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Integrating Tensometer Measurements, Elastic Half-Space Modeling, and Long-Term Pavement Performance Data into a Mechanistic–Empirical Pavement Performance Model

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Abstract: Pavement performance models (PPMs) are utilized to predict pavement network conditions which is an essential part of any sustainable pavement management system (PMS). The reliability of a PMS and its outputs is proportional to the reliability of the PPM used. This article describes a mechanistic–empirical pavement performance model based on pavement response parameters—strains calculated in the pavement layers measured by tensometers embedded in the pavement surface and verified by calculations in the elastic half-space model and supplemented by empirical data from long-term pavement performance monitoring and accelerated pavement testing. Hence, the herein described PPM combines pavement serviceability evaluation, pavement bearing capacity, and the physico-mechanistic properties of paving materials. The analytical methods which were used to ascertain the physico-mechanistic characteristics, the material fatigue degradation model, and the surface degradation, unevenness in particular, are described. A comparison of the empirical PPM created in the last century used by the national road administrator to this day and the newly created PPM is presented. The comparison shows the difference in the calculated socio-economic benefits and subsequent cost–benefit analysis results. The comparison shows that the use of the old PPM may have produced false economic evaluation results that have led to poor decision making, partially explaining the unsustainable trend of road network management in our country.

Keywords: pavement performance; pavement structure; APT testing; pavement modeling

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1. Introduction

The performance of the road pavement and the effects of maintenance are important parameters of the cost of road transport [1]. The performance of the road pavement is directly influenced by its deterioration. Road deterioration occurs as a result of traffic loading and environmental/climatic effects. The fatigue of the paving material manifests itself as fatigue cracks on the bottom of the bound layers due to repeated strain. Other defects such as evenness loss, skid resistance, raveling, surface material displacement, etc., occur as a result of climatic conditions combined with traffic load and a loss of binder quality and aggregate abrasion. The capacity of the pavement structure to withstand these adverse effects is defined as pavement performance. A pavement performance model (PPM) [2] serves as a mathematical description of the road deterioration process and is a crucial input for decision making [3,4], commonly known as a pavement degradation model (PDM). PMSs are utilized to optimize pavement maintenance and rehabilitation (M&R) strategies, including M&R timing and technologies, derived from optimal life cycle management, resulting in reduced costs for road administrators and road users.

Deterministic degradation models represent the prediction of pavement condition as a reliable value that is derived from mathematical functions based on measured data.

These models are the most commonly used method for modeling pavement degradation. The mathematical function of these models expresses the relationship between the independent variables and a parameter that characterizes the serviceability of the pavement. These mathematical models represent the prediction of the deterioration of the parameter of interest [5–7]. Deterministic PPMs can be classified as mechanistic, empirical, and mechanistic–empirical [8].

Mechanistic models are based on the knowledge of the state of stress in the different layers of the pavement structure. The stress state is monitored at different load levels and the individual degradation function models take into account the radial stresses in the bound layers or the deformations in the individual pavement layers. The given models can be verified by incorporating strain gauges in the pavement structure, or they can be formed by a computational model based on response theory, such as the finite element method [9,10].

Empirical models are based on statistical regression analyses of long-term monitored LTPPM pavement sections or APT, on which serviceability variables are continuously evaluated. Empirical degradation models represent a suitable alternative for evaluating a group of individual constructs in a broader context, and it is thus possible to use statistical evaluation of the parameter in a relative definition such as flexible pavements, motorway pavements, arid-climate pavements, etc. [11,12].

Mechanistic–empirical models combine the pavement response to stress and strain in individual pavement layers with the rheological and fatigue properties of materials used in the pavement layers with empirical data from APT and LTPPM. The performance is given by the residual service life calculated from pavement capacity calculations, e.g., elastic half-space calculations, while the serviceability parameters are determined by the degradation function from the empirical measurements [13,14].

Analytical calculations and laboratory measurements are utilized to determine the fatigue parameters and physico-mechanical properties of asphalt materials, i.e., properties that describe how a material behaves under various physical and mechanical conditions. These properties are crucial for understanding the performance of materials in terms of their suitability for application in the pavement structure.

Service life calculation, specifically residual service life, is based on these measurements and analytical calculations using a layered elastic half-space model [15]. The layered elastic half-space model defines stress and deformation in the pavement structure by considering the strength characteristics of the pavement layers and underlying sub-layers. The crucial parameter for calculating the pavement's structural life is the fatigue characteristics of asphalt surface materials. Due to variations in asphalt type, aggregate, additives, and their ratios, the fatigue properties must be determined experimentally. The dynamic modulus (absolute value of complex modulus) method [16] is presented and recommended for this task, as concluded in previous research efforts [17–19].

From a pavement life perspective, economic assessment is required in the planning phase, the pre-design and design phases, and the in-operation phase as part of the decision-making processes of the pavement management system. In all cases, life cycle analysis (LCA), life cycle cost analysis (LCCA), and cost–benefit analysis (CBA) of the pavement are considered.

A cost–benefit analysis is a systematic and quantitative approach used to assess the economic efficiency of a project by comparing the life cycle costs of a road in its current and desired condition. In the context of pavement management, a cost–benefit analysis helps the decision-making process to evaluate and compare different project alternatives and options and to prioritize projects based on their expected economic returns; this approach is called prioritization. More advanced optimization methods are described in [20,21]. Both the herein described and derived polynomial mechanistic–empirical pavement deterioration model and an older exponential empirical pavement deterioration model were used in the LCA and the LCCA to calculate road user costs for both "do nothing" and "do something" scenarios for both PPMs.

The user costs form the socio-economic context of the construction; these costs are not directly translated into the budget of the public management organization, the state budget, or the profit and loss account of the private entity. Nevertheless, in transport construction, they constitute the majority of construction costs. These are primarily costs to users of the road network. These costs are higher when using a road of a lower technical level, i.e., when driving on a damaged carriageway. Here, the impact of both PPMs can be observed as both evaluated PPMs produce different road user costs during the pavement life. The comparison of the LCCA for both scenarios and both PPMs produces the CBA results, i.e., economic efficiency indicators to assess the impact on road administrator's decision making in pavement management operations.

2. Materials and Methods

The following materials and methods were used for the derivation of the experimental pavement performance models:

- The determination of material characteristics of APT pavement structure and related structure service life.
- The incorporation and evaluation of data obtained from sensors placed in the pavement of APT construction.
- An analysis of data obtained from APT testing and long-term pavement performance modeling of long-term monitoring pavement sections.
- Cost–benefit analysis for decision making based on an absolute PPM.

2.1. Experimental Pavement Model

A reliable PMS needs to provide the road administrator with an optimal repair plan for their road network. This plan identifies the optimal time and rehabilitation method for individual road sections. Road sections are constituent elements of the road network, which themselves need to have individual repair plans optimized through a cost–benefit analysis (CBA). A CBA is used to find the optimal time and repair technology, with two pre-requisites:

- Fatigue parameters of asphalt layers.
- Service life, i.e., residual service life.

Pavement structure evaluation aims to provide data regarding the residual service life of a particular pavement and the required overlay thickness. Under in situ conditions, the measurements are usually performed using a falling weight deflectometer or traffic speed deflectometer [22], which create a temporary deflection measured by a series of velocity transducer sensors. This deflection bowl is then used in analytical calculations in the layered elastic half-space model [23].

