

ASSESSING THE IMPACT OF WEATHER ON TRAFFIC INTENSITY

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ABSTRACT

The investigation of weather effects on traffic intensity is important from a road safety point of view, because traffic intensity is noted as the first and primary determinant of traffic safety. Next to traffic safety, weather conditions affect other predominant traffic variables, namely traffic demand and traffic flow. Therefore the main objective of this study is the identification and comparison of weather effects on traffic intensity at different site locations. To assess the impact of weather conditions on traffic intensity, the upstream and downstream traffic of four traffic count locations are considered. The traffic intensity data originate from minute data coming from single inductive loop detectors, collected by the Flemish Traffic Control Center. Data concerning weather events were recorded by the Royal Meteorological Institute of Belgium. The main modeling philosophy envisaged in this study to identify and quantify weather effects is the linear regression approach. Most appealing result of this study for policy makers, is the heterogeneity of the weather effects between different traffic count locations, and the homogeneity of the weather effects on upstream and downstream traffic at a certain location. The results also indicated that snowfall, rainfall and wind speed have a clear diminishing effect on traffic intensity, while maximum temperature significantly increases traffic intensity. Further generalizations of the findings are possible by studying weather effects on local roads and by shifting the scope towards travel behavior. Simultaneously modeling of weather conditions, traffic intensity rates, collision risk and activity travel behavior is certainly a key challenge for further research.

1 BACKGROUND

Increased fuel consumption, economic losses due to traffic delays, and higher crash counts are just some of the policy issues that are often related with adverse weather events. Day-to-day weather conditions such as fog and precipitation can reduce travel demand, for instance when drivers postpone or cancel discretionary trips or activities, but can also have an increasing effect when travel modes are shifted towards motorized vehicles (1). It has long been recognized that road accidents are the consequence of an interaction between behavioral, technological and environmental factors. The absence of any one of these factors could prevent an accident from occurring (2,3). At the network level, adverse weather events increase the uncertainty in system performance, resulting for instance in a network capacity reduction ranging from 10 to 20% in heavy rain (4). Figure 1 displays the interplay between weather conditions, road safety, traffic speed and traffic flow.

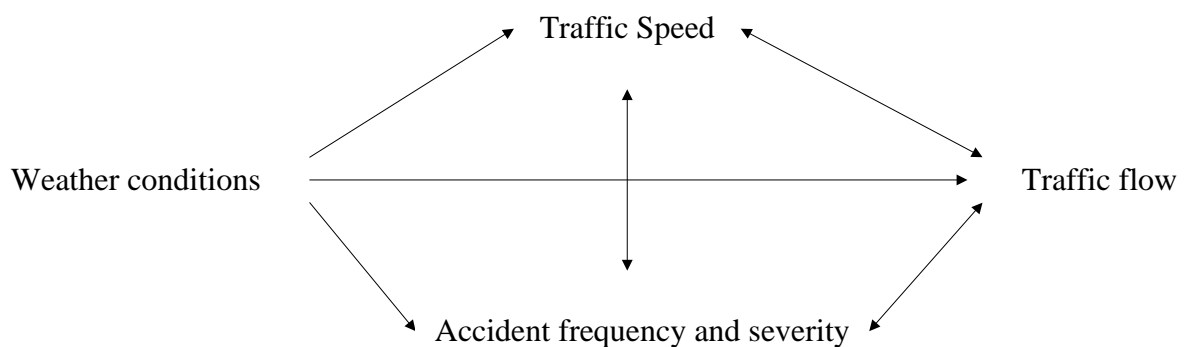


FIGURE 1 Relationship between weather, road safety, traffic speed and traffic flow (5).

The rise of advanced traffic management systems (ATMS) provides transportation agencies the opportunity to implement traffic management strategies that minimize weather-related side-effects on traffic operations (6). A solid understanding of the impact of various weather conditions on roadside crash frequency and traffic flow serves a good knowledge base for developing these strategies (7,8).

The investigation of weather effects on traffic intensity is important from a road safety point of view, because traffic intensity, commonly referred to as exposure in traffic safety literature, is noted as the first and primary determinant of traffic safety (9). Injury accidents are nearly proportionally related with exposure (10), evidencing the strong relationship between traffic flow conditions and the likelihood of traffic accidents (11).

