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Effectiveness of Rumble Strips Positioned at Different Lateral Distances to the Edge Line to Avoid Run-Off-Road Accidents

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Abstract

Epidemiological studies have shown that the share of single vehicle run-off-road accidents caused by inattention, distraction and drowsiness ranges between 20% up to 60%. One measure to avoid these accidents is the installation of rumble strips at or close to the edge line of the hard shoulder. Even though one percent of vehicles drive on the hard shoulder and thus pass the edge line without the drivers being inattentive, distracted or drowsy. Hence the installation of rumble strips would result in unnecessary noise pollution to the people living close to the road.
This study shows at which position to the edge line rumble strips could be installed at the hard shoulder to avoid unnecessary noise pollution and still potentially reduce run-off-road accidents. The analysis of real accidents showed an effectiveness reducing run-off-road accidents with rumble strips of approximately 41% if rumble strips are positioned directly on the edge line. The effectiveness of rumble strips is not influenced much by varying the distance of up to 0.5 m to the edge line. Still approximately 37% of run-off-road accidents might be avoided.

Keywords: Rumble Strips; Run-Off-Road Accidents; Single Vehicle Accidents

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Nomenclature

ADAS	Advanced Driver Assistance Systems
ATP	Audio Tactile Profiled
CEDATU	Central Database for In-Depth Accident Study
FHWA	Federal Highway Administration
KSI	Killed and Severely Injured
LKA	Lane Keep Assist
LKW	Lane Departure Warning
PENDANT	Pan-European Coordinated Accident and Injury Databases
RISER	Roadside Infrastructure for Safer European Roads
ROLLOVER	Improvement of rollover safety for passenger vehicles
ROR	run-off-road
SD	Standard Deviation
STAIRS	Standardization of Accident and Injury Registration System
SVA	Single vehicle accidents

1. Introduction

The challenging target of halving the number of road deaths by 2020 in the European Union is stated in the current White Paper (European Commission, 2010) on the basis of figures for 2010. This is a very ambitious target and a huge effort is needed to achieve this goal (European Commission, 2016a). In 2014, nearly 25,900 road deaths were reported (European Commission, 2016a). This number is above the figures planned (European Commission, 2016c). The member states have developed similar targets and road safety programs, such as the Austrian Road Safety Programme (Bundesministerium für Verkehr and Innovation und Technologie, 2016). The number of road deaths is to be halved by 2020 and the number of severely injured persons reduced by 40%. Traffic accidents are to be reduced by 20%.

Single vehicle accidents (SVA), in particular run-off-road (ROR) accidents, account for a large number of road fatalities. The share of this type of accident varies between the various member states. On average, one third of road fatalities can be attributed to this type of accident (Collin, 2000; European Commission, 2016b). On average approximately 7% of road accidents occurred on motorways in the EU (European Commission, 2016b). Close to 60% of these involve passenger cars. Tomasch et al. (2011) reported a share of ROR accidents in Austria on motorways of 38% for all victims and 44% for fatalities. No figure for ROR on motorways are public available for the EU.

Fatigue, inattention and distraction have been identified as the main causes of ROR accidents. The Federal Highway Administration states that this cause is responsible for between 40 and 60 per cent of accidents. Ewert (2003) states that fatigue causes one fifth of ROR accidents, with motorways and highways being particularly affected. Approximately 24% of ROR accidents were caused by fatigue concluded Anselm and Hell (2002) in their study. Rothe (1995) estimates that around 33% of fatal accidents are due to fatigue and inattention. McLaughlin et al. (2009) identified distraction and inattention (35%) and fatigue (11%) as causes of ROR accidents.

There are several ways to avoid ROR accidents. LKA (Lane Keep Assist) or LDW (Lane Departure Warning) inside the vehicle or the use of rumble strips (ATP: Audio Tactile Profiled Roadmarkings) on the road. Many studies observed that rumble strips are highly effective and highly efficient, both as a measure against fatigue and against distraction and inattention (Cavegn et al., 2008; Corkle et al., 2001; Craig et al., 2015; Elvik and Vaa, 2004; Lerner and Hegewald, 2009; Nambisan et al., 2007). The rumble strips had a particularly positive effect on the number of KSI (Killed and Severely Injured) in ROR accidents. The studies make the assumption that up to 72% of ROR accidents could be prevented by the use of rumble strips at the edge of the road. However, it was noted, that the effectiveness and usefulness of rumble strips will decrease with the market penetration of Lane Departure Warning Systems (Lerner and Hegewald, 2009). Even if all new vehicles are equipped with LKA or LDW, the problem would remain that the majority of vehicles currently on the road still do not have these systems. The advantage of rumble strips is the immediate effect on vehicles after installation. Therefore, rumble strips still represent a very good way to prevent ROR accidents.