The layered elastic half-space model, shown in Figure 1, can be described as a layered elastic body with an infinite lateral extent and depth with loads applied to its horizontal plane surface. Being elastic and orthorhombic, the material has three mutually perpendicular planes of elastic symmetry. The normals to these planes are assumed to be parallel to the vertical, lateral, and longitudinal directions associated with the load.

In the presented case study, a common flexible pavement is used as a trunk road with an average traffic load for such pavement. The wearing course and base course are made from asphalt concrete AC 11 W and AC 16 B, respectively, with parameters stipulated by national technical standards. The sub-base is a mechanically bound aggregate, and the sub-grade is a compressed gravel layer. The earthworks are simulated by a layer of panels made from molded rubber granulate bonded with polyurethane which is laid on top of a concrete slab. The equivalent modulus of this setup equals the modulus of well-compressed sub-soil [24–26]. The pavement was designed according to the standard dimensioning methodology [27]. The designed life expectancy is 2×10^6 design axle loads. The entire pavement section was constructed in the laboratories of the Department of Construction

Management at the University of Zilina. The cross-section of the pavement test section is shown in Figure 2.

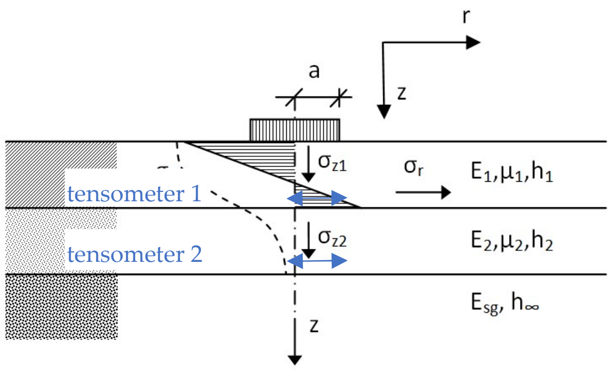

Figure 1. The layered elastic half-space model of bitumen layers with tensometer locations.

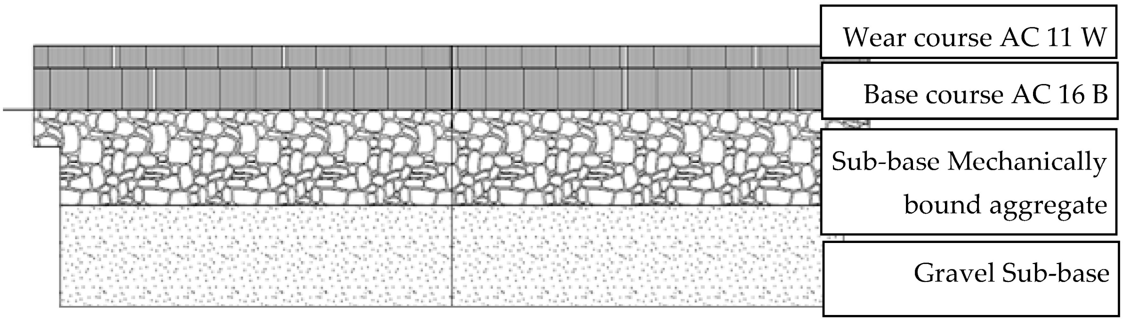

Figure 2. Pavement structure cross-section of experimental pavement test section: trunk road with flexible pavement and service life of 2×10^6 design axle loads.

Pavement structure layers are designed from generic materials defined by national standards. Table 1 contains the material characteristics ascertained from the initial physical measurements of the surface materials.

Table 1. APT pavement material characteristics according to [18,28].

Layer	Dynamic Modulus	Poisson's Ratio	Layer Thickness
AC 11 W [1]	10,900	0.33	40 mm
AC 16 B [2]	8300	0.33	80 mm
MBA [3]	590	0.30	180 mm
Gravel sub-base	360	0.30	200 mm
Sub-grade	100	0.35	-

[1] AC W is wearing course bitumen layer; [2] AC B is base course bitumen layer; [3] MBA is mechanically bound aggregate.

The dynamic modulus of AC11 W and AC16 B was ascertained by a two-point bending test at temperatures of +15 °C and a frequency of 10 Hz. The complete test results of the complex modulus for the critical layer at which the fatigue crack initiates are shown in Figure 3, i.e., the measurements at temperatures ranging from 0 °C to 27 °C and frequencies from 1 to 20 Hz.

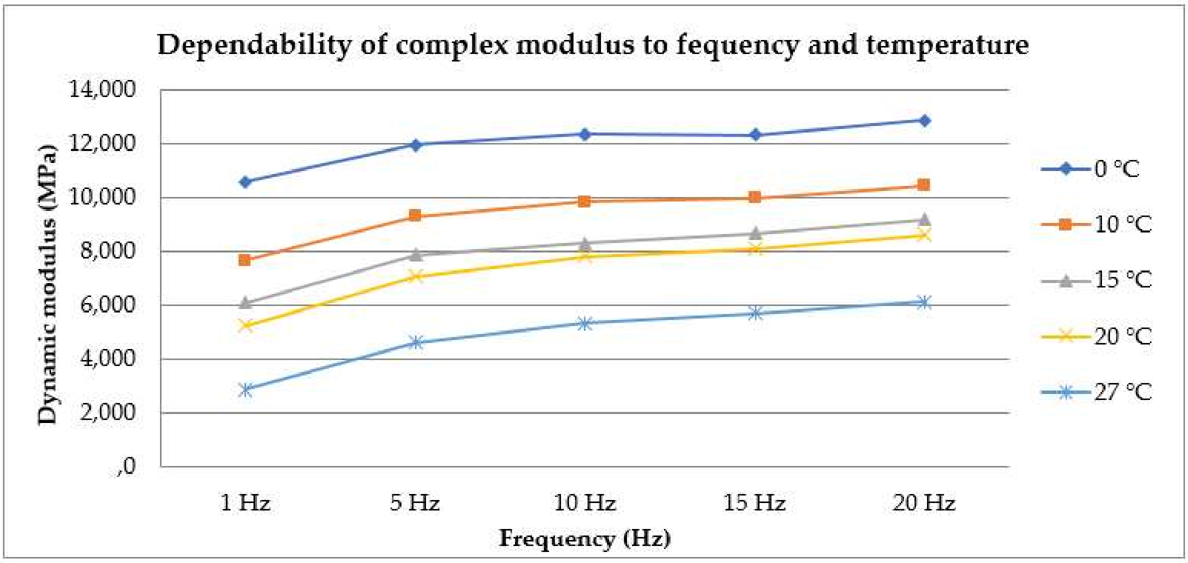

Figure 3. Dependency of dynamic modulus (E) on frequency (F) for temperatures ranging from −10 °C to +27 °C.

2.2. Fatigue Parameters of Asphalt Layers

Fatigue characteristics are utilized in assessing pavement resilience against repeated loading and serve as an input for calculating the residual service life of the pavement construction. We followed the methods outlined by [29]. The input for this calculation involves determining the stress levels to which the material is subjected during the fatigue test. In accordance with the European standard [30], fatigue must be defined through linear regression, typically represented by a logarithmic function:

$$logN = a + \left(\frac{1}{b}\right)\log\varepsilon \quad (1)$$

where ε is the maximum amplitude during the fatigue test [30], a is an intercept of the fatigue line, and $1/b$ is the slope parameter related to the fatigue line. N is the number of load repetitions when the dynamic modulus reaches 50% of its initial value during the fatigue test.

