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Economic Impact Analysis of the Application of Different Pavement Performance Models on First-Class Roads with Selected Repair Technology

Matúš Kozel, Ľuboš Remek , Michaela Ďurínová, Štefan Šedivý , Juraj Šrámek, Peter Danišovič  and Vladimíra Hostačná

Faculty of Civil Engineering, University of Zilina, 010 26 Zilina, Slovakia; kozel@uniza.sk (M.K.); michaela.durinova@uniza.sk (M.Ď.); stefan.sedivy@uniza.sk (Š.Š.); juraj.sramek@uniza.sk (J.Š.); peter.danisovic@uniza.sk (P.D.); vladimira.hostacna@uniza.sk (V.H.)

* Correspondence: lubos.remek@uniza.sk



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Abstract: Mathematical expression of the deterioration of individual pavement parameters is, from the point of optimal repair and maintenance strategy decision-making process, an important part of the application of any pavement management system (PMS). The reliability of individual PMS depends on the quality of the inputs and the reliability of its internal sub-systems; thus, deterioration equations derived from high-quality input data play pivotal roles in a system for the prediction of the pavement life cycle. This paper describes the application of pavement performance models within pavement life cycle analysis (LCA) with the use of the integrated system of economic evaluation (ISEH), which is a calculation tool used for first-class roads with a standardized pavement composition of asphalt binders, where changes in operational capability parameters are modeled using individual model simulations. The simulations presented in this paper demonstrate changes in main economic indicators (net present value and internal rate of return) on two different pavement performance models. Both simulations share the same input parameters (traffic intensity, construction intervention, maintenance costs, discount rate) but differ in deterioration evaluation, all of which were applied to each model (a total of five models).

Keywords: pavement performance models; pavement deterioration models; pavement management system; economic evaluation; user costs; rutting; investment process

1. Introduction

The objective of this study was to evaluate the economic impact of the application of different equations for pavement performance models. The impact of pavement performance models on repair technology and timing is well known [1]; however, there are other economic implications beyond repair technology costs linked to the road user [2]. This paper presents the sensitivity of road user costs and subsequent results of life cycle cost analysis (LCCA) and cost-benefit analysis (CBA) to even small changes in pavement performance models.

In addition, a practical method for deriving such pavement performance models is described. This method uses the synergy between accelerated pavement testing and long-term pavement performance monitoring described in separate sections.

State of the Art

Currently, practitioners understand the importance of reliable and accrued pavement performance models. The pavement management system tools and their accuracy is dependent on the accuracy of the deterioration of the selected pavement parameter. Even more so, if we consider that these tools include LCA forecast that predicts pavement deterioration based on degradation characteristic of selected parameter [3].

Following the Pavement Management Guide (second edition) [4], pavement deterioration models can be classified as deterministic, probabilistic, Bayesian, and subjective (or expert based). Uddin [5] defined three methodologies groups of performance modeling. The first group is defined as regression analysis techniques, (empirical performance models and mechanistic–empirical models). The second is defined as probabilistic performance modeling (Bayesian and Markov probabilistic modeling [6,7]) and the third group is defined as artificial neural networks modeling (back-propagation networks [8]). Nevertheless, despite the wide range of available deterioration models, the deterministic and probabilistic groups are referred to as the basic groups because they attract the greatest attention [9].

These models, which are in the line with the current state of the art of deterioration models, can be also divided into models according to the nature of the data employed for modeling; for example, Justo-Silva [10] proposed various classifications, and, according to the conceptual format, they can be divided as purely mechanistic, purely empirical and mechanistic–empirical. Most common are mechanistic–empirical methods, which are also included in design methodologies as MEPDG (Mechanistic Empirical Pavement Design Guide) from AASHTO (The American Association of State Highway Transportation) [11,12].

The state-of-the-art deterioration models of asphalt pavements combine material science by including the rheological properties of paving materials [13] with real-life pavement monitoring and experimental testing and mathematic simulations [14]. However, currently, there is a growing interest in the literature in regard to artificial neural network (ANN) models [15,16]. ANN application has increased drastically in the past few years and it is commonly used in combination with deep learning techniques. Such a combination can help address complex problems in pavement engineering [17]. Some authors regard ANN application as a “black box”, where the exact relationship between the predicted variable (dependent variable) and the independent one(s) is unknown, and hence, the real influence of each parameter cannot be known [18].

2. Deterioration Models and Model Evaluation

We present an economic comparison of two model cases (application of two different technologies, each on two selected pavement constructions) focused differently on the rut depth (*RUT*) parameter. Both cases have the same inputs, and the single variable is the degradation characteristic of rutting.

Based on the above-described analysis of the current state of the art in pavement operational serviceability modeling, a pavement performance evaluation method was created. This method uses deterministic modeling for which regression analysis was employed. The mathematic derivation of pavement deterioration equations was based on polynomial regression analysis from data collected on road sections through long-term pavement performance monitoring and through APT (accelerated pavement testing). This method was chosen to increase the reliability of derived pavement evolution models, which leads to a higher reliability index when compared with other methods.

The deterioration was formulated as a polynomial function of third-grade Equations (2)–(5) and polynomial function of second-grade Equation (1).

2.1. Deterioration Equations Derived from Measurements on the APT Facility

The principle of accelerated pavement testing is an application of artificially induced load applied in a short period of time on an experimentally built road section. Such facility simulates a real load on the real pavement while providing great control during the experiment, this allows researchers to evaluate different factors of road deterioration throughout the pavement life cycle [19,20].

APT is essentially a laboratory test (Figure 1) at a scale of 1:1, during which a load unit (in our case, a semi-axle of a heavy vehicle) is used to induce a load at a frequency that simulates road performance in a relatively short time, which would otherwise be distributed throughout its whole life cycle [20].



Figure 1. APT facility (left); rutting on the pavement test section under the APT facility (right).

The degradation characteristics obtained experimentally were derived from data collected at the APT facility; the construction and operation parameters of the facility are presented in detail by Mikolaj et al. [21]. Derived functions from APT were already partly presented in several studies [21,22]. This paper presents the deterioration of the pavement performance index—the rut depth (*RUT*). International roughness index (IRI), bearing capacity, and fatigue of selected asphalt layers and their evaluation were previously presented in [22–24]. The *RUT* parameter is selected as a critical deterioration parameter for pavements with unmodified asphalt concrete surfacing.