Unfortunately rumble strips also have negative aspects. The driving line of many drivers is not always at the center of the driving lane. They tend to move into position far to the right. Driving too far to the right may even lead to driving at least partially on the emergency lane or hard shoulder and cause unnecessary noise pollution to residents if shoulder rumble strips are installed. This run-over the rumble strip is due to the driving line and is not caused by the three causes of accidents mentioned above. On average, vehicles were about 0.5m from the edge of the traffic lane (Lennie and Bunker, 2004). About 20% of vehicles were very close to the edge of the traffic lane (<0.3m). One per cent even drove on the emergency lane or hard shoulder.

Studies reported (Gardner et al., 2007; Haron et al., 2012) that residents claimed an undesirable noise and road maintenance authorities started to remove rumble strips. Residents claimed that they are able to hear the noise generated from rumble strips up to an offset of two kilometers from the road (Bahar et al., 2001; Bahar and Parkhill, 2005; Torbic et al., 2009). Road maintenance authorities have thus started to remove rumble strips.

2. Objective

Even though new cars are developed with LKA there are still many cars on the road not equipped with such driving assistances systems. Therefore rumble strips are a good measure to reduce ROR accidents for drivers who are inattentive, distracted or affected by drowsiness. Unfortunately a small number of vehicles drive on the shoulder and thus pass the edge line without the drivers being inattentive, distracted or drowsy. This will result in unnecessary noise pollution to the people living close to the road.

The objective of the study is to assess the effectiveness of the optimized lateral distance of rumble strips to the edge line of the carriageway in order to reduce noise pollution on the one hand side and to simultaneously reduce the number of ROR accidents on the other hand.

3. Method

The trajectory of the center of gravity of a vehicle at the point of lane-departure can be described as a function of lateral distance to the edge of the traffic lane, the velocity and coefficient of friction of the road (Hoschopf et al., 2007; Hoschopf and Tomasch, 2008). The maximum run-off-road angle is a function of centripetal acceleration and the maximum lateral coefficient of friction. It is assumed that a vehicle leaves the road and a ROR angle will be created depending on a combination of the above mentioned parameters. Burgett and Gunderson (2001) and Martin et al. (2003) had similar thinking in their analysis of this issue (Martin et al., 2003). These authors also assume a correlation of velocity, friction conditions and ROR angle.

Tomasch et al. (2016) applied these considerations conversely. Based on a given ROR angle, corresponding vehicle velocity and road condition (dry, wet, etc.) an appropriate width of trafficable surface (e.g. hard shoulder, emergency lane) will be necessary to perform steering maneuvres to avoid a ROR accident and get back into the traffic lane. The authors applied the method to different ROR velocities of a vehicle and different ROR angles. They did not, however, analyze at what lateral position to the traffic lane rumble strips could be installed and still have accident prevention potential.

One of the main factors to avoid an accident is referred to as reaction time. In many studies reaction time has already been analyzed under various situations. The reaction time varies up to 2.5s (Burckhardt, 1985, 1985; Chang et al., 1985; Green, 2000; Olson, 1989; Sens et al., 1989; Sivak et al., 1982). Lerner (1993) investigated the brake perception-reaction time of older and younger drivers and did not find a significant difference between younger and older drivers. At the 85th percentile a reaction time of 1.9s was observed. It must be remarked, however, that most of these studies concern responses to specific visual or auditory signals. A view study alone investigated the reaction time for rumble strips. Kozak et al. (2016) studied the reaction time of sleep-deprived drivers when driving over rumble strips at the edge lane in a driving simulator. On average the reaction time was 0.55s (p=0.06). Stanley (2006) investigated driver behavior when coming off-road. The average reaction time was found to be 1.137s (SD=0.310). The slowest reaction time measured was approximately 1.3s. Edwards et al. (Edwards et al., 2013) found a reaction time of 1.28s for seat vibration stimulus. Furthermore, they found faster reaction time for younger drivers (0.92s) compared to older drivers (1.10s).

