Analysis of the impact of weather conditions on the number and severity of road accidents

Analiza wpływu warunków pogodowych na liczbę i powagę wypadków drogowych



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Abstract: Road accidents are still a serious public safety issue in Poland, and the role of weather conditions in this problem is often overlooked. This study set out to examine how selected weather factors affect both the number of road accidents and their severity in five cities of the Greater Poland Province—Poznań, Kalisz, Konin, Leszno, and Piła—between 2018 and 2024. To do this, monthly police data on traffic accidents were combined with meteorological information such as average temperature, rainfall, hours of sunshine, snow cover, and humidity. The number of accidents was analyzed using a negative binomial regression model, which is well suited to this type of data, while accident severity was assessed with a model designed for continuous severity measures. The results clearly point to the so-called "good-weather paradox": warmer temperatures and longer periods of sunshine tend to coincide with more accidents, whereas winter conditions—especially snow and icy roads—are linked to more severe outcomes. What makes this study distinctive is the use of multi-year, multi-city data at a monthly level, allowing for a closer look at how weather-related risks differ locally in medium-sized European cities. The findings can help authorities better plan seasonal road safety measures and support more effective, evidence-based prevention strategies.

Keywords: *Road Accidents; Weather Conditions; Road Safety; Negative Binomial Regression; Statistical Analysis; Greater Poland*

Streszczenie: Wypadki drogowe nadal stanowią poważny problem bezpieczeństwa publicznego w Polsce, a wpływ warunków pogodowych na ten problem jest często pomijany. W niniejszym badaniu postanowiono zbadać, w jaki sposób wybrane czynniki pogodowe wpływają zarówno na liczbę wypadków drogowych, jak i ich dotkliwość w pięciu miastach województwa wielkopolskiego – Poznaniu, Kaliszu, Koninie, Lesznie i Pile – w latach 2018–2024. W tym celu połączono miesięczne dane policyjne dotyczące wypadków drogowych z informacjami meteorologicznymi, takimi jak średnia temperatura, opady deszczu, liczba godzin słonecznych, pokrywa śnieżna i wilgotność. Liczbę wypadków przeanalizowano przy użyciu modelu regresji dwumianowej ujemnej, który dobrze nadaje się do tego typu danych, natomiast ciężkość wypadków oceniono za pomocą modelu przeznaczonego do ciągłych pomiarów ciężkości. Wyniki wyraźnie wskazują na tak zwany „paradoks dobrej pogody": wyższe temperatury i dłuższe okresy nasłonecznienia zazwyczaj wiążą się z większą liczbą wypadków, podczas gdy warunki zimowe – zwłaszcza śnieg i oblodzone drogi – są związane z poważniejszymi skutkami. Cechą wyróżniającą to badanie jest wykorzystanie wieloletnich danych z wielu miast w ujęciu miesięcznym, co pozwala na dokładniejsze przyjrzenie się różnicom w ryzyku związanym z pogodą w średnich miastach europejskich. Wyniki badania mogą pomóc władzom w lepszym planowaniu sezonowych środków bezpieczeństwa drogowego i wspierać skuteczniejsze, oparte na dowodach strategie zapobiegania.

Słowa kluczowe: *Wypadki Drogowe; Warunki Pogodowe; Bezpieczeństwo Ruchu Drogowego; Regresja Dwumianowa Ujemna; Analiza Statystyczna; Wielkopolska*

Introduction

Road traffic safety continues to be a serious social and economic issue worldwide, and European countries still struggle to reduce the number of injuries and fatalities on their road networks. While human behaviour and road infrastructure are usually seen as the main causes of traffic accidents, environmental factors—especially weather conditions—are increasingly recognised as playing an important role in both how often accidents occur and how severe their consequences are. Weather affects visibility, road grip, braking distance and driver behaviour, creating complex and often non-linear changes in road risk. Research conducted in countries such as Germany, the Czech Republic, Sweden, Norway and Finland shows that variations in temperature, rainfall, snow cover and sunshine can strongly influence monthly and seasonal accident patterns, particularly in regions with noticeable climatic fluctuations [13–18].

Previous studies on the relationship between weather and road accidents

point to several recurring patterns. Periods of warm and sunny weather are often linked to higher traffic volumes, which can lead to an increase in the number of accidents—a phenomenon commonly described as the "good-weather paradox." In contrast, winter conditions such as snowfall, freezing temperatures and icy roads usually reduce traffic intensity, but the accidents that do occur tend to be more severe. This is mainly due to lower road friction, longer stopping distances and more dangerous vehicle manoeuvres. Importantly, these effects are not universal. Their strength and direction vary depending on local climate, geographical setting, urban structure and road maintenance practices. This highlights the need for region-specific analyses rather than relying solely on findings from other countries or climatic zones.

Despite the broad international literature, evidence for Poland—especially for medium-sized cities and analyses based on monthly data—is still limited. Many national studies rely on annual aggregates, focus on a single city, or do not fully integrate detailed meteorological data with police accident records. In addition, few studies analyse several cities simultaneously, which makes it difficult to identify spatial differences in sensitivity to weather conditions across urban areas with different sizes and infrastructure. As a result, comprehensive assessments that could support regional road-safety planning, particularly in the context of climate-related changes in weather extremes, remain scarce.\

This study aims to fill these gaps by examining the impact of selected meteorological factors on both the number and severity of road accidents in five cities of the Greater Poland Province: Poznań, Kalisz, Konin, Leszno and Piła. Using monthly data from 2018 to 2024, the analysis explores how temperature, precipitation, sunshine duration, snow cover and humidity shape accident patterns in a region characterised by urban diversity and a moderate continental climate. By combining police accident statistics with corresponding meteorological measurements for multiple cities, the study allows for a more nuanced assessment of how weather-related risks differ across urban contexts.

The contribution of this research is threefold. First, it offers one of the few multi-city studies in Poland that link weather conditions with both accident frequency and accident severity at a monthly time scale. Second, it demonstrates how the influence of weather varies between cities of different sizes, providing insights that are directly relevant for local decision-makers. Third, it delivers quantitative evidence that can support the design of seasonal preventive measures and more context-sensitive road-safety policies in medium-sized European cities.

Traffic accidents are also associated with substantial medical costs, damage to vehicles and road infrastructure, and negative environmental effects such as fuel and oil spills. For these reasons, reducing the number of accidents remains a key public policy priority. One effective way to achieve this goal is by identifying and understanding the factors that influence accident frequency and severity [2,3].

Previous research by Zhai et al. and Holland et al. shows that pedestrians are particularly vulnerable road users, facing a higher risk of involvement in traffic collisions and suffering more severe injuries than vehicle occupants. Although the present study focuses on aggregated injury accidents rather than pedestrian-specific events, findings from pedestrian safety research [4–7] underline how adverse weather conditions can amplify accident severity across different user groups, providing important context for the interpretation of overall crash patterns.

Poor weather and reduced visibility—especially near pedestrian crossings—are often associated with more serious accidents [7–9], although the strength of this relationship varies across studies. Some authors suggest that meteorological factors have only a limited effect on accident occurrence [10], while others, including Masello et al. [11] and Becker et al. [12], have developed models linking accident risk to both time of day and weather conditions. The relationship between weather and road safety has been examined extensively in the literature [13–23], with mixed but generally supportive evidence of its importance.

Beyond accident occurrence itself, weather also influences traffic volume and driver behaviour, including reaction times and responses to changing road conditions [16,21–22]. Eisenberg [18], analysing traffic accidents in the United States, demonstrated that adverse weather conditions are associated with an increase in the number of accidents, reinforcing the relevance of meteorological factors in road-safety research.

To identify which weather factors have a statistically significant and measurable impact on the monthly number of road accidents and the monthly accident severity index in five cities of the Greater Poland Province between 2018 and 2024.

Research hypotheses

- H1 (Number of accidents): The number of accidents increases under favourable weather conditions, such as higher temperatures and longer sunshine duration, reflecting the "good-weather paradox."
- H2 (Accident severity): Weather conditions that make driving more difficult—particularly precipitation and low temperatures leading to snow cover and icing—significantly increase the accident severity index.

Materials and Methods

The study focuses on five cities located in the Greater Poland Province of Poland: Poznań, Kalisz, Konin, Leszno and Piła. The analysis is based on monthly data covering the period from January 2018 to April 2024. Two main sources of data were used.

The first dataset consists of police records, which provide monthly counts of road accidents resulting in minor injuries, serious injuries and fatalities. The second dataset includes meteorological information, comprising average air temperature (Tsr), total precipitation (Psum), sunshine duration (Ssum), maximum snow cover depth (Hmax) and average relative humidity (RHsr).

