

DO METEOROLOGICAL AND ROAD CONDITIONS INFLUENCE ANIMAL-VEHICLE COLLISIONS?

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Abstract. Significant uncertainty remains regarding the relationship between meteorological conditions and Animal-Vehicle Collisions (AVCs). This study aimed to evaluate the influence of meteorological and related road conditions on AVC occurrence in Lithuania. Meteorological data and collision records from 56 automatic weather stations were linked with 1,632 AVCs reported between 2018 and 2022. Principal Component Analysis (PCA) revealed that meteorological variables form two statistically significant groups with contrasting associations with AVC occurrence. The first group – characterized by higher air and road surface temperatures, greater visibility, and a higher road adhesion coefficient – was positively associated with AVC occurrence. In contrast, the second group, defined by snow and ice cover, rain intensity, and the presence of water on the road surface, showed a negative association with AVC occurrence. These findings suggest that AVC risk increases under favourable driving conditions, likely due to changes in driver behaviour, whereas adverse weather conditions may reduce collision risk as drivers tend to exercise greater caution. Overall, the results provide new insights into the role of meteorological and road conditions in AVC dynamics and highlight the importance of considering human behavioural responses when developing AVC mitigation strategies.

Keywords: human-wildlife conflict, meteorological conditions, traffic safety.

1. Introduction

Economic development is influenced by roads, which also provide important mobility benefits and support social and cultural development. Globally, the total length of roads is estimated to increase by 25 million kilometre by 2050 (Strano et al., 2017). Despite the many advantages of roads, their environmental impact cannot be neglected. Roads have both direct and indirect effects on the environment. The indirect impact includes ecosystem degradation, habitat fragmentation, water and air pollution, and lighting conditions (Madadi et al., 2017; Kourchi et al., 2025). The most noticeable direct negative effect of roads is Animal-Vehicle Collisions (AVCs) (Bennett 2017; Silva et al., 2019). Around one million AVCs occur annually in the United States, and they result in human harm or human fatalities, financial loss, or millions of animal deaths (Roy & Ksaibati, 2021).

Over the past decades, researchers have sought to determine various factors that influence the occurrence of AVCs. These factors include characteristics of roads (Bil et al., 2019; Pagany, 2020; Su et al., 2023), vehicle speed or traffic volume (Jaroszweski & McNamara, 2014; Abraham & Mumma 2021), spatial-temporal factors (Lagos et al., 2012; Neumann et al., 2012; Morelle et al., 2013).

Others have highlighted the importance of species-specific factors (Garrah et al., 2015; Laliberté & St-Laurent 2020; Ortega et al., 2023). Knowledge of these factors' influence can provide a basis for mitigation measures. Nevertheless, considerable uncertainty remains regarding meteorological variables and AVCs.

Among all potential AVCs factors, studies of meteorological conditions were typically conducted outside of the context of animal-related accidents. Previous research on traffic safety has highlighted the influence of meteorological conditions, examining variables such as rainfall, temperature, humidity, snow cover, and fog (Lio et al., 2019; Pińskwar et al., 2023). Nevertheless, the results of these studies may depend on the methods used and various local conditions (Ramp & Roger 2008; Rolandsen et al., 2011; Stevens et al., 2019; Pińskwar et al., 2023). Also, the effects of adverse meteorological conditions on driver behaviour were discussed in relevant studies (Kilpeläinen & Summala 2007; Pavlou et al., 2023). To spot the potential hazards on the road, drivers reduce their driving speed (Yan et al., 2014). Heavy rain was also found to significantly increase driver lane-keeping behaviour (variance of lane position) (Ahmed et al., 2018). Zou et al. (2020) reported that, compared with clear days, the risk of vehicle collisions significantly

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increases on rainy days. Other studies have found that extremely low or high temperatures significantly influence the risk of road traffic accidents due to driver concentration (Zou et al., 2020). During a heat wave, traffic accidents increase by 4.7% (Park et al., 2021). Studies in Europe have shown that fog, mist, and smoke are the main causes of road crash fatalities, followed by rain and snow (Pavlou et al., 2023). In addition, higher wind speeds have a crucial effect on road traffic accidents (Backer et al., 2022; Wang et al., 2024). Even though the number of traffic accidents caused by gale wind is small compared to the total number of traffic accidents, another study (Backer et al., 2022) found that high-speed winds accounted for only 0.3 to 0.5% of traffic accidents. One possible explanation is that higher wind gust results in vehicle spins and rollovers, mainly on bridges and viaducts. In general, current studies have found that icy roads and extreme rainfall significantly increase the occurrence of traffic accidents (Seeherman & Liu 2015; Call & Flynt 2021; Wang et al., 2024).

