Probabilistic Modeling of Impact of Vehicles on the Road Furniture

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Abstract Near driving lanes of roadways, numerous components of transport infrastructure are located along the route. Such components have to be secured by restraint systems, and in many cases different road lanes must also be effectively separated from each other. The focus of the study presented herein is to present a probabilistic approach for the departure of motor vehicles from their intended lane. Presently, assessments of the road infrastructure regarding possible accidents are primarily oriented to evaluating the resistance side. On the other hand, this paper intends to address the impact side by focusing on the likelihood of impact of vehicles on the road furniture. In order to determine the probability of impact, parameters of the traffic composition of the alignment, and of the pavement conditions were studied. A novel methodology is presented herein, which by accounting for these factors assesses the fragility of the infrastructure sub-system. The assessment joins both road engineering physics and expert judgements, and it is incorporated in spreadsheet tool. The feasibility of the tool is demonstrated, and sensitivities of the evaluation process are discussed and evaluated.

Keywords Transportation networks · Reliability analysis · Sensitivity · Road conditions · Routing elements

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1 Introduction

Socioeconomic impacts associated with the recent degradation of bridges have presented civil engineers with great challenges [1–3]. Thus, substantial efforts in the maintenance and assessment of road infrastructure components have been invested by government bodies, highway owners and operators. Since they form a frontline of safety against vehicle traffic–related accidents, a great extent of consideration was directed to the equipment of roads and bridges. To that end, their maintenance absorbs a significant portion of the assets' operational expenditures. Moreover, this can be seen through the fact that that there is a large number of standards and guidelines, which address design calculations, load models, inspection, recalculation, maintenance programs, and reliability assessment of existing components, such as [4–6]. At the same time, a substantial number of scientific investigations are centred on these considerations. However, these standards and research outcomes lack assessment procedures relating to the intensity of events and their likelihood. Furthermore, they fail to consider the interaction of road furniture with the traffic conditions (velocity, mixture of traffic), the surface conditions of lanes, and the routing elements of the lanes.

The main purpose of the study presented in this paper is to develop a framework that allows for a risk-based and significance-weighted performance assessment of road furniture. The reliability concepts applied in the study are coherent with the fundamental notions of [7, 8]. The risk-based assessment concepts focus on the action model that is highly variable, rather than the resistance side of furniture. The detailed objectives of the study can be summarized as follows:

- to deploy, in cooperation with infrastructure owners, a systematic and efficient analytical decision tool for the assessment and the intervention planning of the road equipment using probabilistic safety concepts (PSC),
- to develop a closed analytical solution, which merges the ratings of impacts on road equipment based on RVS [9] together with routing condition characteristics and traffic dynamic parameters,
- to permit an individual regulation of acceptable risks and reliability levels, consequently altering the remaining technical service life of road equipment,

The approach presented in the paper is flexible for incorporation of further properties and can be easily conveyed to other systems based on large input databases. At present, estimations of the road infrastructure regarding possible accidents are always concentrated on the resistance side. On the other hand, this paper focuses on the probability of impact of a vehicle on road furniture, and hence, addresses the impact side. Moreover, this contribution is continuation of previous work done by authors on the topic of likelihood of impact events in transport networks, which can be found in [10].

2 Background

Through large-scale research projects, instruction and guidance on the design of roadside and restraint elements for motorways have been constantly developing. In [11], for the assessment of various road infrastructure components (such as pavements, engineering structures, and road furniture) the introduction of maintenance backlogs is used. In [12], the findings of the ERA NET European project HEROAD (Holistic Evaluation of Road Assessment) are presented. This report is based on literature reviews, interviews, and the participants' experience, and it focuses on existing practices for the assessment of road assets in Europe.