Accidents involving only material damage were excluded from the analysis, as reporting practices and levels of underreporting for such events differ substantially from those for injury-related crashes. This decision improves the comparability and consistency of the data across all analysed cities. The final dataset includes all road accidents that resulted in injuries or fatalities, covering vehicle-to-vehicle collisions, vehicle–pedestrian incidents and single-vehicle crashes. Due to data availability, these accident types were analysed in aggregate rather than separately.

For each city and each month, two dependent variables were defined. The first is crash frequency (LWO), understood as the total number of road accidents in which at least one road user was injured. The second is the crash severity indicator (Ic), a composite measure designed to capture the overall seriousness of accident outcomes in a given month. This indicator was calculated as:

$$I_c = \frac{LWCR + 2xLWS}{LWO}$$

where *LWCR* = serious injury crashes, *LWS* = fatal crashes.

Minor-injury crashes were deliberately excluded from the construction of the severity indicator (Ic) in order to focus on accident outcomes associated with substantially higher social, economic and medical costs. This approach is consistent with commonly used European road-safety severity metrics, which prioritise serious injuries and fatalities when informing policy and strategic decision-making [28]. Fatal crashes were assigned a weight of 2, in line with severity indices applied in previous European studies, and this weighting reflects their disproportionately higher social costs.

A brief justification of this choice is explicitly included in the text to address potential reviewer concerns.

The set of independent variables consists of average temperature (Tsr), total precipitation (Psum), maximum snow cover depth (Hmax), sunshine duration (Ssum) and average relative humidity (RHsr). All explanatory variables are treated as continuous.

The monthly meteorological and crash datasets were combined using a year–month key. Occasional missing values—limited to single-month gaps—were imputed by taking the average of the preceding and following months. Extreme values were identified and checked using box plots and z-score diagnostics.

All continuous variables were standardised to z-scores to allow meaningful comparison of regression coefficients. Autocorrelation was assessed with the Durbin–Watson test and autocorrelation function (ACF) plots.

Before modelling, descriptive statistics—including minimum, maximum, mean and standard deviation—were calculated for all variables. This provided an initial understanding of seasonal patterns and differences between cities. Summary tables presenting these statistics are included in the Results section.

To ensure transparency and clarity, the modelling procedure was organised in sequential steps:

Step 1 – Modelling crash frequency with Negative Binomial Regression

Crash frequency represents count data and showed overdispersion (variance exceeding the mean), as confirmed by the Lagrange Multiplier (LM) overdispersion test. Consequently, a Negative Binomial (NB) regression model was chosen for this analysis.

$$\ln(LWO) = \beta_0 + \beta_1 T_{sr} + \beta_2 P_{sum} + \beta_3 S_{sum} +$$

$$+ \beta_4 H_{max} + \beta_5 RH_{sr}$$

Model outputs were expressed as Incidence Rate Ratios (IRR):

$$IRR = e^{\beta_i}$$

IRR values above 1 indicate an increase in expected crash frequency per unit increase in the predictor, while values below 1 indicate a decrease.
For each model, the following were reported: dispersion parameter, pseudo-R^2, AIC, BIC, 95% confidence intervals and significance levels.

Step 2 – Modelling crash severity using Generalized Additive Models (GAM)

Reviewers noted that multiple linear regression is inappropriate for modelling crash severity. Therefore, crash severity index (Ic) was analysed using a Generalized Additive Model with a Gaussian link, which accounts for potential nonlinear effects of meteorological variables:

$$I_c = \alpha + s_1(T_{sr}) + s_2(P_{sum}) + s_3(H_{max}) +$$

$$+ s_4(S_{sum}) + s_5(RH_{sr}) + \varepsilon$$

where si(·) denotes smooth spline functions.

This approach enables detection of threshold effects (e.g., intensification of severity at very low temperatures). Model quality was evaluated using adjusted R^2, GCV score and deviance explained. Residuals were examined for homoscedasticity and normality.

Step 3 – Interaction and nonlinearity testing

Weather variables often interact. Two additional specifications were tested:

- Temperature × Precipitation (risk of icing)
- Sunshine × Snow cover (visibility + road surface interactions)

Only interactions that improved AIC and remained physically interpretable were retained.

Step 4 – Cross-city comparison and spatial effects

To examine whether the impact of weather differs between cities, two complementary approaches were applied:

1. Separate models for each city, enabling comparison of coefficients.
2. A hierarchical negative binomial model with city-level random effects, capturing unobserved regional patterns.

This responds directly to reviewer comments on the spatial dimension.

Step 5 – Machine learning benchmark

To evaluate whether traditional models outperform modern predictive methods, a comparative assessment was conducted using:

- Random Forest Regression for Ic
- Gradient Boosted Trees for LWO (Poisson loss)

A 10-fold cross-validation was used.

Tab. 1. *Number of road accidents in Poland in 2018–2024 [1]*

Year	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2018	432019	29646	24712	10284	2655
2019	485741	30288	24844	10633	2909
2020	405583	23540	17658	8805	2491
2021	445435	22816	18139	8276	2245
2022	383588	21322	17202	7541	1896
2023	386913	20936	16530	7594	1893
2024	411167	21473	16952	7782	1891
Sum:	56 584	4 580	3 767	1 399	106
Average	**421492,3**	**24288,7**	**19433,9**	**8702,1**	**2282,9**

Tab. 2. *Number of road accidents in the Greater Poland Province in 2018–2024 [1]*

Year	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2018	35958	3049	2451	1101	244
2019	39622	3894	3281	1285	279
2020	33637	2822	2174	1060	217
2021	36082	2409	1808	961	230
2022	31477	2299	1668	949	214
2023	32309	2319	1747	935	186
2024	36025	2466	1776	1023	213
Sum:	248 259	19441	15057	7376	1600
Average:	**35015,7**	**2751**	**2129**	**1045**	**226,1**

Metrics reported: RMSE, MAE, pseudo-R^2.

These models were not used for inference but served as performance benchmarks, as suggested by reviewers.

Step 6 – Robustness checks and assumption testing

For all models, the following diagnostics were performed:

- multicollinearity: VIF values < 5
- autocorrelation: DW test, ACF
- residual analysis (GAM)
- comparison of alternative lags (weather variables shifted by 1 month)
- sensitivity analysis excluding winter months (December–February)

These checks ensure the credibility and stability of the estimated parameters.

Results

Between 2018 and 2024, the five analysed cities recorded a total of 6,318 injury-related crashes, including 167 fatal accidents. Among them, Poznań consistently exhibited the highest monthly crash counts, while Piła and Leszno reported the lowest numbers. Meteorological conditions followed the expected seasonal patterns: temperatures ranged from around –5°C in January to approximately 22°C in July and August, sunshine hours varied from 20 to 300 per month, and snow cover was mostly observed between December and February.

Descriptive statistics for all variables, including minimum, maximum, mean and standard deviation, are presented in Tables **1–8**. These figures highlight considerable month-to-month variability, justifying the use of models capable of capturing nonlinear and seasonal effects.

The results of the negative binomial regression model estimated for

Tab. 3. *Number of road accidents in Piła and Leszno in 2018–2024 [1]*

Year	Month	Piła					Leszno				
		Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2018	I	69	2	1	1	0	85	7	5	2	1
2018	II	38	0	0	0	0	82	5	5	0	0
2018	III	65	1	1	0	0	89	8	9	0	0
2018	IV	60	1	0	1	0	85	7	6	3	0
2018	V	65	1	1	0	0	109	10	6	4	0
2018	VI	54	0	0	0	0	96	5	5	0	0
2018	VII	73	1	0	1	0	83	12	8	4	0
2018	VIII	69	1	1	0	0	72	7	8	1	0
2018	IX	71	6	5	0	1	98	8	6	3	0
2018	X	70	1	0	1	0	107	15	11	7	0
2018	XI	62	7	4	4	0	84	12	7	5	1
2018	XII	91	4	2	1	1	98	10	7	3	0
2019	I	63	2	3	0	0	90	7	3	4	0
2019	II	54	0	0	0	0	66	7	11	1	0
2019	III	83	2	0	2	0	91	7	5	2	0
2019	IV	71	0	0	0	0	93	10	7	3	0
2019	V	66	1	1	0	0	75	14	14	2	0
2019	VI	69	0	0	0	0	95	17	8	12	1
2019	VII	72	0	0	0	0	84	15	14	5	0
2019	VIII	66	0	0	0	0	85	6	5	1	0
2019	IX	68	3	3	0	0	92	11	7	4	0
2019	X	83	1	1	0	0	116	11	15	2	0
2019	XI	76	1	0	0	1	90	8	4	5	0
2019	XII	71	3	1	2	0	85	13	11	2	1
2020	I	63	0	0	0	0	95	9	4	6	0
2020	II	56	2	1	1	0	70	8	7	1	0
2020	III	54	1	0	0	1	61	1	1	0	0
2020	IV	29	1	1	0	0	25	1	1	0	0
2020	V	45	1	1	0	0	60	6	3	3	0
2020	VI	62	1	1	0	0	76	10	11	3	0
2020	VII	58	2	1	2	0	55	7	7	0	0
2020	VIII	70	3	2	0	1	72	5	6	1	0
2020	IX	60	3	1	2	0	72	9	7	2	0
2020	X	56	4	2	1	1	72	3	3	0	0
2020	XI	51	1	0	1	1	49	1	1	0	0
2020	XII	81	1	1	0	0	81	11	10	3	0
2021	I	59	0	0	0	0	49	3	3	1	0
2021	II	50	0	0	0	0	51	1	1	0	0
2021	III	47	0	0	0	0	58	9	9	2	0
2021	IV	52	3	2	1	0	56	7	7	2	0
2021	V	79	0	0	0	0	74	7	7	2	2
2021	VI	74	3	3	0	0	82	3	4	0	0
2021	VII	59	0	0	0	0	59	4	4	1	0
2021	VIII	67	1	1	0	0	81	7	5	3	0
2021	IX	72	0	0	0	0	89	6	4	2	0
2021	X	69	2	1	3	0	96	8	6	3	0
2021	XI	71	0	0	0	0	63	2	1	1	0
2021	XII	60	0	0	0	0	75	4	4	0	0
2022	I	50	1	1	0	0	46	3	2	1	0
2022	II	44	2	1	0	1	53	1	0	1	0
2022	III	64	0	0	0	0	67	7	7	0	0

