

# LIFE CYCLE MANAGEMENT OF CONSTRUCTION FACILITIES

## УПРАВЛЕНИЕ ЖИЗНЕННЫМ ЦИКЛОМ ОБЪЕКТОВ СТРОИТЕЛЬСТВА



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### Residual Resource of Road Surfacing on High-Traffic Roads

Artem N. Tiraturjan  ✉, Mohamed Elsayed Ragab Abdelaal 

Don State Technical University, Rostov-on-Don, Russian Federation

✉ [tiraturjan@list.ru](mailto:tiraturjan@list.ru)



EDN: BOCKDU

#### Abstract

**Introduction.** An urgent task facing the field of road maintenance is an objective assessment of their residual resource. The existing methods are typically subjective or require that complex procedures are carried out. The aim of the study is to develop a new approach to such an assessment based on instrumental measurements.

**Materials and Methods.** The object of the study is road surfacing of highways. The method is based on a model that relates the amount of elastic deflection of the coating to the estimated number of loading cycles until the strength has been exhausted. Deflection was measured using a Falling Weight Deflectometer. The technique allows one to adapt the model to a variety of conditions by calibrating the coefficients.

**Research Results.** Based on the suggested model, a four-level scale of the condition of the road surface has been designed according to the size of the residual resource: a normative, satisfactory, pre-maintenance and critical one. In order to increase the reliability of the estimate, the median value of the resource is used as the calculated value for the measuring point, and its weighted average value is used to characterize the entire site.

**Discussion and Conclusion.** The developed approach makes it possible to quantify the residual resource based on instrumental data. Implementing this technique would increase the objectivity of diagnostics and assist optimal repair planning. The prospects of the study are related to the further adaptation of the model for a variety of road and weather conditions.

**Keywords:** elastic deflection, residual resource, FWD, weighted average estimate, non-rigid road surfacing, road surfacing condition category, coating defects

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Оригинальное эмпирическое исследование

### Остаточный ресурс дорожных одежд на автомобильных дорогах с высокой интенсивностью движения

А.Н. Тиратурян  ✉, М.Э.Р. Абделаал 

Донской государственный технический университет, г. Ростов-на-Дону, Российская Федерация

✉ [tiraturjan@list.ru](mailto:tiraturjan@list.ru)

#### Аннотация

**Введение.** Актуальной задачей в области содержания автомобильных дорог является объективная оценка их остаточного ресурса. Существующие методы часто носят субъективный характер или требуют сложных процедур. Целью данной работы является разработка нового подхода к такой оценке, основанного на инструментальных измерениях.

**Материалы и методы.** Объектом исследования выступают дорожные одежды автомобильных дорог. В основе метода лежит модель, связывающая величину упругого прогиба покрытия с расчетным числом циклов нагружения до исчерпания прочности. Прогиб измерялся с помощью установки ударного нагружения (Falling Weight Deflectometer). Методика позволяет адаптировать модель к разным условиям путем калибровки коэффициентов.

**Результаты исследования.** На основе предложенной модели создана четырехуровневая шкала состояния дорожной одежды по величине остаточного ресурса: нормативное, удовлетворительное, предотказное и критическое. Для повышения надежности оценки в качестве расчетного значения для точки замера используется медианное значение ресурса, а для характеристики всего участка — его средневзвешенная величина.

**Обсуждение и заключение.** Разработанный подход позволяет давать количественную оценку остаточного ресурса на основе инструментальных данных. Внедрение данной методики повысит объективность диагностики и поможет оптимально планировать ремонтные работы. Перспективы исследования связаны с дальнейшей адаптацией модели для различных дорожно-климатических условий.