Apart from the relevance to road safety, the assessment of weather impacts on traffic intensity is also of significant value to travel demand modelers. Khattak and De Palma (12) reported that adverse weather conditions cause important changes in travel decisions: mode changes, changes in departure time and diversions to alternate route, being the most prevalent behavioral adaptations. When multi-agent modeling is considered to be the most appropriate travel demand modeling framework, a deeper understanding of the impact of weather conditions on travel behavior can improve the simulation of the behavioral principles and mechanisms underlying the multi-agent modeling framework. Note that such multi-agent models represent individuals and households as agents that have plans and agendas, and that learn about the environment (and thus about weather conditions) and the consequences of their behavior (13).

Summarizing, weather events affect three predominant traffic variables: traffic demand, traffic safety and the traffic flow relationship (14). Therefore the main objective of this study is the identification and comparison of weather effects on traffic intensity at different site locations. The remainder of this introductory section will address the specific weather variables that influence the above mentioned traffic variables. Section 2 will address the data description, and the employed methodology is described in Section 3. Finally, this paper will present the results and elaborate on their transportation relevant interpretation. Some general conclusions will be formulated and avenues for further research indicated.

1.1 Influence of Weather on Traffic Safety

Most literature on effects of weather on traffic safety focuses on the impact of rain and wet conditions, and snow and slippery road surfaces on collision risk, collision frequency and injury and fatality rates (15). Precipitation in the form of rainfall and snowfall generally results in an increasing number of accidents (16). Andrey et al. (17,18) report an augmentation of collision risk from 50 up to 100 percent during precipitation. Notwithstanding, the effect of precipitation is multifaceted: larger effects of rainfall are observed in autumn than during spring and an increased impact is noted after dry spells (19). Withal, divergent results are found when discussing snowfall. In Denmark, for example, snowfall has a tempering effect on the number of injury accidents (10), while Zhang et al. (20) found a significantly increased risk under snow conditions. Snowstorms on rural Iowa Interstates dramatically exacerbate crash rates by 13 times during moderate-intensity snowstorms and by 25 times in high-intensity snowstorms (14). The severity of snowstorms is influenced by the duration, intensity and wind speed (21).

Next to precipitation, also other weather conditions are relevant in investigating traffic safety, for instance high winds, fog and sunshine radiation and duration, the latter having a negative impact on traffic safety (22,23). The fact that relationships between weather events and traffic safety is not always clear hampers the formulation of general research findings, especially when it is acknowledged that certain human maneuvers before a collision may have a significant impact on whether weather is a contributing factor (24).

1.2 Influence of Weather on Traffic Flows and Traffic Demand

Weather can affect traffic volumes in different ways, including diversions of trips to other modes or other paths, or even cancellations of trips (14). Studies indicate for instance that heavy rain accompanies a smaller exposure for cyclists, while mild winters and warm summers have a stimulating effect on bicycle use (25). Temperature, rain, snow and wind all influence transit ridership in a logical way: good weather increases ridership, while bad weather has a diminishing effect (26). There have been several research studies on the effect of rain, snow and fog. It has become clear that adverse weather can significantly reduce not only capacity but also operating speeds on roadways, resulting in congestion and productivity loss. (27,28).

When the effect of precipitation on traffic operations is explored, almost all studies indicate that speed and capacity are negatively influenced (29,30). The capacity reductions range from 4 to 30%, while speed is reduced by 3 to 15% (7,14). The reductions tend to be larger for precipitation amounts (16). Other factors worthwhile investigating are visibility (fog), wind speed, sunshine hours and temperature, the latter two associated with slight increases in traffic activity (31).

2 DATA

To assess the impact of weather conditions on traffic intensity, the upstream and downstream traffic of four traffic count locations (represented by blue squares in Figure 2) were considered. Weather conditions on this traffic count locations were approximated by the events recorded in the most nearby weather stations (represented by yellow circles in Figure 2).

