Investigating the Impact of Weather Conditions and Time of Day on Traffic Flow Characteristics

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ABSTRACT: Adverse weather such as rain, snow, and fog may significantly reduce visibility or change adhesion properties and, as a consequence, affect drivers' sense of safety, driving comfort, and their reaction to a changing driving environment (i.e., lower speed and increased headways). The changed behavior of individual drivers affects both traffic flow characteristics, that is, average speed and headways, and parameters related to highway performance such as free-flow speed and capacity. Thus, understanding the impact may be important in the context of predicting and assessing traffic conditions on planned or existing road facilities. The paper discusses the effects of adverse weather conditions and time of day on traffic flow characteristics and the parameters related to highway performance. Using real traffic and weather data from a Polish expressway, the paper aims to identify factors related to weather and time of day that significantly influence traffic flow parameters and traffic conditions and to analyze and quantify this impact. The results of the study may help to develop coefficients of weather-related adjustment factors that will make it possible to estimate, for example, average speed of vehicles in the nighttime or in conditions of rain or limited visibility. The results of the study may contribute to a new Polish method for capacity estimation and traffic conditions assessment for uninterrupted traffic facilities.

KEYWORDS: Lightning; Precipitation; Statistical techniques; Transportation meteorology; Visibility

1. Introduction

Adverse weather such as rain, snow, and fog may significantly reduce visibility or change adhesion properties and, as a consequence, affect drivers' sense of safety, driving comfort, and their reaction to a changing driving environment (Chang et al. 2019; Chen et al. 2019; Das et al. 2019). A number of studies have been undertaken in order to investigate the impact of weather on traffic conditions and road safety, distinguishing the impact of fog, rainfall, wind speed, or winter conditions (snowfall, black ice) (Theofilatos and Yannis 2014). Fog is one of the factors that drastically reduces visibility (Gallen et al. 2015; Mueller and Trick 2012; Zolali and Mirbaha 2020). It influences both average speed and headways (Liu et al. 2020; Wu et al. 2018; Zolali and Mirbaha 2020). According to Jiang et al. (2020), fog contributes to the formation of traffic jams. Peng et al. (2018) indicates that the presence of fog influences the behavior of car drivers in more extent than truck drivers. A subject of many studies was an impact of fog on the road safety. It was found that in conditions of fog, the frequency of road accidents (especially rear-end collisions) is higher than in regular weather conditions, although their severity is lower, which results from lower speed maintained by vehicles in the adverse conditions (Shangguan et al. 2020; Wang et al. 2017; Yan et al. 2014). Precipitation and wet road surfaces are also found to have an effect both on traffic conditions and road safety (Borowska-Stefańska et al. 2021; Kempa 2005; Malin et al. 2019; Wang et al. 2017). In their paper of 1988, Brodsky and Hakkert (1988) stated that the risk of accident is 2 to 3 times higher in conditions of rain when compared with regular weather conditions. A number of later studies indicate that the risk actually increases (Bergel-Hayat et al. 2013; Jung et al. 2014; Keay and Simmonds 2006; Omranian et al. 2018); however, some other indicate that the impact is ambiguous and does not apply to all types of accidents or locations (Focant and Martensen 2014). On the other hand, research results from Greece shows the opposite effect—the risk of road accident is lower when it rains when compared with good weather conditions (Karlaftis and Yannis 2010). Precipitation was also found to have an effect on the individual driving behaviors and thus, traffic flow parameters and traffic conditions (Lam et al. 2013; Li et al. 2016). Unrau and Andrey (2006) found that the higher the precipitation intensity, the higher the impact on speed (decrease); at the same time, traffic volume decreases. The last-mentioned was also observed by Keay and Simmonds (2005) based on research in Australia and by Oh et al. (2002) based on research conducted in South Korea. According to Rahman and Lownes (2012), during rain there is an increase in the dispersion of speed. In terms of both traffic conditions and road safety, winter is a particularly important period of the year, with occurrence of low temperatures, precipitation (including snow, hail, sleet), snow-covered road surfaces, or black ice (Feng and Fu 2015; Norrman et al. 2000; Romanowska et al. 2018; Umeda et al. 2021). For road safety, the beginning of snowfall is of particular importance (Fridstrøm et al. 1995; Pennelly et al. 2018). There are also some studies investigating the impact of snowfall and increased road surface slipperiness on drivers' behavior and traffic conditions (Kim et al. 2015; Kwon J et al. 2013; Roh et al. 2016). Rakha et al. (2008) analyzed the effect of rain and snow and visibility on free-flow speed, capacity, speed-at-capacity, and jam density. The analyses covered urban roads in the United States and used a