Two deterioration models were derived from the presented APT facility. The first function was derived after 700,000 cycles of heavy vehicle simulation using Equation (1) and the second after 900,000 cycles using Equation (2). Subsequently, they were compared with other functions in order to present a total difference in economic parameters, which can arise after only 200,000 loading cycles.

The first function derived from the APT is defined by Equation (1) as follows:

$$RUT = -0.0535 \left(\frac{n}{N} \right)^2 - 0.9208 \left(\frac{n}{N} \right) + 1 \quad (1)$$

The second function derived from the APT is defined by Equation (2) as follows:

$$RUT = -3.8013 \left(\frac{n}{N} \right)^3 + 5.5617 \left(\frac{n}{N} \right)^2 - 2.7629 \left(\frac{n}{N} \right) + 1 \quad (2)$$

In both Equations, *RUT* is degradation parameter (a relative value of selected deterioration of *RUT* depth parameter, in the range from 0% to 100% deterioration); *n* is the number of loading at the time of evaluation; *N* is the number of loading when the end-of-life limit is reached.

These deterioration equations were derived from collected data by measurement with three different measurement methods [25,26]. These three measurement methods were as follows:

- A 3D scanning method by total station Leica;
- A 3D scanning method by 3D portable scanner Bibus;
- Measurement of selected profiles via leveling measurement and the straightedge method [27].

At 900,000 cycles, there are no cracks on the pavement surfacing. The first parameter that met the warning level of deterioration was the *RUT* depth; therefore, this paper focused on *RUT* evolution equations.

2.2. Deterioration Models Derived from Long-Term Monitored Sections

Degradation characteristics, derived from long-term monitored sections that are a part of Slovak Road Databank, were identified by evaluating data collected by Profilograf and Linescan devices.

Road survey for long-term monitored sections was collected yearly, approximately 2 times per year. The first *RUT* evolution model is an average function Equation (3) from all long-term monitored sections of all first-class roads in Slovakia [28,29], with pavement construction similar to that under the APT facility.

The first function derived from long-term monitored sections is defined by Equation (3).

$$RUT = -1.0136\left(\frac{n}{N}\right)^3 + 0.6603\left(\frac{n}{N}\right)^2 - 0.6265\left(\frac{n}{N}\right) + 0.9808 \quad (3)$$

where *RUT* is the degradation parameter (a relative value of selected deterioration of *RUT* parameter, in the range from 0% to 100% deterioration); *n* is the number of loading at the time of evaluation; *N* is the number of loading when the end-of-life limit is reached.

For additional comparison with the first *RUT* evolution model in Equation (3), we included a second and a third model derived from long-term performance monitoring on first-class roads with a heavier loaded pavement.

The second function derived from the long-term monitored section is defined by Equation (4) as follows:

$$RUT = -2.0655\left(\frac{n}{N}\right)^3 + 3.1888\left(\frac{n}{N}\right)^2 - 2.1516\left(\frac{n}{N}\right) + 1 \quad (4)$$

Further, the third function derived from the long-term monitored section is defined by Equation (5) as follows:

$$RUT = -2.2814\left(\frac{n}{N}\right)^3 + 2.8134\left(\frac{n}{N}\right)^2 - 1.5315\left(\frac{n}{N}\right) + 1 \quad (5)$$

2.3. Evaluation and Model Parameters

The proprietary ISEH (Integrovaný Systém Ekonomického Hodnotenia) software (Version 2.18, University of Zilina, Zilina, Slovakia, 2021) was developed at the University of Zilina. It was used as an LCCA and CBA tool of the assessment of three case study simulations; the results show the impact of performance models herein presented on economic indicators of a project. The software is currently used by Slovak Road Administration as a tool for evaluation of economic efficiency of investments in repairs and maintenance of roads, while the latest version of the software developed and launched is adapted for use by all administration of roads and highways in the Slovak Republic. All deterioration equations described in previous sections were implemented into ISEH software via Visual Studio 2019.

LCCA and CBA were carried out following the Methodic handbook for preparation of cost-benefit analysis [30,31] for review of transport projects investment in phase 2014–2020 and obtain parameters as its net present value (*NPV*) and internal rate of return (*IRR*).

Net present value (*NPV*) is the difference between the present value of cash inflows and the present value of cash outflows over a period of time. *NPV* is used in capital budgeting and investment planning to analyze the profitability of a projected investment or project. *NPV* is the result of calculations used to find today's value of a future stream of payments. In our case, we used income in form of user cost savings and outcome in form of investment costs. User costs consist of operational costs (as fuel and spare part consumption), travel time loss (effect of speed reduction), and costs of accidents.

$$NPV = \sum_{t=1}^T \frac{R_t}{(1+i)^t} \quad (6)$$

where i is the discount rate (in our case 5%), R_t is net cash inflow–outflows during a single period of time (mainly user costs), T is the number of time periods (analysis of 10-year period), and t is the year of the analysis.

Internal rate of return (IRR) is a metric used in financial analysis to estimate the profitability of potential investments. IRR is a discount rate that makes the NPV of all cash flows equal to zero in a discounted cash flow analysis.

$$0 = NPV = \sum_{t=1}^T \frac{C_t}{(1 + IRR)^t} - C_0 \quad (7)$$

where C_t is net cash inflow during the period of time, C_0 is total initial investment costs, IRR is the internal rate of return T is the number of time periods, and t is the year of the analysis.

3. Functions and Calculation Model

In the initial phase, the most accurate functions were implemented into the ISEH software source code. Based on this correlation, the following waveforms of individual parameters were created, suitable for implementation into the ISEH software environment:

The shape of each of the performance equations is different (Figure 2), and therefore, taking into account the variance, it was necessary to model changes in individual variables in the software environment and monitor their impact on the resulting values of economic indicators. The whole impact analysis in ISEH consists of five alternative performance equations and their final comparison. For the incorporation of deterioration functions into the ISEH via Visual Studio 2019 platform, it is necessary to transform Equations (2)–(6) into values from 0 to 1, in our case, via mathematical recalculation shown in Table 1.