In addition to the reaction time the ROR angle and ROR velocity affect the distance a vehicle will travel into the hard shoulder or road side.

Considering a corresponding reaction time, the lateral distance of rumble strips required to the edge of the traffic lane can be expressed by a given ROR angle and ROR velocity as also by existing friction characteristics (1) (Tomasch et al., 2016). The ROR angle and ROR velocity were measured at the edge of the traffic lane based on reconstructed accident cases. The positioning of the rumble strips depends on the width of the paved surface (emergency lane or hard shoulder) and the lateral distance from the vehicle required at the corresponding speed.

Fig. 1 shows the vehicle movement when coming off road with a subsequent steering movement after driving over the rumble strips.

$$b = c - \left(v \cdot t_r \cdot sin\alpha + \frac{v^2 \cdot (1 - cos\alpha)}{\mu \cdot g}\right) - e \quad [m] \tag{1}$$

Variable	Unit	Description
b	m	Lateral distance of rumble strips from the traffic lane
c	m	Width of paved surface (asphalt, concrete) – emergency lane, hard shoulder
d	m	Required lateral distance of vehicle
e	m	Width of rumble strips
v	m/s	Run-off-road speed
t_r	s	Reaction time
α	°	Run-off-road angle
μ	1	Coefficient of friction
g	m/s^2	Gravitational constant ($g=9.81\ m/s^2$)

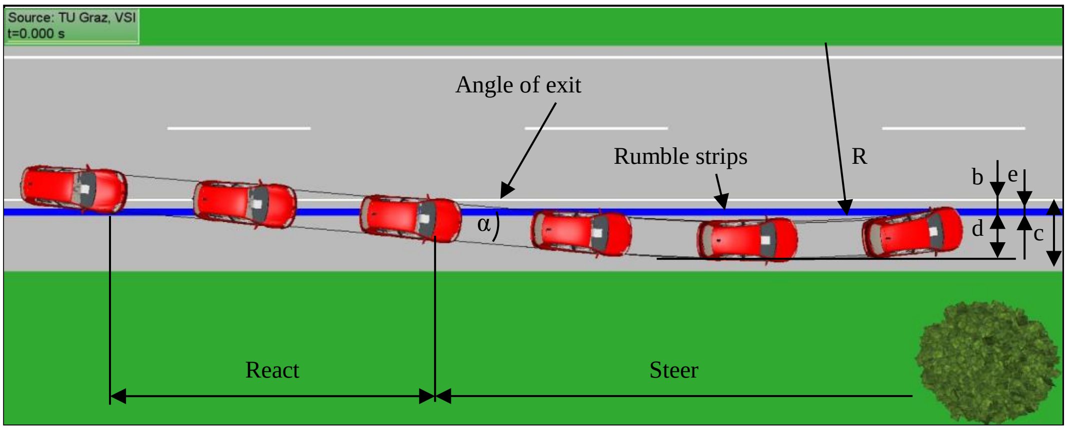

Fig. 1: Lane departure of vehicles with steering maneuvre back onto the traffic lane.

In order to estimate the required (optimized) position of rumble strips, the following assumptions were made:

- The emergency lane or hard shoulder is trafficable, i.e. the surface is not soft and the wheels do not get stuck.
- The friction considered corresponds to the road conditions e.g. dry, wet, ice, etc. for each single accident (dry: μ=0.8, wet: μ=0.5, icy: μ=0.1). Lateral forces transferred from wheels to the road are lower than longitudinal forces. It is assumed that the lateral forces equals the longitudinal forces.
- The vehicle might not have a yaw angle above five degrees at the time when leaving the road. Breuer (2013) associated a yaw angle below five degrees to stable driving motion.
- The width of the rumble strip is set to 0.4 m (FHWA)
- The driver's reaction takes place after driving over the rumble strips i.e. after passing the complete width of the rumble strip. The expected reaction time is between 0.5s and 1.3s (see results of literature review).
- The assumption is that the driver's reaction is a sole steering movement back onto the traffic lane and that no braking maneuvres are made (i.e. a combination of steering and braking maneuvres has not been studied). The steering maneuvre is made immediately after the reaction.
- It is assumed that the driver initiates the steering maneuvre whilst driving over the rumble strip and the driving period will be taken into account accordingly.
- The vehicle traverses a circular arc with a specific radius, which is in the cornering limit speed due to the available friction and the velocity. Therefore, the vehicle does not yet skid.