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calibrated Van Aerde model (Van Aerde 1995). Analysis results showed that, depending on its intensity, rain leads to a drop in free-flow speed by 2%–9%, in speed-at-capacity by 8%–14%, and in capacity by 10%–11%. For snow, it is 5%–16%, 5%–16%, and 12%–20%, respectively. Jam density was not affected by the changed weather conditions. Lam et al. (2013) compared empirical relations between speed and density for a varying intensity of precipitation by calibrating a modified two-phase Greenshields model and comparing the parameters using the weather influence coefficient. The results have shown that as precipitation intensity increases, capacity falls by 9%–17%, free-flow speed falls by 4%–7%, and speed-at-capacity falls by 15%–25% relative to normal conditions. Similar to Rakha et al. (2008), the study concluded that jam density is not affected by adverse weather conditions. Agarwal et al. (2005) observed that depending on the intensity of precipitation average speed falls by 2%–7% and capacity falls by 5%–17%. The effect of snow is much stronger, with speed falling by 10%–15% and capacity falling from 13% to 27%, depending on the intensity. While subzero temperatures have also been found to have an effect, it only appears for temperatures below −20°C and reduces capacity by about 10%. Using data from Spanish motorways, Camacho et al. (2010) analyzed the effect of temperature, rain and snow, visibility, wind speed, and thickness of snow cover on traffic parameters in free-flow traffic. He demonstrated that depending on the intensity of rainfall speed falls by 5.5–7 km h^{-1}. In the case of snow, the drop in speed is greater and reaches 9–13.7 km h^{-1}. He also observed the effect of wind speed (>8 m s^{-1}) on average vehicle speed. In the case of visibility, the drop in speed was only observed for visibility of several hundred meters.

Similar to what happens in adverse weather conditions, some drivers may feel less confident in the nighttime when there is no natural light or at dusk or dawn when the contrast between a fairly bright sky and dark road makes it more difficult for drivers' eyesight to adjust (Evans et al. 2020; Konstantopoulos et al. 2010; Leibowitz et al. 1998). Drivers respond by slowing down and maintaining longer headways. When driver behavior changes, it affects both the traffic flow characteristics, such as average speed or average headways, and the parameters related to highway performance, such as free-flow speed and capacity (Bella et al. 2014; Kempa 2008; Robbins and Fotios 2021). In the nighttime, the risk of accidents also increases (Jafari Anarkooli and Hadji Hosseinlou 2016; Jamroz et al. 2019; Leibowitz et al. 1998). A combination of adverse weather conditions and the nighttime can have an even more negative impact on both traffic conditions and road safety (Awadallah 2007; Gallen et al. 2015; Higgins et al. 2009). Using data from continuous traffic measurement stations on German motorways, Brilon and Ponzlet (1996) demonstrated that speeds drop on wet roadways by 9.5–12 km h^{-1} with capacity falling by 350–500 vehicles per hour, depending on the number of lanes. Under normal conditions during nighttime speed is observed to change mainly in a partly constrained operation (5–7 km h^{-1}). Nighttime precipitation, however, has a stronger effect on free-flow speed (falling by about 10 km h^{-1}). In addition, during nighttime when compared with daytime, capacity falls by from 200 to nearly 400 vehicles per hour regardless of the weather or condition of the road surface. Oh et al. (2002) analyzed the effects of weather conditions on speed using regression models of speed–flow and flow–occupancy relationships. He found that when weather conditions change, function slope falls and the speed–volume curve is shifted downward. He demonstrated that during rain and snow both daytime and nighttime average speed falls by several percent (2%–7%).

Understanding the impact of adverse weather conditions and time of day may be important in the context of predicting and assessing traffic conditions on planned or existing road facilities. For this purpose, highway capacity methods are used, such as United States' Highway Capacity Manual (HCM) or Germany's Handbuch für die Bemessung von Straßenverkehrsanlagen (HBS) (Baier et al. 2015; Romanowska et al. 2019; Transportation Research Board 2016). While these analyses are usually conducted for good weather and daytime, there are several dozen or hundreds of hours in a year when weather conditions are anything but perfect and several to more than a dozen hours a day when the amount of natural light is limited. As a result, the road facility affected may perform below expectations. Most of the highway capacity methods, except HCM (Transportation Research Board 2016) and the Dutch's Handboek Capaciteitswaarden Infrastructuur Autosnelwegen (CIA) (Heikoop and Henkens 2016), were not designed to analyze traffic conditions under adverse weather conditions and/or time of day other than daytime. HCM provides coefficients of capacity adjustment factors and speed adjustment factors that are addressed at different stages of the traffic conditions assessment procedure. Depending on the base free-flow speed (the lower it is, the smaller the effect is) and the intensity of the weather phenomena (the higher the intensity, the bigger the effect): rainfall reduces speed by 4%–9% and capacity by 6%–18%, while snow reduces speed by 6%–19% and 3%–28%, respectively. Low temperatures (<−20°C) reduce speed and capacity by 3%–5% and 7%–10%, respectively. Limited visibility reduces speed and capacity by 4%–9% and 10%–12%, respectively. Time of day is not considered in the HCM. The Dutch method, CIA, provides coefficients of capacity adjustment factors only. The capacity is reduced by 5% in the case of light rain and by 10% in the case of intensive rainfall. In the nighttime the capacity is reduced by 5% or by 3% if the road is illuminated.