The characteristics of fatigue in Equation (1) are for the average size of deformation derived from fatigue lines, which are in turn derived after 10^6 loading cycles in microstrains (μm/m):

$$log\left(\varepsilon_6/10^6\right) = a_j + 6b \quad (2)$$

where a and b are fatigue parameters and ε_6 is the average deformation derived from the fatigue curve after 10^6 loading cycles in microstrains (μm/m).

The number of loads corresponding to the initial deformation in the test sample under specified conditions can be ascertained as follows:

$$N = 10^6\ (\varepsilon_6/\varepsilon_0)^B \quad (3)$$

$$B = -1/b \quad (4)$$

where B is the fatigue characteristics in the range from 3 to 10.

Fatigue must be defined through linear regression, typically represented by a logarithmic function. This function must be based on results that represent the length of fatigue life (N) for ε chosen through the linear regression between the value of log N and the value of log ε—known as Wöhler's diagram. Figure 4 and Table 2 show the required outputs for the residual service life calculation [31].

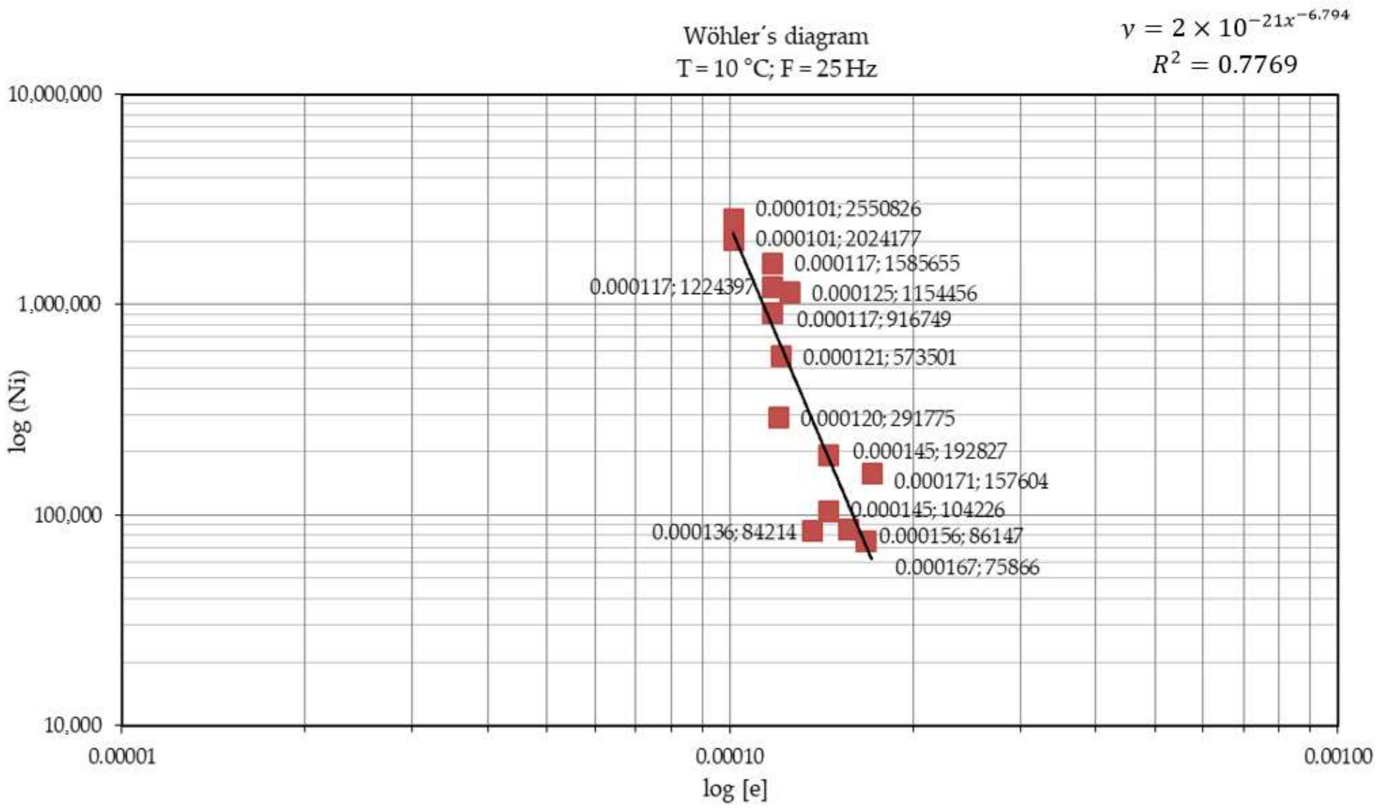

Figure 4. Wöhler's diagram of experimental pavement test section—layer AC16 B.

Table 2. Experimental pavement test section in line with [30,32].

Mixture	Fatigue of Asphalt Mixture (for a Temperature of +10 °C and 25 Hz Frequency)					Tensile Strength
	Fatigue Coefficients			Microstrain		
	a_o	a_1	b	$\varepsilon_6 \times 10^{-6}$	$\varepsilon_0 \times 10^{-6}$	R (MPa)
ACW 11	−13.70	−4.86	−0.21	87.45	117.76	3.2
ACB 16	−20.79	−6.79	−0.15	85.61	113.43	2.4

2.3. The Pavement Structure's Service Life

Pavement structure service life is ascertained through a calculation method for designing the pavement structure [31]. This method assigns a structural value to the surface layers, expressed by comparing the calculated radial stress at the bottom of the considered layer with the strength of the same layer. This strength, subject to repeated loading, is reduced by a fatigue characteristic factor *SN*, as shown in Equation (5):

$$SV \geq \sum_j q_j \frac{\sigma_{rij}}{S_{Ni} \times R_{ij}} \tag{5}$$

where SV is the structural value, σ_{rij} is the radial stress of the critical layer, R_{ij} is the strength of the critical layer material, S_{Ni} is fatigue characteristic factor, q_j is the relative period, and 'j' corresponds to the stress conditions of the structure, assumed to be 0.2 for winter, 0.3 for summer, and 0.5 for spring and autumn.

The radial stress in the surface layers is calculated based on the thickness of the layers, the dynamic modulus, and Poisson's ratio using the layered elastic half-space model described in the previous chapter. The radial stress, σ_{ri}, is influenced by material fatigue caused by repeated loading, which, in the calculation, is expressed as design axle load, i.e., the axle acting on the pavement surface with a force of 2P = 100 kN. The climatic conditions influence material properties; low temperatures make the material brittle and more prone to cracking, while higher temperatures soften the material, making it more prone to plastic deformations. Therefore, winter, summer, and spring/autumn periods are considered, during which the resiliency and elastic modulus change. In our case, the modeling of the pavement construction behavior occurs under constant conditions persisting in the laboratory where the experimental pavement section is built. These conditions constitute medium conditions, i.e., constant temperature above +10 °C.

$$S_{Ni} = 1.0 - 0.11 * logNi_I \tag{6}$$

Finally, the service life of the pavement structure can be calculated by Equation (7), which is created by integrating Equation (6) into Equation (5), where SV = 1.0, i.e., 100% utilization of the structural value:

$$logN_i = \frac{R_i - \sigma_{ri}}{0.11 * R_i} \tag{7}$$

where N_i is the residual service life of layer "i" in standard axle load (SAL); σ_{ri} is the calculated radial stress on the bottom edge of the critical pavement bounded layer "i" in MPa.