- The vehicle is considered as a point mass. The vehicle dynamics of different vehicle types are not taken into consideration.
- No distinction between straight road sections and bends was made.

4. Material

This study focuses on single-vehicle run-off-road accidents on motorways. National statistics are used as the basis for accident analysis to, e.g., highlight trends. The analysis of statistical data provides an overview of accidents. However, there is a lack of information with respect to vehicle speed, ROR angle, etc. and the presence of infrastructure, such as embankments, trees, and other hazards. Further detailed information regarding accidents is necessary, and in-depth databases need to be analyzed.

The in-depth database CEDATU (Central Database for In-Depth Accident Study) was the source for the basic data on real accidents which were then analyzed (Tomasch et al., 2008; Tomasch and Steffan, 2006). The data field basis of CEDATU is the STAIRS protocol (Standardisation of Accident and Injury Registration System) (Ross et al., 1998) which was developed over the course of an EU project with the same name. Building on the STAIRS protocol, data fields were developed using information from the EU projects PENDANT (Pan-European Coordinated Accident and Injury Databases) (Morris and Thomas, 2003), RISER (Roadside Infrastructure for Safer European Roads) (RISER, 2006) and ROLLOVER (Improvement of rollover safety for passenger vehicles) (Gugler and Steffan, 2005). Furthermore, the data fields from national statistics were integrated to enable a direct connection to the latter (Statistik Austria, 2007).

From the in-depth accident cases of CEDATU all SVA were selected. A reconstruction of the complete accident (from conflict point to the rest position) was carried out by numerical simulation using PC Crash. This software has previously been used in many research projects, and the models used are well documented and have been validated by various research organizations (Cliff and Montgomery, 1996; Steffan and Moser, 2004, 1996). Based on the simulation results, parameters such as road departure speed and angle were analyzed. The speed and vehicle angle were determined at the hard shoulder immediately beyond the edge line of the driving lane based on the simulation.

Further the accident database from the RISER (RISER, 2006) project was analyzed. In RISER a total of 211 accidents were investigated. All SVA run-off-road accidents were selected.

5. Results

In total 259 ROR SVA were analyzed from CEDATU. The cumulative share of the run-off-road angle is provided in Fig. 2. The distribution of the findings in CEDATU match very well with the distribution of the ROR angles of the EU project RISER.

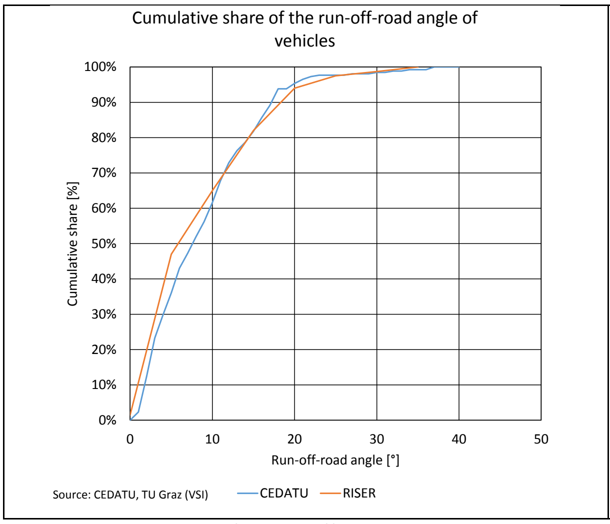

Fig. 2: Cumulative share of the run-off-road angle.

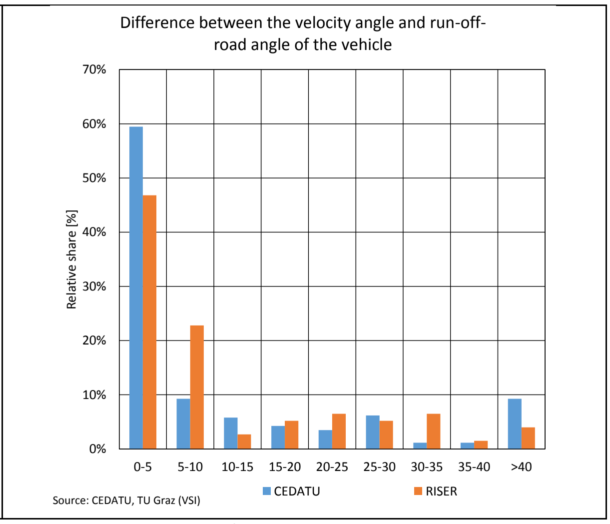

Fig. 3: Cumulative share of the yaw angle.