To summarize the research presented in the literature, it can be concluded that

- rainfall reduces speed by 2%–10% and capacity by 5%–30%,
- snowfall reduces speed by 2%–19% and capacity by 3%–28%,
- in the nighttime there is a slight reduction in the speed and capacity (3%–5%) but the effect increases when it is also raining,
- on wet road surfaces both the speed and the capacity are reduced by ~10%,
- limited visibility causes speed reduction by 4%–9% and capacity reduction by 10%–12%,

- the effect of temperature is noticeable under severe frost conditions ($<-20°C$) when the speed and capacity are reduced by 5%–8% and 7%–10%, respectively, and
- strong wind (>8 m s^{-1}) affects the average speed, but the effect was not determined in the studies.

Between 2016 and 2019 work was under way in Poland on a new method for assessing traffic conditions and estimating capacity on dual carriageways: Metoda Obliczania Przepustowości–Drogi Zamiejskie (MOP-DZ; Olszewski et al. 2020). The method was finally developed in 2019 but has not yet been published. Similar to other methods such as HCM or HBS, the procedure for assessing traffic conditions is based on daytime (in natural light) and good weather data (excluding fog, rain, or snow; wet, snowy, or icy road surface; and extreme temperatures or wind speeds). Thus, the method can be used for predicting or assessing traffic conditions in good weather and for daytime only. Efforts to develop tools for analyzing adverse weather conditions and time of day other than daytime require scientific support and research on the effects of weather and time of day on traffic flow characteristics. The results from foreign literature should not be directly applied if not verified. To that end, data for Polish roads should be used.

The paper presents the results of research on the effects of adverse weather conditions and time of day on traffic flow characteristics and the parameters related to highway performance. The objectives of the article are as follows: to identify factors related to weather and time of day that have an effect on traffic conditions, to analyze the effects of these factors on the particular traffic parameters, to quantify the effects of selected factors, and to propose application of the results in the MOP-DZ method.

The introduction (section 1) presents an overview of the literature on the effects of weather and time of day on traffic flow characteristics. Section 2 gives a description of the data and data method. Section 3 presents the results of the research and section 4 presents possible application of the study results in the MOP-DZ method. Section 5 discusses the study results. Conclusions are given in section 6.

2. Method

a. Data collection

The study is based on data stretching over 36 months (2014–17) from the continuous traffic measurement station located at the S6 expressway in Gdansk, Poland (54°25′ N, 18°29′ E). The road section at which the station is located is a dual carriageway with four lanes running within the conurbation. Annual average daily traffic is 74 000 vehicles per day and up to 100 000 vehicles per day in peak periods. As a result, the full scope of traffic conditions can be analyzed, both for free-flow and congested conditions.

The data (Romanowska and Kustra 2021) were sourced from a continuous traffic measurement station that operates in a double induction loop. The device registers the time a vehicle appears on the detector and its instantaneous speed. It identifies the type of vehicle and lane the vehicle is using. structured query language (SQL) was used for data processing and initial analysis. The data processing was divided into the following stages:

1) Raw traffic data that were provided by the national road authority (General Director for National Roads and Motorways) in the text file format were imported to the database on the installed SQL server.
2) The data were verified in terms of empty rows, zero values, vehicle speeds beyond the expected range, unusual vehicle lengths. The problem of zeros or unusual values concerned ~2% of registered vehicles and had marginal impact on the number of registered vehicles—the records were excluded from further processing.
3) Individual vehicle headways were calculated for each record.
4) The data were aggregated to 5-min intervals that provided information on traffic volume, space-mean speed, share of heavy goods vehicles, and average headways. The traffic volume was calculated into flow rate using passenger car equivalents (Olszewski et al. 2020). Traffic density was determined from the fundamental relationship of traffic flow (May 1990). Free-flow speed was estimated in each interval as speed of passenger cars maintaining headways at least 7 s behind and 4 s in front of adjacent vehicles under low-volume and low-density traffic conditions (<1000 vehicles per hour per lane and <10 vehicles per kilometer per lane).

Data about the weather during the analysis come from a weather station located on the road. The data include condition, intensity (0%–100%), and type of precipitation (classified according to the data source as none, light, continuous, intensive, snow, hail), condition of the road surface (classified as dry, moist, wet, and slippery), and temperature. Data on horizontal visibility (classified as 0–50 m, 50–200 m, 200–500 m, and >500 m) were obtained from the nearest climatological station. The time of day for each interval was determined based on calculations of the position of the Sun relative to the horizon for the given date and location. With that, the particular time intervals were classified as dusk, day, dawn, and night.

Over the analyzed period, more than 26 000 h of the survey consisted of 9100 nighttime hours and 1760 and 1540 h of dawn and dusk, respectively; 1800 h of rain, including 640 h of intensive rain; and 50 h of snow or hail (Table 1). The latest two occurred only in winter season. The road surface was wet for a total of 4160 h and slippery for 1360 h. Visibility below 200 m occurred for a total of 326 h, including 180 h of visibility below 50 m. Subzero temperatures were recorded for nearly 1160 h (the lowest observed temperature was −14°C), including 63 h of temperatures below −10°C. For 160 h, the temperatures were above 30°C but not exceeding 40°C. Intensity of precipitation was the highest in winter season, whereas the lowest occurred during summer (Table 2).

b. Analyses

A one-way analysis of variance (ANOVA) method (Sawyer 2009) was used to examine the relationship between traffic

TABLE 1. Average speed of cars in relation to the type of precipitation.