2.4. Accelerated Pavement Testing

The general principle of APT is the simulation of real-life traffic loading on real-life pavements in a relatively short period. A linear APT facility was constructed due to its low cost and short implementation time. We followed the methods described in [17,18]. This solution is relatively cost-efficient, is easy to build, and can be disassembled and transported. The main parameters of the device described in [33] are listed in Table 3. Figure 5 shows the visualization and main components, while Figure 6 shows the facility itself.

Table 3. APT facility parameters.

Dimensions	
Length	9042 mm
Width	5178 mm
Width with open doors	2452 mm
Height	2452 mm
Technical Parameters	
Construction	Semi-mobile, linear
Type	105-03-01
Maximum velocity	2.22 ms^{-1}
Load	57.5 kN
Maximum acceleration	2 $m.s^{-2}$
Maximum deceleration	5 $m.s^{-2}$
Location	Indoor
Operational temperature	10–40 °C
Operational humidity	30–80% without condensation
Engine power	45 kW
Transition	CLP HC VG 320, MOBIL SHC GEAR 320
Energy requirements	3+N+PE, AC, 50 Hz, 230/400, V, TN-S
Operational temperature	10–40 °C
Engine power	45 kW
Transition	CLP HC VG 320, MOBIL SHC GEAR 320
Energy requirements	3+N+PE, AC, 50 Hz, 230/400, V, TN-S

APT can be substituted or supplemented by long-term pavement performance monitoring [34,35] on existing roads; however, this approach has several weaknesses:

- It is time-consuming.
- Traffic loading is only estimated from traffic surveys.
- Data collection is problematic.

The APT concept addresses these flaws. Data are collected at set traffic load intervals for longitudinal and transversal unevenness, cracking, skid resistance, texture, etc. The sensors are embedded in pavement layers to enhance the PPM by directly measuring strains in the surface, usually calculated only through the layered elastic half-space calculation.

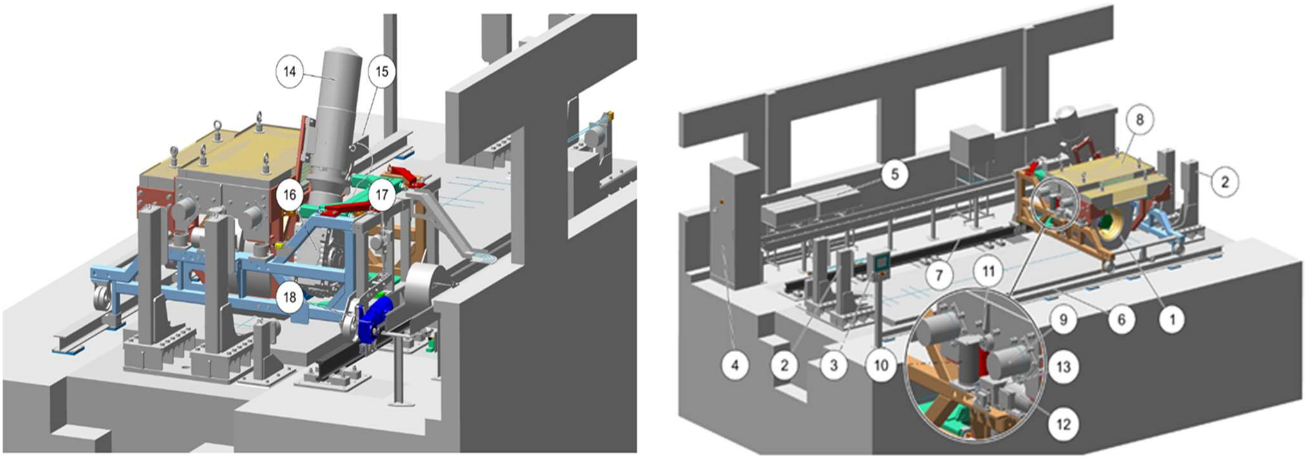

Figure 5. APT facility—construction. 1: Wheels, 2: buffers, 3: control panel, 4: fuselage box, 5: brake heat exchangers, 6: supporting rail, 7: guiding rail, 8: load, 9: rubber buffers, 10: hydraulic liquid container, 11: hydraulic systems, 12: motor for lifting of loading unit, 13: gear box for lifting of loading unit, 14: main electromotor, 15: container for gear box oil, 16: gear box, 17: electromotor for lifting of loading unit, and 18: loading unit [33,36].

Figure 6. APT facility—operational phase.

Collected pavement parameters are mainly used to forecast appropriate rehabilitation technology for the pavement's future. Longitudinal unevenness usually represents the overall ride quality on a given road section and, as such, is used to calculate travel time costs and vehicle operating costs.

Various methods can be employed to collect pavement data [37,38]. For longitudinal and transversal unevenness, we recommend using laser scanning, as shown in Figure 7. This technology usually entails high initial procurement costs, but the results are reliable, easy to collect, and easy to interpret. Handheld 3D laser scanners, such as the ZScanner 800 manufactured in United States by Z Corporation, create a dense point mesh of the scanned surface that can be exported in various formats: DAE, OBJ, FBX, PLY, MA, STL, WRL, ZPR, TXT, and X3D. These formats are subsequently transformed in software such as VX elements into solid surface scans and can be further evaluated [39].

Figure 7. Recommended data collection of transversal and longitudinal unevenness.

2.5. Regression Analysis

To effectively determine the timing for rehabilitation and to select appropriate rehabilitation strategies within the pavement management system, it is essential to consider the loss of pavement performance. Performing rehabilitation prematurely often proves inefficient, while postponing it may result in a decline in the operational functionality of the pavement [2,40].

Absolute pavement performance models are usually in the form of mathematical equations that show the dependable variable, i.e., the degradation of a particular pavement parameter related to time or load cycles. Utilizing accelerated pavement testing, alongside ongoing performance monitoring, is a reliable method for deriving these equations.

Creating an absolute PPM from the collected data is achieved using regression analysis. First, each measurement surface needs to be evaluated for the parameter for which the PPM is to be made. This is shown in Figure 8. Once the parameter value is known, it composes an ordinate for the corresponding loading volume at the time of measurement.

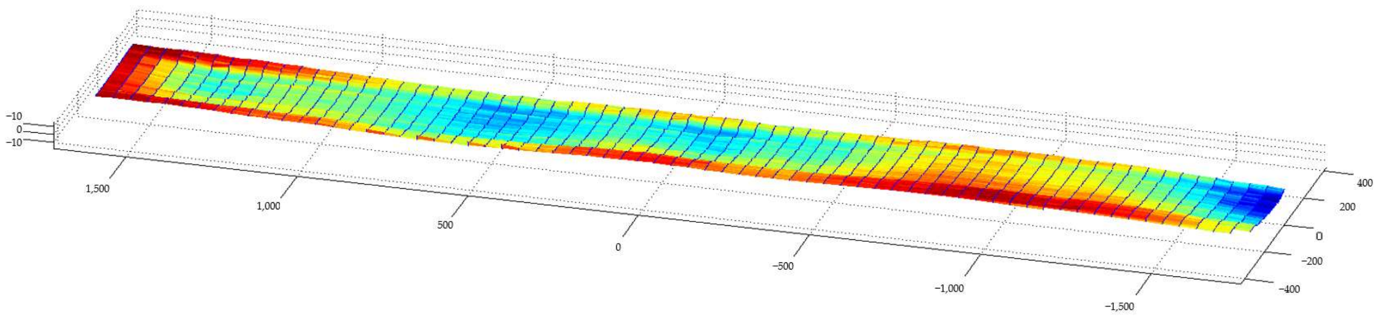

Figure 8. Evaluation of scanned longitudinal unevenness.