For comparison with the findings in RISER the yaw angle was grouped by an increment of five degrees (Fig. 3). A normally operating vehicle i.e. no skidding, shows very little difference between the vehicle trajectory and the heading. A yaw angle below five degrees could be associated to stable driving motion (Breuer, 2013). It could be said that approximately 60% of ROR accidents in CEDATU do not have a big yaw angle.

A small run-off-road angle will clearly have a higher impact on the reduction of ROR accidents independent of the reaction time (Fig. 4). With an increasing reaction time a clear tendency towards to a smaller run-off-road angle is observed. At a reaction time of 0.5s 142 ROR accidents out of 259 whereby at a reaction time of 2.5s 51 ROR accidents out of 259 might be reduced. Fig. 5 shows corresponding run-off-road angles and run-off-road speeds at different reaction times.

A short reaction time will clearly have the highest impact on the reduction of ROR accidents. Further, the position of the rumble strips as close as possible to the edge of the driving lane would reduce ROR accidents. In Fig. 6 the possible reduction of ROR accidents is plotted for a hard shoulder width of three meters and a width of the rumble strips of 0.4 meters. According to Lennie and Bunker (2004) vehicles were on average about 0.5m from the edge of the traffic lane. On a very fast reaction time and a distance of 0.5 meters of the rumble strips to the edge of the driving lane the possible reduction of ROR accidents would be approximately 37%. On a reaction time of up to 1.3 s (Edwards et al., 2013; Kozak et al., 2016; Stanley, 2006) the reduction of ROR accidents would amount to approximately 16%. On a very low reaction time of 2.0 s at a distance of 0.5 meters of the rumble strips to the edge of the traffic lane a possible reduction of ROR accidents of approximately 7% is estimated.

In many countries and states rumble strips have an offset of about 300-400 mm to the edge of the driving lane (FHWA). In Fig. 7 a possible reduction of run-off-road accidents at an offset of 0.5 of the rumble strips to the edge line of the driving lane. Obviously the number of accidents will decrease with increasing the width of the hard shoulder.