		Avg speed of passenger cars (km h^{-1})			
Type of precipitation	No. of intervals	Mean	Std dev	Median	Interquartile range
None	249 721	102.3	9.7	103.2	7.0
Light	6648	98.1	10.7	99.5	7.4
Continuous	7270	96.8	11.3	98.4	7.6
Intensive	7725	94.9	13.0	97.2	8.5
Snow	464	88.6	11.7	90.8	15.5
Hail	152	83.5	12.5	86.4	18.3

flow parameters and weather and time of day related factors. Two dependent variables were examined: free-flow speed and average speed. Independent variables included: time of day, precipitation, road surface conditions, and visibility. To use the method, first its assumptions were tested against the data. With all other conditions met, Welch's correction had to be applied to take account of the failure to meet the condition of equality of variances. The question was whether there is a statistically significant (at 5% significance level) relationship between speed and particular weather conditions and time of day. For the significant relationships, post hoc analyses, using Tukey and Dunnett tests, were additionally conducted to investigate whether the differences are significant between classes of particular conditions (i.e., light and heavy rain) and between particular classes and conditions referred to as "normal" (determined based on Tukey test results; including daylight, no precipitation, dry road surface, and visibility >200 m). The effect on speed was additionally tested at different levels of traffic density in order to investigate, whether it is significant in the whole range of observed densities. For this purpose, t tests were used between group independent samples.

To quantify the effect of weather conditions and time of day the data were assigned to nine scenarios (Table 3). The baseline scenario is scenario 1, which features no rain or snow, dry road surface, and horizontal visibility in excess of 200 m. Scenarios of nighttime do not include low visibility conditions, because such weather conditions were not observed in the data. Scenarios of dawn and dusk cover only good weather conditions because of relatively small samples if adverse weather conditions are additionally included. Table 4 shows the frequency distribution of the particular conditions in the scenarios.

For each scenario, the averaged values of free-flow speed v_{sw}, average speed v, average headway h, and traffic volume q were calculated. For each parameter p, a relative percentage change in the average parameter value dp_i was determined in comparison with the baseline scenario:

$$dp_i = \frac{p_i - p_0}{p_0} \times 100\%, \tag{1}$$

where dp_i is the percentage change of the average parameter value p in scenario i when compared with the baseline scenario (%), p_0 is the average value of parameter p in the baseline scenario, and p_i is the average value of parameter p in scenario i.

TABLE 2. Precipitation intensity (%) in particular seasons.

		Intensity of precipitation (%)		
Season	No. of intervals	Mean	95% confidence interval	Std dev
Spring	77 257	6.95	(6.81, 7.01)	18.53
Summer	78 522	3.86	(3.75, 3.96)	15.44
Autumn	78 361	7.14	(7.01, 7.26)	18.16
Winter	60 891	20.82	(20.63, 21.02)	24.24

Next, the speed–density model developed by Romanowska (2019) was calibrated to estimate values of free-flow speed, speed-at-capacity, and capacity in each scenario:

$$v = \frac{v_{sw}}{\left[1 + (k/k_{opt})^n\right]^{1-(1/n)}}, \tag{2}$$

where v is the average speed (km h^{-1}), v_{sw} is the free-flow speed (km h^{-1}), k is the traffic density (vehicles per kilometer), k_{opt} is the density at capacity (vehicles per kilometer), and n is the shape parameter.

3. Results

Results (Tables 5 and 6) show a significant effect of both time of day [$F(3, 271\,908) = 2353.5$; $p < 0.001$], precipitation [$F(5, 271\,908) = 575.9$; $p < 0.001$], road surface condition [$F(3, 271\,908) = 1192.0$; $p < 0.001$], and visibility [$F(3, 271\,908) = 12.9$; $p < 0.001$] on the average speed. Similarly, a significant effect was also noticed in the case of free-flow speed as a

TABLE 3. Scenarios of weather conditions and time of day used in the analyses.

Scenario	Time of day	Visibility	Type of precipitation	Condition of road surface
1	Day	>200 m	None	Dry
2	Day	≤200 m	None	Dry
3	Day	—	Rain	Moist or wet
4	Day	—	Snow	Wet or slippery
5	Night	>200 m	None	Dry
6	Night	—	Rain	Moist or wet
7	Night	—	Snow	Wet or slippery
8	Dawn	>200 m	None	Dry
9	Dusk	>200 m	None	Dry

TABLE 4. Percentage distribution of the frequency of the particular weather conditions and time of day depending on the scenario (1–9).

