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2 **Investigating the impact of weather conditions and time of day on traffic**  
3 **flow characteristics**

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10 Adverse weather such as rain, snow and fog may significantly reduce visibility or change  
11 adhesion properties and, as a consequence, affect drivers' sense of safety, driving comfort  
12 and their reaction to a changing driving environment (i.e. lower speed, increased headways).  
13 The changed behavior of individual drivers affects both traffic flow characteristics,  
14 i.e. average speed and headways, and parameters related to highway performance including  
15 free flow speed and capacity. Thus, understanding the impact may be important in the context  
16 of predicting and assessing traffic conditions on planned or existing road facilities.

17 The paper discusses the effects of adverse weather conditions and time of day on traffic  
18 flow characteristics and the parameters related to highway performance. Based on real traffic  
19 and weather data from a Polish expressway, the paper aims to: identify factors related to  
20 weather and time of day that significantly influence traffic flow parameters and traffic  
21 conditions, analyze and quantify this impact. The results of the study may help to develop  
22 coefficients of weather-related adjustment factors that will allow to estimate i.e. average  
23 speed of vehicles in the night-time, or in the conditions of rain or limited visibility. The  
24 results of the study may contribute to a new Polish method for capacity estimation and traffic  
25 conditions assessment for uninterrupted traffic facilities.

## 26 **1. Introduction**

27 Adverse weather such as rain, snow and fog may significantly reduce visibility or change  
28 adhesion properties and, as a consequence, affect drivers' sense of safety, driving comfort  
29 and their reaction to a changing driving environment (Chang et al., 2019; Chen et al., 2019;  
30 Das et al., 2019). A number of studies have been undertaken in order to investigate the  
31 impact of weather on traffic conditions and road safety, distinguishing the impact of fog,  
32 rainfall, wind speed or winter conditions (snowfall, black ice) (Theofilatos & Yannis, 2014).  
33 Fog is one of the factors that drastically reduces visibility (Gallen et al., 2015; Mueller &  
34 Trick, 2012; Zolali & Mirbaha, 2020). It influences both the average speed and headways  
35 (Liu et al., 2020; Wu et al., 2018; Zolali & Mirbaha, 2020). According to Jiang et al. (2020),  
36 fog contributes to the formation of traffic jams. Peng et al. (2018) indicates that the presence  
37 of fog influences the behaviour of car drivers in more extent than truck drivers. A subject of  
38 many studies was an impact of fog on the road safety. It was found that in the conditions of  
39 fog the frequency of road accidents (especially rear-end collisions) is higher than in regular

40 weather conditions, although, their severity is lower, which results from lower speed  
41 maintained by vehicles in the adverse conditions (Shangguan et al., 2020; Wang et al., 2017;  
42 Yan et al., 2014). Precipitation and wet road surface are also found to have an effect both on  
43 traffic conditions and the road safety (Borowska-Stefańska et al., 2021; Kempa, 2005; Malin  
44 et al., 2019; Wang et al., 2017). In their paper of 1988 Brodsky and Hakkert (1988) stated  
45 that the risk of accident is 2 to 3 times higher in the conditions of rain when compared to  
46 regular weather conditions. A number of later studies indicate that the risk actually increase  
47 (Bergel-Hayat et al., 2013; Jung et al., 2014; Keay & Simmonds, 2006; Omranian et al.,  
48 2018), however, some other indicate that the impact is ambiguous and does not apply to all  
49 types of accidents or locations (Focant & Martensen, 2014). On the other hand, research  
50 results from Greece shows the opposite effect – the risk of road accident is lower when it  
51 rains when compared to good weather conditions (Karlaftis & Yannis, 2010). Precipitation  
52 was also found to have an effect on the individual driving behaviours and thus, traffic flow  
53 parameters and traffic conditions (Lam et al., 2013; Li et al., 2016). Unrau and Andrey (2006)  
54 found that the higher the precipitation intensity, the higher the impact on speed (decrease); at  
55 the same time traffic volume decreases. The last-mentioned was also observed by Keay and  
56 Simmonds (2005) based on research in Australia and by Oh et al. (2002) based on research  
57 conducted in Korea. According to Rahman and Lownes (2012), during the rain there is an  
58 increase in the dispersion of speed. In terms of both traffic conditions and road safety, winter  
59 is a particularly important period of the year, with occurrence of low temperatures,  
60 precipitation (including snow, hail, sleet), snow-covered road surface or black ice (Feng &  
61 Fu, 2015; Norrman et al., 2000; Romanowska et al., 2018; Umeda et al., 2021). For the road  
62 safety, the beginning of snowfall is of particular importance (Fridstrøm et al., 1995; Pennelly  
63 et al., 2018). There are also some studies investigating the impact of snowfall and increased  
64 road surface slipperiness on drivers' behaviour and traffic conditions (Kim et al., 2015; Kwon  
65 J et al., 2013; Roh et al., 2016). Rakha et al. (2008) analysed the effect of rain and snow and  
66 visibility on free-flow speed, capacity, speed-at-capacity and jam density. The analyses  
67 covered urban roads in the US and used a calibrated Van Aerde model (van Aerde, 1995).  
68 Analysis results showed that depending on its intensity rain leads to a drop in free-flow speed  
69 by 2-9%, in speed-at-capacity by 8-14% and in capacity by 10-11%. For snow it is 5-16%, 5-  
70 16% and 12-20%, respectively. Jam density was not affected by the changed weather  
71 conditions. Lam et al. (2013) compared empirical relations between speed and density for a  
72 varying intensity of precipitation by calibrating a modified two-phase Greenshields model

