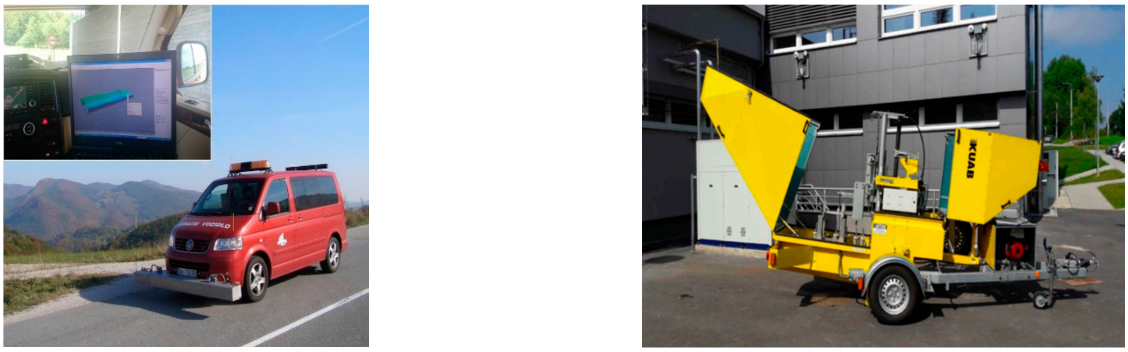
2.2. Experimental Approach

When determining the relationships of degradation functions, it is necessary to know the input data that affect the development of parameters of operational capability and performance that are IRI, rut and pavement bearing capacity. For this reason, in cooperation with the Research Center of the University of Žilina, nondestructive road conditions measurements were carried out. The task of the measurements was to determine the thicknesses of the structural layers of the road, to measure in addition to IRI, rut and the load-bearing capacity, gain knowledge about the subsurface failures of the pavement. Ground-penetrating radar (GPR), laser scanning and falling weight deflectometer technologies were used.

As can be seen at Figure 3 GPR consists of high-performance multi-channel radar control unit with air coupled 2 GHz horn antenna for asphalt layer thickness (from 0 to 0.75 m under surface) and 400 Mhz antenna for sub-base layer information (from 0 to 4 m under surface). The peak load of falling weight deflectometer KUAB 50 which is presented at Figure 4, it can be varied from the keyboard of the computer, by the choice of height of fall. The peak load range is 15–50 kN at 22 ms rise time (=time from start to peak).

(**a**) (**b**) (**c**)

Figure 3. Laser scanner (**a**); Ground-penetrating radar and video inspection (**b**); Diagnostic vehicle-interior (**c**).



(a) (b)

Figure 4. Profilegraph GE (**a**); Falling weight deflectometer KUAB 50 (**b**).

The measurement procedures and used technologies are designed based on many years of best practices, which are described in multiple studies [46–48]. It is very positive that despite the relatively high-quality equipment, developments in non-destructive data collection technologies are moving forward. An example is new approaches based on advanced sensor systems and machine learning that are emerging, which could significantly help improving the data collection process and road surface classification through integration. An example of progress is the identification of road surfaces in vehicles by acquiring the generated vibration in the suspension due to tire rolling [49] or the definition of the relationships between the road roughness and the ratios of individual amplitudes in a specific frequency band of the vehicle body acceleration values [50,51].

The data were evaluated for every 20 m. In Table 2 examples are presented of measurements in the station every 100 m.

Table 2. Example of GPR measurement evaluation (date 9 December 2020).

Direction 1 (from Porubka to Poluvsie)			Direction 2 (from Poluvsie to Porubka)		
Road Stationing (m)	AC Average Thickness [mm]	Road Average Thickness [mm]	Road Stationing (m) (m)	AC Average Thickness [mm]	Road Average Thickness [mm]
100	239	403	100	174	655
200	294	508	200	290	713
300	252	569	300	327	591
400	274	729	400	305	611
500	240	744	500	234	512
600	295	838	600	284	525
700	248	647	700	291	521
800	321	540	800	251	477
900	216	714	900	207	477
1000	263	1024	1000	231	316
Average	**260**	**632**	**Average**	**257**	**563**

In Figure 5 it is possible to see the values obtained by measuring the rut and IRI at the station 0 to 250 m, for both driving directions.