Despite the large body of literature covering various aspects of AVCs, there is limited research on the role of meteorological conditions (Shao et al., 2010; Kazemi et al., 2016; Pagany, 2020; Roy & Ksaibati 2021; Su et al., 2023). A significant barrier to this is the challenge of data collection and the complexity of weather impacts (Lamprey et al., 2024). Nonetheless, research has shown that unfavourable meteorological conditions can influence behavioural changes in wild ungulates. Research revealed that high daytime temperatures may extend ungulate nocturnal activity, increasing the probability of AVC occurrence (Carvalho et al., 2017; Brivio et al., 2024). For example, more vehicle collisions with moose occur during time with high temperatures (Dussault et al., 2006). Due to their high sensitivity to heat, moose seek habitats that act as thermal refuges, leading to more frequent road crossings (Ditmer et al., 2018). Kazemi et al. (2016) note that the number of AVCs increases under extreme meteorological conditions, such as mist, fog, heavy precipitation. Poor visibility may affect driver behaviour by reducing vehicle speed. By contrast, there are only a few studies on the relation between meteorological variables and AVCs. Nevertheless, the conclusions are inconsistent (Dussault et al., 2006; Rolandsen et al. 2011). These rather contradictory results may be attributed to species-specific responses to extreme meteorological conditions and to regional variations in responses to different environmental factors (responses in one region may differ from those in another). This topic remains largely unstudied despite the importance of meteorological influence in traffic safety and AVCs.

Despite previous studies examining AVCs in various regions, there is limited evidence on how meteorological conditions influence AVCs in Lithuania. Our study highlights a research gap in understanding the influence of meteorological conditions on AVCs. This study aimed to evaluate the impact of meteorological and related road

conditions on the occurrence of AVCs. By linking meteorological conditions to AVC occurrences, the goal is to identify patterns that can be used to improve road safety strategies in Lithuania.

2. Materials and methods

From 2018 to 2022, a total of 38,093 road traffic accidents were recorded in Lithuania, of which 23,554 involved collisions with animals, accounting for 61.83% of all registered accidents. It should be noted that more recent collision data were not used due to limitations in data accessibility and obtaining official statistics for the most current years. In Lithuania, it is required to call the police if an accident with an animal occurs. Consequently, data on AVCs represent only those incidents that have been officially reported to the Lithuanian Police. Incidents that were not officially reported are not included in this analysis.

The Road Weather Information System (RWIS), which is based on weather stations on country roads, was first developed in Lithuania in 1999 (Laurinavičius & Juknevičiūtė-Žilinskienė, 2011). Road surface conditions and meteorological data are collected remotely via automatic weather stations. In Lithuania, weather stations provide real-time data at 15-minute intervals. For this study, the National access point database, maintained by Via Lietuva, is the main source of all meteorological data used for further analysis (National Access Point, n.d.). By the end of 2024, a total of 167 weather stations were put into operation on the roads of Lithuania (Road Weather Conditions, 2025). Of these, 99 meteorological stations are located on highways. For further analysis, we first selected stations located only on the highways. However, newly installed meteorological stations whose data could not be linked to the analysed period were excluded from further analysis. Meteorological stations that overlapped within the applied 5 km buffer were also removed. Finally, a total of 56 weather stations (Figure 1) were used for further analysis.

Data about air, road surface temperatures (°C), relative air humidity (%), wind speed (m/s), snow, ice, water cover (mm), visibility (meters), and adhesion coefficient (μ) were taken from each WS Table 1.

Table 1. Meteorological road parameters

Meteorological variables	Units
Road surface temperature	°C
Air temperature	°C
Adhesion coefficient	μ
Ice thickness	mm
Snow thickness	mm
Water thickness	mm
Visibility	meters
Relative humidity	(%)
Wind speed	m/s