73 and comparing the parameters using the weather influence coefficient. The results have  
74 shown that as precipitation intensity increases, capacity falls by 9-17%, free-flow speed falls  
75 by 4-7% and speed-at-capacity falls by 15-25% relative to normal conditions. Similarly to  
76 Rakha et al. (2008), the study concluded that jam density is not affected by adverse weather  
77 conditions. Agarwal et al. (2005) observed that depending on the intensity of precipitation  
78 average speed falls by 2-7% and capacity falls by 5-17%. The effect of snow is much  
79 stronger with speed falling by 10-15% and capacity falling from 13 to 27% depending on the  
80 intensity. While sub-zero temperatures have also been found to have an effect, it only appears  
81 for temperatures below -20°C and reduces capacity by about 10%. Using data from Spanish  
82 motorways Camacho et al. (2010) analysed the effect of temperature, rain and snow,  
83 visibility, wind speed and thickness of snow cover on traffic parameters in free-flow traffic.  
84 He demonstrated that depending on the intensity of rainfall speed falls by 5.5-7 km/h. In the  
85 case of snow the drop in speed is greater and reaches 9-13.7 km/h. He also observed the  
86 effect of wind speed ( $> 8$  m/s) on average vehicle speed. In the case of visibility the drop in  
87 speed was only observed for visibility of several hundred meters.

88 Similarly to adverse weather conditions, some drivers may feel less confident in the  
89 night-time when there is no natural light or at dusk or dawn when the contrast between a  
90 fairly bright sky and dark road makes it more difficult for drivers' eyesight to adjust (Evans et  
91 al., 2020; Konstantopoulos et al., 2010; Leibowitz et al., 1998). Drivers respond by slowing  
92 down and maintaining longer headways. When driver behaviour changes, it affects both the  
93 traffic flow characteristics, such as average speed or average headways, and the parameters  
94 related to highway performance, such as free-flow speed and capacity (Bella et al., 2014;  
95 Kempa, 2008; Robbins & Fotios, 2021). In the night-time, the risk of accidents also increases  
96 (Jafari Anarkooli & Hadji Hosseinlou, 2016; Jamroz et al., 2019; Leibowitz et al., 1998). A  
97 combination of adverse weather conditions and the night-time can have an even more  
98 negative impact on both traffic conditions and road safety (Awadallah, 2007; Gallen et al.,  
99 2015; Higgins et al., 2009). Using data from continuous traffic measurement stations on  
100 German motorways Brilon and Ponzlet (1996) demonstrated that speeds drop on wet  
101 roadways by 9.5-12 km/h with capacity falling by 350-500 veh/h, depending on the number  
102 of lanes. Under normal conditions during night-time speed is observed to change mainly in a  
103 partly constrained operation (5-7 km/h). Night-time precipitation, however, has a stronger  
104 effect on free-flow speed (falling by about 10 km/h). In addition, during night-time compared  
105 with daytime capacity falls by 200 to nearly 400 veh/h regardless of the weather or condition

106 of the road surface. Oh et al. (2002) analysed the effects of weather conditions on speed using  
107 regression models of speed-flow and flow-occupancy relationships. He found that when  
108 weather conditions change, function slope falls and the speed-volume curve is shifted  
109 downwards. He demonstrated that during rain and snow both daytime and night-time average  
110 speed falls by several per cent (2-7%).