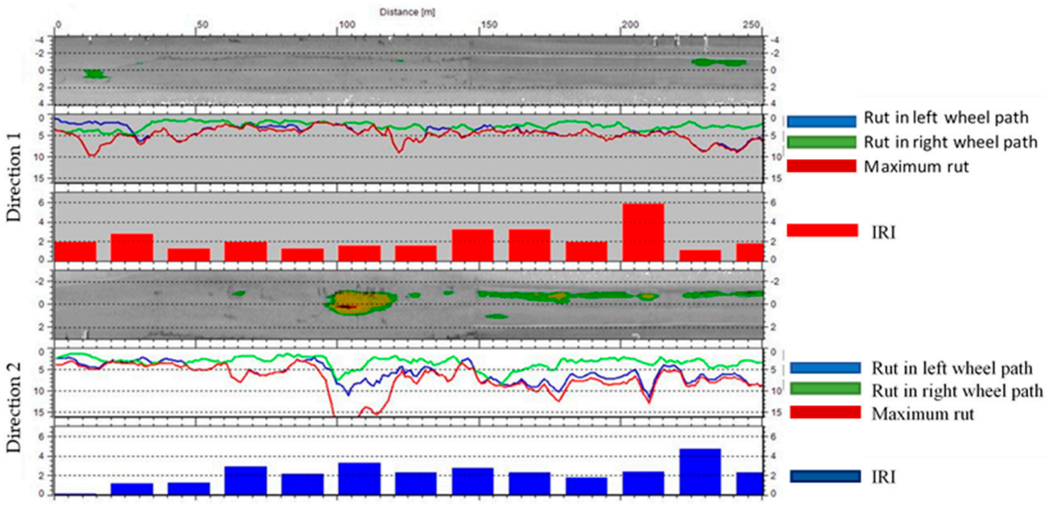


Figure 5. Graphical evaluation of the rutting and IRI parameters detection (date 9 December 2020).

3. Results

Degradation models are created for the rut, IRI characteristics and parameters of road bearing capacity. The next sections present a graphical course of dependencies due to long-time traffic load, whereas in this paper there are presented data for the one direction Poluvsie–Porubka. The derived degradation functions are listed in the individual parameters as follows.

3.1. Results of Rut Characteristics

Based on the available data from the long-term road monitoring, the linear dependence was determined. By mathematical evaluation of the dependence of the decrease in the course of the right and left wheel path on depth to create a linear dependence in the form described in the next graph.

For the Figure 6, as well as for the following Figures 7 and 8 in this section, we state that where y_{left} is RUT—the left rut depth (mm), y_{right} is RUT—the right rut depth (mm), x is the traffic load (mil. vehicles) and R^2 is the determination index.

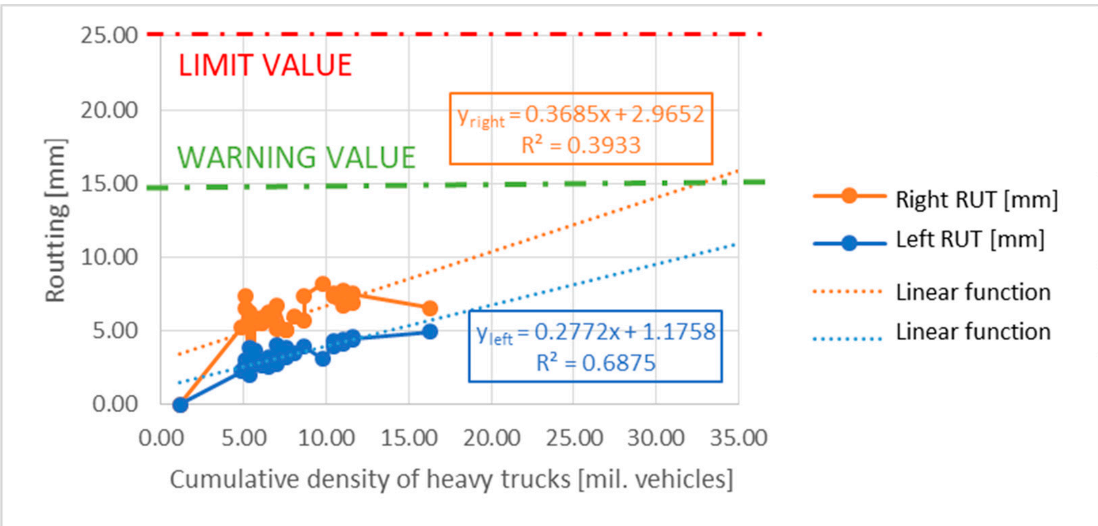


Figure 6. Rutting for left and right rut and probable course.