In [13], a comprehensive presentation of monitoring techniques is presented, where the focus is set on the performance evaluation of a number of road components through manual inspections, fixed safety cameras, satellites, and mapping vehicles. In Austria, "RVS" [14] and Asfinag [15] deliver a description of the outcomes of the project "Asset Service Condition Assessment Methodology" (ASCAM). The project addresses the state of the art regarding condition assessment of road equipment. Furthermore, the "Roadstar" is one of the mapping vehicles developed and used in Austria.

In [16–19], the deliverables of the project "Practical Road Equipment Measurement, Understanding and Management" (PREMIUM) are presented. The project studied road markings, road signs, vehicle restraint systems and noise barriers. The main aim was to recognize key characteristics of each asset, the appropriate monitoring techniques, data interpretation, and the associated management strategies based on surveys. In addition, a risk based asset management methodology is presented in [20]. This methodology addresses wide range of civil engineering structures, such as pavements, structures including bridges and retaining walls, tunnels, road furniture, drainage, and geotechnical assets.

International paradigms and best practices for the design and assessment of roadside structures are provided in the volume of articles presented in [21]. Furthermore, case studies focused on the recent advances in the technology of roadside structures, as well as in the minimization of fatal and serious injuries from vehicle impacts.

In [10], a newly introduced methodology was presented that accounts for road conditions, traffic and routing elements properties in order to assess the fragility of the infrastructure. The evaluation was based on either road engineering physics or expert judgements. The method was incorporated in spreadsheet tool. The feasibility of this tool was demonstrated, and sensitivities of the assessment process were evaluated and discussed. The work presented herein is the continuation of the work performed by authors on the topic of likelihood of impact events in transport networks.

3 Likelihood of Events in Transport Networks

The probability of an impact of a vehicle on a road furniture $p_{S,impact}$ can be determined in accordance with Eqs. (1) and (2). According to [10], Eq. (1) can be classified and divided into three main terms, as follows:

(a) The accepted probability of occurrence of an impact or the accepted probability of failure of a non-compliant traffic flow for standard-compliant routing elements, which is equal to $p_{f,NORM} = 1 \times 10^{-6}$;
(b) The corresponding increase factors $\eta_{F,LN}$, $\eta_{F,QN}$ and $\eta_{F,KR}$ with respect to the longitudinal inclination of lanes (LN), the transverse inclination of lanes (QN), and curvature of the lanes (KR), respectively, which are all calculated on the basis of physical laws of driving dynamics.
(c) Increasing the reference likelihood of an impact ($p_{f,NORM}$) due to peculiarities in the pavement surface, such as the pavement grip $p_{f,G}$, the longitudinal evenness $p_{f,L}$, the pavement damages $p_{f,O}$, the pavement cracks $p_{f,R}$, the pavement ruts $p_{f,SR}$, the traffic volume $p_{f,V}$, and the vehicle velocity $p_{f,\mathrm{GE}}$. In Austria, the influence of the fragilities (f_G, f_L, f_O, f_R, f_S) is based on the recorded data of the mapping vehicle "Roadstar", the fragility f_V is based on actual counts by the road operators, while all are based on fragility related transfer functions ranging between 0 and 1 as described in more detail in the following paragraphs. The influencing factors are assumed based on either experience from road operations or on simplified physics laws in kinematics.

$$p_{s,impact} = p_{f,NORM} + {}^{(\eta_{F,LN} + \eta_{F,QN} + \eta_{F,KR})}\!/_{3} \cdot \left\{ \begin{array}{l} f_G \cdot p_{f,NORM} \cdot \left(\frac{p_{f,G,LIMIT}}{p_{f,G,NORM}} - 1 \right) + \cdots \\ f_L \cdot p_{f,NORM} \cdot \left(\frac{p_{f,L,LIMIT}}{p_{f,L,NORM}} - 1 \right) + \cdots \\ f_O \cdot p_{f,NORM} \cdot \left(\frac{p_{f,O,LIMIT}}{p_{f,O,NORM}} - 1 \right) + \cdots \\ f_R \cdot p_{f,NORM} \cdot \left(\frac{p_{f,R,LIMIT}}{p_{f,R,NORM}} - 1 \right) + \cdots \\ f_S \cdot p_{f,NORM} \cdot \left(\frac{p_{f,S,LIMIT}}{p_{f,S,NORM}} - 1 \right) \end{array} \right\} \cdot f_V \cdot f_{GE} \tag{1}$$

In Table 1, detailed description of the specific parameters of the basic equation of the assessment concept are listed. The presented equations and parameters, enable the calculation and the analysis of the probability of an impact of a vehicle on a road furniture $p_{S,impact}$.