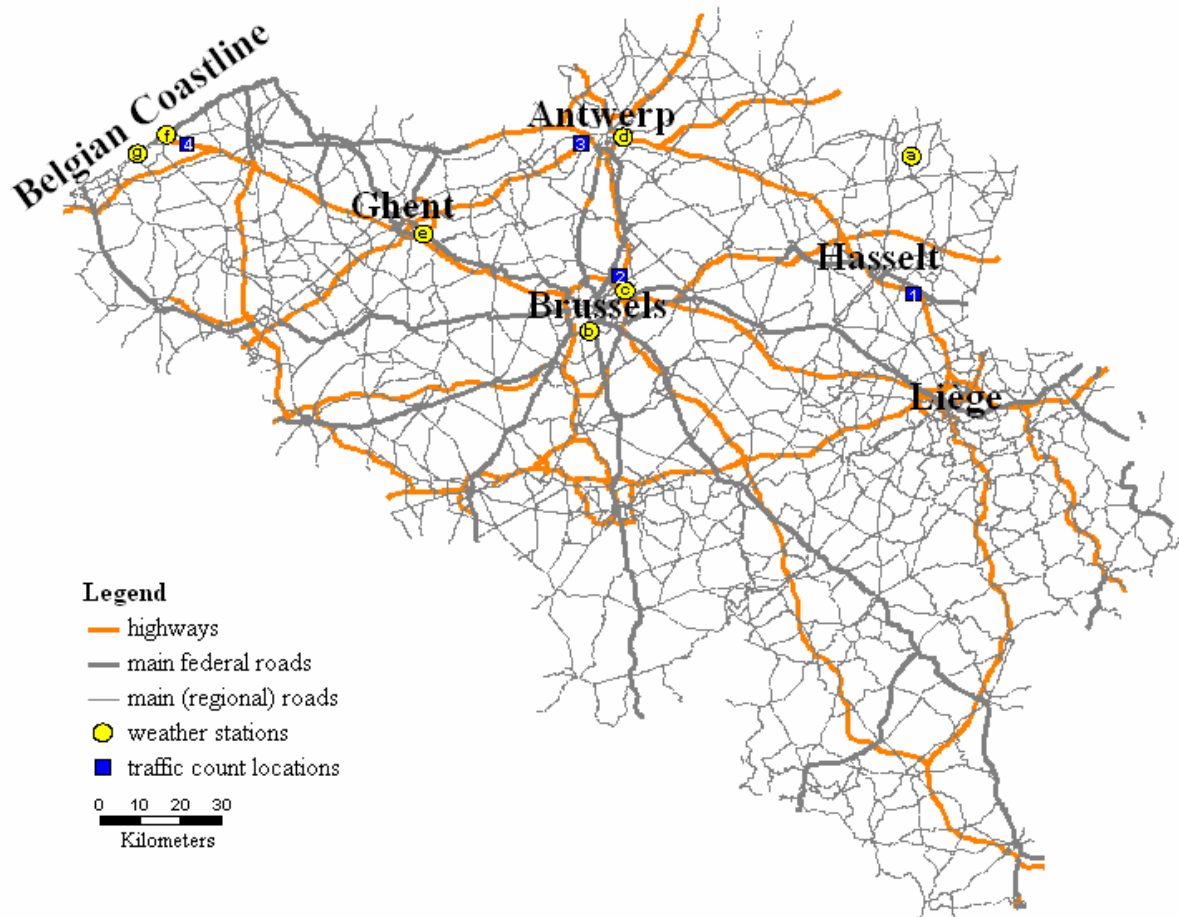


FIGURE 2 Representation of the traffic count locations and weather stations under study.

2.1 Traffic Intensity Data

The traffic intensity data originate from minute data coming from single inductive loop detectors, collected in 2003 and 2004 by the Vlaams Verkeerscentrum (Flemish Traffic Control Center). As indicated earlier, upstream and downstream traffic intensity of four traffic count locations (displayed in Figure 2) are investigated in this study. The first location is a traffic count location measuring upstream and downstream traffic from Hasselt, a provincial city with a population of about 70 000 people. The second traffic count location is situated on one of the entranceways of Brussels, and thus excessively used by commuters. The third location under study is located on one of the entranceways of Antwerp, and the last location is based on one of the accesses to the Belgian seashore, and thus typified by leisure traffic.

Minutely, the loop detectors generate four statistics: the number of cars driven by, the number of trucks driven by, the occupancy of the detector and the time-mean speed of all vehicles (32). Adding up the number of cars and trucks for all lanes in a specific direction, yields a total traffic count for each minute. The aggregation on a daily basis of these minute data then results in daily traffic intensity measures.