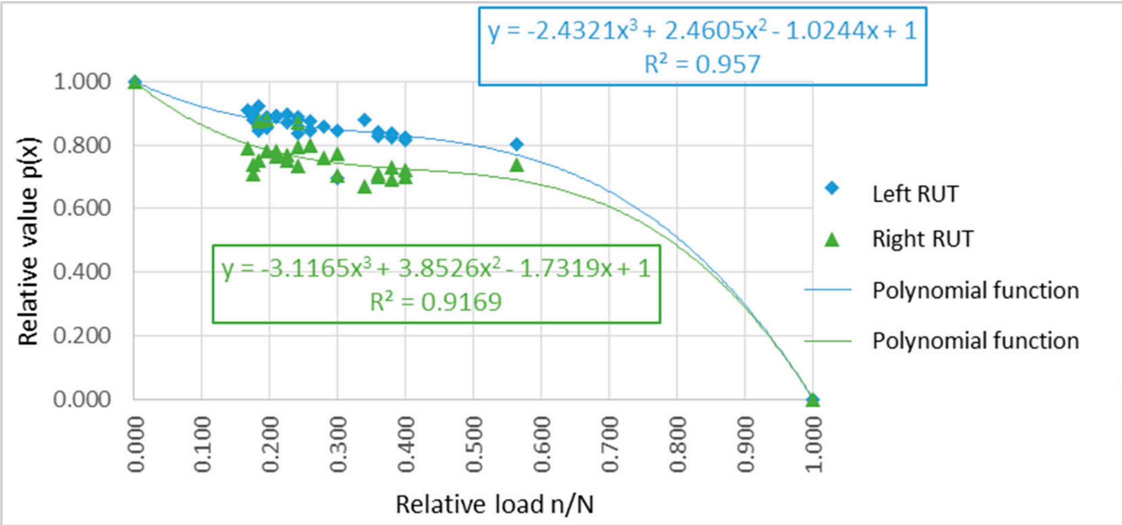


Figure 7. Degradation of the rut depending on the load n/N.

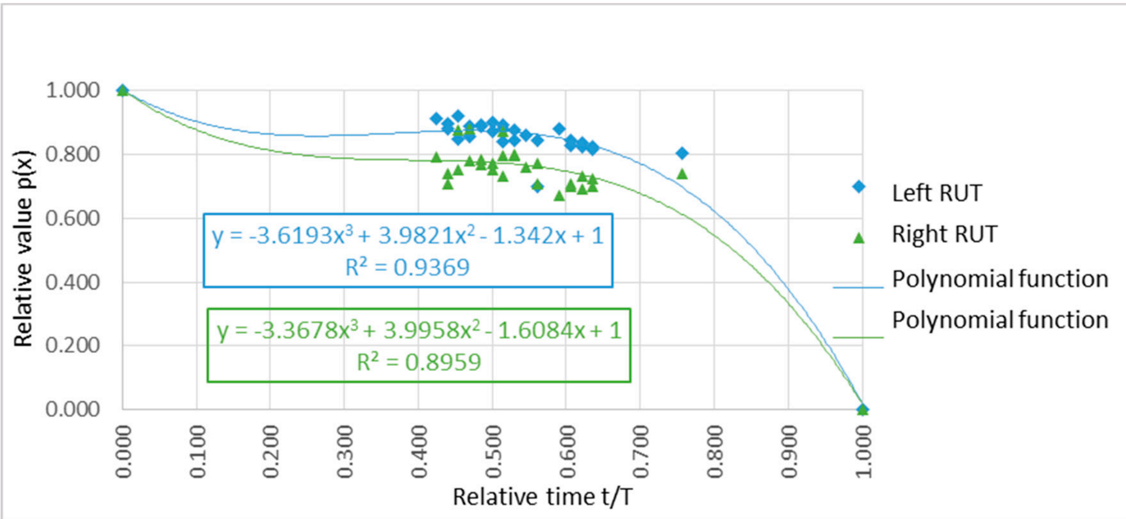


Figure 8. Degradation of the rut depending on the time t/T.

Based on the above dependence, it is relatively easy to monitor the development trend of the monitored parameter together with its prognosis. For cases where we are interested in determining the time when the limit values occur, it is necessary to know the forecasts of the development of traffic load.

Based on the defined magnitude, it was possible to design degradation functions. These confirm the results of several studies. They state that the maximum values of transverse inequalities are achieved mainly in the right wheel path. In addition, higher surface tensions arise in this part, which is caused by the deformations of the road shoulder.

3.2. Results of IRI Characteristics

Based on the available data from the long-term IRI monitoring, the polynomial dependence was determined in the form described in next graph.

For the Figure 9, as well as for the following Figure 10 we state, that y is the IRI (m/km), x is the traffic load (in millions of heavy trucks), $y_{n/N}$ is the IRI depending on load n/N, where $y_{t/T}$ is the IRI depending on the load t/T and R^2 is the determination index. In the above Figure 9 it is possible to notice an interesting trend of IRI where it initially increases, then decreases and then it takes off. To explain this, it can be stated that the staff responsible for the preparation and execution of the experiment, as well as for the subsequent processing of data, always proceed in accordance with the technical regulation of the Slovak Road Administration (TP 056). Although the experimental section was measured three times under the same conditions, very unusual results were found. Due to the fact that the causes of these non-traditionally measured data could not be unambiguously determined, they were not considered in the subsequent parts of the research task and do not affect the results. These data are presented as evidence that the experiments were performed. One of the assumptions as to why this data may have been generated is the possibility that a very rare temporary technical failure has occurred on one of the measuring lasers. However, other influences cannot be ruled out. These are, e.g., locally heavily dirty road surface, the effect of very heavy braking during the measurement or the necessary deviation from the correct measuring line, which we did not consider significant. However, as can be seen, in the end, some of these influences could have largely skewed the resulting values.