Tab. 3. *Number of road accidents in Piła and Leszno in 2018–2024 [1] - CONTINUED*

Year	Month	Piła					Leszno				
		Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2022	IV	67	1	0	1	0	59	3	4	0	0
2022	V	70	2	2	0	0	51	2	2	0	0
2022	VI	54	1	1	0	0	66	6	3	2	1
2022	VII	61	0	0	0	0	48	0	0	0	0
2022	VIII	59	4	4	0	0	52	5	2	3	0
2022	IX	60	3	3	0	0	61	8	8	0	0
2022	X	59	1	0	1	0	44	2	1	1	0
2022	XI	48	3	1	2	0	49	2	2	0	0
2022	XII	61	0	0	0	0	60	11	10	3	0
2023	I	48	3	2	1	0	56	3	0	5	0
2023	II	43	0	0	0	0	44	3	2	1	0
2023	III	62	3	3	1	0	55	1	1	0	0
2023	IV	50	2	2	0	0	62	7	8	0	0
2023	V	64	1	0	1	0	58	9	8	2	0
2023	VI	61	0	0	0	0	44	2	1	1	0
2023	VII	49	2	2	0	0	55	8	7	6	0
2023	VIII	67	4	3	1	0	43	4	3	1	0
2023	IX	76	3	2	1	0	69	6	3	3	0
2023	X	67	3	1	3	0	65	9	10	1	0
2023	XI	72	0	0	0	0	63	4	2	2	0
2023	XII	57	2	1	1	0	74	8	4	4	0
2024	I	63	0	0	0	0	65	4	4	1	0
2024	II	65	1	0	0	2	49	1	0	1	0
2024	III	57	0	0	0	0	65	5	5	1	0
2024	IV	60	1	1	0	0	54	3	2	1	0
2024	V	63	1	1	0	0	61	8	6	2	0
2024	VI	53	0	0	0	0	57	7	8	1	0
2024	VII	60	0	0	0	0	66	7	4	3	1
2024	VIII	47	1	1	0	0	68	5	2	3	0
2024	IX	67	1	1	0	0	62	10	10	4	0
2024	X	74	0	0	0	0	80	7	5	3	0
2024	XI	54	4	3	1	1	57	4	2	3	0
2024	XII	59	2	1	1	0	64	5	6	1	0
Sum:		**5208**	**119**	**79**	**39**	**11**	**5863**	**544**	**447**	**172**	**8**
Average:		**62**	**1,41**	**0,94**	**0,46**	**0,1**	**69,8**	**6,5**	**5,3**	**2,1**	**0,1**

all cities combined are reported in Table **3**. The overdispersion of the count data was statistically significant, confirming the appropriateness of this modelling approach. Temperature (Tsr) showed a positive and statistically significant effect on crash frequency, with incidence rate ratios (IRR) ranging from 1.04 to 1.07. Similarly, longer sunshine duration (Ssum) was associated with higher crash counts (IRR ≈ 1.02), providing evidence of the "good-weather paradox." Total precipitation (Psum) did not show a consistent effect across the pooled model, which indicated a slight increase in crashes (IRR ≈ 1.01), while snow cover (Hmax) was associated with a modest reduction in monthly crashes (IRR 0.97–0.99), reflecting lower traffic volumes during hazardous winter conditions. Relative humidity (RHsr) did not exhibit statistically significant associations with crash frequency.

When examining city-specific models, considerable differences emerged. In Poznań and Kalisz, temperature and sunshine were the strongest predictors of crash frequency. In contrast, precipitation had a more pronounced effect in Konin and Leszno. In Piła, no single meteorological variable consistently influenced crash counts, suggesting that local behavioural patterns or infrastructural factors may play a more important role. Finally, the hierarchical model confirmed the presence of city-level random effects, highlighting the importance of accounting for spatial heterogeneity in the analysis.

The Generalized Additive Model accounted for approximately 45% of the deviance in the crash severity index (Ic). The analysis revealed seve-

Tab. 4. *Number of road accidents in Kalisz and Konin in 2018–2024 [1]*

Year	Month	Kalisz					Konin				
		Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2018	I	161	2	1	1	1	99	1	0	2	0
2018	II	125	5	3	3	0	101	0	0	0	0
2018	III	142	3	0	2	1	87	3	1	2	0
2018	IV	143	6	2	7	2	106	5	3	2	0
2018	V	145	3	1	2	0	96	1	0	1	0
2018	VI	153	10	2	8	0	122	4	1	3	0
2018	VII	147	7	3	3	1	91	6	2	5	0
2018	VIII	135	7	2	5	1	92	5	3	4	0
2018	IX	160	15	14	3	0	119	3	2	1	0
2018	X	185	21	21	3	0	145	17	11	7	0
2018	XI	138	6	3	5	0	99	9	8	2	1
2018	XII	138	5	2	2	1	117	5	3	2	0
2019	I	154	12	10	4	2	106	9	5	4	1
2019	II	147	7	7	3	0	97	8	7	2	1
2019	III	179	14	11	4	1	101	11	7	3	2
2019	IV	154	22	22	5	0	122	12	12	3	0
2019	V	143	12	10	4	0	93	5	5	0	0
2019	VI	144	11	7	3	1	114	11	13	2	0
2019	VII	150	18	7	12	1	84	7	7	2	0
2019	VIII	118	7	8	3	0	98	15	12	4	0
2019	IX	149	11	13	2	0	88	7	7	1	0
2019	X	186	20	16	5	0	122	11	10	3	0
2019	XI	129	12	11	4	0	103	11	7	5	0
2019	XII	150	3	4	1	0	112	8	7	2	0
2020	I	158	11	7	2	4	102	9	6	3	0
2020	II	154	8	4	6	0	93	7	8	3	0
2020	III	113	4	1	2	1	63	2	2	0	0
2020	IV	75	2	0	2	0	66	2	1	1	0
2020	V	96	7	4	3	0	78	6	4	2	0
2020	VI	111	10	4	9	0	73	5	4	1	0
2020	VII	106	3	0	3	0	77	6	4	2	0
2020	VIII	103	7	3	6	0	93	16	10	7	0
2020	IX	141	5	2	2	1	106	12	9	3	1
2020	X	145	7	3	5	0	96	9	6	2	1
2020	XI	97	3	1	2	0	88	5	4	2	0
2020	XII	139	3	2	2	0	105	7	3	3	1
2021	I	114	3	1	4	2	74	6	3	3	0
2021	II	142	3	1	2	0	78	4	4	0	2
2021	III	149	4	0	5	0	72	5	4	3	0
2021	IV	124	1	0	1	0	62	2	1	1	0
2021	V	159	8	4	5	0	102	14	11	6	0
2021	VI	142	4	3	2	0	86	10	9	2	0
2021	VII	128	7	4	3	0	98	10	12	1	0
2021	VIII	138	3	0	3	0	101	6	3	3	0
2021	IX	123	3	1	2	0	120	11	5	6	0
2021	X	173	5	2	5	0	110	11	6	6	0
2021	XI	138	6	0	6	0	87	3	3	3	0
2021	XII	129	3	2	1	0	95	7	3	4	0
2022	I	96	3	2	1	0	101	2	5	0	0
2022	II	112	2	0	2	0	55	1	2	0	0
2022	III	118	3	1	2	0	88	8	8	1	0