The corresponding assessment of impact risk of the road furniture damage is based on the risk assessment index R_i that can be calculated as shown in Eq. (2):

$$R_i = 1 + 4 \cdot \frac{\left[p_{s,impact} - p_{f,NORM}\right]}{p_{f,NORM}} \tag{2}$$

Table 1 Descriptive quantities for computing the vehicle impact-probability according to Eq. (1) [10]

Symbol	Specification	Value
$p_{S,impact}$	Vehicle impact probability according to Eq. (1)	0–1
$p_{f,NORM}$	Standard specific safety standards associated with a vehicle impact probability	1×10^{-6}
$\eta_{F,LN}$	Increasing factor for the impact force—due to the longitudinal inclination of the lane	
$\eta_{F,QN}$	Due to the transverse inclination of the lane	
$\eta_{F,Kr}$	Due to curvature of the lane	
f_G	Fragility associated with the lane grip	0–1
$p_{f,G,NORM}$	Standard specific vehicle impact probability	1×10^{-6}
$p_{f,G,LIMIT}$	Upper threshold of the vehicle impact probability; e.g. $p_f = 2 \times 10^{-6}$	2×10^{-6}
f_L	Fragility associated with the lane longitudinal inclination	0–1
$p_{f,L,NORM}$	Standard specific vehicle impact probability	1×10^{-6}
$p_{f,L,LIMIT}$	Upper threshold of the vehicle impact probability; e.g. $p_f = 2 \times 10^{-6}$	2×10^{-6}
f_O	Fragility associated with the surface damages in the pavement	0–1
$p_{f,O,NORM}$	Standard specific vehicle impact probability	1×10^{-6}
$p_{f,O,LIMIT}$	Upper threshold of the vehicle impact probability, e.g. $p_f = 2 \times 10^{-6}$	2×10^{-6}
f_R	Fragility associated with the surface cracks in the pavement	0–1
$p_{f,R,NORM}$	Standard specific vehicle impact probability	1×10^{-6}
$p_{f,R,LIMIT}$	Upper threshold of the vehicle impact probability; e.g. $p_f = 2 \times 10^{-6}$	2×10^{-6}
f_S	Fragility associated with the ruts in the pavement	0–1
$p_{f,NORM}$	Standard specific vehicle impact probability	1×10^{-6}
$p_{f,S,LIMIT}$	Upper threshold of the vehicle impact probability; e.g. $p_f = 2 \times 10^{-6}$	2×10^{-6}
f_V	Fragility associated with the traffic volume	0–1.2
f_{GE}	Fragility of the traffic velocity to the vehicle impact—fragility	0–1

The consequence of an impact is related with the loss of a single object; hence, the risk in this study is equal to the likelihood of the impact event.

Force increasing or decreasing factors associated with the vehicle impact shown in Table 2, as well as fragility functions of vehicle impacts in traffic networks, are explained in more detail in [10], as regards their nature and their influence on $\eta_{F,LN}$, $\eta_{F,QN}$ and $\eta_{F,KR}$ of Eq. (1).