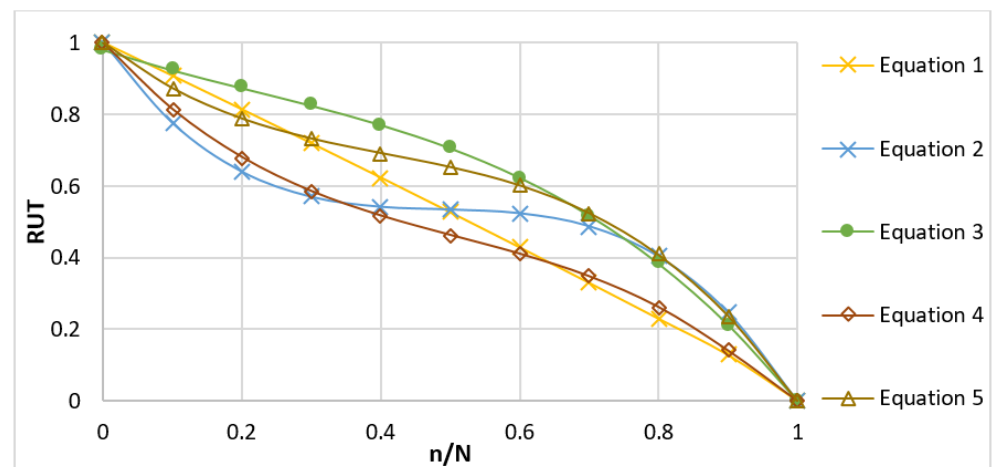


Figure 2. Degradation functions of RUT implemented into ISEH program environment, where RUT is a relative value of selected degradation function, i.e., rut depth; n —number of loading at the time of evaluation; N —number of loading when the end-of-life limit is reached.

Table 1. Mathematical recalculation of performance equations values.

Equation	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Equation (1)	0.907	0.814	0.719	0.623	0.526	0.428	0.329	0.229	0.128
Equation (2)	0.776	0.639	0.569	0.541	0.534	0.523	0.487	0.403	0.247
Equation (3)	0.924	0.874	0.825	0.771	0.706	0.624	0.518	0.383	0.213
Equation (4)	0.815	0.681	0.586	0.517	0.463	0.411	0.348	0.262	0.141
Equation (5)	0.873	0.788	0.732	0.692	0.652	0.601	0.524	0.407	0.237
Maximal value	0.924	0.874	0.825	0.771	0.706	0.624	0.524	0.407	0.247
Minimal value	0.776	0.639	0.569	0.517	0.463	0.411	0.329	0.229	0.128

Limited Conditions of the Computational Model

The economic impact of the rut depth (*RUT*) parameter was assessed for values according to the operational capability stage classification following the currently valid legislation [32] considered for first-class roads. For each category, a maximal *RUT* depth was specified with values of 5, 10, 15, and 25 mm. Stage one and two of classification allow a maximal *RUT* depth after 5 years from construction takeover, which is the warranty period of new constructed or a repaired road (maximal *RUT* after 5 years from the takeover of new or reconstructed construction is 10 mm). Any first-class road with a *RUT* depth value above 15 mm has to be assigned to the warning stage and has to be fitted with warning traffic signs (i.e., “Beware of Surface Roughness”), and maximum speed needs to be reduced from 90 km/h to 60 km/h. If above 25 mm, the *RUT* depth parameter of the selected road has to be considered unsuitable for road traffic. Such pavement is considered a repair priority for road administration.

This classification was chosen to compare the economic indicators of pavement sections at the same level of operational capability. The reference period was considered to be the period at which the pavement is in operation; during this time, the pavement is maintained and produces road user benefits.

The following two model simulations were used:

- 1 Experimental model for section A:
 - *RUT* parameter = 25 mm *RUT* depth (emergency degradation stage);
 - Required construction costs for repair technology = EUR (euro) 17,000 (milling and replacing with new layer);
 - Maintenance in the 6th year of pavement operation = EUR 1700;
 - Annual average daily traffic = 1250 vehicles in one direction per hour, of which 250 are heavy vehicles, and with annual traffic growth of 2.00%;
 - Five different performance Equations (1)–(5) were tested on experimental model A.
- 2 The experimental model for section B:
 - *RUT* parameter = 25 mm *RUT* depth (emergency degradation stage);
 - Required construction costs for repair technology = EUR 50,845.55 (milling and replacing with new layer);
 - Maintenance in the 6th year of pavement operation = EUR 3600.00;
 - Annual average daily traffic = 13,000 vehicles in one direction per hour, of which 1430 are heavy vehicles, and with annual traffic growth of 1.42%;
 - Five different performance Equations (1)–(5) were tested on experimental model B.

A discount rate of 5% and repaired pavement section with a life expectancy of 10 years were applied for both models.

These models were selected to observe the impacts of rutting evolution functions for pavement sections with different construction under different traffic loads.

4. Results of Economic Evaluation on Selected Alternatives of Model Sections

4.1. Parameter–Cumulative Cash Flow

In both model simulations, the repair technology was applied in the emergency degradation stage (*RUT* depth of 25 mm). Simulations had different repair costs. The reference period of economic analysis was 10 years (2021–2031). In both cases, performing maintenance repair action was simulated for the year 2027, i.e., the 6th year of pavement operation. In each year cumulative cash flow of the project was calculated following Equation (8). The cumulative cash flow is influenced by pavement degradation given by individual deterioration equations. Figures 3 and 4 show how different deterioration equations influence cumulative cash flows in both model simulations.