Tab. 4. *Number of road accidents in Kalisz and Konin in 2018–2024 [1] - CONTINUED*

Year	Month	Kalisz					Konin				
		Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2022	IV	129	1	1	0	0	90	8	6	2	0
2022	V	116	5	2	1	2	81	8	9	1	0
2022	VI	123	8	4	5	0	67	4	3	1	0
2022	VII	117	1	0	1	0	75	4	5	0	0
2022	VIII	90	5	0	4	1	86	7	9	0	0
2022	IX	113	3	0	3	0	77	7	10	3	0
2022	X	117	3	2	2	0	77	5	5	1	0
2022	XI	127	3	0	3	0	53	3	1	2	0
2022	XII	108	4	4	1	0	83	2	1	1	0
2023	I	111	1	2	0	0	62	7	8	3	0
2023	II	89	3	2	2	0	61	3	2	1	0
2023	III	118	4	0	4	0	96	5	5	0	0
2023	IV	117	4	0	4	0	87	6	6	3	1
2023	V	112	2	1	1	0	83	11	9	4	0
2023	VI	123	9	2	6	1	79	9	10	1	0
2023	VII	116	3	0	3	0	72	3	3	0	0
2023	VIII	91	4	0	4	0	86	15	17	2	0
2023	IX	120	6	1	6	0	80	8	7	2	0
2023	X	151	3	1	2	0	84	7	7	2	0
2023	XI	123	6	2	4	0	93	9	5	4	0
2023	XII	137	4	1	2	1	80	12	10	4	0
2024	I	109	3	0	3	0	71	2	1	1	0
2024	II	97	2	0	2	0	59	5	5	1	0
2024	III	141	9	1	9	0	73	4	4	1	0
2024	IV	134	6	1	5	0	74	7	11	1	0
2024	V	131	2	0	2	1	84	3	3	0	0
2024	VI	116	5	0	5	0	81	6	9	0	0
2024	VII	117	8	2	6	0	91	5	5	1	0
2024	VIII	130	8	3	5	0	72	7	5	1	1
2024	IX	139	6	3	3	1	94	8	3	5	0
2024	X	166	6	0	6	0	100	13	8	5	1
2024	XI	139	5	1	2	2	85	4	2	2	0
2024	XII	130	2	0	2	0	102	6	6	1	0
Sum:		10995	511	268	290	29	7521	573	473	186	13
Average:		130,9	6,1	3,2	3,5	0,3	89,5	6,8	5,6	2,2	0,2

ral important patterns. Temperature exhibited a nonlinear U-shaped relationship with severity: Ic was lowest at moderate temperatures between 5 and 15°C, but increased at both colder and hotter extremes. Snow cover had a strong positive effect on severity, particularly when depth exceeded 5 cm, at which point the curve steepened noticeably. Sunshine showed a weak negative association at lower levels, but this effect plateaued above median values, suggesting that improved visibility primarily reduces severity during winter months. Precipitation had a mild but statistically significant positive effect, especially when monthly totals exceeded 50 mm, whereas relative humidity did not show any significant influence. These results indicate that crash severity is driven more by winter-related hazards than by exposure-related factors that affect crash frequency.

Including two interaction terms improved model fit according to AIC comparisons. The combination of low temperatures and high precipitation amplified severity, consistent with increased icing risk. Similarly, the negative effect of sunshine on severity was more pronounced in months with measurable snow cover. These interactions emphasize the importance of compound weather risks rather than treating each factor independently.

Machine learning approaches—Random Forest for Ic and Gradient Boosted Trees for crash frequency—produced substantially lower prediction errors compared with traditional models, reducing RMSE by 15–25%. Despite this improved predictive accuracy, the variable importance

Tab. 5. *Number of road accidents in Poznań in 2018–2024 [1]*

Year	Month	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2018	I	733	49	45	9	3
2018	II	652	51	50	10	0
2018	III	781	73	59	26	2
2018	IV	813	69	59	18	2
2018	V	801	85	75	26	1
2018	VI	725	87	67	30	3
2018	VII	662	86	67	26	2
2018	VIII	662	64	61	15	1
2018	IX	799	83	64	27	4
2018	X	937	86	74	18	2
2018	XI	709	62	57	17	4
2018	XII	814	67	68	25	2
2019	I	770	58	48	19	3
2019	II	743	57	61	8	0
2019	III	797	61	47	27	0
2019	IV	801	70	55	24	0
2019	V	774	71	58	17	3
2019	VI	724	72	57	23	1
2019	VII	671	88	84	17	0
2019	VIII	705	109	101	21	2
2019	IX	752	97	88	23	1
2019	X	948	111	105	22	0
2019	XI	782	74	48	30	2
2019	XII	691	64	53	16	1
2020	I	705	60	43	23	3
2020	II	718	67	70	17	1
2020	III	491	36	28	8	1
2020	IV	361	27	25	6	3
2020	V	528	44	32	13	2
2020	VI	626	60	57	12	0
2020	VII	661	61	52	15	1
2020	VIII	668	62	43	28	0
2020	IX	719	80	66	20	1
2020	X	622	57	51	18	0
2020	XI	512	35	32	8	1
2020	XII	611	30	21	13	2
2021	I	527	32	27	10	0
2021	II	582	31	27	10	1
2021	III	714	32	21	13	1
2021	IV	592	31	25	14	2
2021	V	716	44	34	17	0
2021	VI	708	47	35	18	2
2021	VII	575	33	27	8	1
2021	VIII	585	37	34	16	3
2021	IX	660	48	34	18	1
2021	X	727	49	31	26	1
2021	XI	649	49	44	8	1
2021	XII	654	37	33	11	1
2022	I	542	30	23	8	1
2022	II	579	33	25	10	3
2022	III	642	35	28	12	0

Tab. 5. *Number of road accidents in Poznań in 2018–2024 [1] - CONT.*

Year	Month	Number of events	Number of accidents	Number of accidents in which people were slightly injured	Number of accidents in which people were seriously injured	Number of accidents in which there were fatalities
2022	IV	588	37	32	10	0
2022	V	652	54	41	20	0
2022	VI	605	77	63	31	5
2022	VII	552	56	36	28	1
2022	VIII	561	53	35	21	4
2022	IX	551	43	35	14	1
2022	X	636	68	60	17	1
2022	XI	638	29	24	10	1
2022	XII	609	37	26	16	1
2023	I	571	35	32	10	1
2023	II	540	39	29	14	1
2023	III	602	24	17	7	0
2023	IV	582	41	37	7	1
2023	V	613	54	40	15	0
2023	VI	603	55	44	19	0
2023	VII	568	47	34	14	0
2023	VIII	576	59	46	23	0
2023	IX	640	54	42	14	0
2023	X	744	37	31	15	1
2023	XI	721	39	28	14	3
2023	XII	749	50	39	13	2
2024	I	737	36	24	16	0
2024	II	787	32	23	10	0
2024	III	755	44	38	11	0
2024	IV	808	40	31	13	2
2024	V	727	53	41	15	0
2024	VI	725	60	41	24	0
2024	VII	693	77	61	24	5
2024	VIII	655	56	36	25	0
2024	IX	692	56	45	14	1
2024	X	772	62	55	14	2
2024	XI	634	41	33	13	0
2024	XII	689	45	42	11	1
Sum:		**56495**	**4571**	**3760**	**1396**	**106**
Average:		**672,6**	**54,4**	**44,8**	**16,6**	**1,3**

rankings largely mirrored the regression-based findings: temperature, sunshine and snow cover emerged as the strongest predictors. This confirms that while machine learning can enhance forecasting, classical regression remains suitable for interpreting causal relationships.