2.2 Weather Data

Data concerning weather events were recorded by the Royal Meteorological Institute (KMI). Weather events on the relevant traffic count locations were approximated by the events recorded in the most nearby (available) weather stations. The following variables were recorded and considered for the analysis: daily precipitation, conditions of hail, snow and thunderstorm, average and maximum cloudiness, minimum, maximum and average temperature, maximum hourly wind speed, sunshine duration and duration of diminished visibility (due to fog).

2.3 Temporal Effects

Next to the different weather conditions that will be used to (partially) explain variability in traffic counts, it is also necessary to incorporate temporal effects. Cools et al. (33) indicated that day-of-week effects and holiday effects are contributing significantly in unraveling differences in daily traffic intensity. The following holidays occasions were considered: Christmas vacation, spring half-term, Easter vacation, Labor Day, Ascension Day, Whit Monday, vacation of the construction industry (three weeks, starting the second Monday of July), Our Blessed Lady Ascension, fall break (including All Saints' Day and All Soul's Day), and finally Remembrance Day. Next to this defined holiday list, the summer holidays (excluding days regarded in the holidays) were defined as a second holiday category. Next to these holiday effects, also day-of-week effects were taken into account in this study.

3 METHODOLOGY

To get prior understanding of the effects of weather on traffic intensity, some basic descriptive statistics will be provided. For the continuous variables the Spearman correlation between traffic intensity and the weather variables will be calculated. Unlike the traditional Pearson product-moment correlation, the Spearman correlation is a non-parametrical technique, robust for deviations of normality. Technically, the Spearman correlation is computed in the following way:

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)},$$

where d_i is the difference between each rank of corresponding pair of values, and where n equals the number of observations (34). For the categorical variables the group means are provided.

The main modeling philosophy envisaged in this study is the classical linear regression approach. This modeling approach tries to explain a dependent variable with the help of other covariates. Formally, the multiple linear regression model can be represented by the following equation (35):

$$Y_i = \beta_0 + \beta_1 X_{i,1} + \beta_2 X_{i,2} + \dots + \beta_{p-1} X_{i,p-1} + \varepsilon_i,$$

where Y_i is the i -th observation of the dependent variable, $X_{i,1}, X_{i,2}, \dots, X_{i,p-1}$ the corresponding observations of the explanatory variables, $\beta_0, \beta_1, \beta_2, \dots, \beta_{p-1}$ the parameters, which are fixed, but unknown, and where ε_i is the unknown random error. Estimates for the unknown parameters can be obtained by classical estimation techniques. When all underlying assumptions of the classical linear regression model are satisfied, then estimators for the parameters are BLUE (Best Linear Unbiased Estimators). Otherwise some remedial measures, like transformations, are required (35).

Since autocorrelation is present between traffic counts, ignorance of this problem would increase the risk of erroneous model interpretation. To accommodate for this risk, Newey-West heteroskedasticity and autocorrelation consistent (HAC) covariance matrices are used for the estimation process. Note that the use of HAC covariance matrices does not change the point estimates of the parameters, but only the estimated standard errors (36).

To ensure that all parameter estimates are stable and reliable, the models should be checked for multicollinearity. In the presence of multicollinearity (high correlation between explanatory variables) the effect of a single explanatory variable can not be isolated, as the regression coefficients are quite uninformative and confidence intervals very wide. Thus, the individual estimated coefficients should be interpreted with caution, since only imprecise information can be derived from the regression coefficients (37). In this study, Variance Inflation Factors (VIF) are used as a diagnostic tool to assess the level of multicollinearity. These VIF factors measure how much the variances of the estimated regression coefficients are inflated as compared to when the predictor variables are not linearly related. The largest VIF-value among all predictor variables is used as an indicator of the severity of multicollinearity. A maximum VIF-value exceeding 10 indicates that the stability and reliability of the parameter estimates are questionable (35).

4 RESULTS

4.1 Descriptive Analysis

Inspection of the Spearman correlations between traffic intensity and the continuous explanatory variables (Table 1) reveals that weather conditions appear to have divergent impacts on traffic intensity according to the traffic count location under study. In contrast to these differences between locations, weather impacts are quite homogeneous when downstream and upstream (denoted as ‘down’ and ‘up’) intensities of the same locations are compared. The highest correlations with traffic intensity are found for maximum temperature and maximum cloudiness and amount of precipitation. Most appealing are the considerably larger correlations of weather conditions at the seashore traffic count location.