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

134 To summarise the research presented in the literature it can be concluded that:

- 135 • rainfall reduces speed by 2-10% and capacity by 5-30%,
- 136 • snowfall reduces speed by 2-19% and capacity by 3-28%,

- 137 • in the night-time there is a slight reduction in the speed and capacity (3-5%) but  
138 the effect increases when it is also raining,
- 139 • on wet road surfaces both the speed and the capacity are reduced by approx. 10%,  
140 • limited visibility causes speed reduction by 4-9% and capacity reduction by 10-  
141 12%,
- 142 • the effect of temperature is noticeable under severe frost conditions (<-20°C)  
143 when the speed and capacity are reduced by 5-8% and 7-10% respectively,
- 144 • strong wind (>8 m/s) affects the average speed but the effect was not determined  
145 in the studies.

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

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

164 The introduction (section 1) presents an overview of the literature on the effects of  
165 weather and time of day on traffic flow characteristics. Section 2 gives a description of data  
166 and data methodology. Section 3 presents the results of the research and Section 4 presents

167 possible application of the study results in the MOP-DZ method. Section 5 discusses the  
168 study results. Conclusions are given in section 6.

## 169 **2. Methodology**

### 170 *a. Data Collection*

171 The study is based on data stretching over 36 months (2014-2017) from the continuous  
172 traffic measurement station located at the S6 expressway in Gdansk, Poland (54°25' N,  
173 18°29' E). The road section at which the station is located is a dual carriageway with four  
174 lanes running within the conurbation. Annual average daily traffic is 74,000 vehicles per day  
175 and up to 100,000 vehicles per day in peak periods. As a result, the full scope of traffic  
176 conditions can be analysed, both for free-flow and congested conditions.

177 The data (Romanowska & Kustra, 2021) was sourced from a continuous traffic  
178 measurement station which operates in a double induction loop. The device registers the time  
179 a vehicle appears on the detector and its instantaneous speed. It identifies the type of vehicle  
180 and lane the vehicle is using. Structured Query Language (SQL) was used for data processing  
181 and initial analysis. The data processing was divided into the following stages:

- 182 1. Raw traffic data that were provided by the national road authority (General Director for  
183 National Roads and Motorways) in the text file format were imported to the database on  
184 the installed SQL server.
- 185 2. The data were verified in terms of empty rows, zero values, vehicle speeds beyond the  
186 expected range, unusual vehicle lengths. The problem of zeros or unusual values  
187 concerned approx. 2% of registered vehicles and had marginal impact on the number of  
188 registered vehicles – the records were excluded from further processing.
- 189 3. Individual vehicle headways were calculated for each record.
- 190 4. The data were aggregated to five minute intervals which provided information on traffic  
191 volume, space-mean speed, share of heavy goods vehicles and average headways. The  
192 traffic volume was calculated into flow rate using passenger car equivalents (Olszewski  
193 et al., 2020). Traffic density was determined from the fundamental relationship of traffic  
194 flow (May, 1990). Free flow speed was estimated in each interval as speed of passenger  
195 cars maintaining headways at least 7 seconds behind and 4 seconds in front of adjacent

196 vehicles under low volume and low density traffic conditions (<1000 veh/h/lane and <10  
197 veh/km/lane).

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

206 Over the analysed period more than 26,000 hours of the survey consisted of 9,100 night-  
207 time hours and 1,760 and 1,540 hours of dawn and dusk respectively; 1,800 hours of rain,  
208 including 640 hours of intensive rain; 50 hours of snow or hail (Table 2). The latest two  
209 occurred only in winter season. The road surface was wet for a total of 4,160 hours and  
210 slippery for 1,360 hours. Visibility below 200 m occurred for a total of 326 hours, including  
211 180 hours of visibility below 50 m. Sub-zero temperatures were recorded for nearly 1,160  
212 hours (the lowest observed temperature was -14°C), including 63 hours of temperatures <-  
213 10°C. For 160 hours the temperatures were above 30°C but not exceeding 40°C. Intensity of  
214 precipitation was the highest in winter season, while the lowest during summer (Table 1).