Discussion

The results clearly show that weather conditions have a significant impact on both the number and severity of crashes in the Greater Poland region, in line with studies from Germany, the

Tab. 6. *Weather conditions for Piła and Konin in 2018–2024 [28]*

Year	Month	Piła							Konin						
		Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine
2018	I	1.5	-0.6	50.1	13.0	88.7	2.6	32.3	1.9	-0.3	17.8	10.0	84.1	5.5	32.7
	II	-3.0	-5.9	5.0	2.0	81.2	1.9	107.5	1.5	-1.4	9.4	1.0	81.7	4.1	74.6
	III	0.0	-3.8	31.7	5.0	75.7	2.5	137.1	5.5	1.0	28.4	5.0	71.9	4.8	155.2
	IV	12.1	5.9	53.9	0.0	70.4	2.4	265.4	8.7	3.1	26.5	0.0	65.1	4.7	185.9
	V	17.4	10.2	9.5	0.0	57.9	2.4	351.6	13.2	7.6	22.4	0.0	66.1	3.7	229.9
	VI	18.6	12.2	20.3	0.0	60.9	2.3	268.0	17.1	11.2	26.0	0.0	64.2	3.6	231.4
	VII	20.6	14.1	113.1	0.0	66.3	2.1	284.3	20.1	14.0	71.0	0.0	61.4	4.0	270.4
	VIII	20.3	13.9	8.8	0.0	63.9	1.9	285.6	22.5	15.5	19.1	0.0	53.2	4.4	329.3
	IX	15.3	10.0	18.6	0.0	70.5	1.9	207.7	15.8	10.7	28.8	0.0	71.1	3.9	144.6
	X	10.0	5.0	22.2	0.0	77.9	2.2	169.8	8.0	3.8	39.4	0.0	79.4	4.5	82.4
	XI	4.6	2.1	6.7	0.0	87.0	1.9	57.3	6.1	3.4	47.9	3.0	85.6	3.7	48.9
	XII	2.6	0.5	37.5	3.0	90.2	2.3	15.5	5.6	3.2	14.1	0.0	84.3	3.8	53.7
2019	I	-0.2	-2.3	29.1	1.0	89.0	2.5	38.8	-2.5	-5.0	16.1	6.0	85.8	3.6	45.6
	II	2.9	-0.4	5.9	0.0	81.0	2.3	93.8	3.8	1.2	24.4	12.0	83.3	3.9	64.3
	III	5.9	2.2	23.4	0.0	77.3	2.7	115.3	4.5	1.3	31.5	6.0	81.6	3.2	106.4
	IV	10.3	3.7	2.1	0.0	53.7	2.9	282.3	9.5	4.5	11.3	0.0	66.7	3.1	191.0
	V	12.2	6.9	51.2	0.0	68.6	2.3	181.5	15.8	9.6	28.6	0.0	65.0	3.2	280.2
	VI	22.2	14.5	14.5	0.0	57.0	2.4	349.9	18.8	12.6	51.3	0.0	65.8	2.9	296.2
	VII	19.0	13.4	38.4	0.0	62.7	2.4	233.4	19.8	14.4	72.1	0.0	69.6	2.7	218.7
	VIII	20.0	13.7	24.6	0.0	63.5	1.8	255.7	18.9	13.2	23.0	0.0	69.0	2.6	246.5
	IX	13.5	9.2	99.0	0.0	78.4	2.2	139.2	17.2	10.9	7.7	0.0	65.0	2.9	245.1
	X	10.0	6.1	38.9	0.0	84.6	1.8	119.2	8.0	5.6	102.1	0.0	88.6	3.7	51.9
	XI	5.7	3.5	52.7	0.0	89.8	2.4	43.5	3.5	1.0	34.2	0.0	89.3	3.3	52.7
	XII	3.1	0.8	20.7	0.0	86.8	2.2	44.8	1.7	-0.5	37.4	9.0	89.3	3.6	58.3
2020	I	3.1	0.7	38.7	0.0	87.6	2.5	54.4	-3.0	-5.5	8.8	21.0	84.9	3.1	72.0
	II	4.3	1.5	56.0	0.0	80.0	2.9	61.6	0.1	-2.6	22.6	24.0	82.6	4.1	60.1
	III	4.4	0.0	33.8	0.0	68.0	2.5	190.7	7.0	3.1	22.1	4.0	73.3	3.4	133.3
	IV	8.7	0.9	1.6	0.0	53.8	2.3	289.5	8.3	4.0	37.7	0.0	73.6	3.7	139.3
	V	11.4	5.6	48.1	0.0	65.3	2.5	241.7	14.1	9.0	40.4	0.0	72.6	3.3	261.2
	VI	18.2	13.2	102.9	0.0	71.1	2.2	209.7	18.2	12.7	84.6	0.0	70.4	3.4	241.1
	VII	17.9	12.1	51.6	0.0	68.5	2.1	257.9	18.7	13.6	83.2	0.0	75.0	2.6	231.1
	VIII	20.1	14.1	40.8	0.0	69.2	1.9	260.8	20.0	14.5	46.5	0.0	72.2	2.7	251.2
	IX	14.4	8.7	66.7	0.0	81.4	1.8	212.6	14.3	10.6	104.6	0.0	85.1	3.3	115.7
	X	10.4	7.3	67.7	0.0	86.2	2.0	83.3	10.9	7.6	79.5	0.0	84.8	3.7	102.7
	XI	6.1	3.9	8.2	0.0	89.6	2.0	44.6	5.3	3.2	28.2	13.0	88.7	3.3	26.5
	XII	2.1	0.1	37.0	2.0	89.7	2.4	29.7	2.4	0.1	31.9	21.0	86.4	4.1	31.7
2021	I	-0.8	-2.6	62.1	15.0	90.3	2.1	26.5	1.2	-1.4	23.1	15.0	84.2	4.3	38.1
	II	-1.3	-4.9	27.3	15.0	84.1	2.1	100.2	-2.7	-6.0	2.9	2.0	78.0	2.8	97.4
	III	3.5	-0.5	24.4	0.0	76.9	2.1	131.9	1.1	-2.8	19.7	2.0	71.3	3.8	141.9
	IV	5.9	0.7	38.8	4.0	70.4	2.3	163.2	13.4	7.3	20.0	0.0	66.6	3.9	251.0
	V	12.0	6.5	69.8	0.0	70.9	2.3	222.1	17.0	11.0	44.5	0.0	65.4	3.2	331.9
	VI	19.8	12.5	24.8	0.0	61.5	2.1	327.4	18.7	12.8	42.1	0.0	67.0	2.9	232.6
	VII	20.7	15.4	42.8	0.0	71.3	2.1	233.0	20.7	15.1	87.7	0.0	70.3	2.6	197.9
	VIII	17.2	12.3	26.2	0.0	70.0	2.2	183.7	21.4	15.3	26.5	0.0	65.5	2.6	293.6
	IX	14.7	10.0	16.4	0.0	76.0	2.0	168.4	16.7	11.1	30.8	0.0	69.0	2.9	232.6
	X	9.3	4.9	32.9	0.0	81.8	2.0	152.3	11.1	6.2	44.0	0.0	76.7	3.5	164.3
	XI	5.5	3.6	44.7	1.0	92.1	2.2	24.2	5.2	2.6	7.6	0.0	86.2	3.6	24.8
	XII	-0.7	-3.2	36.0	12.0	91.4	2.2	29.6	2.1	0.2	31.9	1.0	88.7	3.7	23.1
2022	I	1.6	-0.7	48.4	4.0	88.7	2.8	54.7	-1.0	-3.1	26.1	4.0	86.1	3.9	23.2
	II	3.7	1.1	74.2	0.0	82.3	3.1	75.7	3.5	-0.2	25.2	10.0	78.8	3.7	125.1
	III	3.4	-2.6	0.1	0.0	63.3	2.0	241.9	6.9	2.8	35.4	0.0	73.9	4.1	144.5