When the group means of the different categorical weather indicators (Table 2) are compared, ambiguity is found in the interpretation of hail and thunderstorm effects: on some locations traffic intensity increases in the presence of these weather conditions, on other locations it decreases. In contrast, the impact of snow is univocal: snow decreases the traffic intensity on all traffic count locations.

TABLE 1 Spearman Correlations Between Traffic Intensity and Continuous Predictors

Weather condition	Down Hasselt	Up Hasselt	Down Brussels	Up Brussels	Down Antwerp	Up Antwerp	Down Seashore	Up Seashore
Cloudiness (Mean)	-0.15	-0.18	-0.09	-0.10	-0.10	-0.20	-0.37	-0.33
Cloudiness (Max)	-0.17	-0.20	-0.09	-0.10	-0.11	-0.19	-0.34	-0.29
Precipitation	-0.10	-0.13	-0.14	-0.12	-0.13	-0.19	-0.26	-0.25
Temperature (Mean)	0.17	0.23	0.02	0.04	0.04	0.13	0.56	0.52
Temperature (Max)	0.20	0.27	0.05	0.07	0.07	0.17	0.61	0.57
Temperature (Min)	0.13	0.18	-0.01	0.01	0.02	0.06	0.45	0.42
Wind speed (Max)	-0.06	-0.09	-0.11	-0.09	-0.08	-0.11	-0.26	-0.25
Sunshine duration	0.15	0.20	0.11	0.13	0.09	0.23	0.45	0.42
Visibility (<500m)	-0.04	-0.03	-0.02	-0.04	-0.03	-0.11	-0.02	0.00
Visibility (<200m)	-0.03	-0.02	-0.04	-0.06	-0.01	-0.06	0.02	0.03

TABLE 2 Group Means of Traffic Intensity by Presence of Weather Condition

Presence weather condition		Down Hasselt	Up Hasselt	Down Brussels	Up Brussels	Down Antwerp	Up Antwerp	Down Seashore	Up Seashore
Hail	Yes	18642	18273	57068	53830	51759	48665	11519	11707
	No	18173	17984	53382	50439	52260	46934	12902	13210
Thunderstorm	Yes	18791	18457	52225	49770	48350	44737	13339	13756
	No	18135	17953	53588	50599	52467	47103	12859	13161
Snow	Yes	17045	16765	51313	47745	50737	44548	11080	11188
	No	18267	18078	53615	50699	52319	47091	12933	13245

4.2 Linear Regression Modeling

Estimates for the variables that were used in the final linear regression models, together with the corresponding standard errors and values for the significance tests, are displayed in Table 3. The VIF-factors assure that the parameter estimates are stable and reliable. The temporal effects (day-of-week effects and holiday effects) are omitted from this table, since this paper focuses mainly on assessing the impact of weather conditions on traffic intensity and because Cools et al. (33) already reported on the impact of temporal effects.

Investigation of Table 3 reveals that the impact of weather conditions is clearly more homogeneous between upstream and downstream traffic at a certain location, than between different locations. This heterogeneity between different locations can be (partially) explained by the underlying travel motives of the road users using these highways. Highways typified by their leisure traffic can be affected more easily than highways that are excessively used by commuters. Underlying reason is the relative high invariability of work activities compared to the flexibility of adapting leisure activities.

The estimated weather effects are consistent with international literature addressing the impact of weather conditions on traffic intensity (38): rainfall, snowfall and wind speed significantly decrease traffic volumes, while temperature has a noticeable increasing effect.