Variable	Value	1	2	3	4	5	6	7	8	9
Traffic volume (vehicles per hour)	<500	2	1	2	3	62	56	37	75	5
	500–999	4	5	5	11	23	21	22	14	25
	1000–1499	7	14	8	9	10	12	22	4	29
	1500–1999	16	28	18	33	4	7	17	2	22
	2000–2499	33	43	36	27	1	3	2	3	10
	2500–2999	26	9	24	14	0	1	0	1	6
	3000–3499	10	0	7	3	0	0	0	0	4
	3500–3999	2	0	0	0	0	0	0	0	0
	≥4000	0	0	0	0	0	0	0	0	0
Visibility (m)	≤200	0	100	0	0	0	0	6	0	0
	>200	100	0	100	100	100	100	94	100	100
Precipitation type	None	100	100	0	0	100	0	0	100	100
	Light	0	0	31	0	0	31	0	0	0
	Continuous	0	0	33	0	0	34	0	0	0
	Intensive	0	0	36	0	0	34	0	0	0
	Snow	0	0	0	78	0	0	81	0	0
	Hail	0	0	0	22	0	0	19	0	0
Road pavement condition	Dry	100	100	0	0	100	0	0	100	100
	Moist	0	0	16	0	0	9	0	0	0
	Wet	0	0	84	2	0	91	0	0	0
	Slippery	0	0	0	98	0	0	100	0	0
Temperature °(°C)	<0	1	86	0	100	5	0	100	2	2
	>0	99	14	100	0	95	100	0	98	98
Time of day	Dawn	0	0	0	0	0	0	0	100	0
	Day	100	100	100	100	0	0	0	0	0
	Dusk	0	0	0	0	0	0	0	0	100
	Night	0	0	0	0	100	100	100	0	0
Season	Spring	32	0	29	0	33	17	0	29	35
	Summer	41	2	25	0	28	7	0	57	34
	Autumn	22	10	20	0	31	31	0	12	23
	Winter	5	88	26	100	8	45	100	2	8

dependent variable: time of day [$F(3,107\,616) = 369.6$; $p < 0.001$], precipitation [$F(5, 107\,616) = 122.7$; $p < 0.001$], road surface condition [$F(3, 107\,616) = 759$; $p < 0.001$], and visibility [$F(3, 107\,616) = 22.9$; $p < 0.001$]. For the analyzed interactions, post hoc Tukey test results showed that at 0.05 significance level, both the average speed and the free-flow speed differed significantly (at $p < 0.05$) in each group within time of day, precipitation, and road surface condition. The average speed did not differ significantly between visibilities of <50 m and 50–200 m, but significant differences were found between both classes and higher visibility ranges. The free-flow speed differed significantly between all visibility levels below 500 m. Based on the Tukey test results, control group for a post hoc Dunnett test was determined as daytime, no precipitation, dry road surface, and visibility above 200 m (referred to as "normal conditions"). The results at 0.05 significance level showed a significant difference between the average speed or the free-flow speed for any weather conditions and time of day deviating from those pointed above ($p < 0.05$).

The average speed in normal and adverse (here referred to as conditions other than normal) conditions was compared for different density levels. The analyses showed that for the wide density range of 0–50 passenger cars per kilometer, which refers to noncongested traffic conditions, the average speed differs significantly in adverse and normal conditions, at $p < 0.05$ (Table 7).

Table 8 presents the average values of the average speed, free-flow speed, headway, and traffic volume in each scenario, and the relative change of each parameter [dp_i—Eq. (1)] from the baseline scenario (scenario 1). We can see that when the

TABLE 5. Results of one-way ANOVA: average speed of passenger cars; df indicates degrees of freedom.

	Sum of squares	df	Mean square	F	Significance level
Time of day	661 562	3	220 521	2353.5	<0.001
Type of precipitation	269 803	5	53 961	575.9	<0.001
Condition of road surface	335 064	3	111 688	1192.0	<0.001
Visibility	3615	3	1205	12.9	<0.001
Error	25 477 995	271 908	94		

TABLE 6. Results of one-way ANOVA: free-flow speed.

	Sum of squares	df	Mean square	F	Significance level
Time of day	91 440	3	30 480	369.6	<0.001
Type of precipitation	50 580	5	10 116	122.7	<0.001
Condition of road surface	187 770	3	62 590	759.0	<0.001
Visibility	5654	3	1885	22.9	<0.001
Error	8 874 843	107 616	82		

weather deteriorates both in daytime and nighttime, the average vehicle speed and the free-flow speed fall and average headways increase. During the daytime, the occurrence of rain causes a fall in the average speed by 6%, in the free-flow speed by 4%, and an increase in headways by about 9%; in case of snowfall the average speed decreases by 11%, free-flow speed decreases by 12%, and headways increase by approximately 27%. When visibility is poor, the average speed does not change and the free-flow speed falls by approximately 2%; average headways increase by about 10%. In the nighttime the average speed is higher than during daytime, but free-flow speed decreases by 2%. When the rain occurs in the nighttime, the average speed falls by 2%, free-flow speed decreases by 7% relative to normal weather conditions during daytime; snowfall at the nighttime causes 14% reduction in the average speed and 17% reduction in the free-flow speed relative to the daytime and normal weather conditions. Average headways increase by several times in the nighttime, and the very high deviations from the average can be noticed. This can be probably explained by low traffic volumes during the nighttime ($q = 529$–842 vehicles per hour). At dawn and dusk, when the amount of the natural light is limited, the observed average speed is higher than in the baseline, but the free-flow speed falls by 3.5% and 0.7%, respectively.

