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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 to 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. 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.

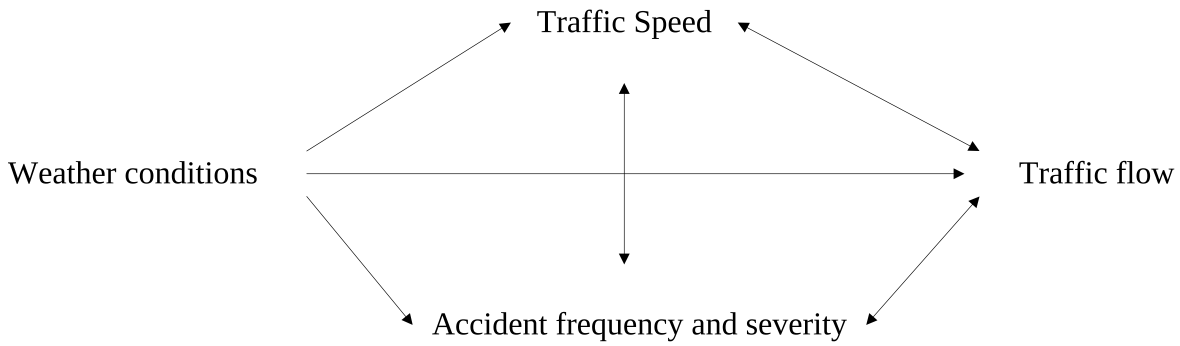

FIGURE 1 Relationship between weather, road safety, traffic speed and traffic flow (*5*).

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.

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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).