215

216 Table 1. Precipitation intensity (%) in particular seasons

| Season | Number of intervals | Intensity of precipitation (%) |                         |                    |
|--------|---------------------|--------------------------------|-------------------------|--------------------|
|        |                     | Mean                           | 95% confidence interval | Standard deviation |
| Spring | 77257               | 6.95                           | (6.81, 7.01)            | 18.53              |
| Summer | 78522               | 3.86                           | (3.75, 3.96)            | 15.44              |
| Autumn | 78361               | 7.14                           | (7.01, 7.26)            | 18.16              |
| Winter | 60891               | 20.82                          | (20.63, 21.02)          | 24.24              |

217

218 Table 2. Average speed of cars in relation to the type of precipitation



| Type of precipitation | Number of intervals | Average speed of passenger cars [km/h] |                    |        |                     |
|-----------------------|---------------------|--|--------------------|--------|---------------------|
|                       |                     | Mean                                   | Standard deviation | Median | Interquartile range |
| none                  | 249721              | 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                |

219 *b. Analyses*

220 A one-way analysis of variance (ANOVA) method (Sawyer, 2009) was used to examine  
221 the relationship between traffic flow parameters and weather and time of day related factors.  
222 Two dependent variables were examined: free-flow speed and average speed. Independent  
223 variables included: time of day, precipitation, road surface conditions and visibility. In order  
224 to use the method, first its assumptions were tested against the data. With all other conditions  
225 met, Welch’s correction had to be applied to take account of the failure to meet the condition  
226 of equality of variances. The question was: is there a statistically significant (at 5%  
227 significance level) relationship between speed and particular weather conditions and time of  
228 day. For the significant relationships, post-hoc analyses, using Tukey and Dunnett tests, were  
229 additionally conducted in order to investigate whether the differences are significant between  
230 classes of particular conditions (i.e. light and heavy rain) and between particular classes and  
231 conditions referred to as “normal” (determined based on Tukey test results; including  
232 daylight, no precipitation, dry road surface, visibility > 200 m). The effect on speed was  
233 additionally tested at different levels of traffic density in order to investigate, whether it is  
234 significant in the whole range of observed densities. For this purpose, t-tests were used  
235 between group independent samples.

236 To quantify the effect of weather conditions and time of day the data were assigned to  
237 nine scenarios (Table 3). The baseline scenario is scenario 1 which features no rain or snow,  
238 dry road surface and horizontal visibility in excess of 200 m. Scenarios of night-time do not

239 include low visibility conditions, because such weather conditions were not observed in the  
 240 data. Scenarios of dawn and dusk cover only good weather conditions because of relatively  
 241 small samples if adverse weather conditions are additionally included. Table 4 shows the  
 242 frequency distribution of the particular conditions in the scenarios.

243

244 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                       |

245

246 Table 4. Percentage distribution of the frequency of the particular weather conditions and  
 247 time of day depending on the scenario

| Variable               | Value     | Scenario |    |    |    |    |    |    |    |    |
|------------------------|-----------|----------|----|----|----|----|----|----|----|----|
|                        |           | 1        | 2  | 3  | 4  | 5  | 6  | 7  | 8  | 9  |
| Traffic volume (veh/h) | <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<br>[m]             | ≤200       | 0   | 100 | 0   | 0   | 0   | 0   | 6   | 0   | 0   |
|                               | >200       | 100 | 0   | 100 | 100 | 100 | 100 | 94  | 100 | 100 |
| Precipitation<br>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<br>pavement<br>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<br>[°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  |

248

249 For each scenario, the averaged values of free flow speed  $v_{sw}$ , average speed  $v$ , average  
250 headway  $h$  and traffic volume  $q$  were calculated. For each parameter  $p$  a relative percentage  
251 change in the average parameter value  $dp_i$  was determined compared with the baseline  
252 scenario (Eq. 1).

$$dp_i = \frac{p_i - p_0}{p_0} \cdot 100\% \quad (1)$$

253 where:  $dp_i$  – percentage change of the average parameter value  $p$  in scenario  $i$  compared with  
254 the baseline scenario [%],  $p_0$  – average value of parameter  $p$  in the baseline scenario [-],  $p_i$  –  
255 average value of parameter  $p$  in scenario  $i$  [-].

256 Next, the speed-density model developed by Romanowska (2019) was calibrated in order  
257 to estimate values of free-flow speed, speed-at-capacity and capacity in each scenario (Eq. 2).

$$v = \frac{v_{sw}}{\left(1 + \left(\frac{k}{k_{opt}}\right)^n\right)^{1-\frac{1}{n}}} \quad (2)$$

258 where:  $v$  – average speed [km/h],  $v_{sw}$  – free flow speed [km/h],  $k$  – traffic density [veh/km],  
259  $k_{opt}$  – density-at-capacity [veh/km],  $n$  – shape parameter.

