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NON-INTRUSIVE ROAD CONDITION DATA COLLECTION FOR POWERED TWO-WHEELERS: A CROATIAN CASE STUDY

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Abstract

Motorcyclists represent a particularly vulnerable group of road users, as shown by the high relative shares of motorcyclists killed in all road deaths, especially on rural roads. Infrastructure elements, such as road alignment or road surface condition, are often one of the most important factors contributing to increased motorcyclist vulnerability. This study investigates the applicability of a motorcycle probe vehicle in non-invasive testing of road conditions from a motorcyclist safety perspective. The analysis combines a previously developed dynamic risk mapping model – based on yaw-, roll-, and pitch-rate behavior - with a newly introduced relative Z-Acceleration clustering approach targeting vertical surface irregularities. Data from multiple rides in both driving directions were spatially aligned at the meter level and aggregated to derive direction-specific risk indicators. The study was conducted on sections of national roads in Croatia in both directions of travel. The results indicate areas with high level of relative proportion of clustered Z-Acceleration areas (approximately 5% of section length) and highlight distinct dynamic risk segments on the analyzed road sections. Although more exploratory in nature, this study demonstrates the potential of using a motorcycle-based probe vehicle to collect data on road conditions. Future research could integrate collected data with additional data on road traffic infrastructure and road crashes to provide a comprehensive understanding of the impact of the infrastructure on motorcycle crash frequency and motorcyclists' injuries.

Keywords: motorcycle, road inspection, road safety, risk mapping, road surface

1 Introduction

Maintaining road users' safety has always been a challenging task, especially when it comes to vulnerable road users (VRUs). Motorcyclists stand out among both other VRUs and motorized road users, as they are more exposed to traffic (no car shell protection, different vehicle dynamics), have smaller dimensions, and a higher power-to-weight ratio. Although significant efforts are being made to analyze and improve the safety of motorcyclists on the roads, the reduction in the number of deaths and serious injuries on motorcycles is not progressing at a satisfactory pace. Between 2019 and 2023, fatalities among car occupants decreased by approximately 1, 000, and pedestrian deaths declined by around 900 in the European Union (EU) [1]. In contrast, the reduction in fatalities among motorcyclists and cyclists was considerably smaller during the same period, with decreases of fewer than 100 in each group.

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Although the absolute number of motorcyclist fatalities decreased by 14% between 2010 and 2019, the relative share of motorcyclist fatalities in total road fatalities increased from 14% to 19% over the same period [2]. A similar trend can be observed among seriously injured motorcyclists, whose share increased from 12% to 14% in the same period. Further, in the territory of the EU, more than 55% of motorcyclist fatalities occurred on rural roads, and the majority of them (about 47%) were between 25 and 49 years of age [3].

1.1 Literature background

In EU, mopeds are typically concentrated in urban areas, while motorcycles are more commonly utilized on rural road networks [4, 5]. Prior studies have shown that the perceived risk level of rural roads is lower than that of urban roads, independent of driver age [6]. On the other hand, rural road environments are associated with a higher level of risk exposure for leisure motorcyclists [7]. Rural roads are frequently characterized by narrow cross-sections and the presence of fixed roadside objects. Hazards such as trees, safety barriers, and other rigid elements present a substantial risk to motorcyclists, especially in curves, where run-off-road crashes are more likely to result in severe or fatal injuries [8, 9].

Some findings suggest that horizontal alignment exerts a more pronounced effect on single-vehicle crash occurrence than lane or shoulder width [10]. Road segments with multiple adjacent reverse curves and tight radii ($R < 200$ m) exhibit a significantly higher crash probability, stressing the decisive role of geometric design characteristics in motorcyclist safety. Furthermore, curved road sections are associated with a heightened risk of head-on motorcycle crashes, largely attributable to limited sight distance at curve entry [11]. Shoulder widening to approximately 2-2.5 m is initially associated with an increase in crashes, whereas further widening is associated with a reduction in crashes [12]. Also, larger minimum horizontal curve radii are related to fewer injury crashes, and steeper vertical grades are associated with higher total crash frequency. Research on geometric design consistency shows that mismatches between design elements and posted speed limits are linked to increased crash frequency and severity [13]. Empirical evidence indicates that higher mean speeds on single-carriageway roads are associated with an increased frequency of crashes [14].

