Stochastic Prediction of Short-Term Friction Loss of Asphalt Pavements: A Traffic Dependent Approach

Christina Plati, Maria Pomoni, Andreas Loizos, and George Yannis

Abstract Pavement friction significantly affects the road safety. Over years, researchers have developed multiple models in an attempt to estimate pavement friction performance. The present study aims at developing a stochastic model for the prediction of short-term friction loss based on field-friction data, which adapts the survival probability analysis in terms of a Kaplan - Meier survival curve. The traffic volume expressed through the Annual Average Daily Traffic (AADT) is the main variable of the developed model, assumed to affect more the friction loss within the short-term period of the investigation. The friction level of the preceding year is the second variable of the model that is assumed to embody other factors affecting short-term friction deterioration in the field. Following the assumptions made, the impact of other factors are deemed to be incorporated in the variable of the friction level of the preceding year. However, this assumption is discussed in the constraints of the proposed methodology. All in all, the results of the study are encouraging and can be a useful tool for timely scheduling future maintenance actions in the framework of proactive asset management.

Keywords Asphalt pavements · Stochastic model · Surface friction · Annual Average Daily Traffic (AADT)

1 Introduction

One of the most significant and determinant performance indicators for pavement serviceability condition, as well as for road safety is the surface friction. The tyre-pavement friction mainly contributes to the driver's ability to maintain vehicle control during braking. The higher the level of pavement friction is, the greater the potential

C. Plati (✉) · M. Pomoni · A. Loizos
Laboratory of Pavement Engineering, National Technical University of Athens (NTUA), 5 Iroon Polytechniou, 15773 Athens, Greece
e-mail: cplati@central.ntua.gr

G. Yannis
Laboratory of Traffic Engineering, National Technical University of Athens (NTUA), 5 Iroon Polytechniou, 15773 Athens, Greece

C. Raab (ed.), *Proceedings of the 9th International Conference on Maintenance and Rehabilitation of Pavements—Mairepav9*, Lecture Notes in Civil Engineering 76,
https://doi.org/10.1007/978-3-030-48679-2_86

vehicle control becomes Hall et al. (2009). In multiple studies, a relationship between pavement friction and accident frequency within a road network has been presented and it appears that accident rate can be reduced significantly by an improvement in pavement friction levels (Omar et al. 2017; Hall et al. 2009).

Pavement friction of asphalt surfaces is mainly affected by the surface characteristics and more specifically the texture (Plati and Pomoni 2019; Rajaei et al. 2017). In addition, friction is affected by the tyre characteristics, vehicle operation and climatic conditions (Goulias and Awoke 2020).

In general, aggregate polishing due to traffic wear affects pavement friction performance. Initially, there is an increase in pavement friction due to removal of the binder material covering surface aggregates thus exposing the aggregate rough asperities. Thereafter, pavement friction tends to decrease over the remaining pavement life as the exposed aggregates become increasingly more polished and smooth (Kane et al. 2010). Higher traffic volume and increases in heavy vehicles flow are known to have a significant effect in the expedited deterioration of the pavement surface properties and thus, the friction deterioration (Hall et al. 2009).

The modern Pavement Management Systems (PMS) comprise established procedures to collect, analyze and maintain quantitative data on road pavements. The identification of areas with friction deficiencies is of vital importance considering their impact on road decision making policies that target at optimum investments for maintaining ride quality, safety and cost-efficiency (Omar et al. 2017).

On these grounds, a multitude of different models for predicting pavement friction has been developed; these models have significant variations and depend directly on the variables examined, the approach in modelling and the initial assumptions (Omar et al. 2017). Other researchers have suggested prediction models for estimating friction loss mainly based on laboratory test data and have subsequently attempted to extrapolate their findings to the field (Hofko et al. 2019; Li et al. 2017). However, many laboratory - tailor made approaches present some limitations, as it is not possible to capture the effect of a multitude of factors in the field, including the impact of traffic, climatic conditions and road geometrics. On the other hand, friction modeling by taking into account field data appears to be a more promising and challenging analysis tool, although there are many obstacles towards achieving a univocally accepted model through this approach. As far as the modeling methods are concerned, so far, the majority of researchers have used deterministic models to predict future friction levels. Nevertheless, according to Li et al. (2017), it seems that friction modeling may be more effective for practical actions as a stochastic process rather than a deterministic one resulting in a model.