**Ключевые слова:** упругий прогиб, остаточный ресурс, FWD, средневзвешенная оценка, жесткие дорожные одежды, категория состояния дорожной одежды, дефекты покрытия

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**Introduction.** Managing road structures is one of the most critical and demanding areas of road management. It requires that clearly defined criteria and rules for assigning the types and timing of repairs, as well as their annual planning are specified. Considering the high economic costs of maintaining road networks in the condition needed, this issue is commonly resolved by means of a preliminary instrumental assessment. However, the approaches to interpreting results of the instrumental assessment in different countries and sources vary broadly depending on the historical experience of designing and constructing road surfaces, as well as the instrumental base conventionally used in particular countries and regions.

All types of management activities in road surfacing management can be generally divided into two types: a network and project one. The network layer involves a general assessment of road surfacing, forecasting changes during their service as well as their remaining life, forming maintenance, repairs and overhaul plans, as well as calculating costs during the life cycle under various operating conditions while choosing the most optimal ones. At the design level, the tasks of calculating and constructing road surfacing are solved within the framework of a decision made on major repairs or reconstruction, and economic estimates are provided for a detailed design solution [1, 2].

The main tasks solved at each level of road surfacing management determine the types of models underlying them. Thus, for the network level of state management, largely phenomenological models based on the concepts of reliability theory, probability theory and mathematical statistics are employed. The design level typically involves use of structural models based on the principles of deformable solid mechanics, fracture mechanics, and mesomechanics [3–5].

The assessment of the condition of highways at the network level is based on a large number of different indicators employed in a variety of pavement serviceability ratings (PSR). A detailed description of these indicators is found in [6, 7]. In particular, in [6] all indicators of the condition of road surfacing are divided into operational, structural and combined ones. Performance indicators are focused on the actual longitudinal evenness of the pavement. The most well-known of them worldwide used ones are the IRI (International Roughness Index); the RCI (ride comfort index) indicator; the RN (ride number) indicator; the PSR (pavement serviceability rating) indicator; in some cases an analog of IRI called PI (profile index) is used to assess a roughness index.

The most common structural indicator used at the network level is the structural number calculated based on the modulus of elasticity of the soil and the equivalent single axle load (ESAL). The dependency for identifying the actual structural number has the form:

$$S_{n,eff} = 0.4728(D_0 - D_{1.5H_p})^{-0.4810}H_p^{0.7581},$$

where  $D_0$  is the elastic deflection in the center of loading;  $D_{1.5H_p}$  is the elastic deflection recorded at a distance equal to  $1.5H_p$ ;  $H_p$  is the thickness of the road surfacing.

The minimum required total modulus of elasticity identified in the Russian Federation at the design stage can be used as an analogue of the structural number  $E_{min}^{TP}$ :

$$E_{min}^{TP} = \sqrt{\frac{p}{600}} \lg(\sum N_{act}) - 3.55,$$

where  $p$  is the design pressure on the pavement surface (800 kPa);  $\sum N_{act}$  is the total number of the design loadings.

The combined indicators combine several indices characterizing the roughness index of the pavement and defects on the surfacing. In some cases, indicators characterizing the operational condition and structural indicators are combined. An example is the Pavement Quality Index (PQI). It includes the Structural Adequacy Index (SAI), the Surface Destruc-

tion Index (SDI), and the Ride Comfort Index (RCI). The key point in designing a combined index is a structured technique for collecting expert opinions. In fact, this is a calibration with its result should be statistically reliable and free from systematic errors. The dependencies for identifying this indicator might vary in different regions. E.g., the calculation of the PQI indicator using the MnDOT [8, 9] (Minnesota Department of Transportation) method is calculated using the formula:

$$PQI = \sqrt{RQI \cdot SR},$$

where  $RQI$  is the ride quality index;  $SR$  is the surface rating.

As the index  $RQI$  is estimated in the range of 0–5, and  $SR$  is in the range of 0–4, the final PQI score can take values in the range of 0–4.5.

In general, it is to be said that all of the above indicators make it possible to effectively characterize the current condition of the road surface, but linking them to the service life is a rather daunting task typically solved subjectively.

