World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Pavement Maintenance Considering Traffic Accident Costs

Rita Justo-Silva[a], Adelino Ferreira[a]*

[a]*Road Pavements Laboratory, Research Center for Territory, Transports and Environment, Department of Civil Engineering, University of Coimbra, Portugal*

Abstract

Worldwide, more than 1.25 million people die annually in road traffic accidents and between 20 and 50 million more are injured. By 2030, highway-related crashes are projected to be the 5th leading cause of death in the world. Road accidents have a number of contributing factors, including roadway conditions, vehicle conditions, and factors related to the road users. While some of these factors have been studied extensively by researchers very few focused on quantifying the relationship between accidents frequency and pavement quality. Before 1990s, due to the lack of pavement data collection technology, it was very difficult to carry out statewide scale studies relating pavement quality and road safety. However, in the past decades, there has been a huge growth and awareness in the importance of road safety as a public health issue, leading to a significant increase of research in the topic. Researchers started to study other contributing factors to accidents occurrence such as the pavements quality. Moreover, with the development of high-speed friction measurement tools, agencies can now include friction into network level Pavement Management Systems (PMSs). Therefore, incorporating safety concerns is one of the urgent needs of PMSs, not only in order to optimize the management of the resources but also, and above all, towards the reduction of road fatalities. The objective of this article is to contribute to the incorporation of safety concerns into Pavement Management. The sensitive analysis performed allowed to draw conclusions in terms of the impact in the agency, user and total costs of performing different maintenance policies.

Peer-review under responsibility of WORLD CONFERENCE ON TRANSPORT RESEARCH SOCIETY.

Keywords: Road Safety; Pavement Management; HDM-4 Models; Accident Prediction Models; Sensitive Analysis.

* Corresponding author. Tel.:+351.239797101; fax:+351.2399797100.
E-mail address: adelino@dec.uc.pt

Nomenclature

AADT	Average annual daily traffic
Years	Number of years
Length	Segment length
SPF	Safety performance function
$N_{predicted}$	Predictive model estimate of crash frequency for year y on site type x (crashes/year)
$N_{SPF\ x}$	Predictive average crash frequency determined for base conditions with the SPF function on site type x (crashes/year)
CMF_{yx}	Crash modification factors for site type x
C_x	Calibration factor to adjust for local conditions for site type x
$N_{expected}$	Expected average crash frequency for the study period
w	Weighted adjustment to be placed on the SPF prediction
$N_{observed}$	Observed crash frequency at the site over the study period
VOC	Vehicle operation costs (€/km/vehicle)
ACA_b	Area of all structural cracking at the end of the analysis year (%)
ACW_b	Area of wide structural cracking at the end of the analysis year (%)
ACX_b	Area of indexed cracking at the end of the analysis year (%)
$SNPK_b$	Adjusted structural number due to cracking at the end of the analysis year
RDM_b	Total mean rut depth for both wheel-paths at the end of the analysis year (mm)
RDS_b	Rut depth standard deviation at the end of the analysis year (mm)
ARV_b	Area of ravelling at the end of the analysis year (%)
NPT_b	Number of pothole units at the end of the analysis year (no/km)
RI_b	Total roughness index at the end of the analysis year (m/km)
PSI_b	Present Serviceability Index at the end of the analysis year
TD_{av}	Annual average texture depth at the end of the analysis year (mm)
SFC_{120}	Sideway force coefficient at traffic speed 120 km/h

1. Introduction

Nowadays, the management of road pavements is a challenging task. On one hand, the economic crisis imposed a reduction of the available budget and, on the other hand, as consequence the national road agencies need now to justify where the public money is spent. Therefore, the road agencies are investing more in new techniques, which allow them to find the most effective and cost-efficient solution to the management of the entire network. Incorporating safety concerns is one of the urgent needs of PMSs, not only in order to optimize the management of the resources but also, and above all, towards the reduction of road fatalities. The development of Accident Prediction Models (APMs) is a key component in the improvement of Road Safety. It allows to identify the factors that cause the accidents and consequently act preventively. The road accidents are function of a set of events influenced by several factors, which partly are deterministic (can be controlled) and partly are stochastic (random and unpredictable). The crashes contributing factors are mainly divided in three categories:

- Human – age, judgement, driver shills, attention, fatigue, experience, sobriety.
- Vehicle – design, manufacture and maintenance.
- Roadway and Environment – geometric alignment, cross section, traffic, signage, visibility, grade, weather, surface friction of the pavement.

According to the Highway Safety Manual (HSM), AASHTO (2010, 2014), a Crash is defined as a set of events that result in injury or property damage due to the collision of at least one motorized vehicle and may involve collision with another motorized vehicle, a bicyclist, a pedestrian, or an object. Crash Frequency is a measure to quantify the number of recorded crashes in a given period (observed crash frequency).

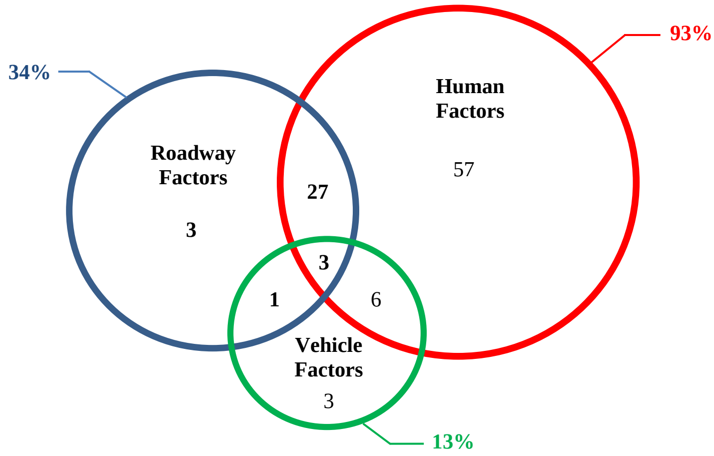

Fig. 1. Crashes contributing factors, adapted from (AASTHO, 2010).

Crashes are random events, which means that crash frequencies fluctuate over time and therefore crash frequency over a short period is not reliable of what Average Crash Frequency is expected under the same conditions over a long period of time. Therefore, the Expected Average Crash Frequency is used to estimate in the long-term the Average Crash Frequency of a site, facility or roadway under given geometric design and traffic volumes in a given period of time (years).

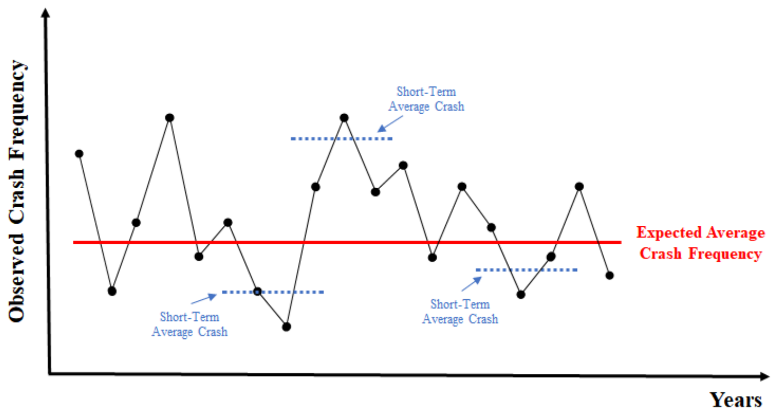

Fig. 2. Variation in short-term observed crash frequency, adapted from (AASHTO, 2010).