Tab. 6. *Weather conditions for Piła and Konin in 2018–2024 [28] - CONTINUED*

Year	Month	Piła							Konin						
		Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine
2022	IV	7.3	1.9	30.7	0.0	64.8	2.6	199.6	10.2	3.8	14.6	0.0	57.6	4.2	282.9
	V	13.4	6.9	42.8	0.0	63.5	2.3	259.1	12.8	7.9	44.7	0.0	72.6	3.1	191.3
	VI	18.7	12.1	30.5	0.0	65.0	2.1	305.8	22.1	15.1	23.7	0.0	63.5	3.1	334.1
	VII	19.2	13.0	36.4	0.0	64.6	2.4	288.8	19.5	13.8	50.7	0.0	64.4	3.1	221.0
	VIII	21.6	15.9	60.2	0.0	66.6	1.9	245.5	20.8	15.0	44.7	0.0	67.2	2.7	268.8
	IX	12.6	8.1	36.4	0.0	76.9	1.9	165.3	15.0	10.1	58.9	0.0	77.2	3.2	165.6
	X	10.7	6.6	33.8	0.0	89.0	1.7	116.5	11.5	7.2	15.2	2.0	82.6	2.8	141.9
	XI	4.5	2.4	16.6	5.0	90.7	2.1	49.8	6.3	3.3	15.1	0.0	87.8	4.0	55.0
	XII	0.7	-1.3	32.8	1.0	90.3	2.2	18.1	3.6	1.2	13.9	7.0	84.4	3.5	38.3
2023	I	3.1	1.3	56.3	4.0	88.9	2.4	18.5	2.9	0.4	20.8	16.0	85.9	3.6	58.7
	II	1.8	-1.0	33.0	1.0	81.6	2.5	73.9	4.7	1.7	56.8	15.0	78.1	4.4	52.8
	III	4.0	0.6	58.4	3.0	79.9	2.3	107.7	5.4	0.7	23.1	15.0	65.0	3.9	196.6
	IV	7.9	3.2	31.8	0.0	72.3	2.3	167.8	9.2	2.0	4.2	28.0	52.6	3.3	298.9
	V	13.1	6.3	13.0	0.0	57.9	2.5	318.5	11.7	6.0	68.2	0.0	67.4	3.1	215.5
	VI	18.5	11.7	57.3	0.0	59.3	2.1	295.6	18.5	13.6	122.2	0.0	77.8	2.8	197.7
	VII	18.9	12.5	67.5	0.0	64.2	2.1	258.0	19.1	13.1	28.0	0.0	67.9	2.7	246.6
	VIII	18.8	14.2	114.5	0.0	76.0	1.9	195.7	20.7	14.9	70.7	0.0	66.3	2.9	267.1
	IX	17.5	11.1	6.3	0.0	75.3	1.6	281.0	16.4	11.2	88.1	0.0	78.9	2.7	168.4
	X	10.1	6.6	76.1	0.0	85.6	2.2	72.8	11.1	8.0	79.4	0.0	86.3	2.8	101.1
	XI	3.9	1.0	81.6	6.0	89.4	2.1	48.1	6.1	3.9	11.0	1.0	88.9	2.9	48.4
	XII	2.3	0.0	78.5	7.0	89.5	2.7	25.6	2.4	0.3	17.9	2.0	87.9	4.2	27.7
2024	I	0.2	-2.6	47.9	7.0	85.9	2.7	51.8	0.9	-2.7	24.8	4.0	85.8	4.0	47.5
	II	5.5	2.9	75.4	0.0	88.3	2.6	34.1	1.8	-1.2	22.9	3.0	80.4	3.8	83.9
	III	6.9	3.0	19.3	0.0	78.5	2.3	130.2	5.0	1.1	26.7	0.0	73.3	3.9	154.1
	IV	10.3	4.7	29.6	0.0	69.9	2.3	179.9	11.4	6.5	37.2	0.0	71.7	3.7	186.2
	V	16.8	10.3	59.2	0.0	61.4	2.5	317.7	16.6	10.0	16.1	0.0	62.2	3.0	313.0
	VI	17.9	11.8	35.7	0.0	69.7	2.1	269.4	19.0	13.5	74.6	0.0	72.2	2.7	254.3
	VII	19.4	13.6	129.8	0.0	71.4	1.9	267.9	20.9	15.0	124.0	0.0	69.9	2.8	305.2
	VIII	19.8	13.7	26.4	0.0	68.2	1.8	304.8	20.6	14.7	45.0	0.0	68.6	2.5	280.6
	IX	16.8	11.7	27.8	0.0	69.7	2.4	232.9	17.6	12.0	60.8	0.0	65.1	3.6	237.4
	X	10.2	6.7	24.3	0.0	82.0	2.1	113.9	10.9	7.0	32.4	0.0	79.2	3.4	158.9
	XI	4.1	2.0	36.4	1.0	90.2	2.2	33.6	4.4	2.3	31.3	0.0	84.0	3.8	42.4
	XII	3.4	1.8	26.0	0.0	92.7	2.4	23.6	3.3	1.5	21.3	1.0	88.3	3.9	30.1

Czech Republic, and Scandinavian countries. The observed positive relationship between temperature and crash frequency aligns with findings from Oslo, Munich, and Prague, where warmer conditions promote higher mobility, recreational travel, and more risk-taking behaviour. Similarly, the increase in severity during snowy and icy conditions reflects research from Sweden and Finland, which highlights the role of reduced traction and longer braking distances in winter driving. The nonlinear, U-shaped relationship between temperature and severity also corresponds to findings in other Central European climates. These comparisons are drawn from post-2010 European studies, ensuring their relevance to current climatic and infrastructural contexts [22–25].

Differences between cities suggest that the impact of weather interacts with local traffic patterns and infrastructure. In Poznań, the largest urban area, exposure-related factors such as temperature and sunshine had the strongest effects. In Konin and Leszno, crash frequency and severity were more sensitive to precipitation, potentially reflecting differences in drainage systems or road geometry. In Piła, the relationships between weather and crashes were weaker, which may be related to lower traffic volumes and more uniform road layouts. These patterns highlight the need for regionally tailored interventions rather than uniform provincial strategies.

The contrasting effects of weather on crash frequency and severity reflect two distinct risk domains. Exposure-driven risk dominates during warm, sunny periods, when increased mobility creates more opportunities for accidents. Hazard-driven risk, on the other hand, is more relevant in winter months, which feature fewer crashes overall but more severe out-

Tab. 7. *Weather conditions for Leszno and Poznań in 2018–2024 [28]*

Year	Month	Leszno							Poznań						
		Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine
2018	I	2.5	0.5	44.8	3.0	81.5	3.9	37.4	2.2	0.1	48.7	4.0	84.6	4.7	41.7
	II	-2.4	-5.4	2.0	1.0	76.6	2.9	135.0	-2.6	-5.5	4.4	1.0	78.9	3.3	101.1
	III	0.9	-3.1	24.8	0.0	73.0	3.6	136.0	1.0	-2.8	29.4	1.0	72.1	4.3	121.2
	IV	13.1	6.3	10.2	0.0	67.2	3.6	277.1	13.4	7.6	28.1	0.0	64.7	4.3	272.7
	V	16.7	9.4	25.6	0.0	64.6	3.2	328.7	17.9	11.2	16.6	0.0	55.9	3.9	350.4
	VI	18.7	12.3	40.0	0.0	64.5	3.4	236.2	19.4	13.9	22.8	0.0	58.1	4.0	271.8
	VII	20.3	14.0	86.1	0.0	67.2	3.1	293.7	20.9	14.9	81.3	0.0	63.7	3.5	310.2
	VIII	21.3	14.6	13.9	0.0	61.3	2.5	285.4	21.7	15.9	9.8	0.0	57.2	3.3	313.1
	IX	15.7	10.4	74.1	0.0	71.6	2.8	228.0	16.1	11.3	40.7	0.0	67.3	3.4	205.9
	X	10.7	5.4	35.9	0.0	75.8	3.3	173.3	10.9	6.3	23.4	0.0	73.6	4.1	161.1
	XI	5.1	2.2	15.1	0.0	85.9	2.9	92.2	5.2	2.7	7.8	0.0	84.3	3.7	60.1
	XII	3.0	0.9	41.4	0.0	88.9	4.0	20.0	2.8	0.8	59.5	2.0	88.4	4.5	15.5
2019	I	-0.1	-2.5	42.8	2.0	87.4	4.3	35.7	-0.2	-2.4	58.7	3.0	88.2	4.6	31.8
	II	3.2	-0.8	10.7	2.0	78.3	3.7	133.4	3.4	0.0	15.9	2.0	77.2	4.2	107.8
	III	6.4	2.2	36.9	0.0	75.8	4.2	131.3	6.4	3.0	39.8	0.0	73.8	4.8	119.4
	IV	10.4	3.8	8.6	0.0	59.4	3.9	270.2	10.9	4.6	7.2	0.0	52.6	4.6	277.7
	V	11.8	6.1	91.7	0.0	74.3	3.2	224.2	12.4	7.4	83.5	0.0	69.7	3.8	208.6
	VI	22.2	14.7	8.8	0.0	60.6	3.1	373.7	23.3	16.6	3.4	0.0	55.5	3.6	378.8
	VII	19.1	12.8	56.5	0.0	65.1	3.2	233.2	19.7	14.3	22.8	0.0	61.7	3.9	248.4
	VIII	20.6	14.4	43.7	0.0	67.0	2.4	266.2	21.2	15.6	32.4	0.0	63.5	3.1	289.9
	IX	14.4	9.5	83.6	0.0	75.5	3.0	180.2	14.6	10.5	40.1	0.0	75.3	3.8	159.4
	X	10.7	6.3	20.9	0.0	82.5	2.6	151.3	10.9	7.0	19.2	0.0	83.6	3.1	114.4
	XI	6.8	3.9	49.4	0.0	85.1	3.1	93.4	6.6	4.3	46.2	0.0	88.4	4.0	63.2
	XII	3.6	0.6	14.3	0.0	82.9	3.4	53.8	3.7	1.4	23.6	0.0	85.9	3.8	40.7
2020	I	2.9	-0.4	20.5	0.0	84.3	3.7	76.2	3.3	1.1	37.4	0.0	87.8	4.1	67.3
	II	5.1	2.1	63.0	0.0	77.9	5.0	79.1	5.0	2.3	76.3	0.0	79.5	5.1	65.4
	III	5.0	0.2	20.4	1.0	66.8	3.8	208.2	5.2	1.0	29.0	0.0	65.7	4.2	120.3
	IV	9.3	1.1	5.7	0.0	54.4	3.3	310.5	9.8	2.7	2.6	0.0	50.2	3.9	234.8
	V	11.8	5.4	45.9	0.0	67.0	3.5	250.7	12.0	6.6	47.5	0.0	63.1	4.1	279.5
	VI	17.9	12.8	52.6	0.0	76.6	3.2	224.3	18.5	13.8	51.3	0.0	70.8	3.7	225.6
	VII	18.8	12.1	31.9	0.0	65.7	2.8	270.7	19.3	14.0	65.3	0.0	61.6	3.6	286.4
	VIII	20.6	14.7	86.4	0.0	68.6	2.8	250.2	21.0	15.7	60.9	0.0	63.4	3.3	265.1
	IX	15.3	9.2	37.9	0.0	76.8	2.5	217.4	15.6	10.2	37.4	0.0	73.5	2.9	189.3
	X	11.0	8.0	87.4	0.0	84.3	2.9	85.0	11.0	8.3	41.0	0.0	83.4	3.4	81.9
	XI	6.0	3.1	15.2	0.0	87.4	2.7	68.3	6.2	4.0	11.8	0.0	88.6	3.3	46.7
	XII	2.6	0.1	13.7	4.0	85.2	3.1	78.7	2.4	0.3	31.5	2.0	88.1	4.0	34.5
2021	I	-0.2	-2.1	24.6	8.0	87.5	3.2	40.8	-0.5	-2.2	53.5	12.0	91.1	3.5	30.5
	II	-0.4	-4.5	15.7	9.0	80.7	3.4	100.8	-0.4	-4.1	35.0	6.0	83.6	3.7	96.2
	III	4.1	-0.1	15.1	0.0	74.6	3.3	157.3	4.1	-0.2	22.1	1.0	75.6	3.5	142.7
	IV	6.4	1.9	32.3	0.0	70.8	3.8	158.0	6.6	2.2	33.7	1.0	69.4	4.2	149.0
	V	12.2	7.2	69.4	0.0	71.5	3.5	210.5	12.6	7.9	62.6	0.0	69.9	4.1	188.2
	VI	19.8	12.7	59.5	0.0	65.6	2.6	310.6	20.7	14.4	92.8	0.0	58.9	3.2	264.9
	VII	20.4	15.0	72.2	0.0	73.1	2.6	220.9	21.2	16.4	32.3	0.0	68.6	3.4	198.0
	VIII	17.4	12.7	126.7	0.0	75.6	2.6	185.7	17.9	13.4	81.7	0.0	70.7	3.4	157.8
	IX	15.3	10.7	19.1	0.0	77.8	2.6	189.6	15.5	11.2	13.8	0.0	74.8	3.4	154.4
	X	10.0	5.0	20.6	0.0	77.3	2.9	167.2	10.3	6.1	25.0	0.0	76.7	3.6	153.2
	XI	5.5	3.1	29.4	0.0	88.6	3.4	47.8	5.7	3.8	38.1	0.0	89.8	4.0	34.4
	XII	0.5	-2.0	36.1	8.0	89.2	3.4	49.9	0.0	-2.5	36.5	8.0	91.1	4.1	43.4
2022	I	2.1	-0.1	29.6	3.0	86.1	4.7	63.4	1.7	-0.5	46.1	4.0	89.0	5.0	50.6
	II	4.4	1.4	48.7	1.0	78.1	5.2	87.1	4.3	1.7	57.2	0.0	78.3	5.5	83.9
	III	4.0	-2.2	0.0	0.0	60.4	3.0	254.7	4.3	-1.4	2.1	0.0	57.0	3.4	229.2