2 Objective

In light of the above, the current study is concentrated on the short-term prediction of friction deterioration, by investigating the effect of traffic volume on future friction levels. Within this scope, the ultimate goal is to propose a useful and practical approach for road agencies with the view to assessing friction condition through Kaplan—Meier survival analysis based on their pre-defined investigatory friction level and second, to predicting friction degradation for the upcoming years. Given this, a stochastic approach for the prediction of short-term friction loss is followed based on real friction data from an in-service asphalt pavement. A model is developed that takes into consideration the traffic volume and the friction level of the preceding year. The traffic volume is expressed through the Annual Average Daily Traffic (AADT) and assumed to be the main influential factor of pavement friction loss within a short-term period of investigation. Whereas, the friction level of the preceding year is expected to inherently incorporate others factors affecting friction deterioration in the field. Through the methodology presented, it is deemed that road authorities may appropriately schedule and allocate funding for potential upcoming maintenance actions, based on a condition-based preventive maintenance perspective in order to improve or even maintain road safety within a road network.

3 Field Study

3.1 Site Characteristics

The investigation was undertaken on an urban highway which has been divided into 32 sub-sections depending on their direction, location, traffic volume and structural characteristics.

The wearing course of all the investigated pavement sections was an open-graded Hot Mix Asphalt (HMA) mixture with interconnecting voids that provides increased safety in wet weather, through reduced surface water and spray during rain as well as limited noise levels. The open graded friction course mixture corresponded to Mix Designation Type II (ASTM D3515 2001) and was produced using a polymer modified bitumen 25–55/75 that ranged between 3–5%. The asphalt mix contained 4% bitumen binder by mass of the mixture and an 11.5% air void content. In addition, steel slag was incorporated into the mix design for the upper wearing course layer.

3.2 Data Acquisition

Field friction and traffic data were acquired through a database and analyzed. The traffic data was acquired in terms of AADT. The field friction data that was considered for the purpose of the present analysis were along the outer wheel path of the right lane considering that faster deterioration occurs in this lane, mainly because of heavy vehicle traffic moving. In addition, only friction data after the wet period (an extended rain period) were utilized in order to limit the effect of summer contaminants that negatively affect friction measurements (Plati et al. 2020). Importantly, based on the structural data the considered pavements were in a structurally sound condition.

The friction database consists of GripTester measurements, which is a fixed-slip device feed (Findlay Irvine 2002). The device consists of a three-wheeled system where the central-test wheel has a smooth-tread tire according to ASTM E1844 standard (2015). The axle of the test wheel is connected to a chain-system that controls the test wheel's slip speed so that a constant slip of 14% to be maintained. Also, GripTester includes a system for depositing a standard amount of water (0.5 mm water-film) in front of the test tyre so that it then passes between the tyre and the surface being measured. The GripTester system continuously measures friction reporting of Grip Numbers (GN) to 0–1 range. For the study, the GN values are the average measurements at 10 m intervals. Hence, the following data analysis was performed using a big set of data elements.

4 Data Analysis and Results

A survival analysis is applied to GN data for the description of friction deterioration. In general, survival analysis is defined as a set of methods for analyzing data, where the outcome variable is the time until the occurrence of an event of interest. It suggests a practical technique regarding hazard-based duration modeling and therefore, it has been utilized in pavement engineering analysis to model cracking (Reger et al. 2013; Loizos and Karlaftis 2005), roughness (Meegoda and Gao 2014), assess the effectiveness of pavement overlays or evaluate pavement performance (Anastasopoulos and Mannering 2015). Survival analysis method assumes an underlying failure distribution of the data (Prozzi and Madanat 2000). As survival function can be expressed explicitly in terms of a parametric distribution function, it is potentially feasible to estimate the coefficients of those parameters, or else, the influence of the affecting factors. However, the need to assume an underlying distribution introduces an obstacle. The shape of the data might not be described by a well-known specific distribution, and this constitutes a major limitation of the method.