Some authors specifically investigate the influence of pavement surface quality, including road roughness. The modelling results indicate that higher friction levels are associated with a reduction in motorcycle crash frequency, whereas greater variability in friction tends to increase crash frequency in specific contexts; additionally, pavement surface characteristics such as macrotexture, roughness, cracking, and rutting have been identified as significant factors influencing motorcycle crash occurrence [15]. Reduced pavement friction caused by asphalt polishing significantly impairs motorcycle stability, particularly on horizontal curves with smaller radii, where the interaction between low friction, speed, and braking increases the risk of loss of control and fall [16]. Research suggests that existing road safety inspection procedures should be refined and adjusted to better address conditions on secondary and local rural road networks [17]. Given that several indicators indicate that rural roads are particularly challenging for motorcyclists, various approaches are being used to collect high-quality data for analyzing risky roads. This is particularly true for collecting infrastructure data, which requires continuous monitoring and the use of innovative technologies. Some of the authors propose handlebar-mounted smartphones as an effective tool for collecting data for surface roughness assessment [18]. In another study, the authors used data on vertical and lateral vibrations collected by an equipped passenger car, showing promising results but noting the limitations of using only lateral vibration data [19]. Further, the motorcycle dynamics parameters, such as Yaw-Rate and lateral acceleration, has been proposed as a potential input for infrastructure-related risk models [20].

1.2 Study's objective

The starting assumption of the research is that the dynamics of riding a motorcycle can provide insight into road conditions, revealing sections that pose increased risk to riders or are more challenging. Previous work featuring the MoProVe concerned investigated correlations between motorcycle dynamics and infrastructure properties [20] and forming risk maps from motorcyclist driving dynamics [21]. The present study applies the MoProVe system for large-scale road condition assessment on selected sections of the Croatian national road network. The objective of this study is to apply motorcycle-based probe vehicle measurements to identify road surface irregularities and infrastructure characteristics relevant to powered two-wheeler safety on selected rural road sections. For these purposes, the methodology for risk mapping [21] will be applied to the data collected on three road tracks in Croatia.
High-resolution time-series data, including vehicle trajectory, speed, acceleration, and angular motion, are analyzed to detect locations with elevated vertical acceleration and atypical riding dynamics. By overlaying data from multiple rides, spatially consistent patterns are identified and linked to road surface conditions. Emphasis is placed on rough surface areas, as such irregularities may affect ride comfort, vehicle stability, and the potential for loss of control. For this purpose, a new indicator based on the relative z-Accelerations on the track will be investigated. Through this approach, the study contributes to a data-driven understanding of the characteristics of road infrastructure that are vital to motorcyclist safety on rural roads.

2 Methodology

2.1 Data collection apparatus

Trajectory information and vehicle dynamics data were collected using a Motorcycle Probe Vehicle (MoProVe) developed by the AIT Austrian Institute of Technology. The probe vehicle (KTM 1290 Super Adventure S) was equipped with an integrated multi-sensor measurement system (Racelogic's VBOX) designed to capture high-resolution trajectory, motion, and traffic interaction data under real traffic conditions. The probe vehicle's position and trajectory were recorded using a satellite-based positioning system, providing continuous information on geographic position, altitude, and instantaneous speed throughout each measurement run. Vehicle dynamic behavior was captured using an onboard inertial measurement unit (IMU). The IMU records tri-axial accelerations (X, Y, Z), corresponding to longitudinal, lateral, and vertical accelerations experienced by the motorcycle during operation. In addition, angular motion was measured using gyroscopes, providing Yaw-, Roll-, and Pitch-rates. To capture traffic interactions during measurements, the probe vehicle was further equipped with a forward-looking distance radar that continuously measured the distance to the vehicle ahead of the probe motorcycle, enabling the identification of the following situations. All sensors were synchronized, allowing the integration of trajectory, vehicle dynamics, and traffic interaction data into a unified dataset for subsequent analysis.

2.2 Test locations

For this study, three test sites were selected on the secondary-level road network in Croatia, listed as state roads. The selected roads are two-lane, two-way, and mostly rural or pass through smaller settlements, i.e., villages with low population density. This enabled data collection under free traffic flow conditions, i.e., with no traffic disturbance. Given the above non-intrusive data-collection method, traffic management measures were not necessary.

Furthermore, a specific road alignment, with numerous horizontal curves and changes in vertical longitudinal slope, characterizes all three roads. Table 1 presents main information about the selected road sites. Data collection was conducted on 29 September 2025 on a dry road surface, and in both driving directions.