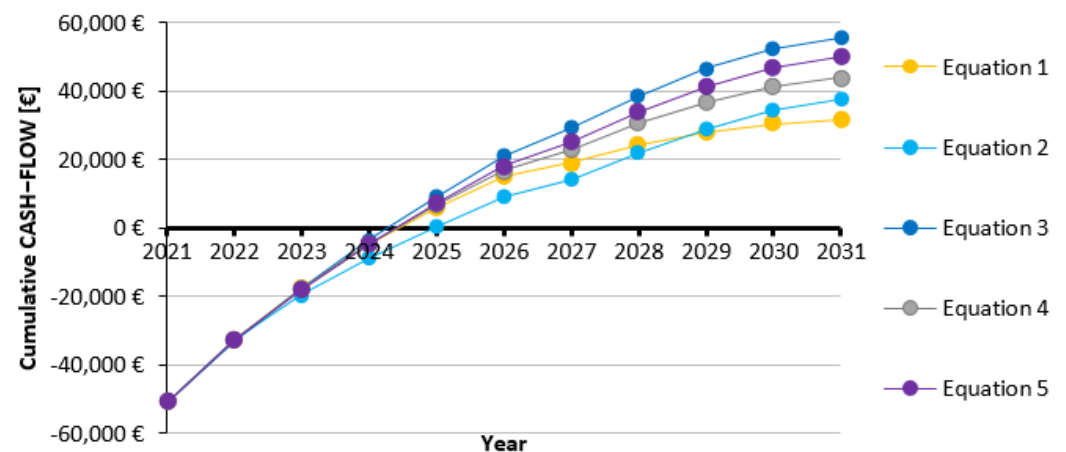


Figure 3. Cumulative cash-flow model A.

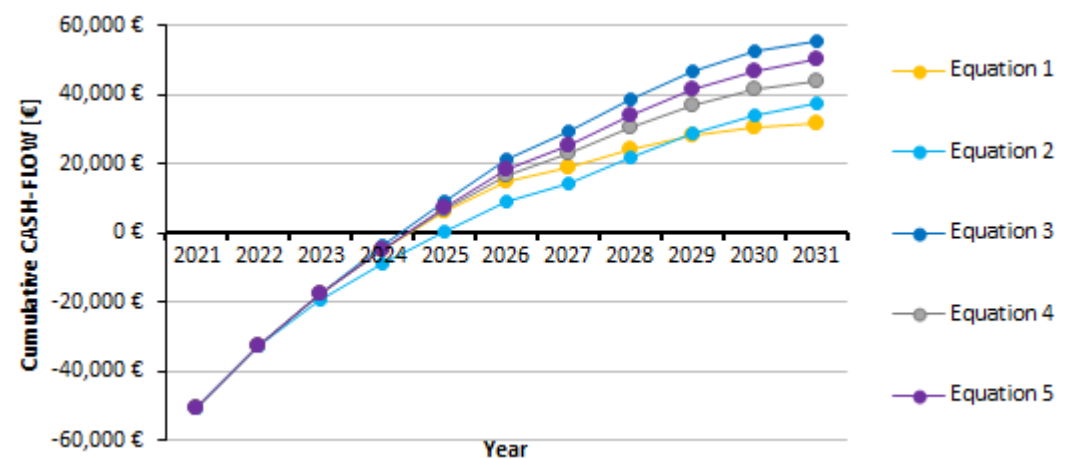


Figure 4. Cumulative cash-flow model B.

The cumulative cash flow is calculated according to Equation (8) as follows:

$$CF_{cumul, n} = CF_{cumul, n-1} + AFC_n + RUB_{TT,n} + RUB_{VO,n} + RUB_{S,n} \quad (8)$$

where $CF_{cumul, n}$ is a cumulative cash-flow in year n , $CF_{cumul, n-1}$ is a cumulative cash flow in the previous year, AFC_n is road administration financial spending on given section in year n (the majority being maintenance), $RUB_{TT,n}$ values are road user benefits for travel time in year n , $RUB_{VO,n}$ values are road user benefits from vehicle operation in year n , and $RUB_{S,n}$ values are road user benefits from increased safety in year n .

4.2. Parameter User Benefits during the Pavement Repair Life Cycle

The benefits of road users due to pavement repairs can be defined as the expression of profit directly for users (drivers, passengers, goods transport, etc.) in the form of a monetary assessment of the reduction of vehicle operating costs and shortening travel times over the period (i.e., 10 years) in a “Take some action” scenario.

Any road user benefits are calculated according to Equation (9) as follows:

$$RUB_{i,n} = RUC_{i,n,DN} + RUC_{i,n,DS} \quad (9)$$

where $RUB_{i,n}$ values are road user benefits of type i (travel time, vehicle operation or safety) in year n , $RUC_{i,n,DN}$ values are road user cost of type i in year n for scenario “Take no

action” (routine maintenance) and $RUC_{i,n,DS}$ values are road user costs of type i , in year n , for scenario “Take some action” (repair, reconstruction, modernization, etc.).

$$RUC_{i,n,j,RUT} = \sum_{j,z} RES_{z,n,j,RUT} \cdot UC_{z,j} \quad (10)$$

where $RUC_{i,n,j,RUT=x}$ values are road user costs of type i (travel time, vehicle operation or safety) in year n of vehicle type j (personal car, bus, articulated truck, etc.) at RUT parameter value; z is the resource type (travel time hour, liter of fuel, tire wear, etc.); $RES_{z,n,j,RUT}$ is the resource consumption of type z in year n of vehicle type j at RUT parameter value; $UC_{z,j}$ is the unit cost (in EUR, GBP, USD, etc.) of resource type z and vehicle type j .

Calculation of resource consumption related to pavement degradation can range from very simple expert-based averages to complex mechanistic–empirical calculation models. ISEH uses empirical indexing of increase in resource consumption for different levels of pavement distress. An example of such indexing is shown in Table 2:

Table 2. Indexing of increase in resource consumption.

Passenger Car								
Gradient [%]	Curvature [deg/km]	RUT [mm]	Fuel	Oil	Travel Time	Tires	Spare Parts	Maintenance
0	0	<5	1	1	1	1	1	1
		10	1.02	1.33	1.08	1.46	1.98	1.45
		25	1.09	1.67	1.27	1.92	3.93	2.15
Heavy Lorry								
Gradient [%]	Curvature [deg/km]	RUT [mm]	Fuel	Oil	Travel Time	Tires	Spare Parts	Maintenance
0	0	<5	1	1	1	1	1	1
		10	1.03	1.11	1.22	1.04	1.56	1.26
		20	1.14	1.22	1.81	1.08	2.12	1.48

The only variable is the performance equation of RUT , ceteris paribus, the difference of cumulative cash flow is produced by the different RUT parameter forecast of evaluated deterioration models. Different RUT values produce different resource consumptions, leading to an increase in road user costs, which, in turn, lead to road user benefits; these produce positive cumulative cash flows. In the first year of the analysis, i.e., 2021, the user benefits equaled 0, i.e., there were no benefits from pavement user repairs; this value is not be stated in the graphs. The user benefits have the same shape as the deterioration equation, as it is the only variable in this comparison. This translates to the calculated cash flow. Annual user benefits for a repair at the RUT value are shown in Figure 5 for model A, and in Figure 6 for model B.