Furthermore, crashes are also rare events, which means that represent only a very small proportion of the total number of events that occur on the transportation system. The circumstances that lead to a crash in one event will not necessary lead to a crash in a similar event, which reflects the randomness inherent in crashes (AASHTO, 2010).

Crash Rate is also used to evaluate safety and it is defined as the number of crashes that occur at a given site during a certain time in relation to a particular measure of exposure (e.g. per million vehicle.km of travel). Crash Rate can alternatively be defined as the probability (based on past events) of being involved in a crash per instance of exposure measure. For example, if the crash rate on a roadway segment is one crash per one million vehicle.km per year then it means that a vehicle has a one-in-a-million chance of being in a crash for every km travelled on that roadway segment (AASHTO, 2010).

$$Crash\ Rate = \frac{Average\ Crash\ Frequency\ in\ a\ Period}{Exposure\ in\ the\ Same\ Period} \quad (1)$$

$$Exposure = 365 \times AADT \times Years \times Length \quad (2)$$

It is worth mention that the use of crash rate incorrectly assumes a linear relationship between crash frequency and the measure of exposure. Research (Zegeer et al., 1981; Council and Stewart, 1999; Kononov and Allery, 2003) has confirmed that while there are often strong relationships between crashes and many measures of exposure, these relationships are usually non-linear.

Several models were developed or calibrated using traffic, length of the section and in some cases geometric characteristics of the road as explanatory variables. One of the main references is the Highway Safety Manual (HSM) developed by AASHTO (AASHTO, 2010, 2014). The HSM presents a predictive method for estimating the expected average crash frequency by total crashes, crash severity or collision types. Different multiple regression models called Safety Performance Functions were developed for specific facility types and base conditions. These models depend on just two variables, the average annual daily traffic (AADT) volumes and the length of the section. For calibration purposes Crash Modification Factors (CMFs) and a Calibration Factor (C) were also developed.

Crash Modification Factors represent the relative change in crash frequency due to the change in one specific condition when all the other conditions remain constant. These factors serve as an estimate of the effect of a particular treatment and they are expressed as the ratio of the crash frequency of a site under two different conditions. Calibration is the process of adjusting the Safety Performance Functions (SPFs) to reflect the different crash frequencies between different jurisdictions. Geographic regions may differ in factors such as climate, driver populations. This process provides a method of incorporating local data to improve estimated crash frequencies for individual agencies or locations (AASHTO, 2010).

$$N_{predicted} = N_{SPF_x} \times \left(CMF_{1x} \times CMF_{2x} \times ... \times CMF_{yx} \right) \times C_x \quad (3)$$

The statistical reliability (probability that the estimate is correct) is improved by combining observed crash frequency and the estimate of the average crash frequency from a predictive model. The Empirical Bayes Method (EB Method) uses a weight factor function of the SPF overdispersion parameter, to combine the two estimates into a weighted average. It is only applicable when both predicted and observed crash frequencies are available. It can be used to site-specific level where crashes can be assigned to a particular location or at a project-specific level where observed data may be known for a particular facility but cannot be assigned to the site (AASHTO, 2010).

$$N_{expected} = w \times N_{predicted} + (1 - w) \times N_{observed} \quad (4)$$

The weighted adjustment factor, w, is a function of the SPF's overdispersion parameter, k, and it is calculated using Equation (5)

$$w = \frac{1}{1 + k \times \left[\sum_{Years} N_{predicted} \right]} \quad (5)$$

Roadway Safety Management is extremely important since provide awareness of sites that could benefit from treatments to reduce crash frequency/severity and the understanding of crash patterns and countermeasures most likely to reduce crash frequency (AASHTO, 2010).

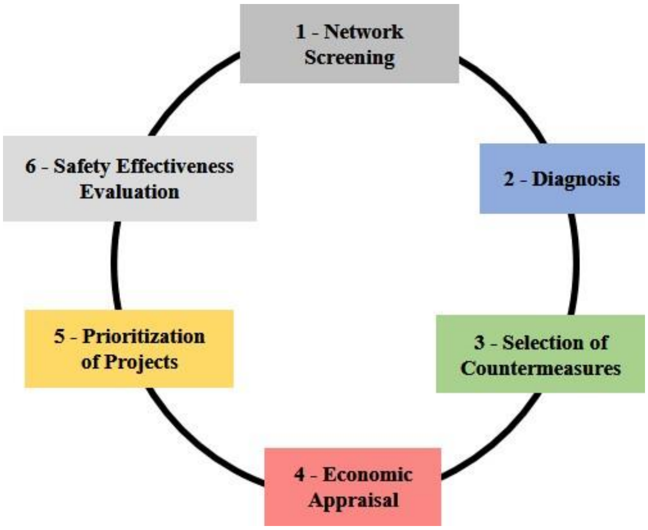

Fig. 3. Roadway Safety Management Process adapted from (AASHTO, 2010).

Several reports (FHWA, 2013a, 2013b, NCHRP, 2014) providing guidelines on the implementation of the methods and procedures were written as a complement of the HSM. In the RISMET Project, (RISMET, 2011a), several APMs for rural junctions based on data from Norway, Austria, Portugal and Netherlands were developed. Within the project an APM with a Poisson Regression Model based on the road network of the German federal state Brandenburg was developed (RISMET, 2011b). The model was then tested on the Portuguese Road IP4 resulting in significant differences in the number of accidents predicted. Researchers justified the fact with the need of calibrating the model to the Portuguese conditions. Other important relevant initiatives are:

- ROSEBUD Handbook, ROSEBUD (2006), assessing user related, vehicle related and infrastructure related measures, by application of Cost-Effectiveness Analysis (CEA) or Cost-Benefit Analysis (CBA);
- SUPREME research project, SUPREME (2007a, 2007b), identifying best practice in road safety measures;
- Handbook of Road Safety Measures, Elvik et al. (2009), which includes a systematic overview of current knowledge regarding the effects of road safety measures and Crash Modifications Factors (CMFs);
- CEDR Reports, CEDR (2008, 2012), investigating in depth specific road infrastructure safety measures;
- "Countermeasures That Work" guide, NHTSA (2013), aimed primarily to legislation, enforcement, training and communication measures and secondarily to infrastructure treatments;
- PRACT Project, PRACT (2016), aimed to develop an European Accident Prediction Model (APM) that could be applied to different European road networks with a proper calibration.

The Web-Based Databases and Road Safety Toolkits are also an extra extremely useful tool to the Road Safety Managers. The most recognized ones are: the FHWA CMF Clearinghouse; the Austroads Road Safety Engineering Toolkit; and the iRAP Road Safety Toolkit.