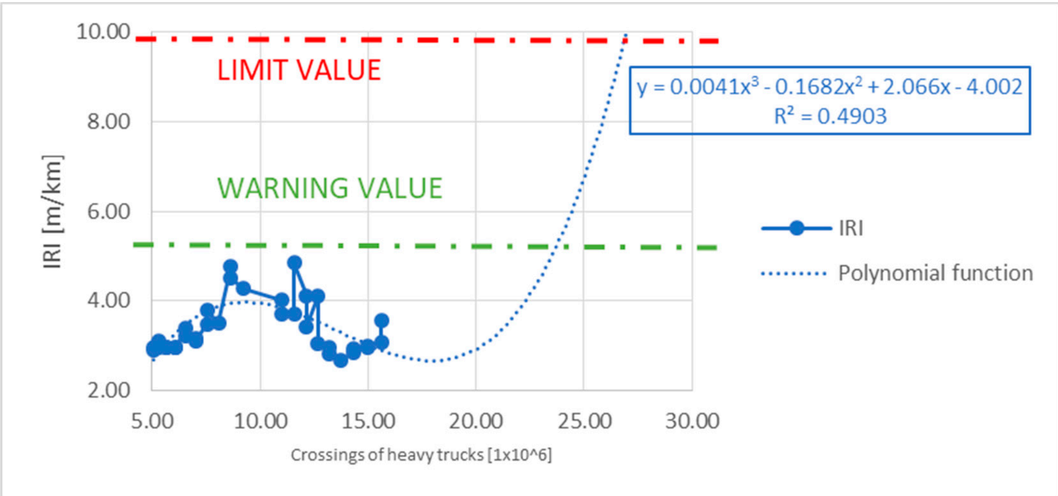


Figure 9. IRI and its probable course.

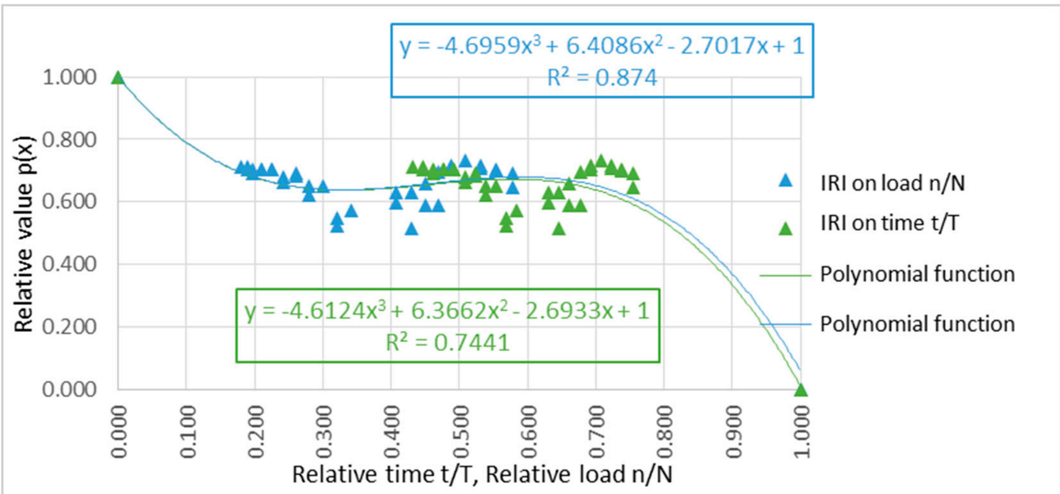


Figure 10. Degradation of the IRI depending on the time t/T and load n/N.

3.3. Results of Road Bearing Capacity

This section expresses the degradation functions for the values of the structural layers modulus of elasticity determined by back-calculation.

3.3.1. Asphalt-Bonded Construction Layers

As a general fact, the modulus of elasticity of asphalt-bonded road construction layers changes under the influence of temperature. The data were therefore divided into three temperature groups. The modulus of elasticity was then calculated for each group by regression analysis.

1. Data group—road temperature 20.01–30.00 °C
2. Data group—road temperature 10.01–20.00 °C
3. Data group—road temperature 5.01–10.00 °C