The key concept in managing road surfacing at the network level is the concept of the residual resource/service life of road surfacing (in a more modern formulation - the remaining service life). The remaining resource is defined as the number of load application cycles or the number of years until the failure of the pavement according to any criterion occurs. Since 2014 when the document [10] was released, instead of the term residual resource, the concept of residual service life (RSL) has come into practice [11–15] that characterizes the remaining time until a certain type of work has been completed, which can be both preventive maintenance as well as repairs and overhaul of highways.

The main methods and models for RSL forecasting are models based on design practices, or empirical models. As regards models based on design practice, the models provided in the document Mechanical Empirical Pavement Design Guide (MEPDG) are prioritized. These models allow us to identify the residual value of ESAL based on the model of the fatigue failure capacity of asphalt concrete and the model for predicting track accumulation<sup>1</sup> [16–18].

The permissible number of load applications for a specified mode of deformation of asphalt concrete pavement is calculated using the formula:

$$N_{fi}(\varepsilon_i) = C_f K_{f1} \varepsilon_i^{K_{f2}} E^{K_{f3}},$$

where  $N_{fi}(\varepsilon_i)$  is the number of application cycles of the design load calculated based on the tensile strain at the lower boundary of a set of asphalt concrete layers  $\varepsilon_i$ ;  $C_f$  is the calibration factor identified based on the results of field and laboratory measurements;  $K_{f1}$  is an empirical parameter in the standard model,  $K_{f1} = 1.2$ ;  $K_{f2}$  is an empirical parameter in the standard model,  $K_{f2} = -3.291$ ;  $K_{f3}$  is an empirical parameter in the standard model,  $K_{f3} = -0.854$ .

The model for forecasting the residual life of track accumulation on the surface of asphalt concrete is presented as

$$\frac{\varepsilon_p}{\varepsilon_r} = K_1 10^{-3.4488T^{1.5606} N^{0.479244}},$$

where  $\varepsilon_p$  is the plastic component of compression deformation in asphalt concrete layers;  $\varepsilon_r$  is the elastic compression deformation in asphalt concrete layers calculated using the elastic layered half-space model;  $T$  is the temperature in degrees Fahrenheit;  $N$  is the total load for the period of operation in the ESAL.

The advantage of these models is their good calibration and their capacity to flexibly adjust to the conditions of the design region due to a large number of empirical coefficients. Their disadvantage is that the implementation of the MEPDG methodology requires a large number of source data typically missing during the operation phase of the highway. As a rule, this significantly disrupts accuracy and efficiency of these models.

Empirical approaches to RSL forecasting include design of survival curves, use of the Failure Cox Proportional Hazard method, probabilistic and statistical models such as Bayesian models, Markov chains, as well as linear and nonlinear regression models [19–22]. More modern approaches include use of artificial neural networks and genetic algorithms [23–25].

In general, it is to be noted that in spite of a variety of approaches, forecasting the residual resource is currently a fairly urgent task. On the one hand, forecasting methods should be based on measurable condition parameters found in the highway diagnostic system of each region and country. On the other hand, the model for forecasting the residual resource must be sufficiently versatile and well-calibrated for various conditions. On top of that, it is important to note that as a linearly extended object, a highway is characterized by significant heterogeneity and thereby a continuous change in the values of the residual resource for each characteristic section. In this case, it is of paramount importance to develop an approach to identifying the value of the residual resource that effectively and informatively characterizes the section of the overall highway.

<sup>1</sup> *Mechanistic Empirical Pavement Design Guide*. Washington, DC: AASHTO; 2020. 600 p. URL: [https://www.fhwa.dot.gov/pavement/materials/hmec/pubs/module\\_e/participant\\_workbook.pdf](https://www.fhwa.dot.gov/pavement/materials/hmec/pubs/module_e/participant_workbook.pdf) (accessed: 01.03.2026).