To estimate the capacity under different weather and time-of-day conditions, the speed–density model [Eq. (2)] was used. For each scenario the model was fitted to the data and calibrated. A constant value of density at capacity was adopted ($k_{\mathrm{opt}} = 52$ passenger cars per kilometer). The other parameters were estimated using the model. The results are given in Table 9. As we can see, as the weather deteriorates, the free-flow speed and speed-at-capacity fall as does capacity. Under conditions of limited visibility, the reduction in capacity is about 3%, with rain causing a drop in capacity by about 5% in the daytime and by 8% in the nighttime. Snowfall causes a drop in capacity by about 9% in daytime and 19% in the nighttime (all in comparison with the baseline scenario 1). During dawn and dusk both the free-flow speed and capacity are lower by approximately 3%.

4. Application of the results

The results presented in the study may contribute to the MOP-DZ method. Figure 1 presents the proposed extension of the MOP-DZ procedure for assessing traffic conditions, that allows to consider weather and time-of-day characteristics. Just as with the HCM method (Transportation Research Board 2016), an additional step is proposed to correct free-flow speed for adverse conditions. In such case, in step 2.2, the estimated or measured (in normal conditions) value of the free-flow speed is adjusted by multiplying it by a correction coefficient:

$$v'_{\mathrm{sw}} = v_{\mathrm{sw}} w_A, \qquad (3)$$

where v'_{sw} is the free-flow speed under adverse weather and/or lighting (km h^{-1}), and w_A is the correction coefficient (Table 10).

In the speed–flow relationships developed for the MOP-DZ method, the average speed and capacity depend on the free-flow speed. As a result, adjusted free-flow speed will have an indirect effect on the new values of both parameters. If traffic volume remains unchanged, reduced speed will increase traffic density, which is the basis for determining the level of service. This way the effect of weather and time of day will be included in the entire traffic conditions assessment procedure thanks to the adjusted free-flow speed.

From the results presented in section 3, coefficients of weather- and time-of-day-related adjustment factors may be proposed for the studied site (Table 10).

5. Discussion

The paper presents the results of the study on the effects of adverse weather conditions and time of day on traffic flow characteristics and highway performance. Using statistical methods, it was proved, that both rain and snow, road surface condition, visibility, and time of day (in reference to the amount of natural light) significantly affect the average speed in the wide range of traffic densities (0–50 vehicles per kilometer). The strength of the effect was estimated by calculating

TABLE 7. The t test results (p values) for the average speed v (km h^{-1}) in normal and adverse conditions, grouped by traffic density.

	Traffic density k (passenger cars per kilometer)						
	0–10	10–20	20–30	30–40	40–50	50–60	>60
Normal conditions	109.0	105.8	101.8	96.0	80.7	53.3	34.9
Adverse conditions	104.2	102.2	98.3	91.4	76.7	52.1	30.0
p value	<0.05	<0.05	<0.05	<0.05	<0.05	0.51	<0.05

TABLE 8. Changes in selected parameters of vehicle flow in the scenarios i = 1–9 of weather and time of day, as defined in Table 3. An asterisk indicates the baseline scenario; NA = not applicable.

	Avg speed v (km h^{-1})			Free-flow speed v_{sw} (km h^{-1})			Avg headways h (s)			Traffic volume q (vehicles per hour)
i	v_i	dv_i	Std dev	v_{sw_i}	dv_{sw_i}	Std dev	h_{t_i}	dh_{t_i}	Std dev	q_i
1*	100.9	NA	11.3	110.7	NA	13.6	3.4	NA	9.8	2254
2	101.3	+0.4%	3.4	108.7	−1.8%	5.4	3.8	+10.2%	2.2	1924
3	94.6	−6.2%	14.4	106.1	−4.2%	12.8	3.7	+8.5%	4.4	2152
4	89.7	−11.1%	10.4	97.3	−12.1%	10.9	4.3	+25.3%	3.0	1876
5	105.2	+4.3%	6.6	108.3	−2.1%	7.5	29.6	+767.8%	248.3	528
6	99.1	−1.8%	9.1	103.0	−6.9%	9.5	32.5	+853.8%	161.6	639
7	86.9	−13.9%	11.5	91.4	−17.4%	11.7	27.0	+692.8%	51.4	842
8	104.6	+3.7%	6.0	106.8	−3.5%	7.2	30.4	+793.1%	33.1	460
9	103.4	+2.5%	6.1	109.8	−0.7%	7.1	6.0	+75.9%	3.8	1439