The most represented temperature group, which covers the whole evaluation period, is group no. 2 with road temperature during measurement 10.01–20.00 °C. The available measured data in this group are the period 1997–2018 and contain 12 representative values. The first temperature group contains only 6 representative values and temperature group no. 3 contains seven representative values. For this reason, data temperature group no. 2 was selected to assess the development of the modulus of elasticity of asphalt-bonded layers in the long-term section. The limit value was determined as 30% of the design value of the modulus of elasticity, i.e., 1650 MPa. Upon reaching this modulus of elasticity, the road is considered unsuitable for road traffic in terms of the modulus of elasticity. The mathematical evaluation of the dependence of the development of the modulus of elasticity recalculated by back-calculation, describes the polynomial dependence of the 3rd degree. To recalculate the modulus of elasticity of the structural layers of the road, a calculation program was used, which works on the principle of creating a model of the road with a layered half-space. The interaction of the layers is simplified and the materials of the layers of the road structure are homogenized. Isotropy and flexibility of the half-space are also considered. The principle of calculation is based on the approximation of the calculated deflection curve to the measured deflection curve at the measuring point until the conditions of the permitted difference between the measured and calculated deflection curve are met. The load on the surface of the model must correspond to the load parameters when measuring the deflection with the FWD deflectometer. The radius of the loading surface of the road model must be equal to the radius of the load plate of the deflectometer. In the experiment, the road section was evaluated as one homogenized unit in the length of 1000 m with 51 evaluated points. After removing the local extremes from the input data, the back modulus of elasticity of the individual structural layers of the three-layer system was recalculated. For deflection curves, the procedure of creating an average deflection curve in one measured year was used. The input data entered (which remain unchanged) are as follows: uniform load; load ring radius; contact in the joints of structural layers; radial coordinates (representing the distance of the sensors from the load axis); vertical coordinates (representing the depth of the structural layers). The input data entered (whose values change in order to monitor the change in the shape of the deflection curve) are the modulus of elasticity of the structural layers; thickness of structural layers and Poisson's ratio. For Figures 11–14 in this section we state that y is modulus of elasticity, x is traffic load (mil. vehicles), $y_{n/N}$ is modulus of elasticity depending on load n/N, where $y_{t/T}$ is modulus of elasticity depending on load t/T and R^2 is determination index.

3.3.2. Road Foundation

The modulus of elasticity of the base layers is not directly affected by the temperature influence during the measurement, as is in the case asphalt-bonded road construction layers. Therefore, it was not necessary to divide the degradation models into three temperature categories. The modulus of elasticity was determined by back-calculation based on traffic load data. Results are presented at Figures 15 and 16.

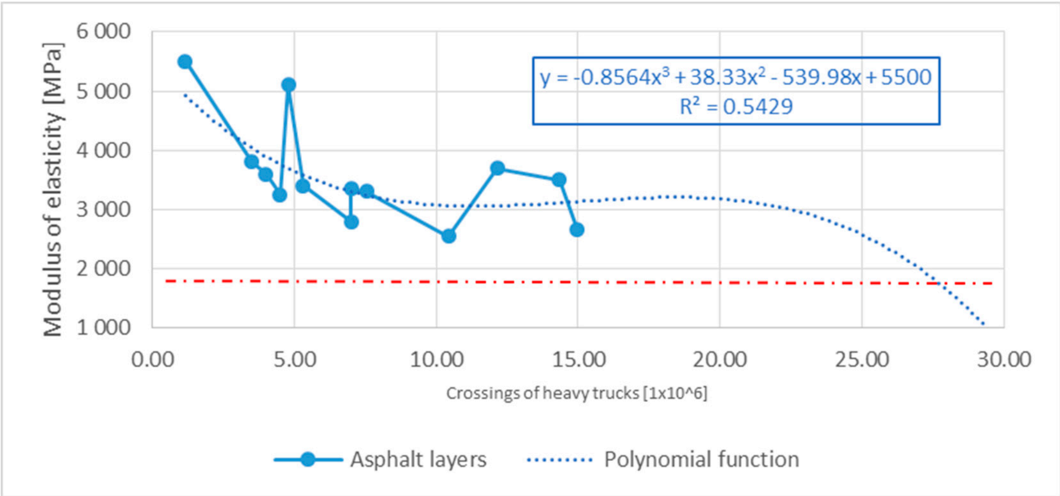


Figure 11. Modulus of elasticity forecast of asphalt-bonded construction layers.