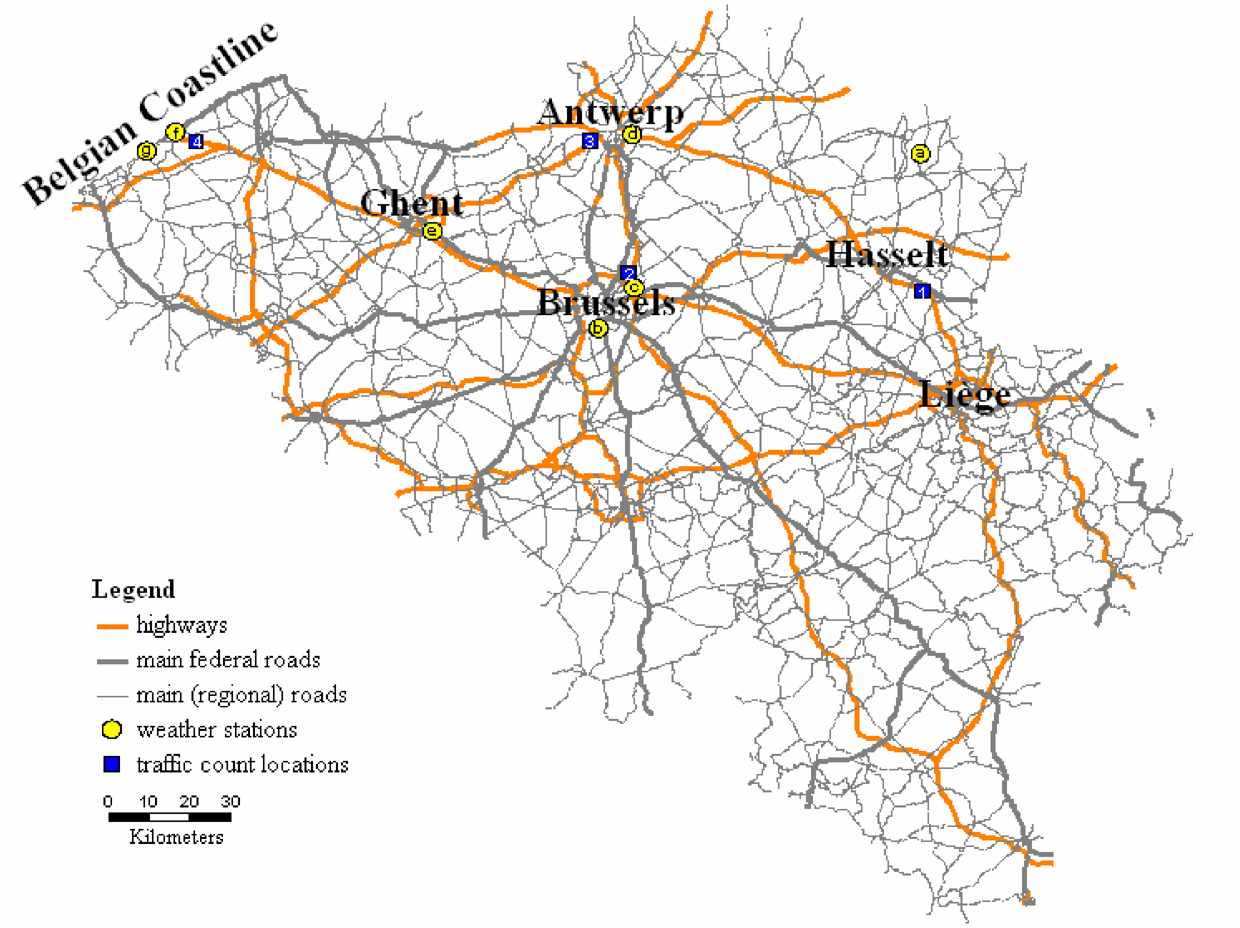

FIGURE 2 Representation of the traffic count locations and weather stations under study.

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. Recall that the Spearman correlation is computed in the following way:

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

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*):

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

where Y_i is the i-th observation of the dependent variable, $X_{i,1}, X_{i,2},..., X_{i,p-1}$ the corresponding observations of the explanatory variables, $\beta_0, \beta_1, \beta_2..., \beta_{p-1}$ 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 underestimation of standard errors for the parameter estimates. To accommodate for this risk, significance levels of 0.025 were used as a conservative alternative of the commonly used 0.050.

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.

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

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 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 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 (*36*): rainfall, snowfall and wind speed significantly decrease traffic volumes, while temperature has a noticeable increasing effect.

Next to the location-specific models, also an overall model was estimated to quantify the influence of weather conditions on traffic intensity. Significance tests for the parameters estimated in this model are shown in Table 4. The significant interaction terms between location and precipitation, temperature and wind speed confirm 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. The impact of cloudiness requires attention, as ambiguous influences are recorded for this weather condition: on one location it increases upstream and downstream traffic flow, while on the remaining locations it reduces traffic.

TABLE 3 Parameter Estimates for Weather Effects

Weather condition	Estimate	Standard Error	T-value	P-value
1. Location-specific model for downstream traffic in Hasselt				
Snowfall	-532.5	233.3	-2.28	0.023
Precipitation	-3.7	1.3	-2.85	0.005
Temperature (Max)	82.4	7.5	10.95	<0.001
Wind speed (Max)	-58.5	24.2	-2.41	0.016
2. Location-specific model for upstream traffic in Hasselt				
Precipitation	-3.5	1.2	-2.86	0.004
Temperature (Max)	88.3	6.6	13.40	<0.001
Wind speed (Max)	-74.8	22.7	-3.29	0.001
3. Location-specific model for downstream traffic in Brussels				
Hail	2147.2	915.1	2.35	0.019
Snowfall	-2267.5	734.9	-3.09	0.002
Precipitation	-15.3	3.8	-4.06	<0.001
Temperature (Max)	135.8	23.5	5.77	<0.001
Wind speed (Max)	-188.4	59.3	-3.18	0.002
4. Location-specific model for upstream traffic in Brussels				
Snowfall	-3008.5	705.2	-4.27	<0.001
Precipitation	-12.4	3.6	-3.43	0.001
Temperature (Max)	92.3	26.8	3.45	0.001
Sunshine duration	2.2	0.7	3.02	0.003
5. Location-specific model for downstream traffic in Antwerp				
Snowfall	-2264.3	936.3	-2.42	0.016
Precipitation	-17.0	4.5	-3.80	<0.001
Temperature (Max)	138.8	27.7	5.01	<0.001
Wind speed (Max)	-199.4	83.6	-2.39	0.017
6. Location-specific model for upstream traffic in Antwerp				
Hail	4383.6	1576.4	2.78	0.006
Snowfall	-2841.5	1230.4	-2.31	0.021
Precipitation	-24.6	5.9	-4.13	<0.001
Temperature (Max)	111.0	43.5	2.55	0.011
Wind speed (Max)	-309.7	109.8	-2.82	0.005
Sunshine duration	4.9	1.2	4.07	<0.001
Visibility (<500m)	-12.1	4.5	-2.71	0.007
7. Location-specific model for downstream traffic in seashore area				
Precipitation (Dum)	-437.0	92.2	-4.74	<0.001
Cloudiness (Mean)	-151.9	22.4	-6.77	<0.001
Temperature (Max)	130.2	6.5	19.91	<0.001
Wind speed (Max)	-48.5	13.9	-3.50	0.001
Visibility (<200m)	4.6	1.4	3.43	0.001
8. Location-specific model for upstream traffic in seashore area				
Precipitation (Dum)	-309.8	106.5	-2.91	0.004
Cloudiness (Mean)	-216.2	25.8	-8.39	<0.001
Temperature (Max)	149.1	7.5	19.85	<0.001
Wind speed (Max)	-62.4	16.0	-3.90	0.001
Visibility (<200m)	4.1	1.6	2.61	0.009