Taking into consideration the aforementioned limitation, the authors use the Kaplan-Meier method (Donev and Hoffmann 2017) to overcome it and calculate the probability distribution of the survival random GN variable. According to Kaplan-Meier method, the survival probability at a given year can be calculated by the multiplication of each of the preceding years' conditional probability of failure. The failure criterion for the friction degradation is the level of surface friction that is below a pre-defined threshold value (Li et al. 2017). Concerning the asphalt pavement sections under investigation, this threshold value is an Investigatory Level (IL) equal to 0.41 GN. It is worth mentioning that the objective of setting an IL is to assign a level of surface friction appropriate for the risk state on the site, at or below, which further investigation is required to evaluate the site-specific risks in more detail (Design Manual for Roads and Bridges 2015).

Hence, the conditional probability of failure in a given year is defined by dividing the number of failures occurring in that year to the number of pavements sections at risk of failure (the risk to be GN $\leq$ IL) at the beginning of that year. The conditional probability p_t of surviving t^{th} year after having survived $t-1$ years is calculated as (Balla 2010):

$$p_t = 1 - \frac{Number\ of\ pavement\ sections\ of\ GN \leq IL\ in\ interval\ t^{th}\ year\ and\ t^{th}+1\ year}{Number\ of\ pavements\ at\ risk\ \text{of GN} \leq \text{IL}\ beginning\ of\ t^{th}\ year} \quad (1)$$

The probability of survival to time t, S(t) is calculated as:

$$S(t) = p_1 \times p_2 \times p_3 \ldots \times p_t \quad (2)$$

The graph of S(t) versus years (t) gives the Kaplan-Meier survival curve. In the current study, survival analysis is used to determine the percentage of the number of sections of which their average surface friction level is GN $\leq$ IL. Figure 1 depicts the survival curve for the particular highway. From years 1 to 13, the percentage of the 32 sub-sections at or above the IL is presented. The use of survival curve illustrates the evolution of the pavement survival probability in terms of surface friction deterioration (i.e. % sections $\geq$ IL). Noticeably, the measured GN values have been utilized for calculating the survival probability each year, up to year 13. The fourth point matches to the 4^{th} year after opening to traffic when database started. The dashed lines after the 13^{th} year indicate potential variability of the evolution in the survival probability.