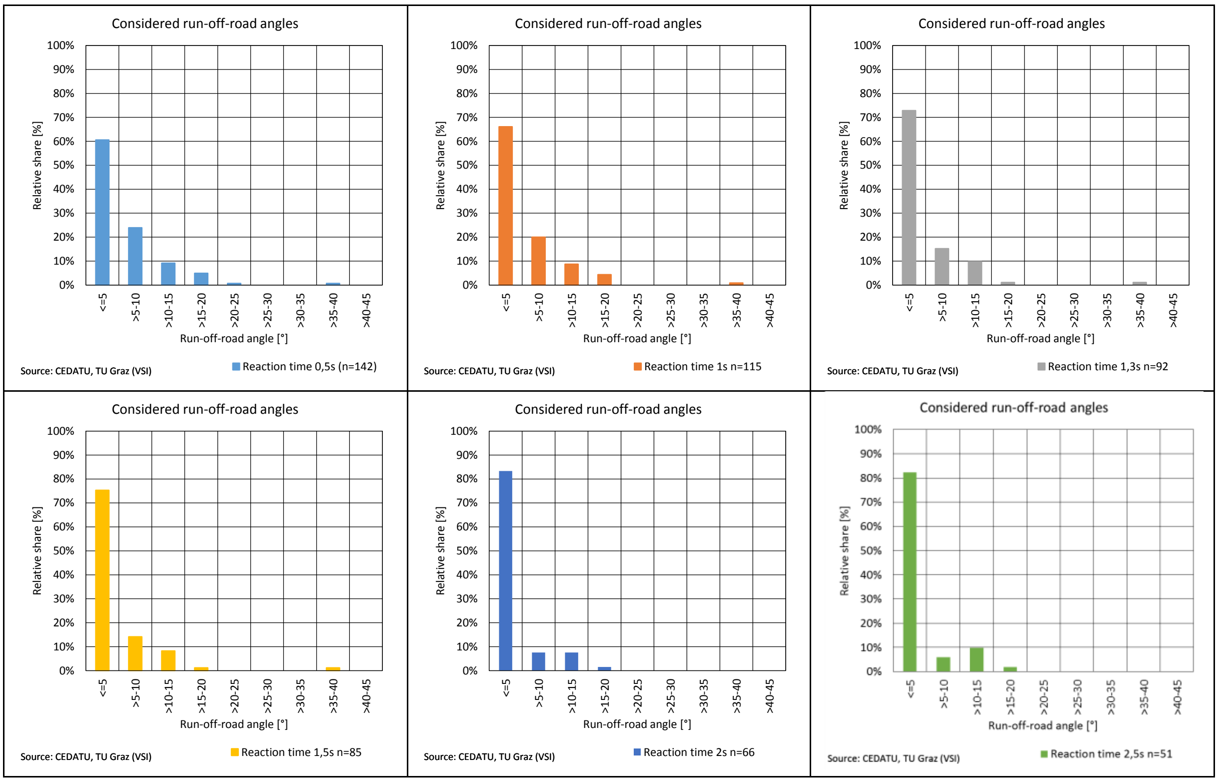

Fig. 4: Run-off-road angles at different reaction times.

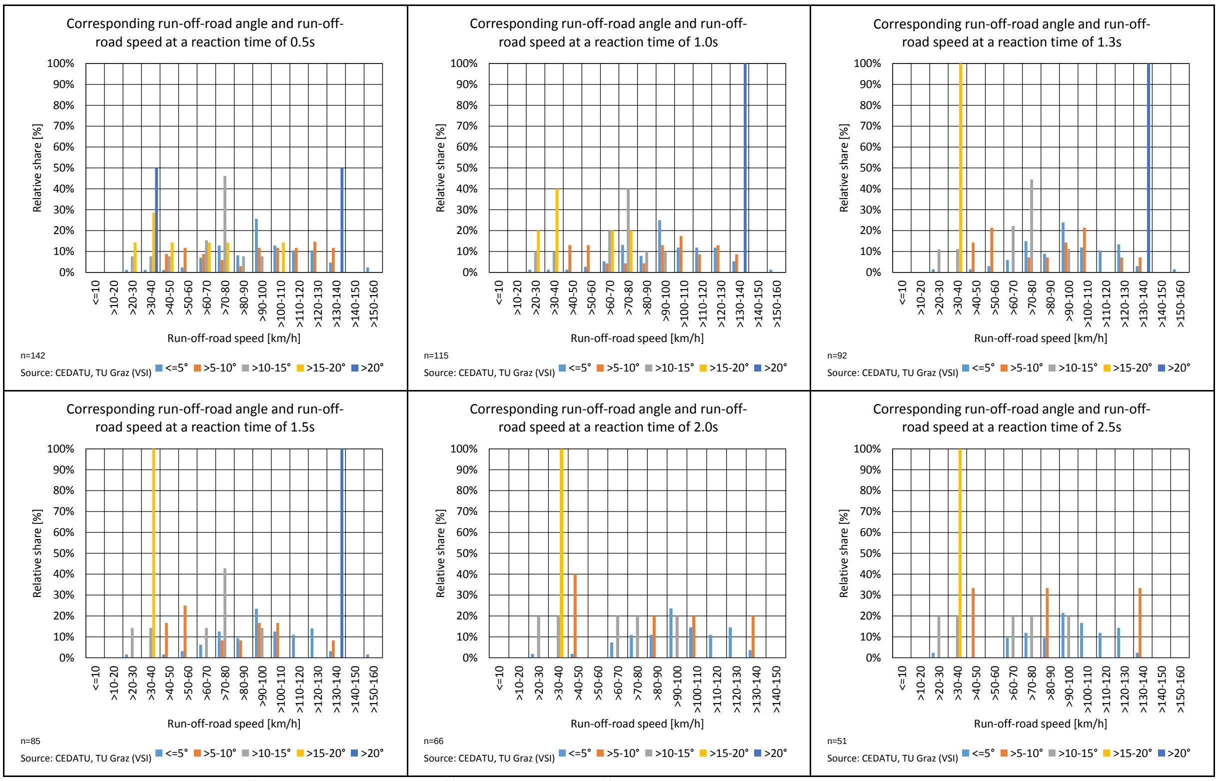

Fig. 5: Corresponding run-off-road angle and run-off-road speed at different reaction times.