4.3. Parameter of Internal Rate of Return (IRR) during the Pavement Repair Life Cycle for Model A

As shown in previous sections, road degradation expressed with the RUT parameter can produce different benefits and resulting cash flows. The cash flow as a result of CBA can be expressed in economic terms by economic indicators. The key economic indicator we used is IRR , as it provides a good perspective on potential future cash flows. Figure 7 shows the dependency of IRR on the RUT parameter. The RUT value means the RUT parameter value at the time of repair. The IRR value shows how the economic result of such repair after 10 years of cash flows is calculated as described in previous sections. For instance, if we repair the pavement at $RUT = 6$ mm, we use pavement deterioration model related to Equation (2), we calculate cash flows for 10 years of operation of the repaired pavement—the resulting IRR would be -19.3% . Figure 8 shows that performing the repair too early, will lead to economically inefficient repair. It is worth noting that, in practice, an

earlier repair would also require cheaper repair technology, but that was not the focus of this analysis. Repair costs were fixed, as we aimed to study the impact of the deterioration model as the single variable and adhered to “the ceteris paribus principle”.

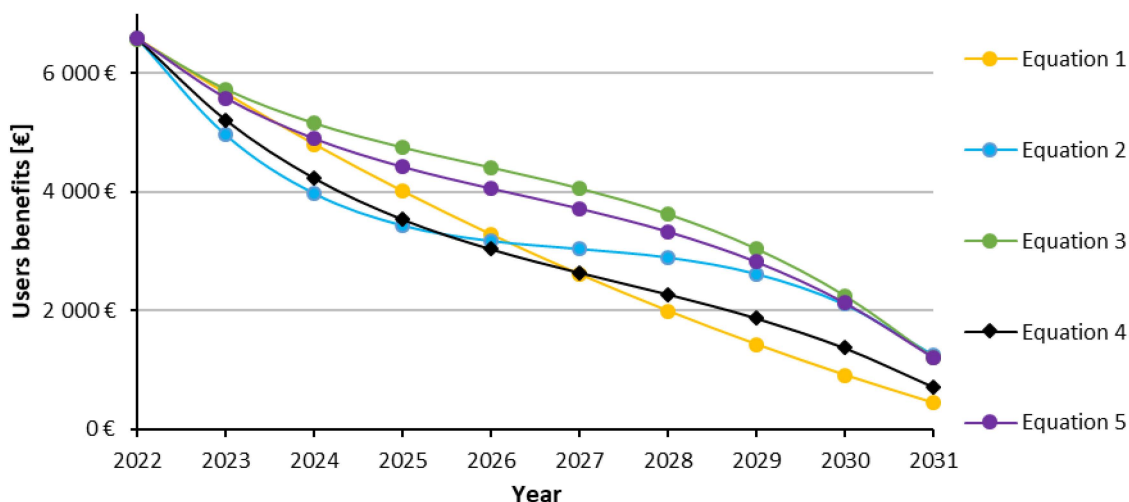


Figure 5. User benefits from the implementation of the repair model A.

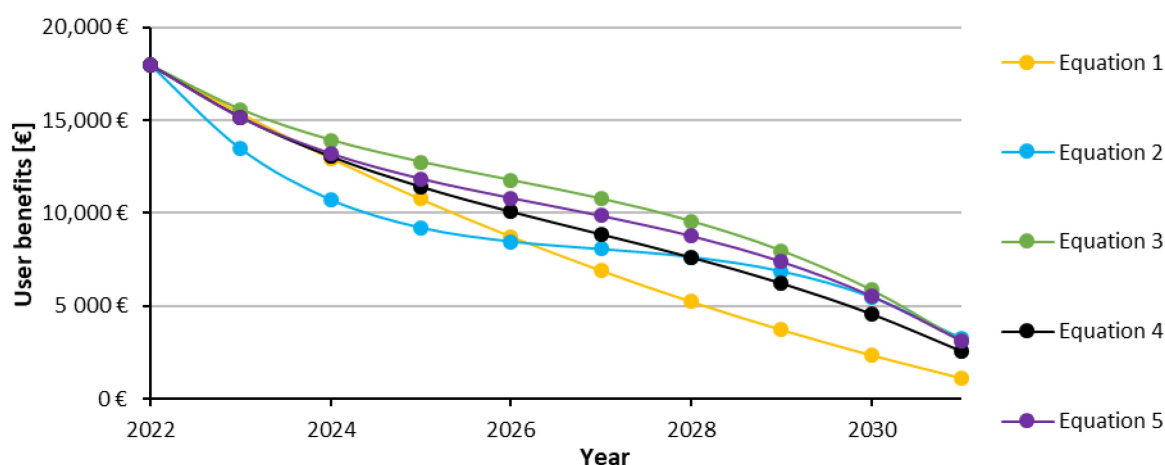


Figure 6. User benefits from the implementation of the repair model B.

The impact of different performance models used for the calculation of cash flows and subsequent *IRR* calculation is very high. Using the function related to Equation (3) for repair at the end of the pavement life cycle ($RUT = 25$ mm) produces an *IRR* of 35%, whereas using the function related to Equation (1) produces an *IRR* of 25.5%. This leaves a 9.5% interval of uncertainty that can influence road administration decision making. These differences are also shown in Figure 8.