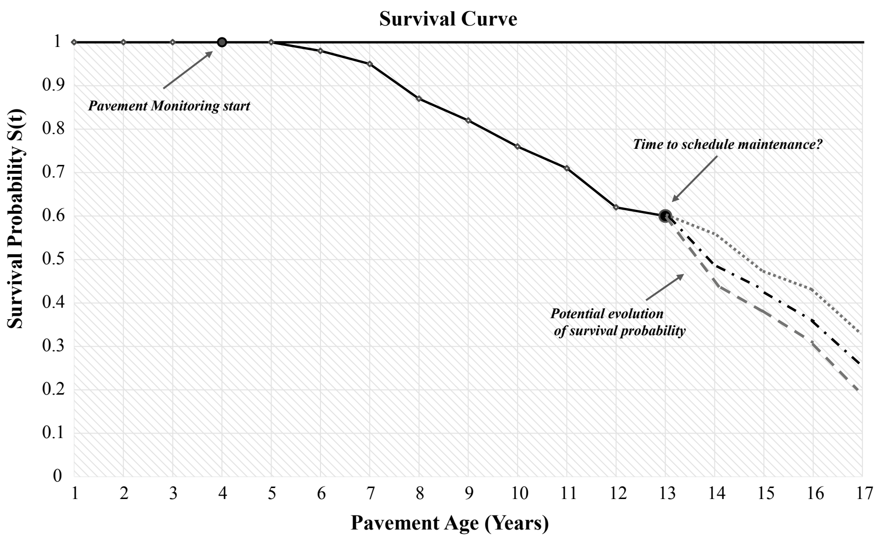

Fig. 1 Survival curve regarding friction levels in regards to IL

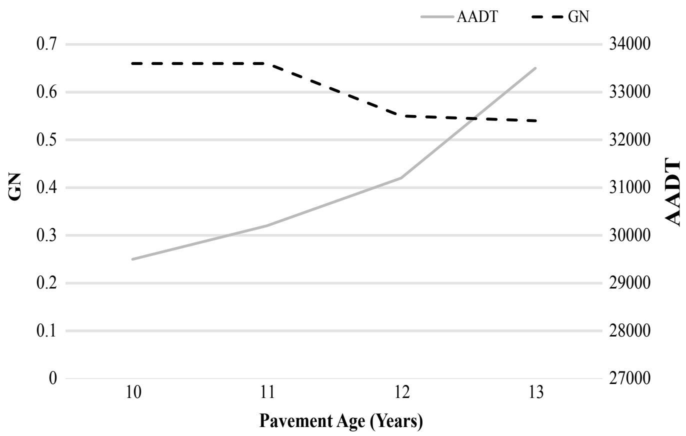

Fig. 2 GN values and AADT—Examples from the sample of the 60% test sub-sections

Thus, it seems that Kaplan-Meier survival curve can give a description on the friction levels which are below or still above IL. Thereafter, an approach is developed for providing an estimation of the surface friction level (the potential one) for the upcoming years (i.e. over year 13) in order to effectively complete the survival curve and gain further insight into the friction condition at a network-level analysis. To accomplish this, randomly 60% of the sections (i.e. 19 sub-sections) are utilized for testing, while the remaining 40% (i.e. 13 sub-sections) are utilized for validating the developed short-term degradation model, impartial of the sections selected (Shmueli et al. 2018). It is worthwhile mentioning that the traffic evolution (trend) cannot be considered stable for the entire period of the pavement monitoring period (10 years). Hence, only the last four years (from year 10 to year 13) are considered representative to describe the most recent trend of traffic evolution (that of a slight increase).

Subsequently, an investigation into friction and traffic trend between years 10-13 was conducted. Figure 2 illustrates the aforementioned trend of the two data sets.

Thereafter, a correlation between the measured friction and traffic data was performed for those four years when the aforementioned trend was observed ($R^2 = 0.85$). Hence, a linear trend between the two components was attempted which may lead to the development of a practical and simple model for the prediction of friction values. With this in mind, all GN and AADT testing data were appropriately correlated and the following empirical form described in Eq. 3 was developed for the calculation of friction coefficient in terms of GN. Through this stochastic model GN for a year (i) is calculated, based on the GN values and AADT of the previous year (i − 1).

$$\mathrm{GNi} = \mathrm{GN}_{i-1} - \left(\mathrm{AADT}_{i-1} * 10^{-5}\right)/\mathrm{A} \tag{3}$$

A = 6, (AADT > 30,000)
A = 2, (AADT ≈ 15,000–30,000, with greater heavy traffic volume)
A = 8, (AADT ≈ 5,000)

where:

GNi	= predicted GN values for a year (i)
GN_{i-1}	= GN values of the previous year (i − 1)
AADT $_{i-1}$	= AADT of the previous year (i − 1)
A	= case-adjusted factor

It is to be recalled that a range of factors affect surface friction (Rajaei et al. 2017). However, the proposed stochastic model includes only two variables assuming that other variables are somehow interrelated to GN_{i-1} for a short-term period so, there would be probably a limited benefit from considering them separately. More specifically, macrotexture level, microtexture level, asphalt mix characteristics, aging of the asphalt-mixture and the long-term effect of climatic conditions are deemed to be embodied in the variable GN_{i-1}, that describes the current friction condition. In other words, those surface characteristics may be considered roughly stable within the short-term period of the model applicability. The developed model is subsequently utilized for validation purposes on the rest sample of GN data.

4.1 Validation Procedure

For the validation process, year 11 was used as the reference year for investigating the applicability of the proposed model and predicting GN values for years 12 and 13, for which traffic data presented a trend of increase. Hence, the developed equation is initially applied on the measured GN data for year 11 (GN_{i-1}) to predict GN values for year 12 (GN_i) and on GN_{12} (predicted values for year 12) to predict GN_{13}. AADT is assumed to increase between the years 11–12 and 12–13 with a rational, stable rate. Thereafter, the measured GN values of these pavement sections for both years 12 and 13 are normally correlated with the corresponding predicted values. The goodness of fit is assessed based on the Root Mean Square Percent of Error (RMSPE) criterion (Eq. 4).

$$RMSPE = \sqrt{\frac{1}{n} * \left[\sum\nolimits_{i=1}^{n} \left(\frac{GNi^{estimated} - GNi^{measured}}{GNi^{measured}} \right)^2 \right] * 100} \quad (4)$$

Figure 3 illustrates indicatively the graphic adaptation of RMSPE criterion on GN measured and GN predictive values. All the results of the validation process are presented in Table 1, where it appears that the proposed two-variables model leads to predictions of acceptable accuracy (RMSPE < 15%).