**Materials and Methods.** It is recommended that the resource of a highway is expressed in the form of the number of applications of the design load over its service life. The estimated resource of a highway is defined as

$$\sum N_{calc} = 0.7 f_{lane} \frac{K_{sum}}{q^{T_l-1}} T N_{calc} k_n,$$

where  $f_{lane}$  is the band ratio that characterizes the percentage of traffic moving in the busiest lane;  $K_{sum}$  is the summation coefficient;  $T_l$  is the service life;  $T$  is the number of design days per year 6/20/2026r;  $N_{calc}$  is the traffic intensity in the design axes during the first year of service life;  $k_n$  is a coefficient taking account the deviation of the actual flow from the forecast one;  $q$  is the coefficient of an increase in the traffic intensity.

$$N_{calc} = \sum N_i k_i,$$

where  $N_i$  is the traffic intensity of the  $i$ -th group of vehicles;  $k_i$  is the coefficient of reduction in the vehicle to the design axial load of 115 kN.

Considering that this dependence is based on the idea of increasing traffic intensity according to the law of geometric progression, the number of loading cycles actually experienced by the road structure can be identified for any year of operation of the highway in the form of the value of the actual running time of the road surfacing  $\sum N_{act}$ . In this case its residual resource can be calculated as  $\sum N_{resid}$ :

$$\sum N_{resid} = \sum N_{calc} - \sum N_{act}.$$

The disadvantage of this approach is the lack of a relationship between the actual residual resource expressed as the number of cycles of the calculated load and the actual structural condition of the pavement. This drawback can be bridged by reformulating the dependency in the form of

$$\frac{pD(1-\mu^2)}{l} = \sqrt{\frac{p}{600}} 98.65 (\lg(\sum N_{act}) - 3.55),$$

$$l = \frac{pD(1-\mu^2)}{113.91(\lg(\sum N_{act}) - 3.55)},$$

$$\sum N_{act} = 10^{\frac{pD(1-\mu^2)}{113.91l} + 3.55}.$$

Due to the fact that dependence (1) describes the design change in the actual total number of applications of the design load from the initial to some maximum permissible condition of the road structure, a similar change is associated with an increase in the elastic deflection on the surface of the structure. Thus, based on the actual elastic deflection recorded on the surface of the pavement, it is possible to directly identify the value of the actual running time of the pavement, and thereby the residual resource. However, the main issue is that as an extended object a highway cannot be characterized by a single value of elastic deflection, modulus of elasticity, or any other characteristic. A number of the results of elastic deflection recording in public roads belonging to the federal and regional road network are shown below (Fig. 1).

As can be seen in the figures, the elastic deflection is characterized by a sufficiently large spread over the linear extent of the site. E.g., the coefficient of variation is  $C_v = 0.16$  (Fig. 1a),  $C_v = 0.55$  (Fig. 1b),  $C_v = 0.47$  for the third area.

In the framework of the study, it is suggested that a weighted average estimate is used based on the value of the actual elastic deflection recorded on the surface, as an indicator based on which the residual resource of an extended section is identified such as