the means of particular parameters and comparing them in nine scenarios depending on weather conditions and time of day. A speed–density model was also used in order to support the analyses and estimate road capacity and the corresponding speed. It was proved that, when compared with normal weather conditions, under conditions of daytime, rain, and wet road surface, the average speed is reduced by 4%–6% (depending on traffic density) and the capacity is reduced by 5%; when it is snowing and the road surface is wet or slippery during the daytime, the average speed is reduced by 9%–12% and the capacity is reduced by 9%; under conditions of limited visibility with no precipitation in the daytime, the average speed is reduced by 0%–4% and the capacity is reduced by 3%. In the nighttime and good weather conditions, the speed and capacity are lower than in the daytime by 2%–4% and 4%, respectively. When it additionally rains at night and the road surface is wet, speed is reduced by up to 9% and capacity is reduced by 8%. During snowfall, speed decreases by 14%–19% and capacity is reduced by 19% when compared with the baseline normal weather conditions during daytime. In the nighttime, the effect of weather conditions is stronger when compared with the daytime. It needs to be noticed that the road at study site is illuminated, which may affect the magnitude of the effect in the nighttime. The effect of dawn and dusk was also evaluated showing that limited natural lighting also affect both speed and capacity that are reduced by 1%–5% and 4%–5%, respectively.

In the case of rain and snow, the results of the study are consistent with the research results in the literature (Agarwal et al. 2005; Brilon and Ponzlet 1996; Camacho et al. 2010; Chen et al. 2019; Heikoop and Henkens 2016; Lam et al. 2013; Oh et al. 2002; Rakha et al. 2008; Transportation Research Board 2016)—the speed and capacity reductions fit within the range defined in the works reviewed (Table 11). There is a difference in the case of limited visibility, with speed and capacity falling less in this work when compared with the literature studies. However, in the case of reduced visibility and nighttime there are only single studies that cover these conditions, and some present the reductions of speed and capacity in original units, making any comparisons of the values difficult.

The article proposes that adverse-weather and time-of-day conditions can be included in the procedure for traffic conditions assessment for uninterrupted traffic facilities in the new MOP-DZ method (Olszewski et al. 2020). This may be done by adjusting the free-flow speed estimated with MOP-DZ procedure or measured in normal conditions for the impact of adverse weather and time of day. For this purpose, the coefficients of weather- and time-of-day-related adjustment factors need to be developed. Such coefficients were proposed based on the results from this study for the studied site. To cover for different road and traffic characteristics, the coefficients need to be developed based on data from different sites. To that end, further research should be conducted.

The most important limitation of the study is lack of representativeness for different road and traffic conditions (i.e., roads with different design, speed limits, location, and share of heavy vehicles). This limitation is strongly related to the poor traffic data availability in Poland. At the time of doing the research, there were only seven permanent traffic counting

TABLE 9. Free-flow speed, capacity, and speed-at-capacity estimated with Eq. (2), and the relative change in relation to the baseline scenarios, for scenarios 1–9. An asterisk indicates the baseline scenario; NA = not applicable.

Parameter	1*	2	3	4	5	6	7	8	9
Free-flow speed v_{sw}	108	104	103	98	104	99	88	105	105
	NA	−3.3%	−4.6%	−9.2%	−3.7%	−8.3%	−18.5%	−2.6%	−3.1%
Capacity C	4010	3880	3820	3640	3860	3680	3270	3910	3883
	NA	−3.2%	−4.7%	−9.2%	−3.7%	−8.2%	−18.5%	−2.5%	−3.2%
Speed-at-capacity v_{opt}	77	74	73	70	74	70	63	74	73
	NA	−3.9%	−5.2%	−9.1%	−3.9%	−9.1%	−18.2%	−3.9%	−5.1%