Table 2 Increase of the vehicle impact force due to the longitudinal lane inclination, the transverse lane inclination, and the curvature of the lane [10]

Symbol	Specification	Unit
$\eta_{F,LN,max}$	Max. increasing factor of the vehicle impact force—due to the longitudinal inclination of the lane	(–)
F_{LN}	Longitudinal inclination of the lane	(°)
$\eta_{F,QN,max}$	Max. increasing factor of the vehicle impact force—due to the transverse inclination of the lane	(–)
F_{QN}	Transverse inclination of the lane	(°)
$\eta_{F,KR,max}$	Max. increasing factor of the vehicle impact force—due to the lane curvature	(–)
R	Radius of the lane curvature	(m)
R_{min}	Minimum radius of the lane curvature	(m)
VM	Mass of the considered vehicle	(kg)
v_{max}	Design velocity	(m/s)
v_{min}	Minimum vehicle speed at impact after braking	(m/s)

4 Risk Assessment and Damage Classes

According to [10], considering the assessment index R_i, the probability evaluation of a vehicle impact can be categorised as follows:

- $1.0 \leq R_i \leq 2.5$: The road geometry, the pavement surface characteristics and the driving dynamics factors (traffic strength and speeds) have negligible or no effects on the impact risk.
- $2.6 \leq R_i \leq 4.0$: The road geometry, the pavement surface characteristics and the driving dynamics factors have negligible effects on the impact risk.
- $4.1 \leq R_i \leq 5.5$: The road geometry, the pavement surface characteristics and the driving dynamics factors have a medium to large effects on the impact risk.
- $R_i > 5.6$: The road geometry, the pavement surface characteristics and the driving dynamics factors have significant effects on the impact risk.

It is important to mention that the assessment index R_i concept is based on the assumption of an impact occurrence probability of $p_{f,NORM} = 1 \times 10^{-6}$ ($R_i = 1.0$) for a lane alignment:

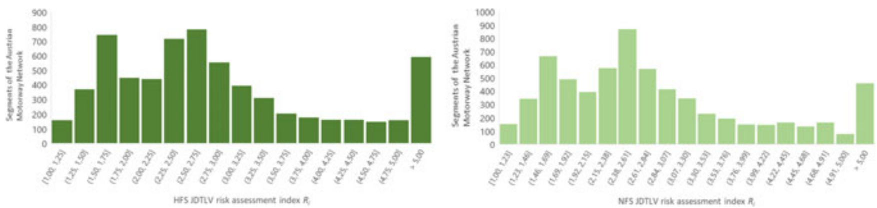
(a) without a longitudinal inclination,
(b) without a transverse inclination,
(c) with a very large radius of curvature,
(d) with an optimal road surface condition,
(e) with a predefined amount of traffic per design, and
(f) a predefined design velocity.

5 Case Studies

The methodology for the assessment of risk in existing road furniture due to vehicle impact that was presented in previous sections was implemented on of real traffic situations, the actual alignment characteristics, and the current road surface conditions identified on the Austrian motorway network (ASFINAG). The grouping potential and variations in the assessment index are the result of the road surface properties, the alignment characteristics, the traffic flows, and the vehicle speeds.

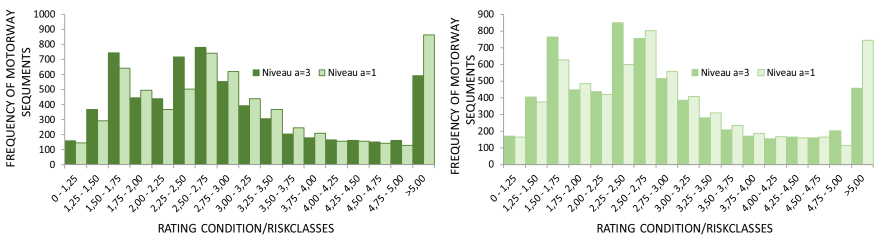
One can easily notice a sample concentration in the ranking regions of 1.5 and 2.5 in the graphs shown in Fig. 1. This can be described by the bi-modal distribution with respective peak concentrations. Furthermore, a further accumulation can also be noticed at classes greater than 5, both in the main and side lanes. Based on the graphs shown in Fig. 1 it becomes apparent that items in high-risk levels ($R_i > 5$) are to some extent more sensitive to main lane traffic. At the same time, low-risk regions are denser for main lane traffic data.