Based on Figure 7, we can derive functions to describe the correlation between the *rut* parameter at which the repair action is performed and economic effectiveness, i.e., *IRR* indicator. Each of the derived functions corresponds to the equation described in Section 2 that was used in the LCCA for which the *IRR* was calculated. The respective equations are as follows:

The correlation between *IRR* and *rut* parameter evolution following Equation (1):

$$IRR = 9.10^{-5} rut^3 - 0.0046 rut^2 + 0.0991 rut - 0.7095 \quad (11)$$

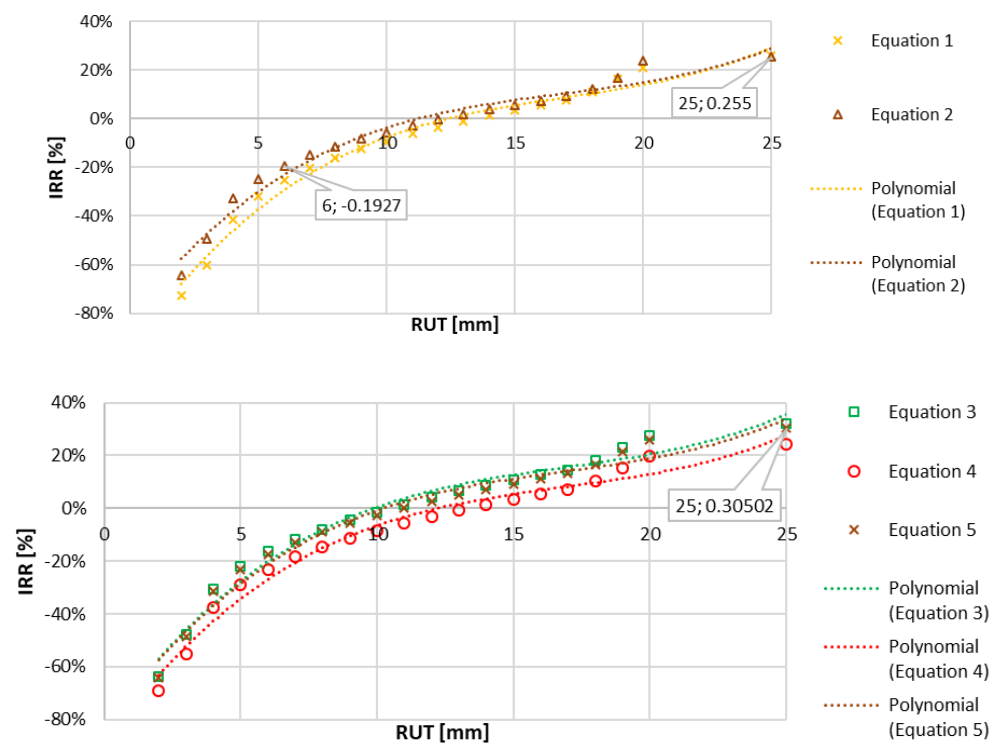


Figure 7. Resulting values of modeling of *RUT* parameter changes in relation to *IRR* for model A.

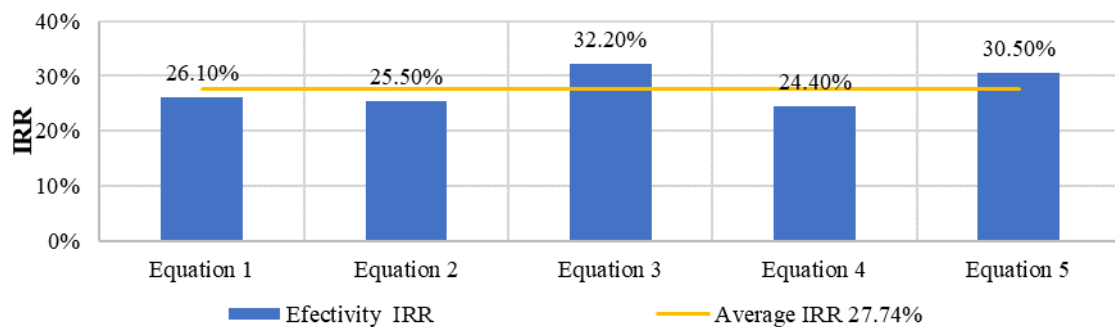


Figure 8. Internal rate of return for model A.

The correlation between *IRR* and *rut* parameter evolution following Equation (2):

$$IRR = 0.0001 \text{ rut}^3 - 0.0073 \text{ rut}^2 + 0.1372 \text{ rut} - 0.8217 \quad (12)$$

The correlation between *IRR* and *rut* parameter evolution following Equation (3):

$$IRR = 8.10 \cdot 10^{-5} \text{ rut}^3 - 0.004 \text{ rut}^2 + 0.0882 \text{ rut} - 0.5715 \quad (13)$$

The correlation between *IRR* and *rut* parameter evolution following Equation (4):

$$IRR = 0.0002 \text{ rut}^3 - 0.0077 \text{ rut}^2 + 0.1446 \text{ rut} - 0.8918 \quad (14)$$

The correlation between *IRR* and *rut* parameter evolution following Equation (5):

$$IRR = 0.0002 \text{ rut}^3 - 0.0077 \text{ rut}^2 + 0.1448 \text{ rut} - 0.8348 \quad (15)$$

where *IRR* is the internal rate of return (%) and *rut* is the *rut* depth (mm) at which the repair action was performed.

For all heretofore presented polynomial functions resulting from the model calculation of the internal rate of return, it was confirmed that the correlation depending showed nearly perfect reliability. The original assumption, i.e., when evaluating repair actions, the pavement performance models have a strong influence on economic results and related road administration decision making was confirmed.

4.4. Parameter of Internal Rate of Return (IRR) during the Pavement Repair Life Cycle: Model B

In the functions related to Equations (2) and (4), the degree from the point of view of efficiency assessment does not indicate changes that would cause significant deviations in their evaluation. From this point of view, it is possible to assume the use of all functions in this model example of pavement repair on a long-term monitored section. A graphical representation of the results of economic efficiency in relation to IRR for the model example No. 2, along with their average values, is shown in Figure 9. The lowest value of IRR is reached when using the function and the average function related to Equation (2), the even degree in this case.



Figure 9. Internal rate of return for model B.