More recently, researchers started to study other contributing factors to accidents occurrence. The introduction of the Condition of the Pavement as a new explanatory variable represented a step forward in the Incorporation of Road Safety into Pavement Management. The parameters describing the texture of pavement are very important for a comprehensive assessment of skid resistance, which is defined as the frictional resistance at the interface between a vehicle tyre and the road surface. The measure of skid resistance is the friction coefficient, closely related to the surface texture. The surface texture ensures draining water from the tire-pavement interface area. The role of skid resistance in road safety becomes particularly relevant when the pavement is moist or wet. Microtexture is defined by the resistance to polishing of coarse aggregate and the content of particles smaller than 2 mm in the aggregate mix used for the wearing course. It corresponds to a wavelength below 0.5 mm and it is assessed indirectly based on Polished Stone Value (PSV) and by measuring the friction coefficient at low slip speed (10-20 km/h) in-situ. Macrotexture is characterized by the type of surface layer and by the particle size distribution of the aggregate mix used. It corresponds to deviations from a flat plane having wavelength between 0.5 and 50 mm. Macrotexture parameters include Mean Texture Depth (MTD) determined by the volumetric method and Mean Profile Depth (MPD) derived from profilometric analysis. Both microtexture and macrotexture evolve under the effect of traffic and weathering. The most rapid evolution of the friction coefficient occurs in the early life of using road pavements after which it stabilizes. In the latter period changes to the friction coefficient are of seasonal nature and depend on the climate zone. Roughness is the largest scale with characteristic wavelengths of 0.1–100 m and it is defined as the irregularities of the pavement surface caused by cracking, rutting, ravelling and potholing. It is measure by the International Roughness Index (IRI) and when presents high values may cause the loss of control during braking and steering. When pavement roughness increases the contact area between tires and pavement decreases leading to a lower brake friction (Chan et al., 2009).

In Europe, the evaluation of road safety measures appears to be the weakest component of PMSs. Only in few countries the evaluation of road safety measures is part of a routine activity with a dedicated budget. Similarly, in the United States almost all states do not use the safety analysis in their Pavement Management Systems.

2. Modelling techniques for safety analysis

The modelling techniques for safety analysis can be divided mainly in: Statistical models, Numerical models, Traffic conflict analysis and Simulation models. For the purpose of this work only statistical models will be referred. Statistical Models study the relationships between the number/severity of crashes with the main safety-related factors. These models are divided into 3 types: Crash count models (or quantitative response models), Crash severity models (or qualitative response models) and the combination of both. A comprehensive review on different statistical methods for crash count modelling can be found in Lord and Mannering (2010). With regard to the evolution of methodological alternatives in accident research, the frequency of crashes has been studied with a wide variety of methods over the years. Because crash frequencies are count data (non-negative integers), the Poisson Regression models have served as a basis in the development of APMs. As research progressed, due to the limitations of the simple Poisson regression models, Poisson variants started to be applied. The Negative Binomial model (or Poisson–Gamma) became widely used because it can handle over dispersed data. Another approach was looked at crashes not as count data per se, but instead as the duration of time between crashes (duration models), which in turn can be used to generate crash frequencies over specified time periods (Castro et al., 2012). Recently, a series of studies have recast Count Models as a restrictive case of a Generalized Ordered-Response model. For the multiple discrete outcome models, multinomial models that do not account for the ordering of injury outcome such as the Simple Multinomial Logit model, the Nested Logit model, and the Random Parameters Logit model have been widely applied. Modelling approaches that do consider the ordering of injury severities, such as the Ordered Probit and Logit model, have also been applied to overcome possible restrictions imposed by traditional ordered-modelling approaches (Castro et al., 2012). In Table 1 some of the studies on the development of APMs considering Pavement Condition parameters as explanatory variables are presented.

Table 1. Summary of the Models Considering Pavement Condition.

Model	Reference	Modelling Technique	Independent Variables	Dependent Variables	Results
1	Karlaftis and Golias (2002)	Hierarchical Tree-Based Regression Models	Geometric Design, Pavement Condition	Traffic Crash Rates	Geometric design and pavement condition variables are key factors
2	Kuttesch (2004)	Simple and Multiple Linear Regression Models	Friction	Wet-Weather Crashes	Skid resistance is statistically significant. Friction data explain only a small portion of the variation
3	Davies et al. (2005)	Poisson Regression Models	Friction, Texture Depth, IRI, Rut Depth, Road Geometry, Roadway Characteristics	Crash Risk	Strong correlation between skid resistance and crash rate
4	Larson et al. (2008)	Simple Linear Regression Models. Multivariate Linear Analysis	Friction, Macrotexture, IRI, AADT	Wet-Weather Crashes	Poor statistical correlations
5	Chan et al. (2009)	Negative Binomial Regression	AADT, Right Shoulder, Left Clearance, PSI, IRI, Rut Depth	Crash Frequency Crash Types	Rut Depth was not significant. Due do collinearity, PSI and IRI cannot be applied in the same model
6	Anastasopoulos and Mannering (2009)	Random-Parameters Count Models	IRI, Pavement Condition Rating	Accident Frequency	
7	Chan et al. (2010)	Negative Binomial Regression Models	IRI, Ruth Depth, PSI	Number of Accidents	IRI had a significant influence
8	Labi (2011)	Negative Binomial Regression Models	Friction, Pavement Condition	Crash Severity	
9	Anastasopoulos et al. (2012)	Multivariate Tobit Model	Pavement Condition	Crash Rates by Severity Levels	Road condition is a significant factor. Effects on collisions was found to vary significantly across roadway segments
10	Izeppi et al. (2015)	Negative Binomial Regression	Grip Number	Crash Rates	Grip Number is significant. Amount of savings obtained by preventing crashes has very high potential
11	Lee et al. (2015)	Bayesian Ordered Logistic Regression Model	Road Condition Index	Crash Severity Levels	Severity levels of most crash types can be reduced when the pavement condition is well maintained

3. Proposed Methodology

3.1. Introduction

The HDM-4 deterministic models are used to predict the incremental deterioration in the road pavements. Pavement deterioration manifests itself in various kinds of distresses, each of which is modelled separately in HDM-4. Pavement deterioration is an inherently complex phenomenon because of the interactions between many of the deterioration mechanisms. For example, the total longitudinal roughness consists of a number of components representing different distresses, all of which contribute in different ways to the overall longitudinal roughness value. Cracks eventually spall and lead to potholes which increase longitudinal roughness, but cracks allow the ingress of water, in turn, weakens the road structure and leads to deformation or rutting which also contributes to longitudinal roughness. The magnitude of all these effects depends mostly on traffic, environment, material qualities and maintenance policy. In order to model road deterioration properly it is necessary to identify homogeneous road sections in terms of physical attributes and condition, so that a particular set of road deterioration relationships can be applied (Odoki and Kerali, 2000).

Road deterioration is predicted through eight separate distress modes, namely:

- Cracking
- Ravelling
- Potholing
- Edge-break
- Rutting
- Roughness
- Texture depth
- Skid resistance

The distress parameters can be considered under the following three categories:

- **Surfacing distress** (cracking, ravelling and potholing), which are characterised by two phases referred to as initiation and progression. The initiation phase is the period before surfacing distress of a given mode or severity develops. The progression phase refers to the period during which the area and severity of distress increases.
- **Deformation distress** (rutting and roughness). Deformation distress modes are continuous and represented by only progression equations. As they are partly dependent upon the surfacing distress, they are computed after the change of surfacing distress in the analysis year has been calculated.
- **Surface texture** (texture depth and skid resistance). Surface texture distress modes are continuous, and like deformation distress modes, they are modelled only through their progression.