### 260 3. Results

261 Results (Table 5, Table 6) show a significant effect of both time of day (F(3,  
262 271908)=2353.5,  $p<.001$ ), precipitation (F(5, 271908)=575.9,  $p<.001$ ), road surface  
263 condition (F(3, 271908)= 1192,0,  $p<.001$ ) and visibility (F(3, 271908)= 12.9,  $p<.001$ ) on the  
264 average speed. Similarly, a significant effect was also noticed in the case of free flow speed  
265 as a dependent variable: time of day (F(3,107616)=369.6,  $p<.001$ ), precipitation (F(5,  
266 107616)=122.7,  $p<.001$ ), road surface condition (F(3, 107616)= 759,  $p<.001$ ) and visibility  
267 (F(3, 107616)= 22.9,  $p<.001$ ). For the analysed interactions a post hoc Tukey test results  
268 showed that at .05 significance level both the average speed and the free flow speed differed  
269 significantly (at  $p<.05$ ) in each group within time of day, precipitation and road surface  
270 condition. The average speed did not differed significantly between <50 m and 50÷200 m  
271 visibilities, but significant differences were found between both classes and higher visibility

12

272 ranges. The free-flow speed differed significantly between all visibility levels below 500 m.  
 273 Based on the Tukey test results, control group for a post hoc Dunnett test was determined as:  
 274 daytime, no precipitation, dry road surface, visibility above 200 m (referred to as “normal  
 275 conditions”). The results at .05 significance level showed a significant difference between the  
 276 average speed or the free flow speed for any weather conditions and time of day deviating  
 277 from those pointed above ( $p < .05$ ).

278

279 Table 5. Results of one-way ANOVA: average speed of passenger cars

|                           | Sum of Squares | df     | Mean Square | F      | Sig.  |
|---------------------------|----------------|--------|-------------|--------|-------|
| Time of day               | 661562         | 3      | 220521      | 2353.5 | <.001 |
| Type of precipitation     | 269803         | 5      | 53961       | 575.9  | <.001 |
| Condition of road surface | 335064         | 3      | 111688      | 1192.0 | <.001 |
| Visibility                | 3615           | 3      | 1205        | 12.9   | <.001 |
| Error                     | 25477995       | 271908 | 94          |        |       |

280

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

|                           | Sum of Squares | df     | Mean Square | F     | Sig.  |
|---------------------------|----------------|--------|-------------|-------|-------|
| Time of day               | 91440          | 3      | 30480       | 369.6 | <.001 |
| Type of precipitation     | 50580          | 5      | 10116       | 122.7 | <.001 |
| Condition of road surface | 187770         | 3      | 62590       | 759.0 | <.001 |
| Visibility                | 5654           | 3      | 1885        | 22.9  | <.001 |
| Error                     | 8874843        | 107616 | 82          |       |       |

282

283 The average speed in normal and adverse (here referred to as conditions other than  
284 normal) conditions was compared for different density levels. The analyses showed that for  
285 the density range of 0÷50 pc/km the average speed differs significantly in adverse and normal  
286 conditions,  $p < .05$  (Table 7). The effect was not found significant in the case of higher  
287 densities.

288

289 Table 7. T-test results (p-values) for the average speed in normal and adverse conditions  
290 grouped by traffic density

| Average speed $v$ [km/h] | Traffic density $k$ [pc/km] |                |                |                |                |            |             |
|--------------------------|-----------------------------|----------------|----------------|----------------|----------------|------------|-------------|
|                          | 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        |
| <i>p-value</i>           | <i>&lt;.05</i>              | <i>&lt;.05</i> | <i>&lt;.05</i> | <i>&lt;.05</i> | <i>&lt;.05</i> | <i>.51</i> | <i>n.d.</i> |