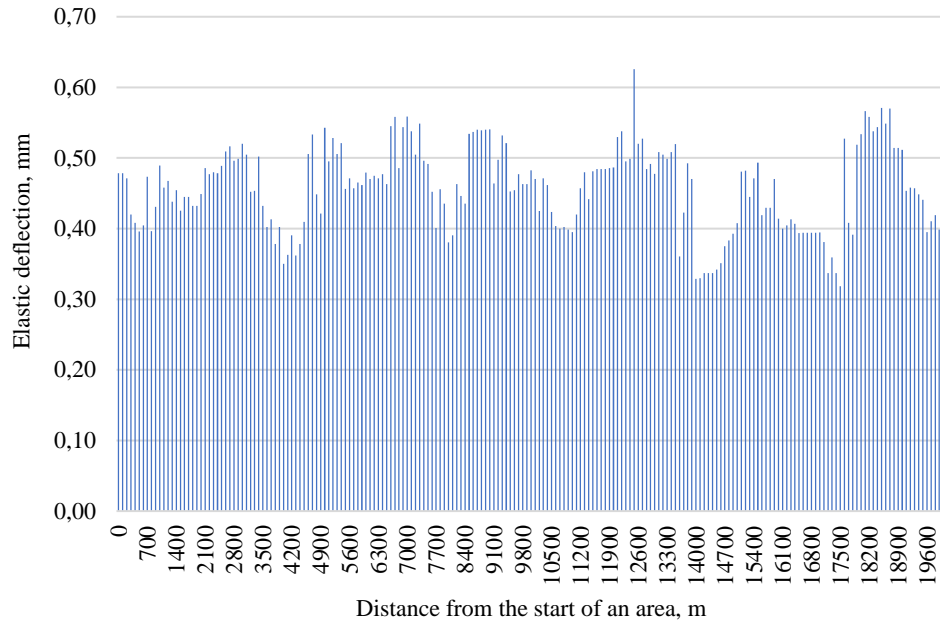
$$\bar{x} = \frac{\sum \omega_i \alpha_i}{\sum \omega_i}.$$

$\alpha_i$  taken as a weighed parameter and the length of the site is assumed to be in a normative, satisfactory, unsatisfactory condition in terms of the residual resource and instead of  $\omega_i$  the value of the actual operating time of the road structure is taken directly:

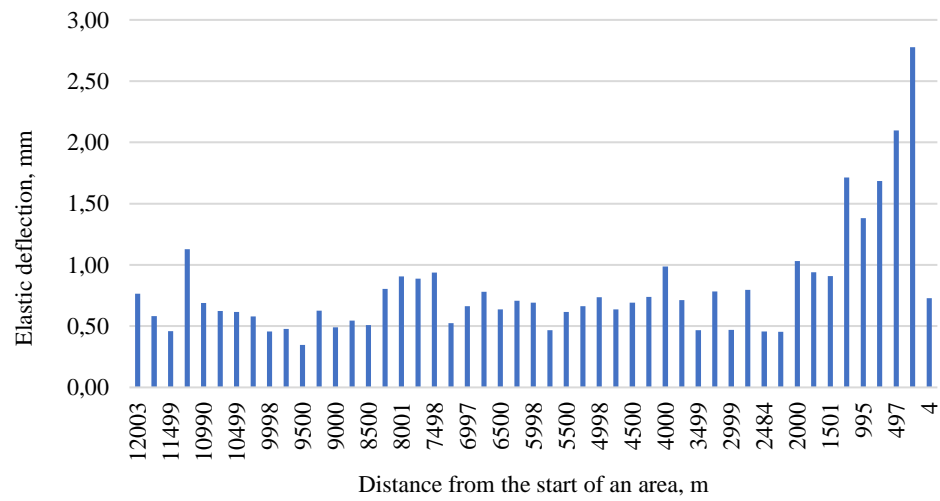
$$\sum N_{act} = \frac{\sum N_{act}^i l_i}{\sum l_i}.$$

Thus, the main task for applying this approach is to rank sites on four levels depending on the amount of actual operating time. In order to address this issue, it is recommended that a regression model between the values of the actual operating time and the operational condition of the pavement is designed. This relationship was designed based on tests on 60 sections of the highways (Fig. 2). A FWD Primax 1500 falling load deflectometer was used to record the deflection bowl, and a diagnostic laboratory with a panoramic camera unit was used to record defects on the pavement surfacing.