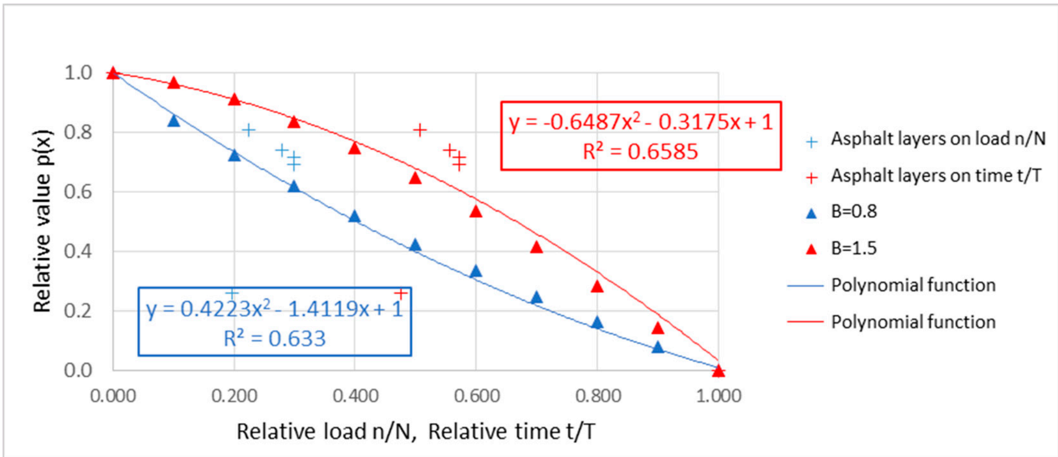


Figure 12. Degradation of the modulus of elasticity depending on the time t/T and load n/N (20.01–30.00 °C).

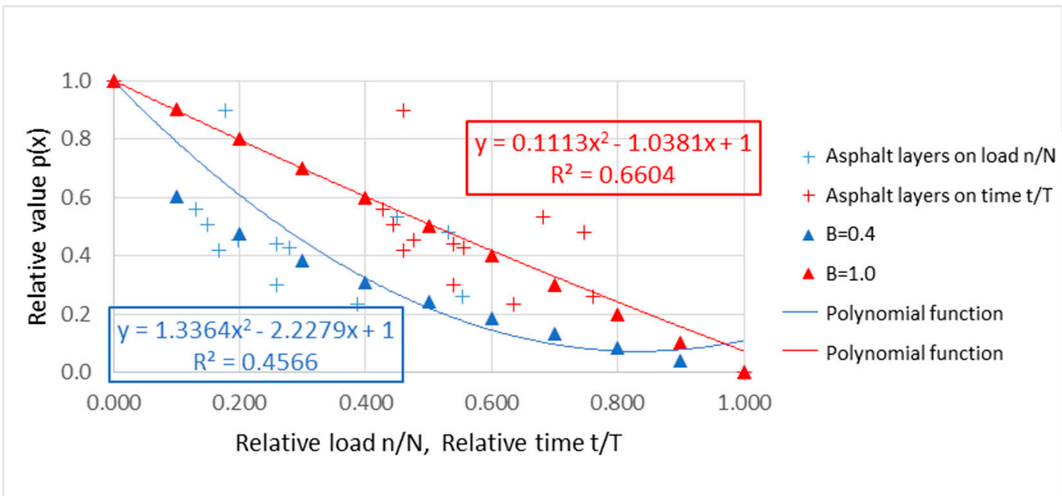


Figure 13. Degradation of the modulus of elasticity depending on the time t/T and load n/N (10.01 –20.00 °C).

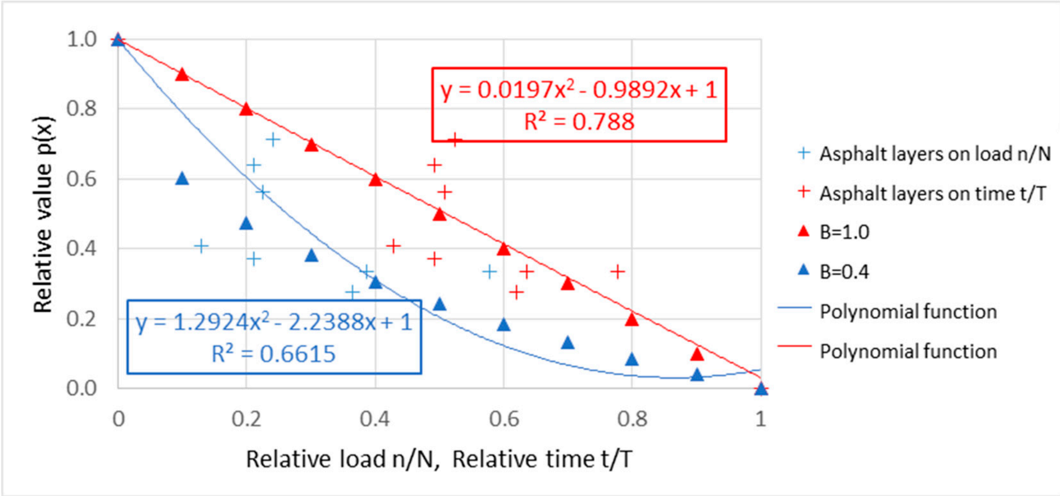


Figure 14. Degradation of the modulus of elasticity depending on the time t/T and load n/N (5.01–10.00 °C).