In terms of APM a model based on the methodology of the HSM, which is defined by Equation x was used to predicted the crash rate (McCarthy, 2015).

$$CR = e^{-0.35+1.25\times ln\left(AADT/10000\right)-1.19\times GN} \quad (6)$$

Then, the crash rate value was transformed in number of predicted accidents according to Equations (1, 2). Finally, in order to calculate the accident costs it was considered that 2% of the total number of accidents resulted in fatalities, 8% in seriously injured and 90% in slightly injured victims. Since, the number of accidents observations was different from the number of predicted the EB method was tested but not applied for the total period of analysis. Even though, in the years in which the EB method was tested the final results of the model were closer to the observed ones.

3.2. Hierarchy of works

An M&R operation is triggered when any one or a combination of the user-specified threshold criterions has been met. When more than one works activity meets the criteria for being applied in a given analysis year, the highest placed operation for the particular road feature is selected. The warning/thresholds levels used in this research are defined in Table 2.

Table 2. Warning levels by distress type.

Distress type	**Warning level**
Fatigue Cracking	Index Cracking ≤ 20.0%
Rutting	Mean Rut Depth ≤ 15 mm
	IRI ≤ 3.5 m/km for 100% of the section length
Longitudinal Roughness	IRI ≤ 2.5 m/km for 80% of the section length
	IRI ≤ 1.5 m/km for 50% of the section length
Macrotexture	Mean Profile Depth ≥ 0.7
Skid Resistance	SCRIM ≥ 0.4 (50 km/h)
	SCRIM ≥ 0.2 (120 km/h)
Present Serviceability Index	PSI ≥ 2

3.3. Definition of the M&R operations

The types of M&R operations and actions performed in each operation are defined in Table 3. The M&R operation 1 corresponds to “do nothing” and can only be applied when none of the pavements condition parameters reached the warning levels. The next two M&R operations are defined to restore the functional aspects of the pavements. Operation 2 should be performed whenever the friction levels or the texture depth are below the warning levels. Operation 3 is designed to seal the cracks and patching. The remaining M&R operations are defined to restore the structural capacity of the pavements and they are ordered by increasing strength and costly operations. Operation 4 is triggered if cracking, rutting or longitudinal roughness (IRI) are above the warning levels. Similarly, the operation 5 is also triggered if cracking, rutting or IRI are above the warning levels. The difference between Operation 4 and 5 is that the latest provides a bigger benefit in the long-run since the structural capacity associated with this operation is higher, however is more expensive. Operation 6 is triggered if there are problems of cracking and rutting simultaneous or IRI and PSI. Also, in the case of having the PSI levels below the warning levels operation 6 is applied. Finally, operation 7 is activated when the life cycle of the pavement is in the end, meaning that the area of cracking is close to 90%, rutting and IRI are above the warning levels and in addition PSI is below the warning level. It is equivalent to the construction of a new pavement with the characteristics defined in Table 3.

3.4. Definition of the Benefits and Costs of each M&R Operation

The efficiency of an M&R operation is defined as the time between its application to the pavement and the moment when the pavement reaches the minimum level for that M&R operation.

Agency Costs

Agency costs are the costs to construct and maintain pavement structures above a certain quality level including the initial costs such as construction and administration costs among others and the costs associated with the M&R actions of the pavements. M&R Operation Costs, as construction costs, normally represent an important percentage of the total agency costs, therefore it is essential to adopt cost effective maintenance policies and measures to ensure Agency costs are the costs to construct and maintain pavement structures above a certain quality level including the initial costs such as construction and administration costs among others and the costs associated with the M&R actions of the pavements. M&R Operation Costs, as construction costs, normally represent an important percentage of the total agency costs, therefore it is essential to adopt cost effective maintenance policies and measures to ensure the pavements quality level desired. The option of doing nothing for a road over a period of typically 20 years is rarely a wise option. Although being more expensive than corrective maintenance actions, preventive maintenance actions are more cost-effective in the long run, since they delay deterioration, extending the pavements service life.

Table 3. Definition of the M&R Operations.

M&R Operation	Description	M&R Actions
1	Do nothing	• Do nothing
2	Restitution of the levels of friction	• Micro-milling • Cold double asphalt concrete micro-aggregate
3	Crack sealing and patching	• Micro-milling (0.05 m ≤ thickness depth ≤ 0.10 m) • Binder layer AC20 bin with thickness = 0.05 m • Modified tack coat • Replacement of failed area with reposition • Cold double asphalt concrete micro-aggregate
4	Light structural reinforcement	• Micro-milling (0.05 m ≤ thickness depth ≤ 0.10 m) • Complementary milling (0.05 m ≤ thickness depth ≤ 0.10 m) • Binder layer AC20 bin with thickness = 0.05 m • Modified tack coat • Replacement of failed area with reposition • Wearing course AC14 surf with thickness = 0.05 m
5	Medium structural reinforcement	• Micro-milling (0.05 m ≤ thickness depth ≤ 0.10 m) • Reshaping AC4 reg with thickness = 0.02 m • Modified tack coat • Replacement of failed area with reposition • Binder layer AC20 bin with thickness = 0.07 m • Wearing course AC14 surf with thickness = 0.05 m
6	Heavy structural reinforcement	• Micro-milling (thickness depth > 0.10 m) • Complementary milling (0.05 m ≤ thickness depth ≤ 0.10 m) • Reshaping AC4 reg with thickness = 0.02 m • Modified tack coat • Replacement of failed area with reposition • Binder layer AC20 bin with thickness = 0.09 m • Wearing course AC14 surf with thickness = 0.06 m
7	Reconstruction	• Total pavement removal • Sub-base layer ABGE with thickness = 0.15 m • Base layer ABGE with thickness = 0.15 m • Penetration prime coat • Modified tack coat • Base layer AC32 base with thickness = 0.10 m • Binder layer AC20 bin with thickness = 0.09 m • Wearing course AC14 surf with thickness = 0.06 m

Table 4. Definition of the Alternative M&R Operations.

M&R Operation	Alternative M&R Operations						
	1	2	3	4	5	6	7
1	a), b)	b)	b)	b)	b)	b)	b)
2		a)	b)	b)	b)	b)	b)
3			a)	b)	b)	b)	b)
4				a)	b)	b)	b)
5					a)	b)	b)
6						a)	b)
7							a)

a) Policy I
b) Policy II

Table 5. Definition of the Benefits and Costs of the M&R Operations.

M&R Operation	**Description**	**Structural Number**	**PSI reab**	**Expected Life Span (years)**	**Cost (€/m^2)**
1	Do nothing	ΔSN=0	ΔPSI=0	-	0
2	Restitution of the levels of friction	ΔSN=0	ΔPSI=0	2	3.5
3	Crack sealing	ΔSN=0	ΔPSI is calculated considering the current PSI value and assuming cracking=0	2	4.2
4	Light structural reinforcement	ΔSN=1.26	PSI reab=4.50	5	11.6
5	Medium structural reinforcement	ΔSN=1.65	PSI reab=4.50	10	17.5
6	Heavy structural reinforcement	ΔSN=2.10	PSI reab=4.50	10	25.8
7	Reconstruction	SN=7.37	PSI reab=4.50	20	32.2

Table 6. Definition of the Alternative M&R Operations.