Table 1 Description of examined roads

Track	Examined section	Section length (km)
Track 1	Plitvička – Rakovica	17.6
Track 2	Planina Gornja – Laz Bistrički	8.9
Track 3	Riječka – Stubica	37.8

2.3 Data analysis

Data from multiple test rides by two experienced MoProVe users was collected on each of the three tracks (at least 3 rides going in each driving direction). Data processing was performed in the statistical computing language R [22]. Driving data was saved separately for different driving directions on each track. The time series for driving speeds, X-, Y-, and Z-Accelerations and Yaw-, Roll-, and Pitch-Rates of the MoProVe's internal sensors were extracted from the in-vehicle CAN-Bus. An example of the Yaw-Rate is shown in figure 2a. Similarly, GNSS data (latitude and longitude in WGS84 Format) were extracted for each ride.

For all rides on a given track, a joint starting reference point (in a location passed by all ride trajectories) was chosen, and the nearest measurement to this reference point was used as the start of the valid measurement data, to ensure that all data could be aligned spatially. The same procedure was repeated with regard to a reference endpoint. For opposite driving directions, the roles of start and endpoint were reversed. Following this, the trajectory data was assigned to per-meter segments along the investigated track, so that it could be consistently assigned to a particular meter of the track. Based on this association between data and road meters, for driving speeds, X-, Y-, and Z-Accelerations and Yaw-, Roll-, and Pitch-Rates, each meter was associated with the mean value of each variable of all-time series data assigned to that meter per ride (see figure 2b for an example). Finally, a separate average was calculated for each variable across all rides per meter.

The first analysis to be performed using this data is the risk mapping procedure described in [21]. For this purpose, the Yaw-Rate, Roll-Rate, and Pitch-Rate (per ride per meter) are used, as well as a derived measure of driven curvature (see [21] for details), and are split into positive and negative parts. Furthermore, their first differences are calculated and also split into positive and negative parts. These 16 variables per ride (track- and direction-specific) are then multiplied by previously fit risk model weights (derived in [21]) in a linear model, and the resulting values are subjected to a logistic function, normalizing their output to a risk value between 0 and 1. The individual risk estimates per direction and meter are then averaged into a joint/averaged risk estimate, again taking values between 0 and 1. Values above 0.6 for this joint estimate are considered moderate/medium risk warnings, and values above 0.8 are considered high risk warnings, localized to specific meters and thus forming a first risk map.

Secondly, rough spots on the road surface are both relevant to safety (potentially loss of control, fatigue) and to riding comfort in general; thus, the present analysis focusses on noticeable Z-Accelerations along the investigated tracks as follows: to determine a relatively noticeable Z-Acceleration on a given track, we center the Z-Accelerations values (subtracted the mean) and find values that are at least 2 standard deviations above or below the centered Z-Accelerations.

For further analysis, the Z-Accelerations that were above 2 standard deviations are treated separately from the ones that were below 2 standard deviations. Isolated peaks are not the primary focus of this analysis; instead, areas of repeated, relatively high peaks are sought. To cover roughly one driving second at a speed of 100 kilometers per hour, the preceding 15 meters and the following 15 meters around each candidate peak are investigated for the occurrence of other Z-Acceleration peaks above or below two standard deviations (depending on the peak). If the total number of Z-Acceleration peaks is above 15, i.e., roughly every second meter around the investigated peak is itself a peak point of the Z-Acceleration. The area around the peak is considered a potential investigation site.

3 Results

As stated, data analysis was performed on the three road sections in both directions. Data was aligned by meter and driving direction and averaged as described above in section 2. For the initial risk mapping, data per ride and per direction was weighted with risk weights as described in section 2 and in [21]. The obtained risk estimates were averaged into a joint risk estimate per road, riding direction and meter. The resulting graphs can be seen in figure 1. The areas covered in risk warnings can be seen in table 2.