Absolute PPMs can therefore be derived from periodic measurements of existing pavements according to Equation (8). The parameter value may be relative to time, t/T, or traffic load.

$$p(x) = 1 - \left(\frac{t}{T}\right)^{B} \tag{8}$$

where $p(x)$ is the parameter value where $x = t$; T is life cycle duration in years; B is the coefficient in exponential functions which indicates the convex or concave shape of the curve; and T is the time ordinate.

The downside of this simple solution is that the exponential function might not accurately represent the actual deterioration, and true degradation is forcibly approximated by regression analysis into the exponential shape. Absolute PPMs will use a polynomial function which better describes the deterioration process. The advantage is that this function describes initiation, progression, and failure in more detail. The difference between PPMs expressed as an exponential function and a polynomial function is shown in Figure 9.

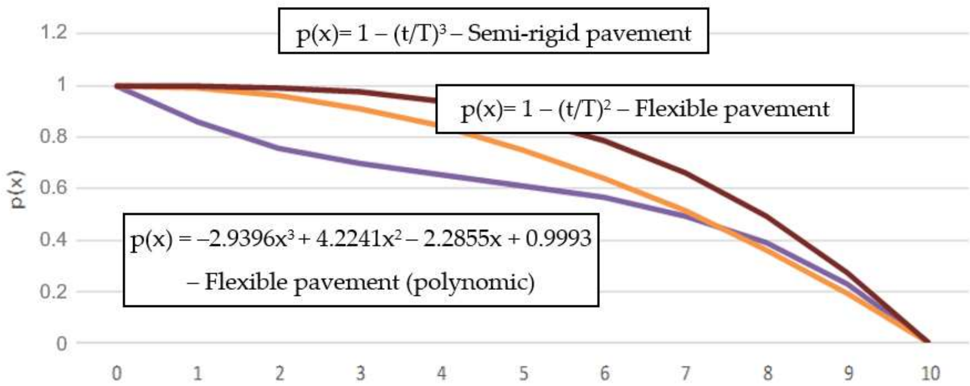

Figure 9. Longitudinal unevenness PPM—exponential and polynomial.

2.6. Cost–Benefit Analysis: Decision Making Based on Absolute PPMs

Structure service life calculations and analytically derived performance models are the basis for optimal decision making when creating pavement rehabilitation plans, which are based on the results of a cost–benefit analysis [41].

Three economic indicators, namely, the payback period, internal rate of return, and net present value, are employed to assess the economic feasibility of each rehabilitation scenario. It is essential to monetize socio-economic costs and benefits associated with pavement surface rehabilitation to determine these indicators accurately. The benefits are linked to the disparity in pavement surface quality and its degradation between scenarios with and without rehabilitation. These benefits encompass both internal, i.e., user-related, and external benefits [42]. For this case study, internal benefits such as road user operation costs and travel time costs were utilized, as they can be quantified using the methodology endorsed by the World Bank. External benefits, including environmental savings and broader economic impacts, were excluded due to the subjectivity associated with available monetization techniques, as deemed by road administration authorities. The overall road user benefits considering factors like proposed rehabilitation technology, investment costs, road administrator expenses, rehabilitation timing, and discount rate can be computed using Equation (9).

$$RUB = \sum_{t=1}^{z} [(RUC_{DS} - RUC_{DN}) \cdot k_{DEG} \cdot k_{ATG}]_t \tag{9}$$

where *RUB* is road user benefits in (EUR); *RUCDS* is road user costs in the “do something” variant in (EUR); *RUCDN* is road user costs in the “do nothing” variant in (EUR); *kDEG* is the coefficient of unevenness degradation function; and *kATG* is the annual transportation growth coefficient.

The degradation coefficient *kDEG* significantly influences the economic results on the basis of which decisions will be made. The value of the coefficient represents the $p(x)$ value of longitudinal unevenness in particular years described in Section 3.2, and the value is derived from either an exponential or, preferably, polynomic function.

3. Results

The results encompass the values of the voltages measured on the individual strain gauges and the overall waveform of the voltages during the device's operation. Additionally, the outcome includes the degradation function of the pavement structure under consideration, on which the APT device is applied. Another result consists of the CBA of the various types of degradation functions derived using the procedure described in the previous section.

3.1. Evaluation of Longitudinal Strains of the Bottom Edge of Base Course

The sensors are plugged into the National Instruments' PXI platform, part of Emerson's new test and measurement business group. The data are processed in NI DIAdem software created by National Instruments, USA.

The PXI platform, shown in Figure 10, is designed for research and development, laboratory use, as well as production and test operations. The PXI platform offers more powerful modular instrumentation and additional synchronization. It includes the control computer itself, with applications providing sensing, analysis, evaluation, and data storage. The solution consists of one NI PXI-1078 manufactured by National Instruments, USA, 8-slot chassis with NI PXIe-8101 and modular instrumentation: 4 modules for dynamic load measurement (strain gauging)—totaling 32 channels, 1 module for temperature measurement (8 channels), 1 module for vibration measurement (4 channels), and 1 module for humidity measurement (via RS485, 8 channels) are evaluated.

Figure 10. NI PXI platform, National Instruments, USA.

DIAdem software, used as a customized application for the APT device, provides simultaneous sensing of all channels from all sensors, real-time data display (colored, scalable graphs), ratio analysis, and data storage in a database or files. A custom architecture has been developed in LabVIEW software to work with the measured data, see Figure 11, the tensometer raw data are in the Supplementary Files.

The maximal values of radial stress of the wearing course and base course (as a critical layer) are shown in Table 4. The stress values are listed at various stages of the life cycle depending on the number of loads or expected years of the life cycle. The evaluated sensors (tensometers) are embedded in the pavement body, placed perpendicularly to the loading axis, recording the radial real elongations (με) of the tensometers caused by the loading. Evaluated radial stress represents the maximal stress increase (the difference between the sensor without and with the load application), which was subsequently recalculated using Hooke's Law into radial stress in MPa.