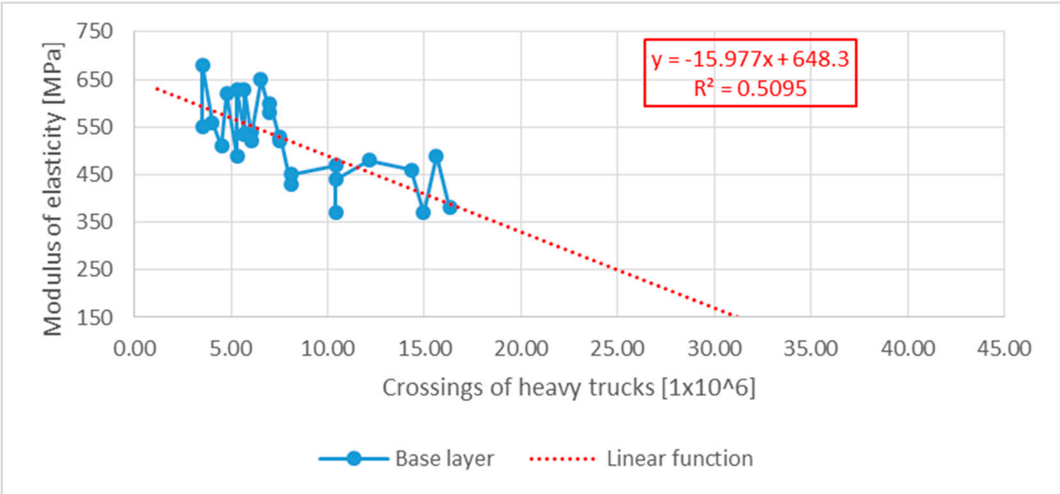


Figure 15. Modulus of elasticity forecast of road foundation.

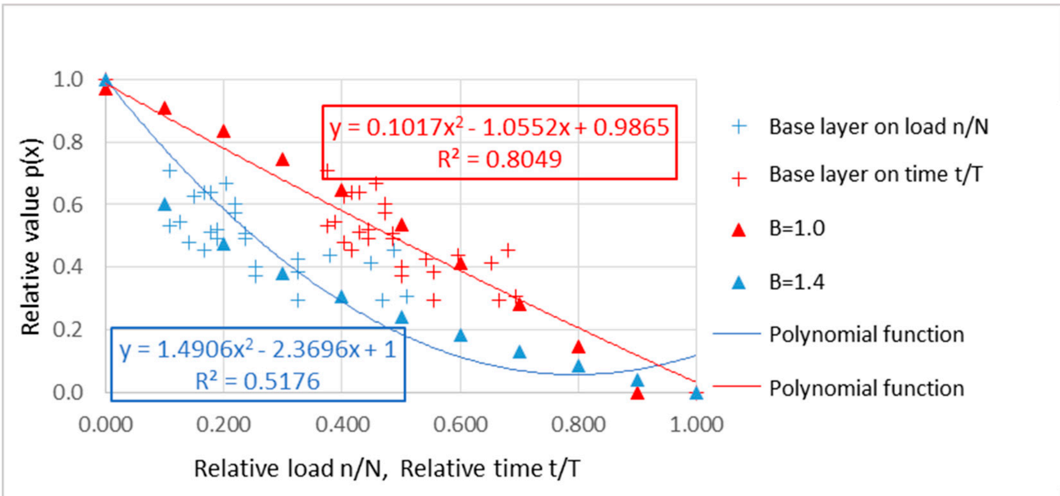


Figure 16. Degradation of the modulus of elasticity depending on the time t/T and load n/N.

3.3.3. Subsoil

Based on the experimental measurements, it is clear that from the traffic load analysis it is not possible to create a degradation model describing the dependence of the development of the modulus of elasticity of the subsoil on the dependence. For this Figure 17 we state that x is traffic load (millions of heavy trucks).

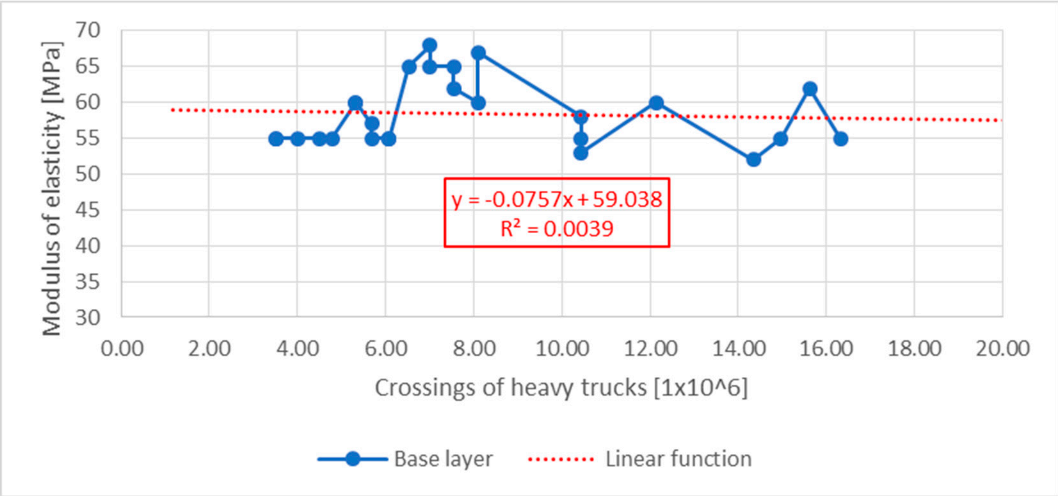


Figure 17. The subsoil Modulus of elasticity course.