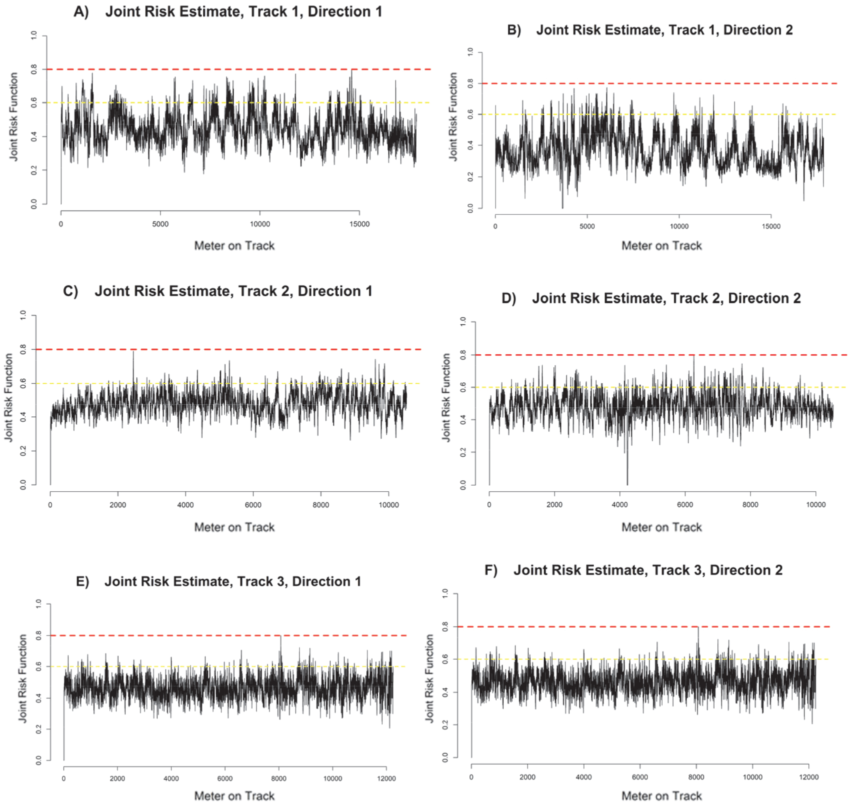

Figure 1 Averaged risk estimates on the 3 examined roads; left column and right column represent two different driving directions; rows represent the track investigated (Track 1 – top, Track 2 – middle, Track 3 – bottom); a yellow horizontal line at value 0.6 indicates the threshold for medium risk track meters; a red horizontal line at 0.8 indicates the threshold for high-risk track meters

Table 2 Meters of the track with risk warnings (medium and high) per direction

Examination track	Medium risk warning meters	High risk warning meters
Track 1 – Direction 1	1236	2
Track 1 – Direction 2	496	0
Track 2 – Direction 1	428	0
Track 2 – Direction 2	721	0
Track 3 – Direction 1	48	0
Track 3 – Direction 2	334	0

When extracting areas with noticeable Z-Accelerations, we need to consider two indicators: firstly, how many peaks indicating rough areas we find, and secondly, how much area they cover, as peaks surrounded by many other peaks (of the same sign) tend to cluster together. Figure 2 shows the outcome of this clustering for driving directions and for each sign of Z-Acceleration deviation.

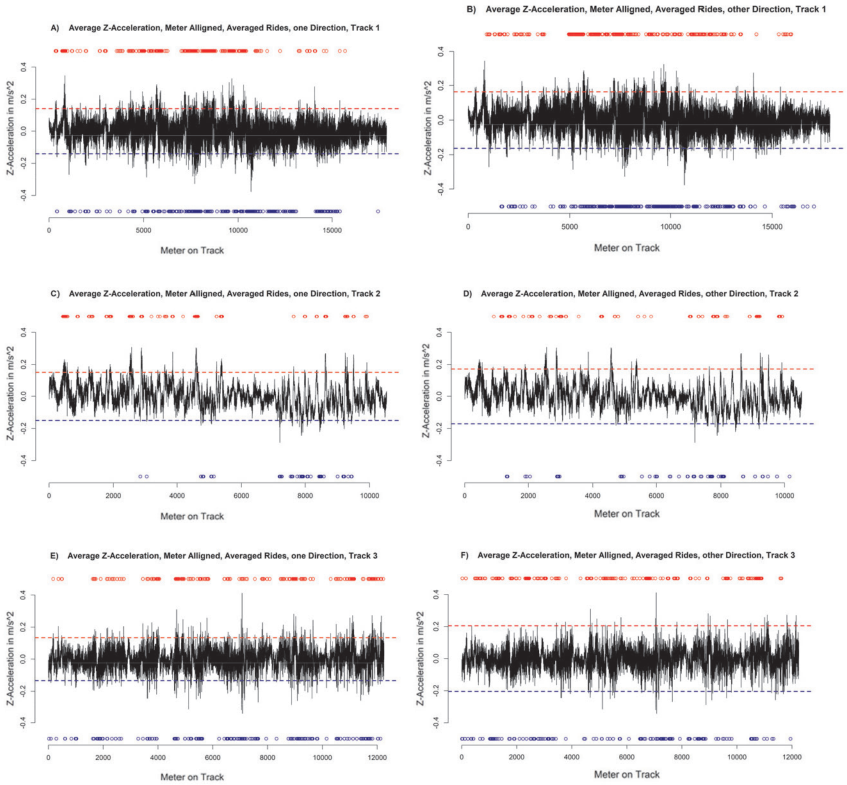

Figure 2 Averaged Z-Accelerations on the examined roads; left column and right column represent two different driving directions; lines represent the track investigated (Track 1 – top, Track 2 – middle, Track 3 – bottom); dots on the upper end of the graph represent locations of values above 2 standard deviations; dot on the lower end of the graph represents values below 2 standard deviations

The numerical values of area covered can be seen in table 3, with the percentage of coverage per direction shown.