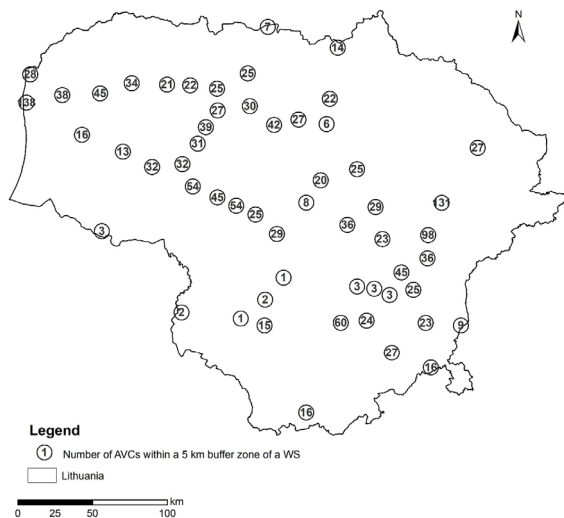


Figure 1. Distribution of AVCs within buffer zone of WS during 2018–2022

A buffer zone in this evaluation is defined as an area within 5 km of radius from the WS. The AVCs that fell into the buffer zone of WS during the period 2018–2022 (Figure 1) were selected for further analysis. Data about AVCs were taken from the Lithuanian Road Police Database. Totally, the 1632 AVCs were linked to precise meteorological data. The data indicate that roe deer (*Capreolus capreolus*) account for 65.75% of all recorded cases (Table 2). This finding suggests that this ungulate is the most frequently detected species within the study area, likely reflecting its high population density, spatial distribution, and ability to adapt to changing environments. XLSTAT and Principal Component Analysis (PCA) with a Spearman correlation matrix were used to analyze the statistical significance of meteorological factors on AVCs.

Table 2. Main species involved in AVCs within 5 km buffer zone in Lithuania between 2018 and 2022.

Species	Percentage of accidents (%)
Roe deer (<i>Capreolus capreolus</i>)	65.75
Moose (<i>Alces alces</i>)	9.07
Unidentified	9.99
Wild boar (<i>Sus scrofa</i>)	4.41
Red deer (<i>Cervus elaphus</i>)	3.25
Fox (<i>Vulpes vulpes</i>)	1.90
Dog (<i>Canis familiaris</i>)	1.53
Others *	4.11

Note: *Includes 11 species of wild and domestic animals that comprise < than 5% of total accidents.

3. Results

The results of analyzes of distribution of AVCs between day and night also did not distinguish the factor that

would be statistically significant. The only difference is that the higher numbers of AVCs occur at night.

Barlett's sphericity test (Chi-square (observed value) – 1422.1; Chi-square (critical value) – 61.7; $DF = 45$, p -value < 0.0001) showed that the correlations between the variables is significantly different from 0. Together, PC1 and PC2 capture 52.16% of the total variability in the dataset.

Results of PCA showed that the most important factors to occur AVC are higher air and road temperature (0.97, $p < 0.05$) together with less significance of visibility and adhesion coefficient (0.42, $p < 0.05$) (Figure 2b). On the contrary poor weather conditions like ice cover (–0.61, $p < 0.05$), snow cover (–0.62, $p < 0.05$), rain intensity (–0.53, $p < 0.05$) and water cover (–0.68, $p < 0.05$) formed the second group of factors (Figure 2a).

PCA showed that meteorological variables distributed into two main groups: a) significant for less possibility of occurrence of AVCs and b) significant for occurrence of AVCs. Wind speed and relative humidity did not show any significant correlation between meteorological factors.

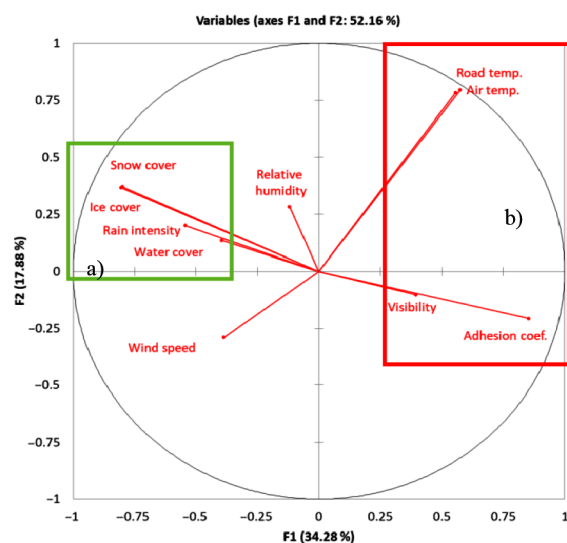


Figure 2. Principal component analyzes (PCA) of meteorological variables of AVCs: a) significant for less possibility of occurrence of AVCs; b) significant for occurrence of AVCs

4. Discussion

In this study, we analyzed the distribution of animal-vehicle collisions on Lithuanian highways in relation to meteorological variables. Our findings demonstrate that AVCs increase significantly during the nighttime. The results presented in this study align with previous research showing higher rates of ungulate collisions during periods of low visibility, as animals tend to be more active during dark hours (Su et al., 2023; Torres et al., 2025). On the other hand, drivers may improve their attention

and adjust their driving behavior to the road conditions. For instance, low visibility can result in reduced vehicle speed (Kioko et al., 2015). Other studies have demonstrated that low visibility and driving in fog can reduce speed by up to 10% compared with clear weather (Khan et al., 2018).