291

292 Table 8 presents the average values of the average speed, free flow speed, headway and  
293 traffic volume in each scenario and the relative change of each parameter ( $dp_i$  – Eq. 1) from  
294 the baseline scenario (scenario 1). We can see that when the weather deteriorates both in  
295 daytime and night-time, the average vehicle speed and the free flow speed fall and average  
296 headways increase. During the daytime, the occurrence of rain causes a fall in the average  
297 speed by 6%, in the free flow speed by 4%, and an increase in headways by about 9%; in case  
298 of snowfall the average speed decreases by 11%, free flow speed decreases by 12%, and  
299 headways increase by approximately 27%. When visibility is poor, the average speed do not  
300 change and the free-flow speed falls by approximately 2%; average headways increase by  
301 about 10%. In the night-time the average speed is higher than during daytime but free-flow  
302 speed decrease by 2%. When the rain occurs in the night-time, the average speed falls by 2%,  
303 free-flow speed decreases by 7% compared to normal weather conditions during daytime;  
304 snowfall at the night-time causes 14% reduction in the average speed and 17% reduction in  
305 the free-flow speed compared to the daytime and normal weather conditions. Average  
306 headways increase by several times in the night-time and the very high deviations from the

307 average can be noticed. This can be probably explained by low traffic volumes during the  
 308 night-time ( $q = 529 \div 842$  P/h). In the dawn and dusk, when the amount of the natural light  
 309 is limited, the observed average speed is higher than in the baseline, but the free-flow speed  
 310 falls by 3.5% and 0.7% respectively.

311

312 Table 8. Changes in selected parameters of vehicle flow in the scenarios of weather and  
 313 time of day

| Scenario <i>i</i> | Average speed<br>$v$ [km/h] |             |              | Free flow speed<br>$v_{sw}$ [km/h] |             |                 | Average headways<br>$h$ [sec.] |             |              | Traffic<br>volume<br>$q$ [veh/h] |
|-------------------|-----------------------------|-------------|--------------|------------------------------------|-------------|-----------------|--------------------------------|-------------|--------------|----------------------------------|
|                   | $v_i$                       | $dv_i$      | Std.<br>dev. | $v_{sw_i}$                         | $dv_{sw_i}$ | <i>st. dev.</i> | $h_{t_i}$                      | $dh_{t_i}$  | Std.<br>dev. | $q_i$                            |
| <b>1*</b>         | <b>100.9</b>                | <b>n.a.</b> | <b>11.3</b>  | <b>110.7</b>                       | <b>n.a.</b> | <b>13.6</b>     | <b>3.4</b>                     | <b>n.a.</b> | <b>9.8</b>   | <b>2254</b>                      |
| 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                             |

314 \* baseline scenario; n.a. = not applicable

315

316 In order to estimate the capacity under different weather and time of day conditions, the  
 317 speed-density model (Eq. 2) was used. For each scenario the model was fitted to the data and  
 318 calibrated. A constant value of density at capacity was adopted ( $k_{opt} = 52$  pc/km). The other  
 319 parameters were estimated using the model. The results are given in Table 9. As we can see,  
 320 as the weather deteriorates, the free flow speed and speed-at-capacity fall as does capacity.

321 Under conditions of limited visibility the reduction in capacity is about 3% with rain causing  
 322 a drop in capacity by about 5% in the daytime and by 8% in the night-time. Snowfall causes a  
 323 drop in capacity by about 9% in daytime and 19% in the night-time (all compared to the  
 324 baseline scenario 1). During dawn and dusk both the free flow speed and capacity are lower  
 325 by approximately 3%.

326

327 Table 9. Free flow speed, capacity and speed-at-capacity estimated with Eq. 2 and the  
 328 relative change in relation to the baseline scenarios

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

329 \* baseline scenario; n.a. = not applicable

330

### 331 4. Application of the results

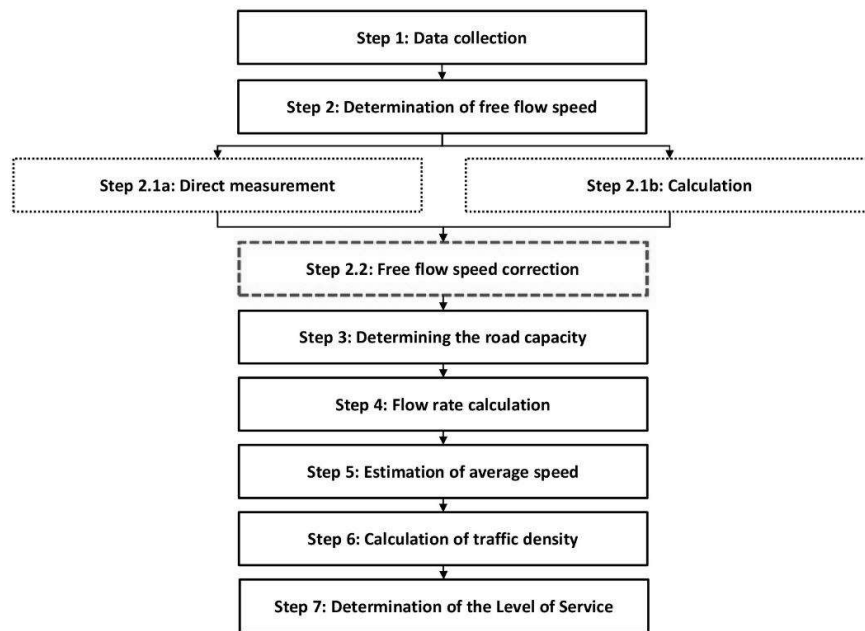
332 The results presented in the study may contribute to the MOP-DZ method. Fig. 1 presents  
 333 the proposed extension of the MOP-DZ procedure for assessing traffic conditions, that allows  
 334 to consider weather and time of day characteristics. Just as with the HCM method  
 335 (Transportation Research Board, 2016), an additional step is proposed to correct free-flow  
 336 speed for adverse conditions. In such case, in the step 2.2 the estimated or measured (in  
 337 normal conditions) value of the free flow speed is adjusted by multiplying it by a correction  
 338 coefficient (Eq. 3).