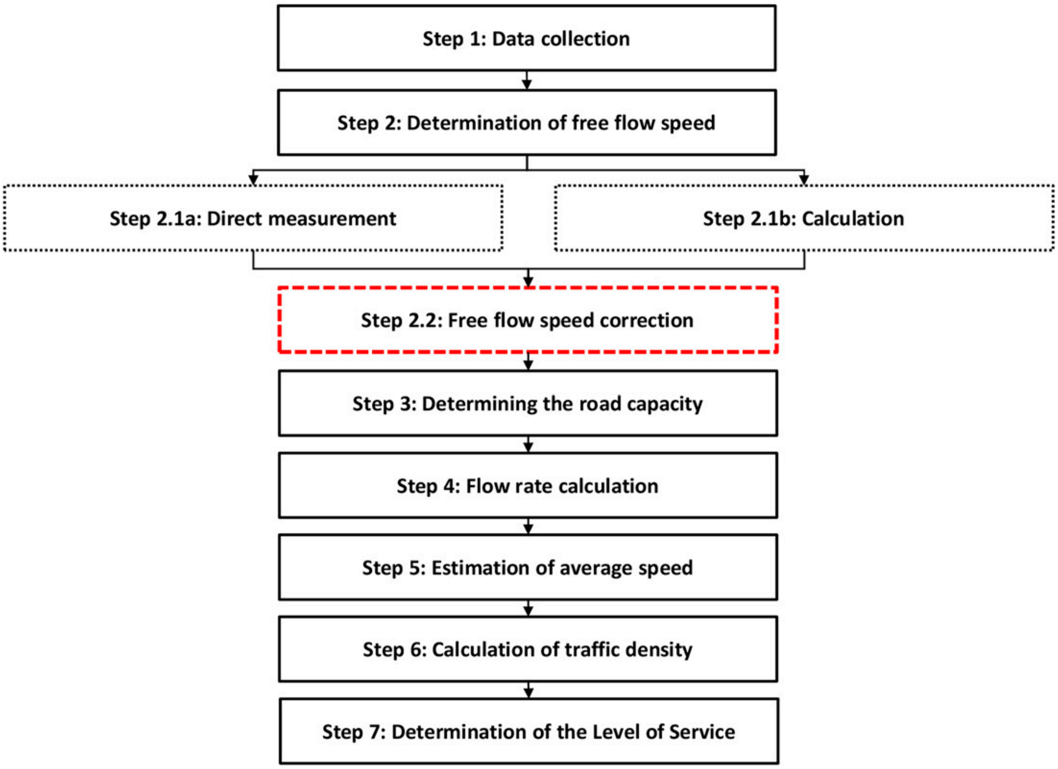

FIG. 1. Procedure of traffic conditions assessment using the MOP-DZ method including the effects of weather.

stations that could provide eligible data (with regard to the data format and measured traffic parameters). Most of them were located on low-volume roads (annual average daily traffic below 25 000 vehicles per day). If higher traffic volumes are not observed on a site, the research cannot cover for the entire range of traffic conditions (both free-flow traffic and congested traffic) and the impact of weather and time of day can only be studied for free-flow traffic and low densities. In the case of the studied site, high traffic volumes reaching up to 100 000 vehicles per 24 h were observed, and the impact of weather and time of day could be studied for the full range of traffic conditions. Another issue related to data availability is that weather measurement stations need to be located in the proximity of a site, and this condition was also not met in most cases. These conclusions may be important for road authorities in the context of choosing locations for installing permanent traffic counting stations in the road network.

While comparison of results from this study with literature showed consistent findings, further research is needed to investigate whether the results apply to roads with different characteristics.

6. Conclusions

The specific goals of the study presented in the paper included identification of factors related to weather and time of day that have an effect on traffic conditions, analysis, and quantification of the effects of these factors on the particular

TABLE 10. The proposed (dimensionless) coefficients of weather- and time-of-day-related free-flow speed adjustment factors.

Time of day	Visibility	Type of precipitation	Condition of road surface	Correction factor
Day	>200 m	None	Dry	1.00
	≤200 m	None	Dry	0.97
	—	Rain	Moist or wet	0.95
	—	Snow	Wet or slippery	0.91
Night (illuminated road)	>200 m	None	Dry	0.96
	—	Rain	Moist or wet	0.92
	—	Snow	Wet or slippery	0.81
Dawn	>200 m	None	Dry	0.97
Dusk	>200 m	None	Dry	0.97

TABLE 11. Percentage reduction of speed and capacity in adverse weather and natural lighting conditions—comparison between study results and the literature.

	Rain		Snow		Reduced visibility		Nighttime, good weather	
Literature	v	C	v	C	v	C	v	C
Rakha et al. (2008)	2%–9%	10%–11%	5%–16%	12%–20%				
Oh et al. (2002)	2%–7%		2%–7%					
Lam et al. (2013)		9%–17%						
Agarwal et al. (2005)	2%–7%	5%–17%	10%–15%	13%–27%				
Transportation Research Board (2016)		10%–12%	6%–19%	3%–28%	4%–9%	10%–12%		
Heikoop and Henkens (2016)		5%–10%						3%–5%
This study	4%–6%	5%	9%–12%	9%	0%–4%	3%	2%–4%	4%

traffic parameters and application of the results to the MOP-DZ method. The way to achieve these goals and the obtained results are presented in the paper. This lets us assume that the goals set in the introduction were achieved. To summarize the findings, we state the following:

- There is a statistically significant effect of weather and time of day on both traffic flow characteristics and parameters related to highway performance. The effect is observed at a wide range of traffic densities.
- Depending on the time of day and weather conditions, average speed may decrease by even 19% and capacity by even 18% when compared with normal weather conditions in the daytime. The higher the intensity of weather phenomena, the higher is the effect it has on traffic flow.
- There is a group of conditions that were not covered by the study, that is, extremely low or high temperatures. This kind of conditions did not occur at the study area within the study period and, because of low frequencies, may be difficult to study with data from Polish sites.
- The research results may contribute to the new Polish highway capacity manual MOP-DZ. The extended traffic conditions assessment procedure was proposed that allows for including adverse weather and time of day in the analysis.
- The research provides coefficients of the weather- and time-of-day-related free-flow speed adjustment factors for the studied site that are based on the long-term measurements covering entire range of traffic conditions (from free-flow to congested). Determination of such coefficients for different types of roads may notably increase the scope of possible applications of the MOP-DZ method.
- Efforts to develop tools to account for adverse weather and time of day in assessing traffic conditions require further scientific support.

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Data availability statement. The data presented in this study are openly available from the MostWiedzy repository (https://doi.org/10.34808/8xkq-7714; Romanowska and Kustra 2021).

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