In order to reduce the assets risk speed reduction measures can be implemented on the network. This is thought to be an optimal solution between the risk of asset loss and road network performance. Using the fragility curve the influence of the pavement grip on the rating of the vehicle impact risk is accomplished, as shown in Fig. 2. To that end, a fragility curve is observed as the assessment of the probability of



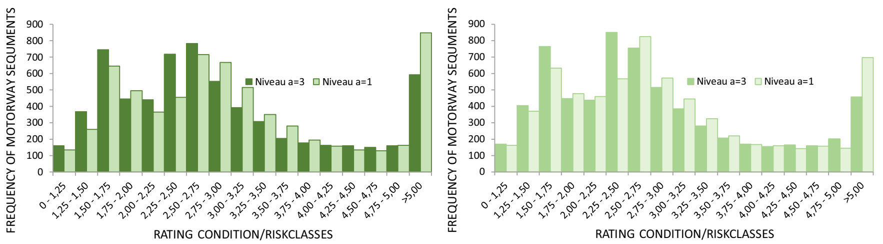
(a) HFS - JDTLV (b) NFS - JDTLV

Fig. 1 Risk assessment index R_i, in relation to actual traffic statistics from the Austrian motorway and road network, with: HFS = main lane, NFS = side lane, and JDTLV = annual average traffic density for trucks (indicative cases elaborated in [10])



(a) HFS - JDTLV (b) NFS - JDTLV

Fig. 2 Risk assessment index R_i, in relation to actual traffic statistics from the Austrian motorway and road network, with emphasis on pavement grip properties (indicative cases elaborated in [10])



(a) HFS - JDTLV

(b) NFS - JDTLV

Fig. 3 Risk assessment index R_i, in relation to actual traffic statistics from the Austrian motorway and road network, with emphasis on pavement ruts (indicative cases elaborated in [10])

exceeding a specific damage state according to the degradation process. The fragility curves used herein were derived based on expert knowledge and national standards and guidelines. For detailed overview of used fragility curves, see [10].

As it can be seen in Fig. 2, the man risk level in the network lies in the region of 2.25–3.25.

Through the fragility curves, also the influence of the pavement ruts on the risk rating of the vehicle impact is described. In Fig. 3, it can be seen that the proportion of traffic situations in class >5 is increased for all traffic situations considered.

6 Conclusions

In the paper, the influences of the longitudinal and the transverse gradient, and the curvature are evaluated by physical driving dynamics. A reference configuration with a failure probability $p_f = 10^{-6}$ was assumed. The road surface conditions, such as damage extent and grip are evaluated by adjusted fragility curves, based on empirical values and rating. The presented method is in agreement with the rating classification of RVS 13.03.51 [22]. To that end, it allows for an automatized risk evaluation taking into account the traffic composition, the surface measurement data retrieved by mapping vehicles, the JDTLV values, the occupancy level of the lanes, and the alignment.

The implementation of the methodology on the infrastructure network of a road operator allowed the efficient risk assessment, i.e. reduction of risk ranking. The reduction of risk ranking was accomplished by the measures of: (i) 20% speed reduction, (ii) renewal of the surface grip, and (iii) repair of road ruts. The used fragility curves in the paper were obtained based on expert knowledge and occasional national standards and guidelines.

Main findings can be summarized as follows:

- In the research project that served as the base for the paper, authors developed an analytical decision tool for the assessment and the maintenance forecasting of the road equipment, based on the probabilistic safety concepts (PSC);
- The authors showed how to associate traffic dynamic parameters and routing characteristics to a closed analytical solution for a RVS [22] based rating of impacts on road equipment;
- A specific adjustment of the acceptable reliability level, the acceptable risk and in consequence the remaining technical service life are all supported by the presented probabilistic based analytical decision method.

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