M&R Operation	**Alternative M&R Operations**						
	1	2	3	4	5	6	7
1	a), b)	b)	b)	b)	b)	b)	b)
2		a)	b)	b)	b)	b)	b)
3			a)	b)	b)	b)	b)
4				a)	b)	b)	b)
5					a)	b)	b)
6						a)	b)
7							a)

a) Policy I
b) Policy II

User Costs

Adding to this, the increase in users' satisfaction, increase in safety and the decrease in noise and pollutant emissions are additional benefits related with adopting preventive policies. The primary safety benefits that are provided from PM treatments come from these three ways:

- Since roads are maintained in good condition for a longer period of time, there are present fewer safety-related defects such as potholes, weathering, ravelling, and rutting;
- Certain M&R actions can restore surface texture, which improves surface friction (both wet and dry) while also reducing the amount of water spray, hydroplaning, and road noise.
- Since the construction period associated with M&R actions is very short, there are fewer disruptions in traffic flow patterns which help to reduce the number of crashes due to construction activities.

Therefore, User Costs are important in economic evaluation of pavements. Unfortunately, many highway agencies still do not accept the validity of user costs and thus seldom use them in decision making (Haas et al., 2015). Firstly, highway agencies advocate that these costs are difficult to estimate accurately. Secondly, and perhaps the most decisive reason, they defend that such costs are external to their own expenditure. The survey carried out by Rangaraju et al. (2008) showed that approximately 60% (19 out 32) of the US State Highway Agencies do not consider user costs in Life-Cycle Cost Analysis (LCCA) calculations. Despite the resistance evidenced by highway agencies with respect to inclusion of user costs into LCCA systems, many authors have expressed a contrary point of view. Ozbay et al. (2004) underlined that the inclusion of user costs is one of the most important gaps between state-of-the-practise and state-of-the-art of LCCA. FHWA (2002) stated that incorporating user costs into LCCA enhances the validity of the results, though it is a challenging task. Thoft-Christensen (2010) referred that for society (and users in particular) it is of great importance that maintenance, rehabilitation, or replacement of an infrastructure is performed in such a way that all costs are minimised, and not merely the owners' cost. Talking about user costs imply to reflect on what originate them and how they are "felt" by the road user. For pavement projects, Walls and Smith (1998) stated that the user costs can be classified at light of two dimensions: user costs categories (work-zone category and normal operation category) and user costs components (VOCs, time delay costs and accident costs).

Vehicle operation costs

The VOCs are a component of user cost that are depending on running motorized vehicles on the highway, including the expenses of fuel consumption, tires, engine oil, maintenance and the depreciation attributable to highway distance travelled (Ellis and Herbsman, 1997). The fuel consumption is referred in the literature as the main component of VOCs. In normal operation conditions, the VOCs are generally a function of the pavement condition (Flintsch and Kuttesch, 2004). The pavement condition has been reported to have the greatest influence on rolling resistance force, one of the resistive forces acting on the vehicle. The other resistive forces are the gradient, the inertia, the curvature, and the aerodynamic forces. A large and historic body of research is available on the effects of pavement condition on fuel consumption. The AASHTO (2003) provides two procedures for calculating fuel consumption costs as a function of speed or delay. The relationship between speed and fuel consumption is described for both automobiles and trucks. FHWA (2005) proposes a fairly complex methodology in which VOCs are calculated for seven vehicle types (two automobiles types and five truck types) as a function of fuel, oil, tires, maintenance and repair, and, mileage-based depreciation. The process is done in three steps, which include: constant speed operating cost, which are calculated as a function of average speed, average grade, and pavement condition; excess operating costs due to speed change cycles; excess operating costs due to the road curvature. The results of these three steps are summed up to give the total VOCs. In Portugal, the VOCs models that have been proposed to integrate PMS are based on empirical relationships with the surface roughness.

$$VOC_t = 0.39904 - 0.03871 \times PSI_t + 0.00709 \times PSI_t^2 - 0.00042 \times PSI_t^3 \quad (7)$$

Accident costs

Road accident cost components have emerged as the most important theme in the category of social aspects. They refer to the economic value of damages caused by vehicle crashes, which include fatality, injury and property damages. They can occur not only during normal operation of the highway but also as a consequence of the work-zones. Typically, these costs are estimated by multiplying the number of crashes for each crash type by the average cost per crash. There are several methods used in estimating the economic and social cost of road accidents and no consensus exists regarding the best method. The Human Capital or Gross Domestic Product (GDP Method) is based on the production potential of the fatal or disabled individual during his lifetime in the absence of a road accident. It consists in comprising the accident costs associated to the loss of future production, hospital costs, property damages, administrative and non-monetary costs. The Court Compensation Method considers that society can assess accident costs through indemnity awarded by courts, a proxy measure of real costs. The Life insurance method is based on the use of the insurance premium that an individual would be willing to pay, coupled with the probability of being killed or injured in a road accident. One of the criticisms made to this approach is that it only focuses on compensation provided to third parties and overlooks fatal victims, which – naturally – cannot be compensated. Finally, the Willingness-to-Pay Method considers the maximum amount that a person would be willing to pay to reduce the probability of having an accident and being killed or injured. While the willingness-to-pay approach has many supporters, and from a theoretical point of view is the best approach, assessing it empirically has turned out to be very difficult. Studies have been reported in many countries, but the results vary enormously. In view of this, there is a need for more research concerning how best to elicit willingness-to-pay for improved road safety (ANSR, 2012).

In Table 7 the average costs of accidents used by the National Authority for Road Safety (ANSR) are presented.

Table 7. Definition of the Accident Costs (ANSR, 2012).

Accident Type/Severity	Average Cost
With Fatalities	735,428.0€
With Serious Injured Victims	121,429.0€
With Slightly Injured Victims	31,944.0€
Per Mortal Victim	663,800.0€
Per Serious Injured Victim	96,100.0€
Per Slightly Injured Victim	23,100.0€

4. Case study

4.1. Introduction

The data used in this research is part of a National Road Agency database and included the attributes of the sections (see Table 8) and the crash counts from 2007 until 2015.

Table 8. Definition of the Attributes of the Sections.

Attributes	Sections		
Section ID	1	2	3
Road class	Highway	Highway	Highway
Length (m)	100	100	100
Width (m)	7	7	3.75
Age (years)	1	1	1
Annual average daily traffic	22603	9179	8634
Annual average daily heavy traffic	3476	1513	604
Annual growth average rate (%)	2	2	2.36
Truck factor	5.5	5.5	5.5
Sub-grade CBR (%)	12	12	12
Modified Structural Number (SNC)	8.18	7.49	7.05
Thickness of asphalt layers (mm)	90	100	90
Structural Cracked Area (%)	0	0	0
Mean Rut Depth (mm)	1.35	0.70	0
Ravelling Area (%)	0	0	0
Number of Potholes	0	0	0
IRI (m/km)	0.86	1.50	1.53
PSI	4.50	4.50	4.50
Texture Depth (MPD)	1.56	1.05	1.26
Grip Number	0.44	0.50	0.61

For the definition of long-term (20-year) M&R plan two different M&R policies were considered:

- Policy I: The simplest M&R operation is applied in the year in which the state parameter threshold is violated;
- Policy II: The M&R operation is performed in the year immediately before the state parameter threshold is violated, over the planning time-span.