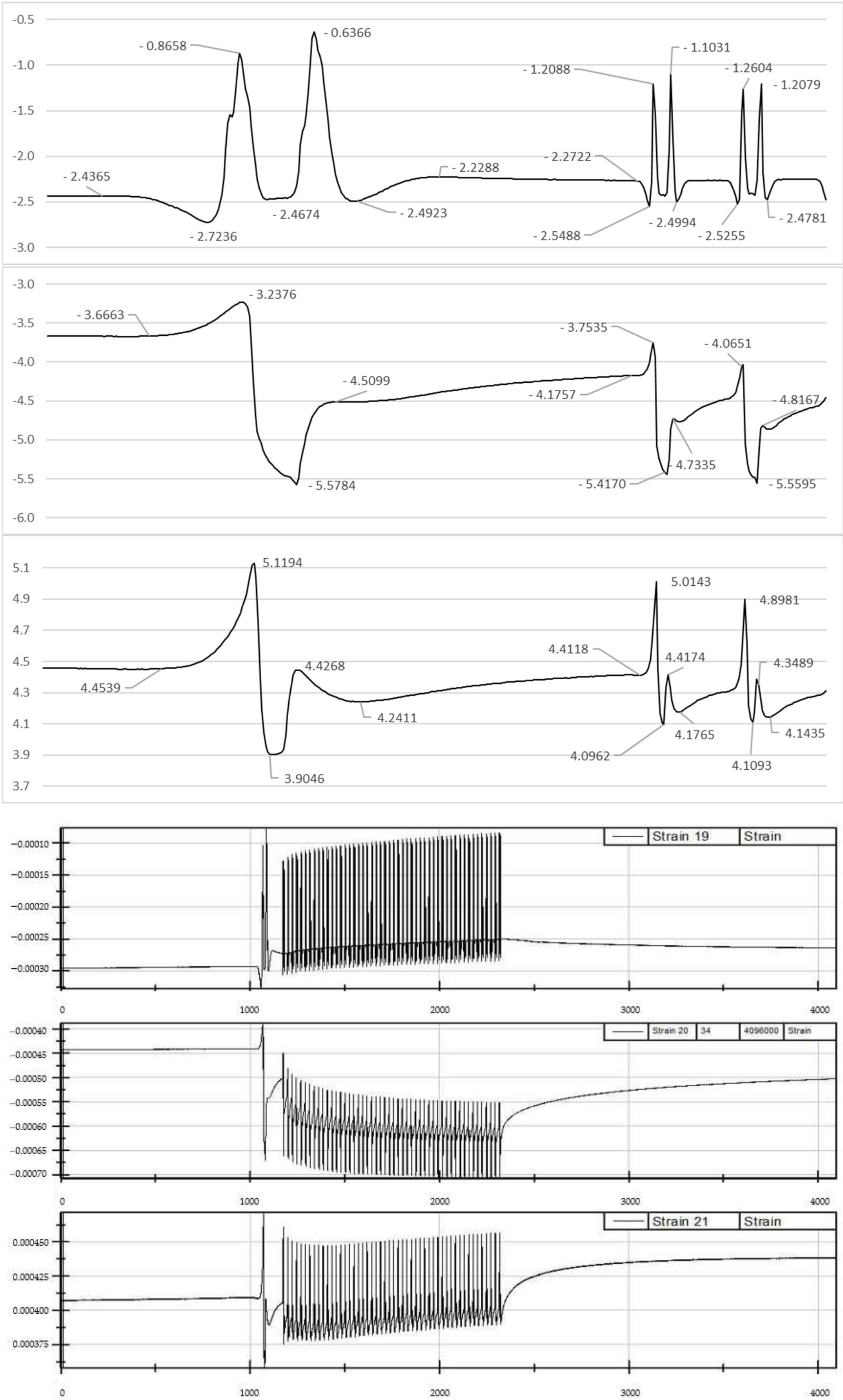

Figure 11. Radial stress values evaluated from NI PXI data (microstrains).

Table 4. Radial stress and strength resilience values in surface layers based on Ni.

Year	Strain Increase (Mpa) of Wearing Course	Strain Increase (Mpa) of Base Course
1	0.4427	0.6243
2	0.4702	0.6733
3	0.4977	0.7223
4	0.5252	0.7713
5	0.5527	0.8203
6	0.5802	0.8693
7	0.6077	0.9183
8	0.6352	0.9673
9	0.6627	1.0163
10	0.6902	1.0653
11	0.7177	1.1143
12	0.7452	1.1633
13	0.7727	1.2123
14	0.8002	1.2613
15	0.8277	1.3103
16	0.8552	1.3593
17	0.8827	1.4083
18	0.9102	1.4573
19	0.9377	1.5063
20	0.9652	1.5553

When the selected pavement construction is calculated using the elastic half-space method, the maximal value of the calculated stress for the critical base course layer is 0.678132 MPa, which, when compared with the measured stress determined by the tensometers installed in the given layer in the first year of operation (Table 4), represents an 8% difference compared to the maximum value recorded in the given sensor. When the calculated stress is evaluated using Equation (7), we obtain a residual service life of 3.5×10^6 SAL.

The pavement structure's service life, expressed by the utilization of structural values according to Equation (9), is shown in Figure 4. Based on calculations, we can conclude that the life cycle of the surface in the testing pavement section is 3.5 million design axle loads. In this case, the annual traffic load will be a maximum. of 175,000 design axle loads, which equals a life expectancy of 20 years.

3.2. Creation of RUT Deterioration Function

The other parameter evaluated during the operation of the APT facility was the RUT resistance. In the first pre-operative stage, the pavement surface was measured via total station and ZScanner and a point cloud of the pavement surface was created. Then, two average sections in the middle of the APT track were selected for cyclic monitoring and evaluation. The profiles were selected in sections where the loading unit moved at a constant speed. The results of the RUT progress in relation to the DAL loading are shown in Figure 12 color coded for 0 (light blue), 200,000, 400,000, 450,000 and 500,000 (red) load cycles.

The two APT functions are shown in Figure 13 (right) and an average APT function is presented in Equation (10). Two complementary functions were created from LTPPM sections located in Slovakia, the Žilina region (GPS 49.140747, 18.718033 and 49.209219, 18.784072). These functions are shown in Figure 13 (left) and an average function is presented in Equation (11). Both functions are shown in Figure 14, with an average function combining APT and LTPPM average functions presented in Equation (12). The regression analysis data for this function are shown in the Supplementary Files.

$$p_x = -3.7867x^3 + 5.5442x^2 - 2.7578x + 0.9998 \tag{10}$$

$$p_x = -2.0924x^3 + 2.9039x^2 - 1.8132x + 0.9988 \quad (11)$$

$$p_x = -2.9396x^3 + 4.2241x^2 - 2.2855x + 0.9993 \quad (12)$$

where p_x is a dependent variable of pavement distress and x is the ratio of load cycles to total bearing capacity in the life cycles.

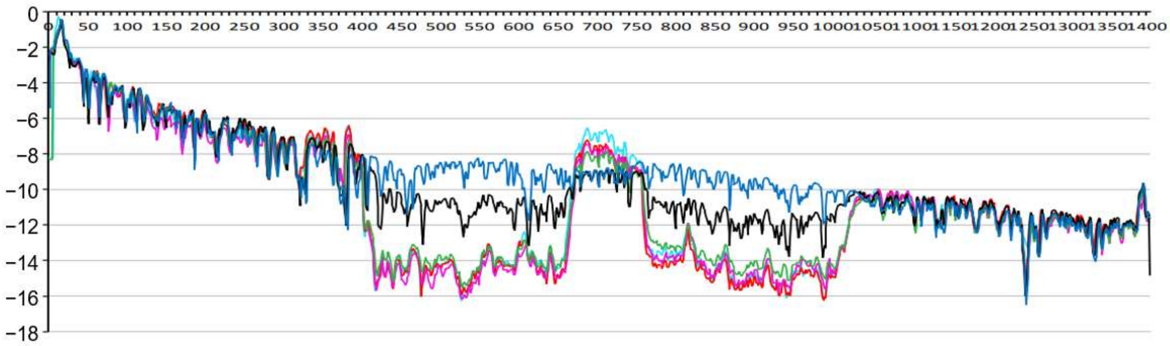

Figure 12. The RUT parameter increases in the first 500,000 loading cycles.