Tab. 7. *Weather conditions for Leszno and Poznań in 2018–2024 [28] - CONTINUED*

Year	Month	Leszno							Poznań						
		Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine
2022	IV	7.6	2.4	34.2	0.0	67.5	3.8	189.8	7.9	2.7	36.3	0.0	63.3	4.3	168.8
	V	14.6	7.6	51.3	0.0	62.9	3.1	281.3	14.9	8.7	22.6	0.0	57.1	3.9	233.1
	VI	19.5	12.2	39.4	0.0	64.1	2.8	295.9	19.9	13.5	63.4	0.0	60.5	3.5	244.6
	VII	19.9	13.1	45.7	0.0	59.6	3.4	286.8	20.2	14.7	22.7	0.0	59.2	4.1	238.9
	VIII	21.3	15.6	89.1	0.0	69.2	2.7	245.6	22.1	16.6	52.8	0.0	64.4	3.3	222.3
	IX	13.3	8.7	50.6	0.0	77.0	2.6	189.0	13.4	9.0	31.6	0.0	73.6	3.3	171.6
	X	11.7	7.0	44.9	0.0	84.5	2.5	170.8	12.0	7.9	28.3	0.0	83.6	3.0	149.9
	XI	4.8	1.7	10.4	0.0	87.8	2.6	70.0	4.8	2.6	16.3	6.0	89.7	3.4	54.1
	XII	1.5	-0.8	28.1	0.0	86.5	3.3	32.7	1.3	-0.8	35.2	1.0	89.4	3.8	27.3
2023	I	3.4	1.2	37.8	2.0	86.1	3.6	35.5	3.4	1.5	53.3	6.0	89.1	3.8	27.3
	II	2.5	-0.5	43.8	1.0	80.3	4.1	87.0	2.2	-0.8	40.1	0.0	82.1	4.5	82.2
	III	5.0	1.0	36.0	5.0	77.4	3.8	101.1	4.8	1.2	51.4	1.0	79.2	4.0	89.9
	IV	7.7	3.1	31.2	0.0	75.8	3.2	145.5	8.4	4.0	36.8	0.0	72.3	3.7	148.8
	V	13.2	6.9	23.8	0.0	64.1	3.3	295.5	13.8	7.6	29.5	0.0	58.9	3.9	308.2
	VI	18.3	11.0	62.6	0.0	64.0	2.7	275.7	19.4	13.2	38.7	0.0	56.7	3.3	287.0
	VII	20.1	12.9	36.4	0.0	62.4	2.9	283.8	20.5	14.3	61.7	0.0	56.8	3.5	280.2
	VIII	19.7	15.0	145.9	0.0	75.7	2.6	222.9	19.8	15.2	156.1	0.0	70.7	3.1	219.9
	IX	17.9	11.4	11.6	0.0	74.4	2.2	284.7	18.6	12.6	3.3	0.0	68.6	2.8	292.8
	X	11.5	7.8	101.3	0.0	84.4	2.9	89.3	11.1	7.5	78.4	0.0	82.6	3.6	75.1
	XI	5.2	2.6	70.2	3.0	85.0	3.5	76.9	4.7	1.6	84.5	4.0	85.6	3.8	67.6
	XII	2.9	0.6	70.9	7.0	86.9	4.1	33.7	2.7	0.5	76.7	5.0	86.1	4.7	35.9
2024	I	0.7	-2.2	29.4	4.0	81.6	4.4	74.8	0.5	-2.1	48.9	6.0	82.3	4.7	64.0
	II	6.7	4.0	79.6	0.0	85.7	4.0	47.0	6.3	3.8	74.4	0.0	85.8	4.4	34.3
	III	8.2	3.9	12.6	0.0	75.2	3.1	140.7	7.7	3.7	20.0	0.0	76.2	3.8	136.9
	IV	11.3	5.9	24.6	0.0	70.1	3.2	184.9	11.3	6.1	49.5	0.0	68.9	3.7	172.2
	V	17.2	10.9	35.0	0.0	63.2	2.8	300.7	17.3	11.1	52.2	0.0	60.0	3.7	303.0
	VI	18.8	13.2	93.7	0.0	72.1	2.7	237.0	18.8	13.8	97.1	0.0	68.6	3.4	241.8
	VII	20.3	14.6	86.2	0.0	73.2	2.6	283.9	20.6	15.2	75.3	0.0	66.9	3.1	272.5
	VIII	20.7	15.0	150.1	0.0	72.4	2.4	286.9	21.3	15.5	38.8	0.0	63.2	3.2	286.2
	IX	16.9	12.3	69.7	0.0	74.5	3.5	221.0	17.5	12.8	56.3	0.0	67.8	4.1	210.6
	X	11.2	7.5	16.9	0.0	83.5	2.9	142.1	10.9	7.2	20.0	0.0	80.4	3.5	138.5
	XI	4.4	2.1	29.8	3.0	91.5	3.3	35.9	4.4	2.5	31.9	0.0	88.1	3.6	26.1
	XII	2.8	0.7	14.9	0.0	90.7	3.3	41.8	3.3	1.6	18.0	0.0	90.0	3.8	27.5

comes. Behavioural adaptations also play a role: drivers often reduce speeds in harsh weather but may drive faster under dry, sunny conditions, contributing to higher crash counts but lower average severity.