4.5. Parameter of Net Present Value (NPV) during the Pavement Repair Life Cycle: Model A

NPV for the pavement from the A and B model section APT (Figures 10 and 11) reaches the highest value of the function related to Equation (3), at $RUT = 25$ mm—namely, approximately EUR 22,515, and the function related to Equation 4, with the value $NPV = EUR 13,181$. The remaining functions, defined in Equations (1), (2), and (5), reach the value of NPV in the range between these two functions. Obviously, these are significant differences for each of the selected functions, which are due to their mathematical expression. The processing range for rut depth is at least 2 mm because none of the economic indicators could be determined below this RUT value. As with IRR and rut parameter relation, the same principle can be applied to find functions describing the correlation between the rut parameter at which the repair action was performed and economic effectiveness expressed with the NPV indicator. Each of the derived functions corresponds to the equation described in Section 2 that was used in the LCCA for which the NPV was calculated. The respective equations are as follows:

The correlation between NPV and rut parameter evolution following Equation (1):

$$NPV = 1.1425 \text{ rut}^3 - 48.539 \text{ rut}^2 + 1970.7 \text{ rut} - 23,355 \quad (16)$$

The correlation between NPV and rut parameter evolution following Equation (2):

$$NPV = 1.2562 \text{ rut}^3 - 53.368 \text{ rut}^2 + 2166.7 \text{ rut} - 23,861 \quad (17)$$

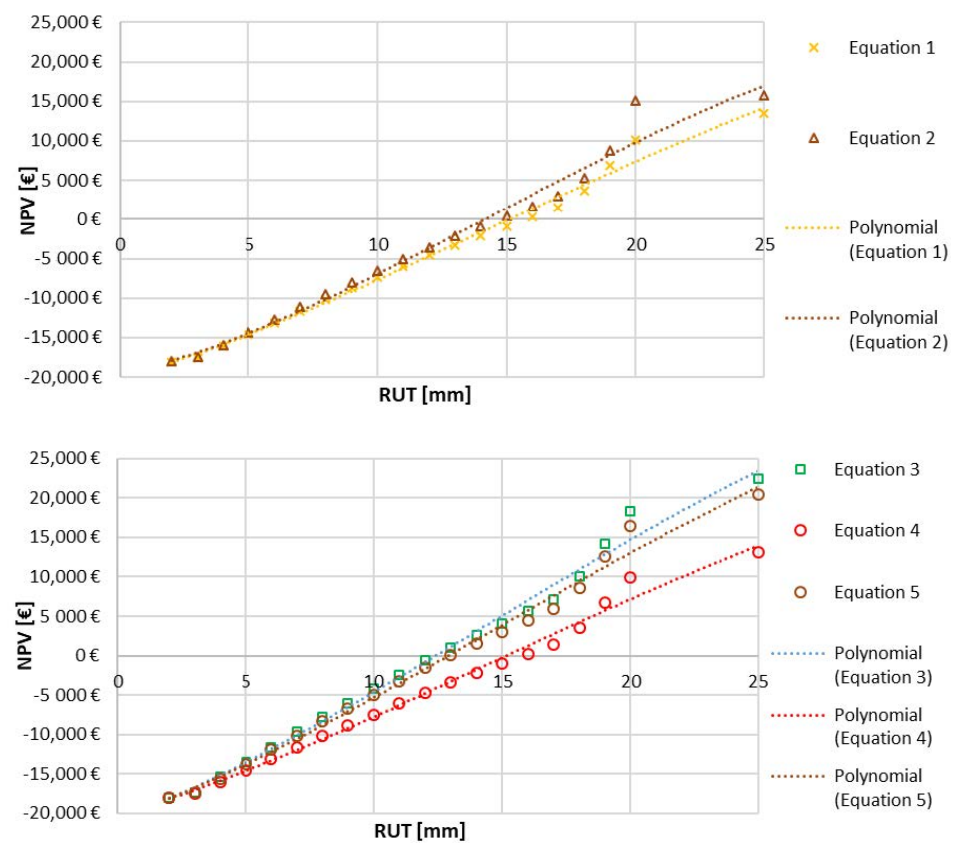


Figure 10. NPV–RUT relation for model A.

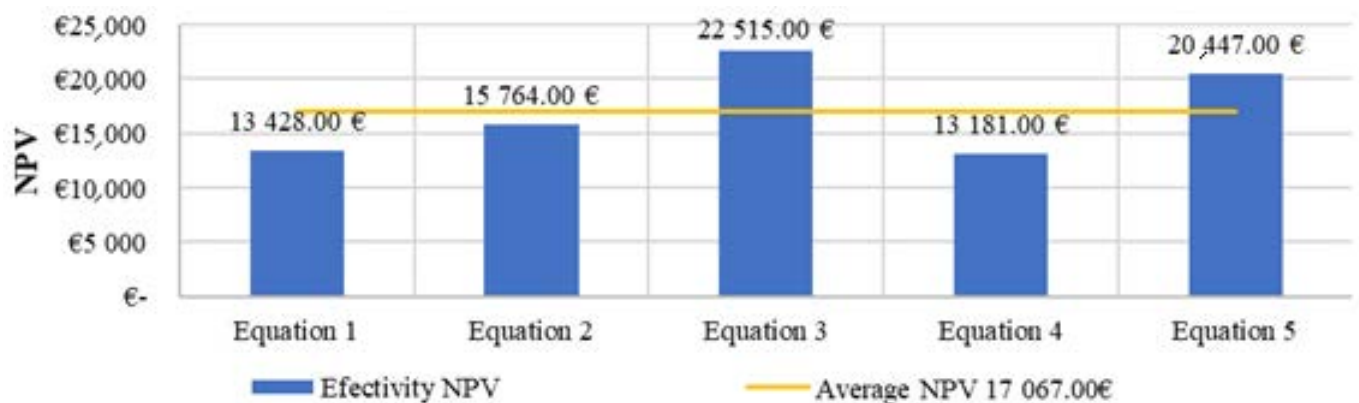


Figure 11. NPV for model A.