TABLE 4 Significance Tests for Overall Traffic Intensity Model

Explanatory Variable	DF	F-value	P-value
(1) Day-of-week	6	304.30	<0.001
(2) Holiday	2	190.46	<0.001
(3) Interaction effect (1) & (2)	12	15.03	<0.001
(4) Location	7	730.20	<0.001
(5) Precipitation	1	31.90	<0.001
(6) Cloudiness (Mean)	1	20.76	<0.001
(7) Temperature (Max)	1	129.57	<0.001
(8) Wind speed (Max)	1	23.69	<0.001
(9) Snowfall	1	15.65	<0.001
(10) Hail	1	18.59	<0.001
(11) Visibility (<200m)	1	6.85	0.009
(12) Interaction effect (4) & (5)	7	2.81	0.006
(13) Interaction effect (4) & (6)	7	2.42	0.018
(14) Interaction effect (4) & (7)	7	3.68	0.001

TABLE 5 Parameter estimates for Overall Traffic Intensity Model

Weather condition	Estimate	Weather condition	Estimate
General estimates			
Hail	1916.6	Wind speed (Max)	-137.9
Snowfall	-1354.1	Visibility (<500m)	-5.0
Location specific estimates			
Precipitation (Downstream Hasselt)	-5.1	Cloudiness (Downstream Antwerp)	-192.4
Precipitation (Upstream Hasselt)	-7.4	Cloudiness (Upstream Antwerp)	-449.5
Precipitation (Downstream Brussels)	-11.1	Cloudiness (Downstream Seashore)	-178.2
Precipitation (Upstream Brussels)	-8.4	Cloudiness (Upstream Seashore)	-200.0
Precipitation (Downstream Antwerp)	-14.8	Temperature (Downstream Hasselt)	81.0
Precipitation (Upstream Antwerp)	-26.7	Temperature (Upstream Hasselt)	86.1
Precipitation (Downstream Seashore)	-2.6	Temperature (Downstream Brussels)	79.2
Precipitation (Upstream Seashore)	-3.2	Temperature (Upstream Brussels)	89.3
Cloudiness (Downstream Hasselt)	40.5	Temperature (Downstream Antwerp)	118.6
Cloudiness (Upstream Hasselt)	65.1	Temperature (Upstream Antwerp)	212.0
Cloudiness (Downstream Brussels)	-237.7	Temperature (Downstream Seashore)	162.0
Cloudiness (Upstream Brussels)	-227.6	Temperature (Upstream Seashore)	177.7

4.3 Results Summary

Table 6 provides a brief overview of the estimated relationships between weather conditions and traffic intensity. Recapitulating one can conclude that snowfall, rainfall and wind speed have a clear decreasing effect on traffic intensity, while temperature increases traffic volume. At least some evidence is provided that sunshine durations and hail also have an increasing effect. The influence or 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	0	+
Snowfall	-	0	-	-	-	-	0	0	-
Precipitation	-	-	-	-	-	-	-	-	-
Temperature (Max)	+	+	+	+	+	+	+	+	+
Wind speed (Max)	-	-	-	0	-	-	-	-	-
Sunshine duration	0	0	0	+	0	+	0	0	0
Reduced visibility	0	0	0	0	0	-	+	+	-
Cloudiness (Mean)	0	0	0	0	0	0	-	-	?
R-square	0.79	0.69	0.86	0.85	0.75	0.52	0.65	0.67	0.93

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 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. 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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