It seems that the proposed stochastic model can accommodate the specific friction data. In addition, it is observed that the RMSPE for year 13 is mainly higher than for year 12, an issue that will be further discussed below. Overall, the proposed methodology could be considered as an efficient and practical tool for road transport agencies

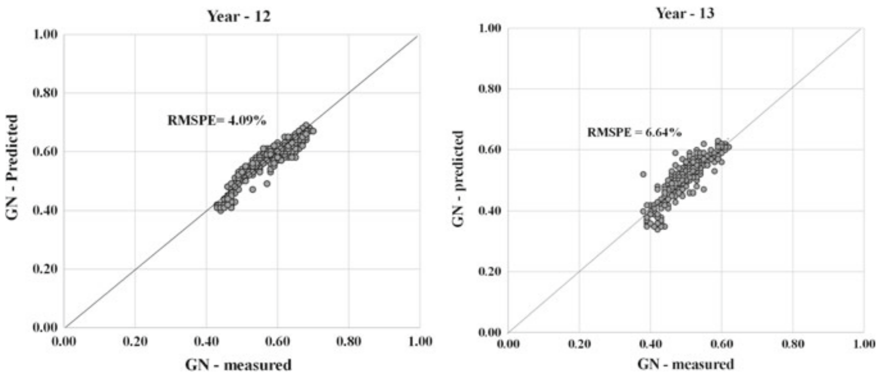

Fig. 3 RMSPE for a section where A = 8, (AADT ≈ 5,000)

Table 1 Total validation results of RMSPE criterion for the 40% of the subsections

Section	AADT	RMPSE %–year 12	RMPSE %–year 13
1	15000	8.54	9.67
2	20000	14.36	12.28
3	30000	9.02	9.04
4	20000	4.90	7.53
5	30000	4.80	6.10
6	>30000	8.33	9.80
7	>30000	6.07	12.58
8	30000	9.98	10.18
9	30000	12.97	14.74
10	15000	9.48	14.75
11	15000	13.69	14.64
12	15000	8.02	12.43
13	5000	4.09	6.64

in estimating the degradation in surface friction levels for the short—upcoming years to more efficiently plan routine maintenance actions and upgrade surface friction, if levels are expected to fall under the IL.

5 Discussion

A range of factors affect surface friction but road authorities need simple and effective tools to draw strategic planning of routine maintenance activities based on rational priorities and budgets assignment. Thus, the use of models with a multitude of variables may not be an effective approach for them. On these grounds, the presented methodology assumes that within a specific highway, yearly friction is mainly affected by traffic volume for a short-term period.

However, on a long-term basis the variables assumed to be stable in this approach will not remain constant, while traffic volumes will face changes that may affect the particular case-adjusted factor—A. Hence, a re-calibration may be needed after a period to incorporate these changes. Given this, a suggestion could be to define the calibration time based on sharp increases on RMSPE values. Also, it has to be pinpointed that the model is based on GripTester data and some discrepancies may occur in case of another measuring device. Another constraint concerning the suggested methodological approach is the inability to consider the effect of intermediate maintenance activities for surface improvement. The consideration of such an issue would raise the complexity of friction modeling. Thus, it means that the developed stochastic model can be adapted only between subsequent periods of major maintenance activities with no further intermediate maintenance in the meantime.

6 Concluding Remarks

In this study, a methodology that captures the short-term friction deterioration for an in-service pavement was presented. The developed stochastic approach adapted the survival probability analysis in terms of a Kaplan—Meier survival curve and then, a model development was proposed. The presented methodology was considered to be useful for road agencies that need to assess and predict the degradation in pavement friction and schedule routine maintenance actions. The effect of traffic volume was deemed to be critical and was embodied in the developed empirical two-variable model in terms of AADT. The basic assumption of the model was that other factors that potentially influence the yearly loss of pavement friction within a highway do not significantly change over a short-period of time. Also, it was assumed that the effect of those factors can be expressed through the level of the friction of the previous year which was the second variable of the model. The different magnitude of traffic volumes was incorporated through a case-adjusted factor—A, which is a traffic dependent parameter. Potential improvements however, may be achieved through proper adjustments to factor A in order to consider significant changes in traffic volume and the heavy vehicle traffic as well, an issue that seeks further investigation.