$$v'_{sw} = v_{sw} * w_A \quad (3)$$



339 where:  $v'_{sw}$  – free-flow speed under adverse weather and/or lighting [km/h],  $w_A$  – correction  
 340 coefficient (Table 10).

341 In the speed-flow relationships developed for the MOP-DZ method, the average speed  
 342 and capacity depend on the free-flow speed. As a result, adjusted free-flow speed will have  
 343 an indirect effect on the new values of both parameters. If traffic volume remains unchanged,  
 344 reduced speed will increase traffic density which is the basis for determining the level of  
 345 service. This way the effect of weather and time of day will be included in the entire traffic  
 346 conditions assessment procedure thanks to the adjusted free-flow speed.  
 347



348

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

351

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

354

355 Table 10. The proposed coefficients of weather and time of day related free flow speed  
 356 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                  |

357

## 358 5. Discussion

359 The paper presents the results of the study on the effects of adverse weather conditions  
360 and time of day on traffic flow characteristics and highway performance. Using statistical  
361 methods it was proved, that both rain and snow, road surface condition, visibility and time of  
362 day (in reference to the amount of natural light) significantly affect the average speed in the  
363 wide range of traffic densities (0÷50 veh/km). The strength of the effect was estimated by  
364 calculating the means of particular parameters and comparing them in nine scenarios  
365 depending on weather conditions and time of day. A speed-density model was also used in  
366 order to support the analyses and estimate road capacity and the corresponding speed. It was  
367 proved that when compared to normal weather conditions: under conditions of daytime, rain  
368 and wet road surface the average speed is reduced by 4-6% (depending on traffic density) and  
369 the capacity is reduced by 5%; when it is snowing and the road surface is wet or slippery  
370 during the daytime the average speed is reduced by 9-12% and the capacity is reduced by 9%;  
371 under conditions of limited visibility with no precipitation in the daytime, the average speed  
372 is reduced by 0-4% and the capacity is reduced by 3%. In the night-time and good weather  
373 conditions the speed and capacity are lower than in the daytime, by 2-4% and 4%

374 respectively. When it additionally rains at night and the road surface is wet speed is reduced  
 375 by up to 9% and capacity is reduced by 8%. During snowfall speed decreases by 14-19% and  
 376 capacity is reduced by 19% when compared to the baseline normal weather conditions during  
 377 daytime. In the night-time, the effect of weather conditions is stronger when compared to the  
 378 daytime. It needs to be noticed that the road at study site is illuminated, which may affect the  
 379 magnitude of the effect in the night-time. The effect of dawn and dusk was also evaluated  
 380 showing that limited natural lighting also affect both speed and capacity that are reduced by  
 381 1-5% and 4-5% respectively.

382 In the case of rain and snow the results of the study are consistent with the research  
 383 results in the literature (Agarwal et al., 2005; Brilon & Ponzlet, 1996; Camacho et al., 2010;  
 384 Chen et al., 2019; Heikoop & Henkens, 2016; Lam et al., 2013; Oh et al., 2002; Rakha et al.,  
 385 2008; Transportation Research Board, 2016) – the speed and capacity reductions fit within  
 386 the range defined in the works reviewed (Table 11). There is a difference in the case of  
 387 limited visibility with speed and capacity falling less in this work compared with the  
 388 literature studies. However, in the case of reduced visibility and night-time there are only  
 389 single studies that cover these conditions, some present the reductions of speed and capacity  
 390 in original units making any comparisons of the values difficult.