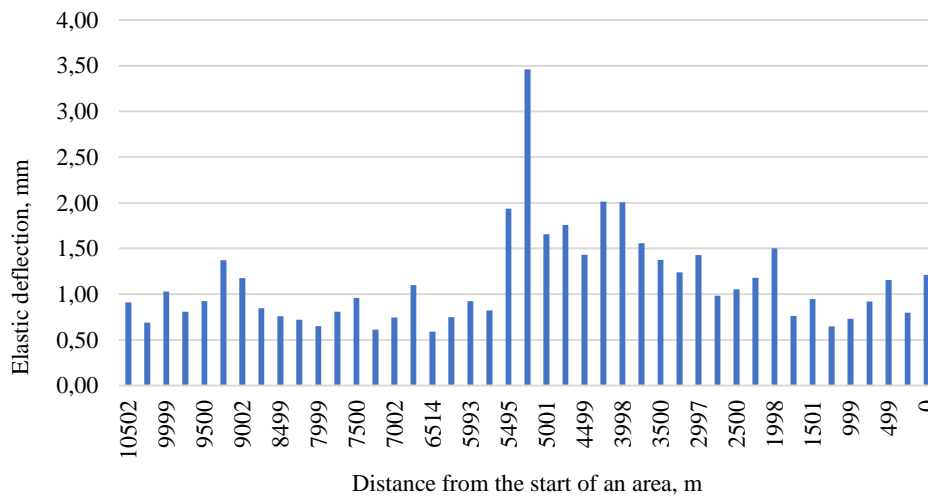
According to the visual assessment, the average score of 1–2.5 corresponds to the presence of defects such as crack grids covering from 30 to 90% of the length of the rolling strip, frequent potholes, single crack grids, a track depth of more than 4 cm. The average score of 2.5–3.5 corresponds to the surfacing defects in the form of longitudinal lateral cracks, frequent transverse cracks, and tracks 2–3 cm deep. Defects rated with an average score of 3.5–4.5 include defects in the form of rare transverse cracks, and defects rated above 4.5 include minor defects in the form of single transverse cracks, a longitudinal central technological crack.



*a*



*b*



*c*

Fig. 1. Actual measurements of elastic deflection on sections of operated highways: *a* is a federal category I highway, *b* is a federal category II highway, and *c* is a regional category IV highway

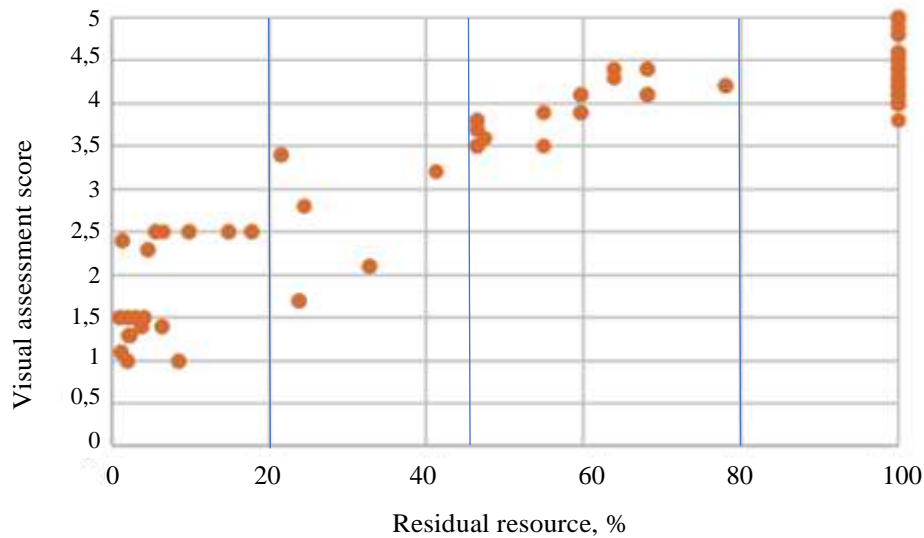


Fig. 2. Dependence of the residual resource on the condition of the surfacing

The final table of the relationship between the value of the residual resource and the corresponding category of condition of the pavement on the site has the following form (Table 1).

Table 1

Classification of the condition of the road surfacing according to the size of the residual resource

Residual resource	Condition category
< 20 %	Critical
20–45 %	Pre-maintenance
45–80 %	Satisfactory
> 80 %	Normative

The median of each range of values of the residual resource is substituted directly into the formula for calculating the weighted average estimate as a value that is not subject to outliers and extreme values.