3.4. Interpretation of Results and Sensitivity Analysis

In addition to determining the degradation functions, correlation analyzes were also processed in parallel. Their aim was to determine the level of dependence between the obtained data on the quality of the road, the road temperature during the measurement and the traffic load. Subsequently, it was possible to treat these effects in the creation of mathematical functions of degradation.

The result of the analysis confirmed the dependence of the average temperature of the road surface during the measurement on the change of the modulus of elasticity of the asphalt-bonded layers, expressed by the Pearson coefficient with the value up to $r \doteq 0.808$. The dependence between the base layers and the average road surface temperature is $r \doteq -0.370$ and the correlation between the road surface and the average road surface temperature is $r \doteq 0.250$. The correlation analysis for asphalt-bonded structural layers was also influenced by the performance of road maintenance. For this reason, the observed period was divided into three categories, while the correlation coefficients are as follows—the period before maintenance -0.79, the period between maintenance -0.83 and the period after maintenance -0.86.

The processing of the dependence between the modulus of elasticity of the individual structural layers and the traffic load showed the following results. An overview of approaches for evaluating the quality of roads and their parameters for the underlying layers is $r \doteq -0.71$, which means a strong dependence. No dependence was found between the development of the subsoil elasticity modulus and the traffic load. When assessing the dependence between the development of the modulus of elasticity of asphalt-bonded layers and the traffic load, the bond was again evaluated with a division into periods according to the performance of construction maintenance. At the same time, the effect of temperature was applied here. In all cases, strong dependence was confirmed. In the following Table 3 it is possible to see the degree of dependence between the increase of the rut or IRI and the decrease of the load-bearing capacity of the structural layers of the road.

Table 3. Overview of Pearson coefficient for the road construction layers.

	Road Foundation	Subsoil	Asphalt-Bonded Construction Layers *		
			20.01–30.00 °C	10.01–20.00 °C	5.01–10.00 °C
Rut (left)	r = −0.73	r = −0.31	r = −0.77	r = −0.43	r = −0.73
Rut (right)	r = −0.54	r = −0.38	r = −0.88	r = −0.58	r = −0.22
IRI	r = −0.70	r = −0.21	r = −0.73	r = −0.70	r = −0.70

* Divided by surface temperature during measurement.

From the point of view of correlation evaluation, it can be stated that there is a medium to strong dependence between rut and the modulus of elasticity of the base layers. There is a medium dependence between rut and the modulus of elasticity of the substrate, there is a strong dependence between IRI and the modulus of elasticity of the subsoil.

At the same time, it was shown that there is a medium to strong dependence between the rut and the decrease in the load-bearing capacity of the asphalt-bonded structural layers. There is a strong relationship between the IRI and the decrease in the load-bearing capacity of asphalt-bonded structural layers.

4. Discussion and Conclusions

This paper presents the results associated with the creation of degradation functions of the 1st class road in Slovakia in the section between the villages Porúbka and Poluvsie. Approaches of non-destructive data collection for a period of 20 years were used in the work, in combination with mathematical modeling and application of the results of sensitivity analysis using a simple Pearson's coefficient. The result is the creation of highly sought-after road degradation functions. These are expressed by polynomial functions of at least the third degree, as they best express the dependences between the traffic load and the development of longitudinal and transverse inequalities. At the same time, the measurements confirm the conjecture that the right wheel path (within one direction) deforms faster. On the measured section of the road, the difference between the values of deformations in places was up to 38% more. This is mainly due to the insufficient width of the road, despite its importance. The vehicles are forced to drive close to the curb, which creates a higher surface tension in the right part of the road in the right wheel path. This also causes earlier damage to the curb and subsequent cracks due to water seepage into the lower layers of the road. The study also verified the assumptions associated with the effect of temperature and traffic load on the values of rut, IRI and road load capacity. The biggest impact is on the top layer of the road. Mathematical performance models have not yet been validated in detail with degradation models by other researchers. However, the author team initiated several new activities with its partners, which could unify the boundary conditions for data collection. This would ensure that there are not too many gaps when comparing the same road design. Subsequent work will have the character of application of the identified degradation functions to other long-term monitored sections of roads with the same design properties to bring verification of mathematical modeling. Among the new ideas that emerged during the study, it is possible to include the continuation of measurements, but under improved technical conditions. This means that the tests are carried out in such a way that climatic similarity is observed, measurements at different seasons and, in particular, measurements at the same places on the road. At the same time, it is appropriate to focus on the application of new technological tools in the form of sensors that could simplify and improve the entire data collection process.

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