Table 3 Meters of the track covered in Z-Acceleration warnings

Examination track	Covered – Direction 1	% of Direction 1 length	Covered – Direction 2	% of Direction 2 length
Track 1	88	0.50	39	0.22
Track 2	451	5.07	467	5.25
Track 3	0	0.00	83	0.22

It can be seen that the most noticeable areas for Z-Acceleration investigation are on the first two tracks (track 1 and track 2), while only a few are found on track 3. These results are also bound to the driving direction on each track. For further work, the found indicators can now be used to investigate road conditions and potentially direct maintenance measures.

4 Conclusion

The results demonstrate that it is possible to identify spatially consistent dynamic patterns that correspond to potentially critical infrastructure conditions. The application of the risk mapping model [21] and the relative Z-Acceleration indicator yielded coherent and direction-sensitive warning areas across the investigated road sections. Due to the specific driving dynamics and tire contact characteristics that depend on lean angle, motorcycles are sensitive to minor geometric and surface irregularities. Considering that the examined tracks are rural roads with significant transit and local traffic, it was expected that the measurement would show specific potentially critical locations. The results of the dynamic risk mapping (table 2) show differences between the examined lanes and between the directions of traffic. Tracks 1 and 2 have considerably more medium-risk warnings than Track 3. In contrast, Track 3 has relatively limited risk warnings, especially in the first direction, suggesting a generally lower dynamic demand. Regarding the high-risk indicators, they were only located on Track 1 and in the first direction. Furthermore, the consistent directional asymmetry across the three lanes confirms that the methodology is sensitive to the specific geometric or operational characteristics of each lane. When normalized by section length (table 3), Track 2 exhibits the highest relative proportion of clustered Z-Acceleration areas in both directions (approximately 5%), indicating more critical characteristics compared to the other two tracks. Track 1 showed limited but distinct clustered areas (< 1%). On the other hand, Track 3 presented minimal warnings overall, with only 0.22% of the section flagged in one direction. Although Track 3 displays the lowest relative coverage, an apparent directional asymmetry remains visible (the presence of 334 m of medium-risk warnings and 83 m of clustered Z-Acceleration peaks in Direction 2). These direction-specific findings likely reflect differences in geometric alignment, longitudinal gradient, or lane-specific pavement wear. Further, the higher concentration of warnings on Tracks 1 and 2 is consistent with their more complex horizontal and vertical alignment. Previous research emphasizes the decisive role of geometric design and pavement condition in motorcycle crash occurrence, particularly on rural roads [10, 15, 16].
These areas of heightened Z-Acceleration serve to guide road inspections. Within the project CAMBER the relation of warnings such as these Z-Acceleration indications to actual road surface damages will be investigated. Track 3 giving the least indications of clustered Z-Acceleration spikes is consistent with the fact that the track is less rural and leads through more urban sections.

Thus, driving dynamics are likely less demanding. Likely for the same reason also the risk mapping model of [21] notes fewer risky meters in Track 3, demonstrating the plausibility of the results. Results are preliminary, as the applied risk weights used for each rider are still subject to optimization (which might affect, in particular, the number of high-risk meters in the risk mapping).

The present findings demonstrate that dynamic probe vehicle data can detect infrastructure-related riding demands without the need for intrusive measurement techniques. The complementary use of dynamic risk modelling and vertical acceleration clustering provides a broader perspective on infrastructure screening. While the risk model captures riding complexity associated with curvature and vehicle attitude, the Z-Acceleration indicator highlights potential surface irregularities. Together, these methods offer a promising approach for prioritizing inspection and maintenance interventions on rural road networks. The results obtained using the described road examination can be very useful and applicable to road authorities, for example, for identifying candidate sites for friction or surface measurements.

There are some limitations to be noted. The study was exploratory, limited to dry conditions, and two experienced riders performed the test rides. Further research should include validation against detailed pavement inspections and multi-season measurements to refine threshold values and enhance the methodology's applicability. Furthermore, combining the results gathered through the described road examination with spatial and traffic data on road crashes could add value to the findings.

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