Depending on the weighted average assessment of the condition of the site, a decision is made on control actions to extend the service life or ensure a standard maintenance service life. Such measures might include road maintenance with a choice of the type of wear layers and protective layers applied to the pavement; repairs with local reinforcement of the base layers or only with replacement of worn coating layers; major repairs involving complete or partial disassembly of the pavement structure.

**Research Results.** The approach set forth in the research to the operational assessment of the residual life of road pavements based on instrumental measurements of elastic deflection on their surface has been implemented on a number of sections of highways with high traffic intensity. In all of these areas, the values of elastic deflection were characterized by great heterogeneity, which made it challenging to select and assign management decisions on the timing and types of repairs. The results of instrumental studies are indicated below, and the weighted average values of the remaining resource for the surveyed sections of federal highways with high traffic intensity are calculated (Table 2).

Thus, the condition of the surveyed sites can be classified as:

- km 492 + 000–517 + 000 in the straight and reverse direction — a normative one;
- km 877 + 000–892 + 000 in the straight and reverse direction — a satisfactory one;
- km 892 + 000–907 + 000 in the straight and reverse direction — a satisfactory one;
- km 354 + 000–365 + 000 in the straight direction — a satisfactory one, in the reverse direction — a pre-maintenance one;
- km 548 + 000–556 + 000 in the straight and reverse direction — a satisfactory one
- km 1138 + 000–1146 + 000 in the straight and reverse direction — a critical one.

Based on the results, recommendations were formulated to restore the condition in the surveyed areas. Thus, in the areas where the regulatory status has been fixed, the main type of control actions on road pavements is installation and subsequent renewal of wear layers made of crushed stone-mastic asphalt concrete with a frequency of 4–5 years. In the areas in a satisfactory condition, this measure can also be implemented, but taking into account the reduced renewal time

of the wear layers, i.e., in the range of 2–3 years. In the areas in a pre-maintenance condition, repairs are underway on the surfacing with local reinforcement of the base layers. Major repairs of the road structure are required in the areas in a critical condition. The specific volumes and forks of work to restore the condition of the pavement to the required operational level are identified during engineering surveys at the design level, involving identifying the modulus of elasticity of the structural layers of the pavement as well as of the most weakened elements and corresponding calculations of the strength of the road structures.

Table 2

Assessment of the residual resource on a section of highway on various sections of the M4 DON highway

Area	Residual resource based on the actual condition of a road structure							
	km 492 + 000–517 + 000							
Direction	Straight				Reverse			
Residual resource	< 20 %	20–45 %	45–80 %	> 80 %	< 20 %	20–45 %	45–80 %	> 80 %
% of the length of the section corresponding to the values of the residual resource	0	2	5	93	2	0	0	98
Median	—	26	67	88	10	—	—	90
Total	85.71				88.4			
km 877 + 000–892 + 000								
% of the length of the section corresponding to the values of the residual resource	16	16	6	61	6	10	0	84
Median	11	31	59	83	15	25	—	83
Total residual resource	63.05				73.12			
km 892 + 000–907 + 000								
% of the length of the section corresponding to the values of the residual resource	6	10	0	84	13	16	6	65
Median	17	24	—	91	7	24	55	83
Total residual resource	79.86				62.00			
km 354 + 000–365 + 000								
% of the length of the section corresponding to the values of the residual resource	8	18	2	71	42	28	10	20
Median	15	26	63	85	7	20	60	81
Total residual resource	68.17				30.74			
km 548 + 000–556 + 000								
% of the length of the section corresponding to the values of the residual resource	0	23	4	71	22	18	2	58
Median	—	33	72	84	9	31	53	83
Total residual resource	71.54				56.76			
km 1138 + 000–1146 + 000								
% of the length of the section corresponding to the values of the residual resource	46	54	0	0	55	37	8	0
Median	4	24	—	—	6	22	47	—
Total residual resource	14.80				15.20			