The correlation between NPV and rut parameter evolution following Equation (3):

$$NPV = 1.4701 \text{ rut}^3 - 62.455 \text{ rut}^2 + 2535.7 \text{ rut} - 24,813 \quad (18)$$

The correlation between NPV and rut parameter evolution following Equation (4):

$$NPV = -0.8953 \text{ rut}^3 + 39.409 \text{ rut}^2 + 937.95 \text{ rut} - 20,179 \quad (19)$$

The relation between NPV and rut parameter evolution following Equation (5):

$$NPV = -1.1022 \text{ rut}^3 + 48.515 \text{ rut}^2 + 1154.7 \text{ rut} - 20,620 \quad (20)$$

where NPV is the net present value (EUR), and rut is the rut depth (mm) at which the repair action was performed.

4.6. Parameter of Net Present Value (NPV) during the Pavement Repair Life Cycle: Model B

Both in the course of *IRR* and *NPV*, changes in the variance of the monitored indicator of economic efficiency can be observed (Figure 12). The lowest *NPV* indicators, in this case, are achieved when using the function related to Equation (1), and the highest when using the function related to Equation (3). The function that is closest to the average *IRR* value is related to Equation (2).

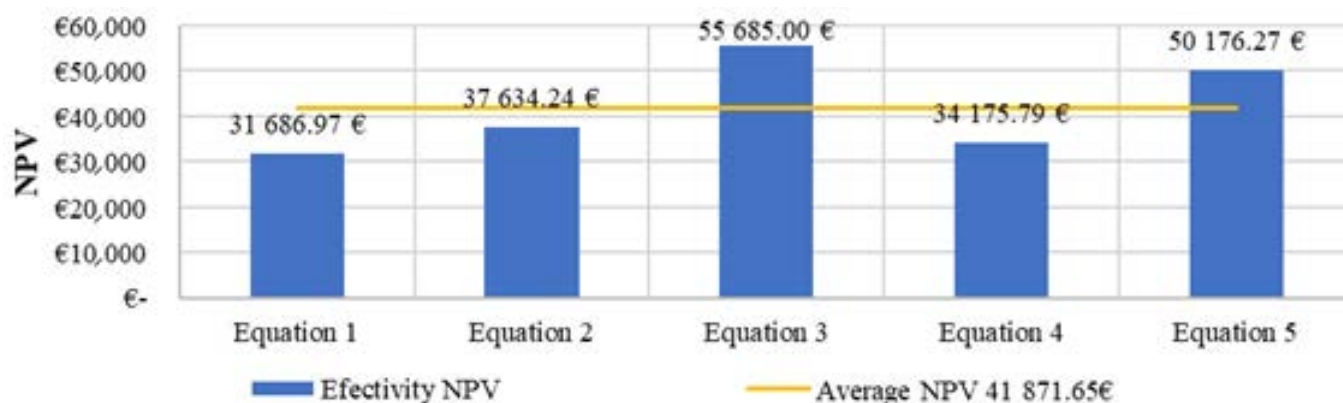


Figure 12. NPV for model B.

5. Discussion

All performance models presented here were established with scientifically proven methods. Thorough understanding of observed pavement construction, thorough measuring methods, and sampling frequency, all prerequisites for establishing pavement deterioration models were met. The nature of APT and long-term pavement monitoring produces evolution curves of similar shapes, reflecting the familiar degradation initiation and progression phase. In this sense, the presented deterioration equations are all valid. The main variation is the “steepness” of the progress. As demonstrated, these changes may seem negligible at first glance, but in reality, when incorporated in the PMS, they produce significant aberration in economic results. Road administration decision making is usually heavily influenced by, if not completely dependent on, project economic indicators. In this sense, errors in deterioration models translate into faulty decision making. Wrong projects can be chosen at the wrong time, producing sub-optimal repair planning and economic loss to society. This is shown in Table 3, in which the breaking point of project effectiveness fluctuates with different evolution equations used for the calculation.

- ATP functions related to Equations (1) and (2): In the economic efficiency analysis, these functions are very similar, producing similar economic results when used in the CBA. In model simulation A (average traffic load), the *IRR* variation interval is 0.6%. In model simulation B (heavy traffic loaded), *IRR* variation is 0.19%. *NPV* variation for model simulations A and B is EUR 2336 and EUR 8052, respectively. Thus, the *IRR* difference is negligible (less than 1%). However, if the decision is based on *NPV* in model simulation B, the variation produced by different performance models will be 25.41%.
- Functions related to Equations (3)–(5): These equations, derived from Long-term pavement monitoring of pavements in operation, are also similar for both model simulations. For model A, the *IRR* variation ranges from 1.7% to 7.8%, and for *NPV*, from EUR 2068 to EUR 9334. For model simulation B, *IRR* variation ranges from 4.41% to 6.07% and *NPV* from EUR 16,000 to EUR 21,509. As in ATP functions, this variation is in line with the assumption that change in deterioration models can have a considerable impact.

Table 3. Breakin point values of repair efficiency in the application of individual deterioration evolution characteristics.

<i>RUT</i> Calculated by	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Equation 1																								
Equation 2																								
Equation 3																								
Equation 4																								
Equation 5																								

6. Conclusions

Considering the evaluated data, we can draw the following conclusions: *IRR* is a more suitable economic indicator, as it is more resilient to variations produced by pavement performance models.

If the road administrator has access to more than one pavement performance model for a particular pavement parameter, he should follow one of these three approaches:

1. Use of a performance model that is most suitable for the evaluation of particular pavement sections—if the road administration has access to several deterioration equations for the same parameter, he can add additional levels of classification (classification by climatic conditions, pavement layer thickness, pavement equivalent modulus of elasticity, bearing capacity, etc.). He can then use functions that most truly represent evaluated pavement sections.
2. Picking the best functions based on reliability (most information on pavement construction, traffic loading, high measurement frequency, etc.)—the road administration should pick the most reliable function and use it in all his economic evaluations; thus, any errors and aberrations from a real-time application will copy themselves evenly into all economic analysis results. This lowers the uncertainty by preventing advantages to some projects while handicapping other projects. This will ensure a valid precedence of priority and order of projects in the repair action plan.
3. The average function—multiple deterioration equations of one parameter can be used to calculate an average deterioration equation; this has all the benefits of the second approach described above and is best used if the best function can be reliably identified.

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