It has already been shown that unfavorable weather conditions can strongly influence the total accident risk (Van Langevelde & Jaarsma, 2005; Barrientos & Boloño, 2009; Laliberté & St-Laurent, 2020). While the influence of wind on rollover and sideslip accidents has been widely studied, its effects on AVCs remain relatively underexplored (Eltemasi & Behtooiey, 2024). Nonetheless, some indirect assumptions on wind effects on AVCs can be drawn from previous findings. For instance, Baur et al. (2021) described the influence of high wind velocity on ungulate harvest success. This may support the assumption that ungulates reduce their activity at high wind speeds. Higher wind speeds lead to higher noise levels; for example, for ungulates such as roe deer, it is more difficult to identify potential risks, which increases vigilance and the use of safe environments (Baur et al., 2021).

The potential influence of relative humidity on AVC occurrence has not yet been examined in previous studies. The relationship between relative humidity and animal-vehicle collisions is complex. Environmental factors, such as humidity, can influence animal movement patterns and specific behaviours. On the contrary, an increase in relative humidity has been negatively correlated with road mortality among birds (Raymond et al., 2021).

Road surface and air temperature are environmental factors beyond human control. Additionally, air temperature can strongly affect animal behaviour (Attias et al., 2018; Zhou et al., 2022). It was found that in cold weather, ungulates seek shelter in forested environments, thereby minimizing their exposure to adverse meteorological conditions (Rivrud et al., 2014). Dus-sault et al. (2006) found that more moose-vehicle collisions occur on days with high atmospheric pressure and temperatures. Researchers think the reason may be increased nocturnal activity or seeking cover to avoid biting insects. High temperatures can also significantly affect harvest rates. Rivrud et al. (2014) found that the probability of being harvested decreased with increasing temperature.

The slipperiness of a road surface varies with environmental factors. Our findings indicated that most AVCs occurred on high-adhesion-coefficient roads. Road adhesion conditions play a crucial role in traffic safety, as poor adhesion can impair drivers' ability to assess road conditions and substantially increase the risk of skidding or crashing (Li et al., 2023). Conversely, Meng et al. (2020) noted that the safe driving speed in inclement weather conditions is linearly related to the road adhesion coefficient. As the adhesion coefficient decreases, the safe driving speed decreases accordingly.

Seasonal variation in ice, snow, and water cover significantly alters animal movement behavior, often forcing wildlife to seek alternative routes that intersect with roads, thereby increasing the risk of AVCs (Cunningham et al., 2022). Our findings indicated that the majority of AVCs occurred when the road surface was dry, especially during nighttime. The effects of snow cover and ice thickness are not statistically significant, likely because most AVCs occur when there is no snow cover on roads. Conversely, Garrett and Conway (1999) reported a slightly higher number of car accidents when the roads are wet and slushy.

The aim of AVC research is to develop dynamic and effective approaches to minimize collision risks for both wildlife and humans. By integrating AVC datasets with environmental, spatiotemporal, or meteorological analyses, it becomes possible to identify and model spatial and temporal risk patterns more accurately. Such risk assessments should enable the projection of collision risks into future periods and their application to regions lacking comprehensive analysis. Nevertheless, challenges related to temporal forecasting, data quality, spatial transferability, and the integration of detailed meteorological variables remain key limitations that must be addressed to improve the reliability and applicability of AVC risk modelling.

5. Conclusions

The analysis of AVCs data around 56 meteorological stations in Lithuania led to the following conclusions:

No meteorological factor demonstrated statistically significant differences in the distribution of AVCs between day and night, although a consistently higher number of AVCs occurred during the night, suggesting a general but not statistically significant temporal tendency.

Overall, the study demonstrates that by using Principal Component Analysis, higher air and road temperatures are the most influential factors associated with increased AVC occurrence, while visibility and road adhesion showed weaker but still significant contributions. Together, the first two principal components explained 52.16% of the total variance, confirming the relevance of temperature-related variables in shaping AVC patterns. Adverse weather conditions – including ice cover, snow cover, rain intensity, and water cover – were associated with a reduced likelihood of AVC occurrence and formed a distinct group of negatively correlated variables. This may support the hypothesis that increased driver attentiveness under such circumstances plays a more critical role than changes in animal movement patterns.

This study also shows that wind speed and relative humidity did not demonstrate significant relationships with AVC occurrence, indicating limited influence within the analyzed meteorological framework.

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