**Discussion and Conclusion.** Based on the results, the suggested approach is appropriate for large organizations that are tasked with managing the condition of the road network assigned. The current system for assigning repairs based on strength, evenness and adhesion coefficients is excessively rigid, as it calls for major repairs to be performed when the condition is met:

$$K_{str} = l_{act} / l_{req} < 1.$$

where  $K_{str}$  is the strength coefficient of the road surfacing;  $l_{act}$  is the actual elastic deformation recorded under shock loading;  $l_{req}$  is the required elastic deformation for a corresponding road category.

Residual life forecasting systems conventionally used in the software of FWD shock loading setups such as PRIMAX, ELMOD, etc., can be effectively used at the design level while selecting the road surfacing design. However, in this case the system of collecting pavement structures should be focused on calculating and forecasting fatigue damage in asphalt concrete layers and plastic deformations along the rolling strips. In all other cases, the direct application of these approaches also requires adaptation to the conditions of each state or region.

It is to be noted that this approach is relatively effective in the case of adoption and adjustment of planned decisions on the types and timing of repairs. Hence, e.g., in the cases of the section "km 354 + 000-365 + 000" instead of the decision initially considered by the owner of this road to carry out mandatory major repairs in both directions, it was decided to restore the layers of wear in the straight direction and repair the reverse direction of the highway. Also, unlike the method of forecasting the residual service life based on survival curves, this approach requires less statistical data and model refinement based on the results of a set of statistics.

The study presents a new concept for estimating the residual life of non-rigid road surfacing based on data from field measurements of elastic deflection in the center of the deflection bowl by the FWD shock loading unit. The advantage of this model is its versatility and capacity to adapt to any diagnostic tool base involving use of FWD shock loading units.

A scale of road surfacing conditions has been developed depending on the actual residual resource identified based on field measurements. In this scale, for the first time, the concept of a pre-maintenance condition for road surfacing has been introduced, which corresponds to the values of a residual resource of 20–45%. Depending on the condition, recommendations are formulated on the types of control actions that is capable of ensuring the safety of a road structure.

The defects observed on the surface of the surfacing of non-rigid pavement and the values of the residual resource identified by means of instrumental measurements have been found to correspond. It has been found that the critical defects on the surfacing correspond to the values of the residual resource of 0–20%.

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**About the Authors:**

**Artem N. Tirturjan**, D.Sc. (Eng.), Professor, Professor of the Department of Highways of the Don State Technical University (1 Gagarin Square, Rostov-on-Don, 1344003, Russian Federation), [ScopusID](#), [ORCID](#), [tirturjan@list.ru](mailto:tirturjan@list.ru)

**Mohamed Elsayed Ragab Abdelaal**, PhD student, Don State Technical University (1 Gagarin Square, Rostov-on-Don, 1344003, Russian Federation), [ORCID](#), [mabdelaal@donstu.ru](mailto:mabdelaal@donstu.ru)

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**Об авторах:**

**Тиратурян Артем Николаевич**, доктор технических наук, профессор, профессор кафедры автомобильных дорог Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [ScopusID](#), [ORCID](#), [tiraturjan@list.ru](mailto:tiraturjan@list.ru)

**Абделаал Мохамед Эльсайед Рагаб**, аспирант Донского государственного технического университета (344003, Российская Федерация, г. Ростов-на-Дону, пл. Гагарина, 1), [ORCID](#), [mabdelaal@donstu.ru](mailto:mabdelaal@donstu.ru)

**Заявленный вклад соавторов:**

**А.Н. Тиратурян:** научное руководство, анализ результатов исследований, доработка текста, корректировка выводов.

**М.Э.Р. Абделаал:** формирование основной концепции, цели и задачи исследования, проведение расчетов, подготовка текста, формирование выводов.

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