In Policy I the M&R operations are only applied when the values of the quality state parameters (cracking, rutting, longitudinal roughness, surface disintegration, texture depth, skid resistance and PSI) reach their corresponding warning level (WL). The objective to be achieved through Policy II was to assess the effect (in terms of Agency Costs, User Costs and Total Costs) of applying the corresponding M&R operation in the year immediately before reaching the threshold levels or to apply a higher M&R Operation than the one resulted from Policy I.

4.2. Modelling logic

The overall computational procedure for modelling road works that is applied in each analysis year can be summarised by the following steps:

1) Calculate the evolution of all the State Parameters according to the HDM-4 models.
2) Check the intervention criteria and stop evolution when the threshold is violated.
3) Identify and apply the M&R operation.
4) Compute works effects and reset modelling parameter values to reflect post-works road geometry, pavement structure, strength, history and condition.
5) Calculate the costs of M&R operations by applying the unit costs to the damaged State Parameters areas.
6) Calculate the effect on the section's asset valuation.
7) Store results for economic analysis and for use in the following analysis year.
8) Repeat the process until the end of the Period of Analysis (20 years)

4.3. Discussion of results

In section 1, for Policy I, M&R operation 3 was applied due to cracking problems in year 10, 15 and 20. It is important to know that, since this section did not present initial rutting and the value of longitudinal roughness was not significant these results were expected. The detailed condition of section 1, for each iteration it is presented in Table 10.

Table 9. Programmed M&R operations Policy I to be applied in section 1.

	Policy I - Scenarios																			
	Year																			
Section 1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	1	1	1	1	1	1	1	1	1	**3**	1	1	1	1	**3**	1	1	1	1	**3**

Table 10. Parameters Condition for Policy I for section 1 in each iteration.

	Policy I – Parameters Condition													
	Year	**Date**	**ACA_b**	**ACW_b**	**ACX_b**	**$SNPK_b$**	**RDM_b**	**RDS_b**	**ARV_b**	**NPT_b**	**RI_b**	**PSI_b**	**TD_{av}**	**$SFCS_{120}$**
Section 1	10	2019	16.14	10.97	20.32	8.04	7.93	3.25	0.00	4.78	1.78	3.91	1.20	0.30
	15	2024	31.66	20.79	27.74	7.83	10.72	4.26	0.00	19.58	2.46	3.49	1.20	0.30
	20	2029	31.66	20.79	27.74	7.62	13.83	5.11	0.00	19.84	3.26	3.45	1.20	0.30

Also, in section 1 for Policy II, M&R operation 3 was applied in year 9 (immediately before violating the cracking threshold). In the second iteration, M&R operation 3 was applied in year 14 because the cracking threshold was violated). Finally, the M&R operation 3 was applied in year 19 due to cracking problems again. For this section it can be concluded that the M&R operation has an efficiency of 4 years and after that it must be applied again until.

Table 11. Programmed M&R operations Policy II to be applied in section 1.

	Policy II - Scenarios																			
	Year																			
Section 1	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	1	1	1	1	1	1	1	1	**3**	1	1	1	1	**3**	1	1	1	1	**3**	1

Table 12. Parameters Condition for Policy II for section 1 in each iteration.

Policy II – Parameters Condition														
	Year	Date	ACA_b	ACW_b	ACX_b	$SNPK_b$	RDM_b	RDS_b	ARV_b	NPT_b	RI_b	PSI_b	TD_{av}	$SFCS_{120}$
Section 1	9	2018	16.14	4.01	11.57	8.12	7.40	3.03	0.00	0.00	1.64	4.26	1.20	0.30
	14	2023	31.66	20.79	27.74	7.91	10.13	4.07	0.00	19.21	2.28	3.51	1.20	0.30
	19	2028	31.66	20.79	27.74	7.69	13.17	4.95	0.00	19.54	3.05	3.46	1.20	0.30
	20	2029	2.19	0.00	1.36	7.69	13.81	5.10	0.00	0.00	3.20	4.50	1.20	0.31

From the results in Table 13, it can be concluded that for Policy I the user costs are much higher than the agency costs. This fact is a consequence of having small damaged areas in sections of 100 meters of length. However, the residual value of the pavement is higher in Policy I than in Policy II because the final condition of the pavement is also higher. In Policy II the agency costs are lower than the obtained in the Policy I. The user costs are also much higher than the agency costs, but slightly lower than in the ones resulted from Policy I. Therefore, the total costs are slightly lower in Policy I.

Table 13. Comparison between the costs due to M&R operations applied in section 1.

	Costs	Policy I	Policy II
		a)	a)
Section 1	**1 – Agency Costs**	2,228.32€	1,970.96€
	a - VOC	2,980.80 €	2,920.31€
	b - Accident	1,043,620.78€	991,439.74€
	2 - Users Costs (a + b)	1,046,601.58€	994,360.06€
	3 - Residual Value of pavements	1,407.71€	808.86 €
	Total Costs (1 + 2 - 3)	**1,047,422.19€**	**995,522.15€**

In section 2, for Policy I, M&R operation 3 was applied (cracking problems) in year 13, followed by M&R operation 4 in year 18 due to simultaneous cracking and longitudinal roughness problems. Policy II also provides better results in terms of agency, user and total costs in section 2.

Table 14. Programmed M&R operations Policy I to be applied in section 2.

Policy I - Scenarios																				
	Year																			
Section 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	1	1	1	1	1	1	1	1	1	1	1	1	**3**	1	1	1	1	**4**	1	1

Table 15. Parameters Condition for Policy I for section 2 in each iteration.

Policy I – Parameters Condition														
	Year	Date	ACA_b	ACW_b	ACX_b	$SNPK_b$	RDM_b	RDS_b	ARV_b	NPT_b	RI_b	PSI_b	TD_{av}	$SFCS_{120}$
Section 2	13	2022	35.94	20.79	30.39	7.20	6.09	2.88	0.00	7.93	2.88	3.68	0.67	0.27
	18	2027	31.66	20.79	27.74	6.97	7.68	3.57	0.00	8.67	3.68	3.70	0.67	0.27
	20	2029	0.00	0.00	0.00	8.23	0.47	0.30	0.00	0.00	0.56	4.50	0.67	0.38

Table 16. Programmed M&R operations Policy II to be applied in section 2.

Policy II - Scenarios																				
	Year																			
Section 2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	1	1	1	1	1	1	1	1	1	1	1	**3**	1	1	1	1	**4**	1	1	1

Table 17. Parameters Condition for Policy II for section 2 in each iteration.