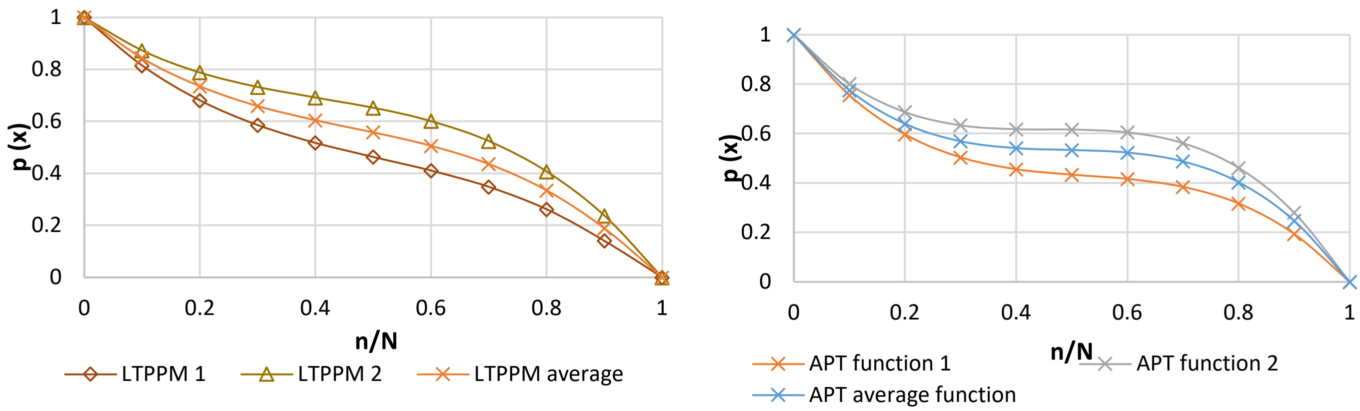

Figure 13. The relative form of the APT functions (**right**) and the LTPP sections (**left**).

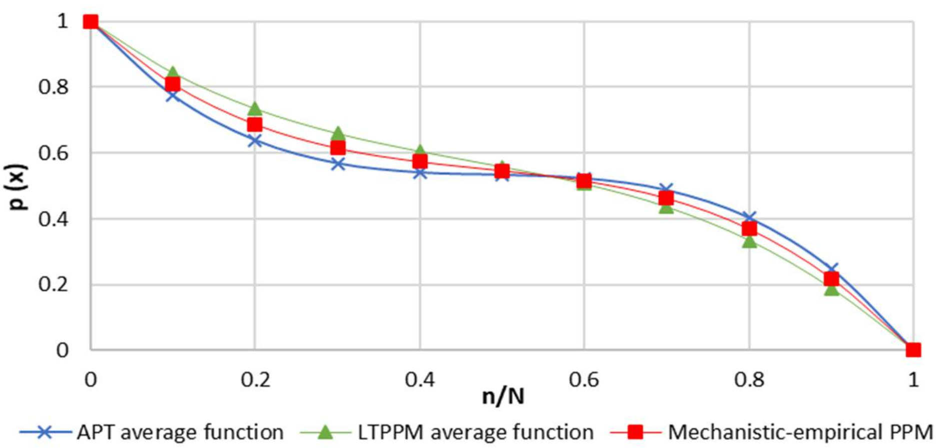

Figure 14. The relative form of the combined RUT deterioration function.

3.3. Comparison of Polynomic and Exponential Functions

To illustrate the impact of the generic exponential function vs. the APT/LTPPM-derived polynomic function on the road user benefits and economic results, we present this case study in which the feasibility of pavement rehabilitation of an existing trunk road pavement was evaluated. The road section is 2126 m of a 7.5 m wide flexible pavement in poor-to-very poor conditions. AADT is 4522 with an annual traffic growth of 3%. Overall rehabilitation costs are EUR 215,996, the life cycle is set to 20 years, and the discount rate is 3%. The generic exponential degradation PPM based on the generic exponential degradation from Equation (9) yields the results shown in Figures 15 and 16.

Figure 15. The RUB calculated by Equation (10) for the first year (2019) after rehabilitation—exponential degradation.

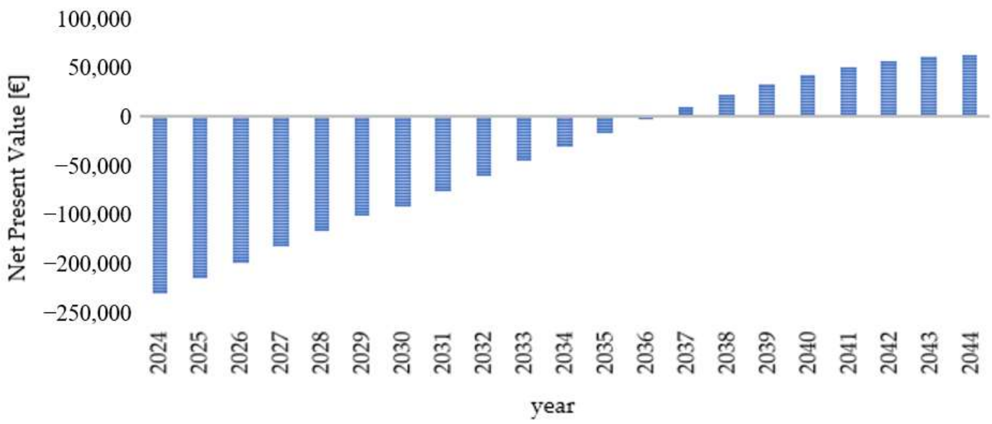

Figure 16. Net present value—exponential degradation.

The overall results are as follows:
Internal rate of return: 6.756%.
Net present value: EUR 75,270.26.
Payback period: 2031.

The APT-derived polynomic degradation PPM based on the APT/LTPPM-derived polynomic degradation yields the results shown in Figures 17 and 18.

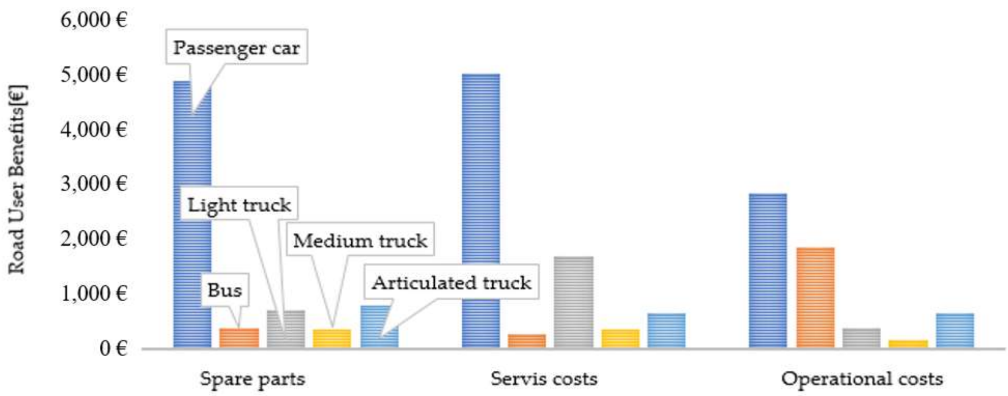

Figure 17. The RUB calculated by Equation (10) for the first year (2024) after rehabilitation—polynomic degradation.