The findings further demonstrate that weather variables rarely act in isolation. The most severe risks arise from combined conditions, such as precipitation during freezing temperatures or low visibility in snowy months. This is consistent with evidence from Scandinavia showing that mixed precipitation and thaw–freeze cycles dramatically increase the likelihood of severe crashes.

These results have several practical implications for road-safety management. Seasonal maintenance should be intensified during winter months, including salting, drainage management, and rapid snow removal. Enforcement strategies should account for weather conditions: for example, increased policing during warm, high-exposure periods may help counteract the "good-weather paradox." City-specific measures can further enhance safety: Poznań may benefit from speed management in warm and sunny months; Konin and Leszno from improved drainage and wet-surface monitoring; and Piła from better detection of rare but severe winter events. Integrating weather forecasts into intelligent transport systems, especially during icing-prone periods, can also support proactive interventions.

As requested by reviewers, limitations have been moved to the conclusion. Key constraints include the absence of traffic-volume data, the use of monthly rather than daily meteorological measurements, and the lack of information on infrastructure conditions. Aggregating weather

Tab. 8. *Weather conditions for Kalisz in 2018–2024 [28]*

Year	Month	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine
2018	I	1.8	-0.2	24.7	7.0	87.1	4.6	40.5
	II	-2.7	-4.9	1.8	1.0	83.6	3.1	116.4
	III	1.0	-2.4	29.8	4.0	77.3	3.9	125.7
	IV	13.8	8.3	18.7	1.0	68.6	4.0	258.3
	V	17.4	11.7	51.2	0.0	67.3	3.3	332.6
	VI	18.7	13.5	34.0	0.0	69.3	3.2	230.5
	VII	20.6	14.8	45.1	0.0	70.9	2.8	273.8
	VIII	21.5	16.0	33.1	0.0	65.5	2.8	270.6
	IX	16.4	11.4	39.6	0.0	70.8	3.4	209.7
	X	11.1	6.9	38.5	0.0	78.2	4.0	148.6
	XI	5.4	3.1	6.4	0.0	87.5	3.3	84.4
	XII	2.2	0.4	41.1	1.0	93.4	4.3	26.2
2019	I	-0.8	-2.9	37.8	4.0	90.0	4.4	33.4
	II	3.1	0.0	26.2	11.0	77.9	4.1	129.2
	III	6.2	2.7	28.7	0.0	77.8	4.9	120.3
	IV	10.5	4.7	19.8	0.0	60.4	3.9	240.6
	V	12.2	7.6	47.7	0.0	76.7	3.4	187.1
	VI	22.6	16.3	24.2	0.0	62.2	3.1	345.6
	VII	19.4	14.0	28.9	0.0	64.9	3.0	205.5
	VIII	21.0	15.7	37.4	0.0	66.6	3.0	242.6
	IX	14.7	10.5	50.3	0.0	77.9	3.6	162.6
	X	11.2	7.3	17.0	0.0	83.3	3.4	150.6
	XI	6.6	3.8	23.2	0.0	89.6	3.8	58.9
	XII	3.6	1.5	14.9	0.0	87.4	4.0	52.7
2020	I	2.5	0.4	24.6	0.0	89.8	4.2	71.9
	II	4.4	1.9	58.2	0.0	81.9	5.5	66.5
	III	5.0	1.0	20.7	2.0	68.3	4.3	186.5
	IV	9.7	3.1	4.5	0.0	53.4	3.6	283.2
	V	11.7	6.7	73.1	0.0	71.2	3.5	227.1
	VI	18.1	13.8	79.2	0.0	79.1	3.3	274.3
	VII	18.9	13.4	41.6	0.0	68.8	2.8	173.1
	VIII	20.5	15.4	92.9	0.0	69.8	2.9	255.2
	IX	15.7	11.1	70.6	0.0	78.0	2.9	202.9
	X	10.8	8.4	90.2	0.0	88.4	3.3	85.9
	XI	5.9	3.8	17.5	0.0	92.5	3.3	54.3
	XII	2.2	0.5	19.1	1.0	91.6	3.7	51.1
2021	I	-0.9	-2.7	28.2	13.0	92.8	3.2	35.2
	II	-0.8	-3.9	19.8	10.0	86.5	2.8	82.8
	III	4.2	0.9	12.6	0.0	77.8	3.0	137.4
	IV	6.5	2.5	36.4	0.0	72.5	4.1	148.9
	V	12.4	7.9	80.7	0.0	73.6	4.1	194.7
	VI	20.2	14.5	31.4	0.0	64.9	2.7	324.4
	VII	21.1	16.2	102.4	0.0	73.3	2.8	199.8
	VIII	17.3	13.4	122.6	0.0	77.9	3.2	157.2
	IX	15.1	10.9	8.1	0.0	77.2	3.2	149.4
	X	10.3	6.2	12.7	0.0	75.4	4.0	128.4
	XI	5.3	3.5	32.0	4.0	89.3	4.2	61.5
	XII	-0.4	-2.6	26.5	7.0	91.1	3.8	32.1
2022	I	1.3	-0.6	27.3	6.0	88.0	5.3	41.6
	II	3.7	1.2	34.6	0.0	80.0	5.9	66.5
	III	4.3	-0.5	0.2	0.0	59.0	3.3	241.0
	IV	7.6	3.2	30.8	0.0	66.3	4.5	160.4

Tab. 8. *Weather conditions for Kalisz in 2018–2024 [28] - CONT.*

Year	Month	Average temperature	Average minimum temperature	Total precipitation	Maximum snow cover depth	Average humidity	Average wind speed	Sunshine
2022	V	14.7	9.0	36.9	0.0	60.8	3.4	276.0
	VI	19.8	14.0	55.1	0.0	65.7	2.9	295.9
	VII	19.6	14.2	88.4	0.0	66.2	3.1	253.7
	VIII	21.1	16.1	61.4	0.0	73.5	2.7	248.5
	IX	12.9	8.7	50.6	0.0	79.5	3.0	173.0
	X	12.1	8.2	19.0	0.0	84.5	3.1	152.4
	XI	4.4	2.1	8.8	0.0	90.1	2.9	63.1
	XII	1.1	-0.9	24.1	8.0	92.7	4.0	20.3
2023	I	3.3	1.7	26.7	5.0	91.5	4.1	43.7
	II	1.9	-0.3	27.1	1.0	87.8	4.5	57.3
	III	4.9	1.5	28.0	2.0	81.6	4.2	85.7
	IV	8.1	4.3	27.1	0.0	75.8	3.5	128.2
	V	13.5	8.3	31.1	0.0	60.8	3.4	277.9
	VI	18.8	13.0	30.5	0.0	61.7	3.0	277.1
	VII	20.9	14.9	47.9	0.0	59.0	3.2	250.2
	VIII	20.2	15.9	59.7	0.0	72.8	3.3	212.8
	IX	19.1	13.6	18.9	0.0	68.8	2.8	261.5
	X	11.4	8.0	55.3	0.0	85.5	3.8	80.7
	XI	4.7	2.3	64.0	0.0	87.6	4.1	59.5
	XII	2.4	0.5	43.0	7.0	88.9	4.9	26.0
2024	I	0.4	-1.8	27.4	3.0	84.5	5.1	60.4
	II	6.5	4.1	51.4	4.0	86.4	4.6	48.6
	III	8.0	4.4	12.4	0.0	77.3	3.7	128.1
	IV	11.7	7.2	24.3	0.0	69.4	3.9	161.0
	V	17.1	11.1	31.6	0.0	62.6	2.9	293.8
	VI	19.1	14.4	88.5	0.0	73.4	2.9	240.8
	VII	20.9	15.5	93.5	0.0	70.9	2.7	269.5
	VIII	20.8	15.9	138.0	0.0	71.9	2.6	261.1
	IX	17.4	12.7	79.7	0.0	72.5	3.8	214.4
	X	11.0	7.4	22.6	0.0	83.8	3.3	143.4
	XI	4.0	2.0	27.8	0.0	89.8	3.8	41.5
	XII	3.0	1.4	15.7	0.0	92.4	4.0	43.1

data to monthly averages may underestimate the impact of acute events, as daily conditions can differ substantially from monthly means. This could introduce bias in parameter estimates, potentially downplaying the effects of extreme precipitation or temperature spikes. Sensitivity analyses, such as excluding outlier months, were conducted to mitigate this issue, but future studies should aim to use daily-resolution data for more precise causal inference.

Overall, the findings confirm that meteorological variability plays a crucial role in shaping both crash frequency and severity in mid-sized Polish cities. The study expands the regional

evidence base and provides practical, data-driven insights for managing road safety under weather-sensitive conditions. ◄

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