Policy II – Parameters Condition														
	Year	**Date**	**ACA_b**	**ACW_b**	**ACX_b**	**$SNPK_b$**	**RDM_b**	**RDS_b**	**ARV_b**	**NPT_b**	**RI_b**	**PSI_b**	**TD_{av}**	**$SFCS_{120}$**
Section 2	12	2021	24.06	10.97	19.20	7.35	5.77	2.73	0.00	2.09	2.69	4.01	0.67	0.27
	17	2026	31.66	20.79	27.74	7.11	7.32	3.42	0.00	8.51	3.46	3.71	0.67	0.27
	20	2029	0.00	0.00	0.00	8.37	0.71	0.45	0.00	0.00	0.60	4.50	0.67	0.38

Table 18. Comparison between the costs due to M&R operations in section 2.

	Costs	Policy I	Policy II
		a)	a)
Section 2	**1 – Agency Costs**	9,013.53€	8,684.38€
	a - VOC	1,121.41€	1,110.57€
	b - Accident	134,761.41€	133,447.87€
	2 - Users Costs (a + b)	135,882.82€	134,558.44€
	3 - Residual Value of pavements	8,120.00€	8,120.00€
	Total Costs (1 + 2 - 3)	**136,776.35€**	**135,122.82€**

In section 3, for Policy I, M&R operation 3 was applied (cracking problems) in year 14, followed by M&R operation 4 in year 14 due to simultaneous cracking and longitudinal roughness problems.

Table 19. Programmed M&R operations for Policy I to be applied in section 3.

Policy I - Scenarios																				
	Year																			
Section 3	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
	1	1	1	1	1	1	1	1	1	1	1	1	1	**3**	1	1	1	1	**4**	1

Table 20. Parameters Condition for Policy I for section 3 in each iteration.

Policy I – Parameters Condition														
	Year	**Date**	**ACA_b**	**ACW_b**	**ACX_b**	**$SNPK_b$**	**RDM_b**	**RDS_b**	**ARV_b**	**NPT_b**	**RI_b**	**PSI_b**	**TD_{av}**	**$SFCS_{120}$**
Section 3	14	2019	29.31	20.79	26.28	6.86	4.18	2.40	0.00	4.22	2.86	3.83	1.17	0.30
	19	2024	31.66	20.79	27.74	6.64	5.18	2.90	0.00	4.63	3.61	3.79	1.13	0.30
	20	2025	0.00	0.00	0.00	7.90	0.15	0.10	0.00	0.00	1.55	4.50	1.23	0.43

In section 3, for Policy II scenario a), M&R operation 3 was applied (cracking problems) in year 13, although the cracking was below the threshold level. Due to this action, which lowered the contribution of cracking in the longitudinal roughness, M&R operation 3 was applied again in year 18 (instead of M&R operation 4 of Policy I). However, in the end of year 20, section 3 presented longitudinal roughness problems and therefore M&R operation 4 was applied. In terms of costs, Policy II scenario a) presents higher agency, user and total costs than Policy I. Since, Policy II scenario a) was a worse solution, Policy I scenario was analyzed again and Policy II scenario b) tested. This scenario consisted in applying M&R operation 4 in year 14 (instead of M&R operation 3). The results showed that there was no need to apply any other M&R operation until the end of the period of analysis. Moreover, the agency, user and total costs were much lower than the ones obtained from Policy I.

Table 21. Programmed M&R operations for Policy II to be applied in section 3.

Policy II - Scenarios																					
		Year																			
		1a	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Section 3	**a)**	1	1	1	1	1	1	1	1	1	1	1	1	**3**	1	1	1	1	**3**	1	**4**
	b)	1	1	1	1	1	1	1	1	1	1	1	1	1	**4**	1	1	1	1	1	1

Table 22. Parameters Condition for Policy II for section 3 in each iteration.

	Policy II – Parameters Condition													
	Year	**Date**	**ACA_b**	**ACW_b**	**ACX_b**	**$SNPK_b$**	**RDM_b**	**RDS_b**	**ARV_b**	**NPT_b**	**RI_b**	**PSI_b**	**TD_{av}**	**$SFCS_{120}$**
Section 3	13	2018	18.80	10.97	15.93	6.97	3.98	2.29	0.00	0.00	2.69	4.12	1.17	0.30
	18	2023	31.66	20.79	27.74	6.49	4.77	0.51	0.00	4.54	3.25	3.79	1.13	0.30
	20	2025	6.06	0.00	3.76	6.33	5.16	0.61	0.00	4.56	3.52	4.38	1.21	0.30
	14	2019	29.31	20.79	26.28	6.86	4.18	2.40	0.00	0.4.22	2.86	3.83	1.17	0.30
	20	2025	0.00	0.00	0.00	8.12	0.91	0.57	0.00	0.00	1.86	4.50	1.18	0.43

Table 23. Comparison between the costs due to M&R operations applied in section 3.

	Costs	**Policy I**	**Policy II**	
		a)	**a)**	**b)***
Section 3	**1 – Agency Costs**	8,892.57€	9,403.86€	8,120.00€
	a - VOC	1,107.58€	1,246.91€	707.55€
	b - Accident	113,827.29€	114,973.20€	108,113.69€
	2 - Users Costs (a + b)	114,934.88€	116,220.10€	108,821.24€
	3 - Residual Value of pavements	8,120.00€	8,120.00€	8,120.00€
	Total Costs (1 + 2 - 3)	**115,707.45€**	**117,503.97€**	**108,821.24€**

Analyzing all sections, it can be concluded that Policy II would allow to save 60,439.80€ for just three sections with 100 m of length. However, the solutions presented are not optimum and can be improved significantly.

5. Conclusions

The objective of this article was to contribute to the incorporation of safety concerns into Pavement Management through a sensitive analysis. This sensitive analysis aimed to test the impact in terms of agency, user costs (including accident costs) and total costs of applying two different maintenance policies. The first one applies the M&R operations when the state parameter threshold is violated, while in the second one M&R operations can be applied before these values reach the thresholds levels or, in alternative, apply a stronger M&R operation than the one that is needed to correct the problem. In general, it can be concluded that Policy II is more flexible and presents better results. However, in order to achieve improved solutions, it is necessary to: first of all, to calibrate HDM-4 models to the Portuguese data. Secondly, develop APMs or at least to calibrate as well to achieve better fitting results. Finally, to find the optimum solution or a really good approximation, all the scenarios must be generated and analysed using optimization techniques. These improvements will be issued in the following developments of this research.

Acknowledgements

The author Rita Justo-Silva is grateful to the Portuguese Foundation of Science and Technology for her MIT-Portugal PhD Grant (PD/BD/113721/2015). The authors wish to acknowledge the reviewers for their valuable comments and suggestions.

References

AASHTO, 2003. User benefit analysis for highways manual. NCHRP Project 02-23, American Association of State Highway and Transportation Officials. ECO Northwest and Kittelson and Associates, Inc., Parsons.

AASHTO, 2010. Highway Safety Manual, First Edition, American Association of State and Highway Transportation Officials, Washington DC.

AASHTO, 2014. Highway Safety Manual, First Edition, 2014 Supplement, American Association of State and Highway Transportation Officials, Washington DC.

Anastasopoulos, P. C. and Mannering, F. L., 2009. A note on modeling vehicle accident frequencies with random-parameters count models. Accident Analysis and Prevention, Vol.41(1):153-159.