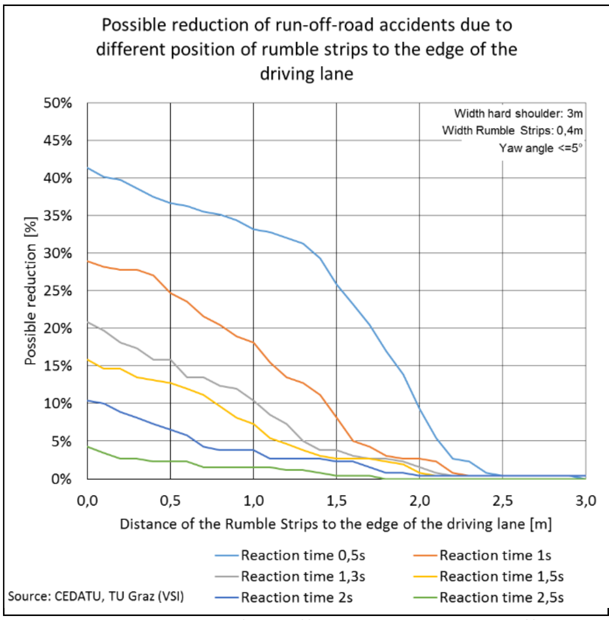

Fig. 6: Possible reduction of run-off-road accidents due to different positioning of rumble strips to the edge of the driving lane and a hard shoulder width of three meters.

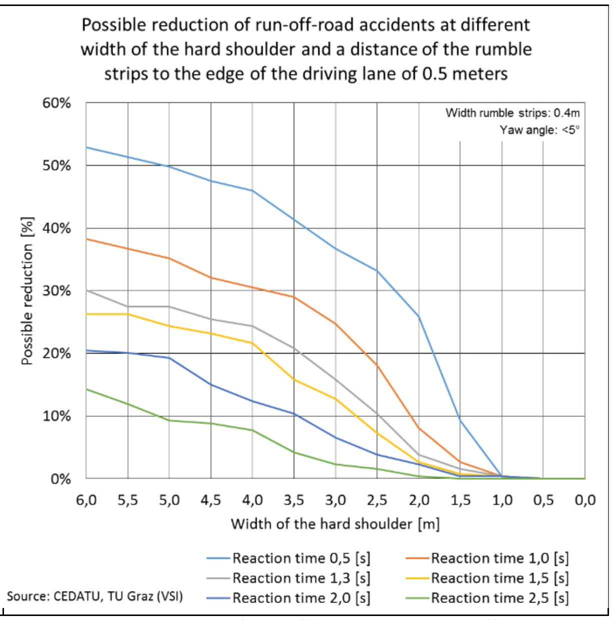

Fig. 7: Possible reduction of run-off-road accidents at different widths of the hard shoulder and a distance of rumble strips to the edge of the driving lane of 0.5 meters.

6. Summary

Studies showed that rumble strips are an appropriate measure to prevent ROR accidents. Unfortunately, rumble strips produce unreasonably high levels of noise if drivers do not keep far enough away from the side lines and drive over the rumble strips. Some residents claimed that they are able to hear the noise generated from rumble strips up to two kilometers away (Bahar et al., 2001; Bahar and Parkhill, 2005; Torbic et al., 2009). To keep the unnecessary noise pollution as low as possible a method to position rumble strips at an optimum distance to the edge of the driving lane was already established by Tomasch et al. (2016). In the present study the method was applied to real accidents and each single accident was associated to the method.

In many countries and states the rumble strips offset to the edge of the driving lanes is approximately 0.3m (FHWA). According to Lennie and Bunker (2004) there will still be a small number of normal driving vehicles beyond this distance. In this context moving the rumble strips 0.5m away from the edge of the driving lane was considered. At a hard shoulder width of 3.0m the theoretical reduction potential was calculated to approximately 37% at a reaction time of 0.5s. Assuming that the drivers are inattentive or drowsy the reaction time would be even longer. Driving simulator studies (Edwards et al., 2013; Kozak et al., 2016; Stanley, 2006) showed a reaction time of up to 1.3s driving over rumble strips. At this reaction time rumble strips might reduce ROR accidents by approximately 16%. Even if the width of the hard shoulder would be 2.0m a theoretical reduction potential is given. At a reaction time of 0.5s the theoretical reduction potential was calculated to approximately 26%. At a reaction time of 1.3s rumble strips might reduce ROR accidents by approximately 4%. Due to the method used, obviously no impact is expected at a hard shoulder with of 1.0m. However, the width of the hard shoulder or even a recovery area at the road side would have a huge impact.

7. Acknowledgement

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