TABLE 3 Parameter Estimates (HAC) for Weather Effects

Weather condition	Estimate	Standard Error	T-value	P-value	VIF
<i>1. Location-specific model for downstream traffic in Hasselt</i>					
Precipitation	-3.0	1.3	-2.33	0.020	1.22
Cloudiness (Mean)	-57.3	28.6	-2.01	0.045	1.30
Temperature (Max)	84.2	8.1	10.40	<0.001	1.33
Wind speed (Max)	-55.0	23.1	-2.38	0.018	1.15
<i>2. Location-specific model for upstream traffic in Hasselt</i>					
Precipitation	-2.9	1.3	-2.20	0.028	1.22
Cloudiness (Mean)	-55.4	26.7	-2.08	0.038	1.30
Temperature (Max)	84.0	7.4	11.42	<0.001	1.33
Wind speed (Max)	-66.2	21.3	-3.11	0.002	1.15
<i>3. Location-specific model for downstream traffic in Brussels</i>					
Hail	2085.7	804.2	2.59	0.010	1.06
Snowfall	-2358.4	1077.0	-2.19	0.029	1.19
Precipitation	-13.4	3.9	-3.43	0.001	1.27
Temperature (Max)	106.7	26.9	3.96	<0.001	1.97
Wind speed (Max)	-170.1	59.7	-2.85	0.005	1.20
Sunshine duration	1.5	0.7	-2.08	0.038	1.68
<i>4. Location-specific model for upstream traffic in Brussels</i>					
Hail	2020.1	805.9	2.51	0.012	1.06
Snowfall	-3049.8	1025.2	-2.97	0.003	1.19
Precipitation	-11.6	3.5	-3.35	0.001	1.27
Temperature (Max)	93.3	25.8	3.62	<0.001	1.97
Wind speed (Max)	-126.4	54.6	-2.32	0.021	1.20
Sunshine duration	1.9	0.7	2.78	0.006	1.68
<i>5. Location-specific model for downstream traffic in Antwerp</i>					
Precipitation	-16.8	4.1	-4.08	<0.001	1.15
Temperature (Max)	161.3	30.4	5.31	<0.001	1.19
Wind speed (Max)	-202.9	70.9	-2.86	0.004	1.13
<i>6. Location-specific model for upstream traffic in Antwerp</i>					
Hail	3927.1	1144.3	3.43	0.001	1.07
Precipitation	-24.3	6.4	-3.78	<0.001	1.22
Temperature (Max)	140.0	45.6	3.07	0.002	1.79
Wind speed (Max)	-332.9	104.3	-3.19	0.002	1.19
Sunshine duration	4.7	1.2	3.85	<0.001	1.68
Visibility (<500m, Dum)	-3266.9	822.3	-3.97	<0.001	1.08
<i>7. Location-specific model for downstream traffic in seashore area</i>					
Precipitation (Dum)	-437.2	89.1	-4.91	<0.001	1.50
Cloudiness (Mean)	-152.1	21.2	-7.19	<0.001	1.40
Temperature (Max)	129.4	7.3	17.67	<0.001	1.26
Wind speed (Max)	-49.3	13.9	-3.56	<0.001	1.22
Visibility (<200m, Dum)	615.0	278.6	2.21	0.028	1.03
<i>8. Location-specific model for upstream traffic in seashore area</i>					
Precipitation (Dum)	-308.1	105.9	-2.91	0.004	1.53
Cloudiness (Mean)	-217.2	26.5	-8.20	<0.001	1.41
Temperature (Max)	148.5	8.7	17.01	<0.001	1.26
Wind speed (Max)	-62.3	17.0	-3.66	<0.001	1.24
Visibility (<200m, Dum)	642.5	220.3	2.92	0.004	1.05

Next to the location-specific models, also an overall model was estimated to quantify the influence of weather conditions on traffic intensity. To accommodate for differences in magnitude of the traffic volume between the eight traffic count locations (e.g. magnitude of the traffic volume of downstream traffic in Brussels are almost three times the magnitude of the traffic volume of downstream traffic in the seashore area), the percentage of the traffic volumes relative to their location specific mean were modeled instead of the absolute numbers. The significance tests for the parameters estimated in this model are shown in Table 4. The significant interaction term between location and temperature confirms the finding that weather conditions have a differential impact according to type of location. Estimates for the weather conditions of this overall model are provided in Table 5. Similar conclusions can be drawn from these estimates for this overall model as compared to the location specific models: temperature, sunshine duration and hail have an increasing effect on traffic flows, while precipitation, snowfall, cloudiness and wind speed reduce traffic intensity.