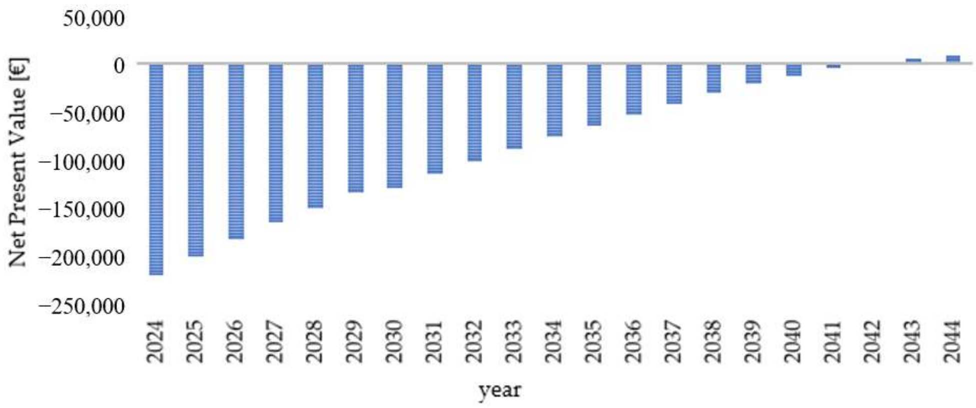

Figure 18. Net present value—polynomic degradation.

The overall results are as follows:
Internal rate of return: 3.419%.
Net present value: EUR 7568.92.
Payback period: 2036.
A comparison of the presented PPMs is presented in Table 5.

Table 5. Comparison of PPMs.

PPM	Generic Exponential Degradation	APT/LTPPM-Derived Polynomic Degradation
Internal Rate of Return	6.756%	3.419%
Net Present Value	EUR 75,270.26	EUR 7568.92
Payback Period	2036	2042

The economic payback year as an economic indicator is the year in which the social benefits (social savings), minus the operating costs, reach the investment costs. An acceptable investment construction project achieves a payback year before the end of the useful life of the construction work. The importance of this indicator is low and serves an informational purpose.

The economic internal rate of return is a key indicator in the evaluation of this project because it provides a result that is not influenced by the discount rate and allows projects with different financial volumes to be compared. The internal rate of return (IRR) should be higher than the interest rate of any loan on which the private investment is to be made. The internal rate of return—IRR—should be higher than the opportunity cost, i.e., the rate of interest that can be achieved by other conventional investment methods (e.g., by depositing money in a monetary institution). The internal rate of return—IRR—should be higher for public works than the prescribed discount, which reflects the externalities on the project and is a guarantee that the investment in question will not be at a loss even under certain expected inflationary developments. The importance of this indicator is crucial.

The economic net present value is the value of the discounted economic flows of the project in financial terms. As an economic indicator, the net present value should be used in the decision-making process in conjunction with the internal rate of return, as this indicator does not distinguish between what period the economic result has been achieved. It is the difference between the present value of expected benefits and the present value of expected costs. The need to supplement the previous methods with the economic method in question, the net present value, stems from the unit of measurement in which it is expressed in financial terms, which significantly complements the previous two economic methods. If the investment is efficient, then the resulting net present value is at least non-negative. This economic result is strongly influenced by the level of the discount rate used and hence is very important but not crucial. The conclusion from Table 5 is that the generic exponential degradation PPM yields a higher RUB compared to the APT/LTPPM-derived polynomic degradation PPM. If a road administrator were to use the generic exponential PPM for their decision making, the overly optimistic PPM would result in a net loss of EUR 67,701.34 during the 20-year life cycle of the pavement.

4. Discussion

Road network administrators, particularly those from low- and middle-income countries, are hesitant to develop or implement advanced pavement performance models complemented by basic empirical and probabilistic solutions. Of course, there is no one-size-fits-all or "one best approach" for pavement management systems, but considering that these models are generalized for a particular type or group of pavements and do not take into account pavement structure and paving material properties, they are not usable for decision making in terms of pavement comparison within that type or group of pavements. In addition, as shown in this article, false results can be obtained when using generalized empirical pavement performance models.

Road network administrators need to stop defining themselves by the assets that they manage, but rather by the service that they deliver and the customer's needs and expectations. These needs and expectations center around ride quality and safety. Failing to predict pavement performance during the pavement life prevents them from addressing those needs and expectations and from implementing plans to meet them in the future. As seen in the case study presented in this article, this miscalculation of socio-economic value changed the project payback period by 5 years, the net present value by EUR 67,701.34, and the internal rate of return by 3.337%. This makes a project initially identified as safe and very profitable actually very risky and barely profitable.

The capability of deriving mechanistic–empirical deterioration models is limited by the fact that simulating seasons in APT is very difficult and expensive. However, the comparison of individual functions can also be biased by the choice of functions. An exponential function can have a much more generalized form than a polynomial one. There may also be a bias in the comparison between the APT model and the LTPPM model concerning the total traffic load. In LTPPM, a specific traffic flow is applied, while in APT, the load is applied at the exact design axle size. Another interesting experiment could be the application of the load and its progression in the pavement design for different tire types or different inflation levels. Load accumulation and load fluctuation in the footprint of heavy vehicles may also have an impact. Combining LTPPM with APT partially addresses this limitation by introducing data influenced by both traffic load and climatic conditions. In relation to LTPPM, it is also possible to outline the direction of further research that should be directed toward relating the course of degradation of the individual parameters monitored to the specific effects of external climatic factors on the individual types of newly applied asphalt-bound mixtures (using self-healing materials or nanomaterials, for example, as presented in studies [43–46], or secondary raw materials in the production of asphalt-bound mixtures, for example, as presented in [47]).

5. Conclusions

Pavement performance significantly changes road user benefits during the pavement life cycle. This makes value-based decision-making models highly sensitive to the prediction of pavement performance. The use of empirical pavement models generalized for a particular group or type of pavement does not allow for meaningful socio-economic value-based comparison and can produce inaccurate false results for the prioritization or optimization of pavement rehabilitation or road network development. Mechanistic–empirical pavement performance models combine measured or calculated pavement responses to stress and strains and, combined with deformational properties and fatigue of the asphalt mixtures, can predict pavement failure due to the loss of bearing capacity and the accelerated pavement deterioration in the later stages of pavement life.

The application of empirical models generally faces applicability issues. Several assumptions and simplifications are necessary for the application of the presented model:

1. Traffic intensity, composition, and growth are based on traffic data collection and prediction; no probability models are used to account for unexpected deviations.

2. Pavements in operation may differ from APT pavement sections and LTPPM pavement sections; this model is used for flexible pavements with a life expectancy of 3.5 mil SAL. These pavements constitute an overwhelming majority of pavements in secondary and tertial road networks that are the intended targets of this model.

3. The model presumes that the pavement structure was always constructed following technical standards; it does not account for faults in constructions due to non-compliance with construction regulations.

4. The model accounts for slight significant variations in climatic conditions; this reflects the majority of conditions in the country where it is used. While it is used also for pavements in mountainous regions and southern lowlands, the results that it provides may carry slight errors due to the different climatic conditions in these regions.

This article presents the summarized methodology and selected input data acquisition for the creation of a mechanistic–empirical pavement performance model and highlights the impact on the reliability of socio-economic value-based decision-making. The methodology may seem laborious, but much of it can be automated by the use of appropriate software solutions, and the potential costs of its implementation are outweighed by a PMS that produces credible results. Considering the magnitude of rehabilitation works performed every year, all costs incurred in the implementation of this method or similar methods are negligible compared to the benefits from an optimized road network rehabilitation program.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/app14093880/s1, Raw data for analysis and support data for Figures 4, 9, 11, 13 and 14.

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