Anastasopoulos, P. C., Shankar, V. N., Haddock, J. E., and Mannering, F. L., 2012. A multivariate Tobit analysis of highway accident-injury-severity rates. Accident Analysis and Prevention, Vol.45(1):110-119.

Castro, M., Paleti, R., and Bhat, C., 2012. A latent variable representation of count data models to accommodate spatial and temporal dependence: application to predicting crash frequency at intersections. Transportation Research Part B, 46(1):253–272.

CEDR, 2008. Best Practice on Cost Effective Road Safety Infrastructure Investments, Conference of European Directors of Roads (CEDR) Report.

CEDR, 2012. Forgiving Roadsides Design Guide, Conference of European Directors of Roads (CEDR) Report.

Chan, C., Huang, B., Yan, X., and Richards, S., 2009. Relationship Between Highway Pavement Condition, Crash Frequency, and Crash Type. Journal of Transportation Safety and Security, Vol.1:4:268-281.

Chan, C., Huang, B., Yan, X., and Richards, S., 2010. Investigating effects of asphalt pavement conditions on traffic accidents in Tennessee based on the pavement management system (PMS). Journal of Advanced Transportation, Vol.44(3):150-161.

Council, F. M. and J. R Stewart., 1999. Safety effects of the conversion of rural two-lane to four-lane roadways based on cross-sectional models. In Transportation Research Record 1665. TRB, National Research Council, Washington, DC, pp. 35–43.

Davies, R., Cenek, P., and Henderson, R., 2005. The effect of skid resistance and texture on crash risk. International Conference on Surface Friction for Roads and Runways. Christchurch, NZ.

Donário, A. and Santos, R., 2012. The Economic and Cost of Road Accidents. The Portuguese Case. Lisboa, Portugal.

Elghriany, A., 2015. Investigating Correlations of Pavement Conditions with Crash Rates on In-Service U.S. Highways.

Ellis, R. and Herbsman, Z., 1997. Development for improved motorist user cost determinations for FDOT construction projects. Report no 0510748, University of Florida, Department of Civil Engineering, pages 1–276. Gainesville, Florida, USA.

Elvik R., Hoye A., Vaa T., 2009. Sorensen M.: The Handbook of Road Safety Measures, 2nd Edition, Emerald Group Publishing Ltd.

Fernandes, A., 2010. Programas de Manutenção de Características da Superfície de Pavimentos Associados a Critérios de Segurança Rodoviária.

FHWA, 2002. Life-cycle cost analysis primer. FHWA-IF-02-047, Federal Highway Administration, pages 1–36. Office of Asset Management, Washington, D.C., USA.

FHWA, 2005. Highway economic requirements system - state version (HERS-ST). Technical report, Federal Highway Administration, Office of Asset Management, pages 1–372. Washington D.C., USA.

FHWA, 2013a. Safety Performance Function Decision Guide: SPF Calibration vs. SPF Development. The University of North Carolina Highway Safety Research Center.

FHWA, 2013b. Safety Performance Function Development Guide: Developing Jurisdiction- Specific SPFs. The University of North Carolina Highway Safety Research Center.

Haas, R., Hudson, R. W., and Falls, L. C., 2015. Pavement Asset Management. Wiley-Scrivener.

Odoki, J. B. and H.R.G. Kerali, 2000.HDM-4 – Analytical Framework and Model Descriptions – Volume 4 of the Highway Development and Management Series. International Study of Highway Development and Management (ISOHDM), World Road Association PIARC, Paris. ISBN: 2-84060-062-5.

Izeppi, E., Katicha, S., Flintsch, G. and McCarthy, R., 2015. Pavement Friction Management Program Pilot Demonstration, Virginia Center for Transportation Innovation and Research.

Karlaftis, M. G. and Golias, I., 2002. Effects of road geometry and traffic volumes on rural roadway accident rates. Accident Analysis and Prevention, Vol.34(3):357-365.

Kononov, J. and B. Allery., 2003. Level of Service of Safety: Conceptual Blueprint and Analytical Framework. In Transportation Research Record 1840. TRB, National Research Council, Washington, DC, pp. 57–66.

Kuttesch, J., 2004. Quantifying the relationship between skid resistance and wet weather accidents for Virginia data. Master's thesis.

Labi, S., 2011. Efficacies of roadway safety improvements across functional subclasses of rural two-lane highways. Journal of Safety Research, Vol.42(4):231-239.

Larson, R. M., Hoerner, T. E., Smith, K. D., and Wolters, A. S., 2008. Relationship between skid resistance numbers measured with ribbed and smooth tire and wet accident locations.

Lee, J., Nam, B., and Abdel-Aty, M., 2015. Effects of Pavement Surface Conditions on Traffic Crash Severity. Journal of Transportation Engineering, Vol.11:1-11.

Lord, D. and Mannering, F., 2010. The statistical analysis of crash-frequency data: a review and assessment of methodological alternatives. Transportation Research Part A: Policy and Practice, 44(5):291-05.

McCarthy, J. R., 2015. Performing Network Level Crash Evaluation Using Skid Resistance, Master Thesis, Virginia Polytechnic Institute.

NCHRP, 2014. User's Guide to Develop Highway Safety Manual Safety Performance Function Calibration Factors. National Cooperative Highway Research Program (NCHRP) Project No. HR 20 – 7(332). NAVIGATS Inc.

NHTSA, 2013. Countermeasures that work: A Highway Safety Countermeasure Guide For State Highway Safety Offices. 7th edition. National Highway Traffic Safety Administration Report No. DOT HS 811 727, Washington DC.

Ozbay, K., Jawad, D., Parker, N., and Hussain, S., 2004. Life-cycle cost analysis: state of the practice versus state of the art. Transportation Research Record: Journal of the Transportation Research Board, Vol.1864:62–70.

PRACT, 2016. Predicting Road Accidents – A transferable methodology across Europe. Inventory and Critical Review of existing APMs and CMFs and related Data Sources. CEDR Call 2013: Safety, 2016.

RISMET, 2011a. Accident Prediction Models for Rural Junctions on Four European Countries. Deliverable Nr 6.1.

RISMET, 2011b. Applying speed prediction model models to define road sections and to develop accident prediction models: A German case study and a Portuguese exploratory study.

ROSEBUD, 2006. Examples of assessed road safety measures – a short handbook. Research Project.

SUPREME, 2007a. Handbook for measures at the Country level. SUPREME Consortium, research project.

SUPREME, 2007b. Handbook for measures at the European level. SUPREME Consortium, research project.

Thoft-Christensen, P., 2010. Infrastructures and life-cycle cost-benefit analysis. Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance, Vol. 8(5):507–516.

Walls, J. and Smith, M., 1998. Life-cycle cost analysis in pavement design - in search of better investment decisions. Federal Highway Administration, pages 1–107. Washington, D.C., USA.

Zegeer, C. V., R. C. Deen, and J. G. Mayes, 1981. Effect of lane width and shoulder widths on crash reduction on rural, two-lane roads. In Transportation Research Record 806. TRB, National Research Council, Washington, DC, pp. 33–43.