TABLE 4 Significance Tests for Overall Traffic Intensity Model

Explanatory Variable	Numerator DF	F-value	P-value
(1) Day-of-week	6	82.79	<0.001
(2) Holiday	2	4.63	0.010
(3) Location	7	14.96	<0.001
(4) Interaction effect (1) & (3)	42	37.77	<0.001
(5) Interaction effect (2) & (3)	14	7.40	<0.001
(6) Hail	1	19.79	<0.001
(7) Snowfall	1	21.24	<0.001
(8) Precipitation	1	47.35	<0.001
(9) Cloudiness (Mean)	1	9.68	0.002
(10) Temperature (Max)	1	103.34	<0.001
(11) Wind speed (Max)	1	54.73	<0.001
(12) Sunshine duration	1	5.84	0.016
(13) Interaction effect (3) & (10)	7	14.00	<0.001

TABLE 5 Parameter estimates for Overall Traffic Intensity Model

Weather condition	Estimate	Weather condition	Estimate
<i>General estimates</i>			
Hail	3.385	Cloudiness	-0.427
Snowfall	-4.154	Wind speed (Max)	-0.425
Precipitation	-0.023	Sunshine duration	0.003
<i>Location specific estimates</i>			
Temperature (Downstream Hasselt)	0.340	Temperature (Downstream Antwerp)	0.182
Temperature (Upstream Hasselt)	0.346	Temperature (Upstream Antwerp)	0.399
Temperature (Downstream Brussels)	0.154	Temperature (Downstream Seashore)	0.983
Temperature (Upstream Brussels)	0.172	Temperature (Upstream Seashore)	1.131

4.3 Results Summary

A final overview of the estimated relationships between weather conditions and traffic intensity is provided in Table 6. Recapitulating one can conclude that precipitation, cloudiness and wind speed have a clear decreasing effect on traffic intensity, while temperature, sunshine duration and hail increase traffic volumes. At least some evidence is provided that hail, unlike snowfall and rain, has an increasing effect on traffic intensity. The decreasing effect of snowfall and rain can be accounted for by the diminished capacity of the highway network, caused by a reduction in speed, while the increasing effect of hail can be attributed to the shift towards car as travel mode due to the unfavorable weather conditions. The influence of reduced visibility due to fog and cloudiness remains inconclusive.

TABLE 6 Summary of Relationships between Weather Conditions and Traffic Intensity

Weather conditions	Down Hasselt	Up Hasselt	Down Brussels	Up Brussels	Down Antwerp	Up Antwerp	Down Seashore	Up Seashore	Overall model
Hail	0	0	+	+	0	+	0	0	+
Snowfall	0	0	-	-	0	0	0	0	-
Precipitation	-	-	-	-	-	-	-	-	-
Temperature (Max)	+	+	+	+	+	+	+	+	+
Wind speed (Max)	-	-	-	-	-	-	-	-	-
Sunshine duration	0	0	+	+	0	+	0	0	+
Reduced visibility	0	0	0	0	0	-	+	+	0
Cloudiness (Mean)	-	-	0	0	0	0	-	-	-
R-square	0.79	0.69	0.86	0.85	0.75	0.51	0.65	0.67	0.70

5 CONCLUSIONS AND FURTHER RESEARCH

In this study the impact of various weather conditions on traffic intensity was investigated. Most appealing result for policy makers, is the heterogeneity of the weather effects between different traffic count locations, and the homogeneity of the weather effects on upstream and downstream traffic at a certain location. Consequentially, traffic management strategies that minimize weather-related side-effects on traffic operations must adopt an approach that takes into account local weather effects.

The results in this paper also indicated that precipitation, cloudiness, and wind speed have a clear diminishing effect on traffic intensity, while maximum temperature, sunshine duration and hail significantly increase the traffic intensity. These significant impacts of weather conditions on traffic intensity underline the necessity of incorporating weather conditions in future traffic safety research not only in a direct way, but also indirectly by modeling the effects of weather conditions via traffic intensity. Because of the previously discussed inherent relationship between traffic intensity, weather and traffic safety, the results indicate that preferably location specific traffic safety policies need to be developed next to a global country-wide strategy.

Further generalizations of the findings are possible by studying weather effects on local roads and by shifting the scope towards travel behavior. Linking travel behavior research, traffic flow modeling, and safety research by simultaneously modeling of weather conditions, traffic

intensity rates, collision risk and activity travel behavior is certainly a key challenge for further research.

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