Acknowledgements This research is co-financed by Greece and the European Union (European Social Fund- ESF) through the Operational Programme «Human Resources Development, Education and Lifelong Learning» in the context of the project "Strengthening Human Resources Research Potential via Doctorate Research" (MIS-5000432), implemented by the State Scholarships Foundation (IKϒ).

References

Anastasopoulos P, Mannering F (2015) Analysis of pavement overlay and replacement performance using random parameters hazard-based duration models. J Infrastruct Syst 21(1):04014024

ASTM (2001) Standard Specification for Hot-Mixed, Hot-Laid Bituminous Paving Mixtures (Withdrawn 2009). ASTM D3515-01, West Conshohocken, PA

ASTM (2015) Standard Specification for a Size 10 × 4–5 Smooth-Tread Friction Test Tire. ASTM E1844-08, West Conshohocken, PA

Balla CK (2010) Prediction of remaining service life of pavements. Master Thesis, University of Toledo, Digital Repository

Design Manual for Roads and Bridges (2015) "Skidding Resistance". HD 28/15, 7, (3), Part 1

Donev V, Hoffmann M (2019) Condition prediction and estimation of service life in the presence of data censoring and dependent competing risks. Int J Pavement Eng 20(3):313–331

Findlay Irvine Ltd (2002) Road base grip tester survey software for roads. User manual

Goulias D, Awoke GS (2020) Novel approach to pavement friction analysis with advanced statistical methods using structural equation modelling. Int J Pavement Eng 21(2):236–245. https://doi.org/10.1080/10298436.2018.1454922

Hall JW, Smith KL, Titus-Glover L, Wambold JC, Yager TJ, Rado Z (2009) Guide for pavement friction. Contractor's Final Report for NCHRP Project 01-43, NCHRP, Transportation Research Board of the National Academies, Washington, DC, pp 19–37

Hofko B, Kugler H, Chankov G, Spielhofer R (2019) A laboratory procedure for predicting skid and polishing resistance of road surface. Int J Pavement Eng 20(4):439–447

Kane M, Do MT, Piau JM (2010) On the study of polishing of road surface under traffic load. J Transp Eng 136(1):45–51

Li L, Guler SI, Donnell ET (2017) Pavement friction degradation based on pennsylvania field test data. Transp Res Rec 2639:11–19

Loizos A, Karlaftis M (2005) Prediction of pavement crack initiation from in-service pavements: a duration model approach. Transp Res Rec 1940:38–42

Meegoda JN, Gao S (2014) Roughness progression model for asphalt pavements using long-term pavement performance data. J Transp Eng 140(8): 04014037, 7 p

Omar LG, Halim AE, Ismail K (2017) Investigating the predictability of pavement friction on rural roads in Ontario Canada. In: 96th Annual Meeting, Transportation Research Board, Washington, D.C, 13 p

Plati C, Pomoni M (2019) Impact of traffic volume on pavement macrotexture and skid resistance long-term performance. Transp Res Rec 2673:314–322

Plati C, Pomoni M, Georgouli K (2020) Quantification of skid resistance seasonal variation in asphalt pavements. J Traffic Transp Eng 7(2):237–248. https://doi.org/10.1016/j.jtte.2018.07.003

Prozzi JA, Madanat SM (2000) Using duration models to analyze experimental pavement failure data. Transp Res Rec 1699:87–94

Rajaei S, Chatti K, Dargazany R (2017) A review: pavement surface micro-texture and its contribution to Surface Friction. In: 96th annual meeting, transportation research board, Washington, D.C., 19 p

Reger D, Christofa E, Guler I, Madanat S (2013) Estimation of pavement crack initiation models by combining experimental and field data. J Infrastruct Syst 19(4):434–441

Shmueli G, Bruce PC, Yahav I, Patel NR, Lichtendahl Jr. KC (2018) Data Mining for Business Analytics Concepts, Techniques, and Applications in R. Wiley, Hoboken