391

392 Table 11. Percentage reduction of speed and capacity in adverse weather and natural  
 393 lighting conditions - comparison between study results and the literature

| Literature            | Rain |        | Snow   |        | Reduced visibility |   | Night-time, good weather |   |
|-----------------------|------|--------|--------|--------|--------------------|---|--------------------------|---|
|                       | 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% |                    |   |                          |   |

|                          |      |        |       |       |      |        |      |      |
|--------------------------|------|--------|-------|-------|------|--------|------|------|
| HCM (2016)               |      | 10-12% | 6-19% | 3-28% | 4-9% | 10-12% |      |      |
| Heikoop & Henkens (2016) |      | 5-10%  |       |       |      |        |      | 3-5% |
| This study               | 4-6% | 5%     | 9-12% | 9%    | 0-4% | 3%     | 2-4% | 4%   |

394

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

404 The most important limitation of the study is lack of representativeness for different road  
405 and traffic conditions (i.e. roads with different design, speed limits, location, heavy vehicles  
406 share). This limitation is strongly related to the poor traffic data availability in Poland. At the  
407 time of doing the research, there were only seven permanent traffic counting stations which  
408 could provide eligible data (with regard to the data format and measured traffic parameters).  
409 Most of them were located on low-volume roads (annual average daily traffic below 25  
410 thous. vehicles per day). If higher traffic volumes are not observed on a site, the research  
411 cannot cover for the entire range of traffic conditions (both free-flow traffic and congested  
412 traffic) and the impact of weather and time of day can only be studied for free-flow traffic  
413 and low densities. In the case of the studied site, high traffic volumes reaching up to 100,000  
414 veh/24h were observed and weather and time of day impact could be studied for the full  
415 range of traffic conditions. Another issue related to data availability is that weather  
416 measurement station need to be located in the proximity of a site and this condition was also  
417 not met in most cases. These conclusions may be important for road authorities in the context  
418 of choosing locations for installing permanent traffic counting stations in the road network.

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

## 422 **6. Conclusion**

423 The specific goals of the study presented in the paper included identification of factors  
424 related to weather and time of day that have an effect on traffic conditions, analysis and  
425 quantification of the effects of these factors on the particular traffic parameters and  
426 application of the results to the MOP-DZ method. The way to achieve these goals and the  
427 obtained results are presented in the paper. This lets us assume that the goals set in the  
428 introduction were achieved. In order to summarize the findings, it can be stated that:

- 429 • There is a statistically significant effect of weather and time of day on both traffic  
430 flow characteristics and parameters related to highway performance. The effect is  
431 observed at a wide range of traffic densities.
- 432 • Depending on the time of day and weather conditions, average speed may  
433 decrease by even 19% and capacity by even 18% when compared to normal  
434 weather conditions in the daytime. The higher the intensity of weather  
435 phenomena, the higher is the effect it has on traffic flow.
- 436 • There is a group of conditions that were not covered by the study, i.e. extremely  
437 low or high temperatures. These kind of conditions did not occur at the study area  
438 within study period and due to low frequencies may be difficult to study based on  
439 data from Polish sites.
- 440 • The research results may contribute to the new Polish highway capacity manual  
441 MOP–DZ. The extended traffic conditions assessment procedure was proposed  
442 that allows for including adverse weather and time of day in the analysis.
- 443 • The research provides coefficients of the weather and time of day related free flow  
444 speed adjustment factors for the studied site that are based on the long-term  
445 measurements covering entire range of traffic conditions (from free-flow to  
446 congested). Determination of such coefficients for different types of roads may  
447 notably increase the scope of possible applications of the MOP-DZ method.

- 448           • Efforts to develop tools to account for adverse weather and time of day in  
449            assessing traffic conditions require further scientific support.

450

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453 RID 2B project which is designed to develop methods for estimating capacity and assessing  
454 traffic conditions on Poland's dual carriageways. The outcome of the project is the Polish  
455 Highway Capacity Manual, with procedures for assessing traffic conditions and identifying  
456 the capacity of rural and agglomeration roads (Olszewski et al., 2020).

457 *Data Availability Statement.*

458       The data presented in this study are openly available in MostWiedzy repository at  
459 <https://doi.org/10.34808/8xkq-7714> (Romanowska & Kustra, 2021).

460

461

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