The dual role of weather forecasts on changes in activity-travel behavior

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Abstract

A deeper understanding of how human activity-travel behavior is affected by various weather conditions is essential for both policy makers and traffic managers. To unravel the ambiguity in findings reported in the literature, the main objective of this paper is to obtain an accurate assessment of how weather forecasts trigger changes in Flemish activity-travel behavior. To this end, data were collected by means of a stated adaptation experiment, which was administered both on the Internet and via traditional paper-and-pencil questionnaires. To address the main research question of this paper, two statistical techniques were adopted. The first technique is the computation of Pearson chi-square independence tests. The second approach is the estimation of a GEE-MNL-model. The results from both techniques underscore the dual role of weather forecasts on changes in activity-travel behavior. On the one hand, the results clearly illustrate the significant effect of forecasted weather; the likelihood of changes in activity-travel behavior significantly depends on the weather forecasted. On the other hand, different methods of acquiring weather information (exposure, media source, or perceived reliability) do not impact the probability of behavioral adaptations. This duality may be partially attributable to the discrepancy that exists between weather forecasts and true traffic and roadway conditions. Therefore, the implementation of a road weather information system that is directly linked to the weather forecasts is recommended.

Keywords: dual role, weather forecast, activity-travel behavior

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1. Introduction

As discussed by Cools et al. (2010a), a deeper understanding of how various weather conditions affect human activity-travel behavior is essential for policy makers and traffic managers. It provides insights that might help alleviate negative effects of the road network that are often associated with adverse weather. A multitude of changes in activity-travel behavior can be triggered by different weather conditions. These include (*i*) trip cancelations (elimination of the activity from the activity agenda) (e.g., Madre et al. (2007), Wilton et al. (2011), Kim et al. (2010)); (*ii*) changes in the location where the activity is performed (e.g., Hagens (2005), Koetse and Rietveld (2009)); (*iii*) changes in the timing of the activity or the corresponding trip (e.g., Chung et al. (2005), Maze et al. (2006)); (*iv*) changes in the transport mode (e.g., Akar and Clifton (2009), Guo et al. (2007), Kuhnimhof et al. (2010)); and (*v*) changes in the route for the trip (e.g., Lam et al. (2008), Sumalee et al. (2011)).

In addition to actual weather conditions, weather reports and forecasts (information on current and future weather conditions) influence travel behavior. In this regard, it is worth consulting reports regarding traffic information provision, for instance, advanced traveler information systems (ATIS). These systems have the potential to increase the efficiency of transportation systems as well as their usefulness to individual travelers (Wang et al., 2009). The provision of traffic information can induce a similar range of changes in activity-travel behavior as the responses to different weather conditions (e.g., Rodríguez et al. (2011), Casas and Kwan (2007), Son et al. (2011), Son et al. (2011), Tseng et al. (2012)). Nonetheless, the impact of the provided information should not be overestimated, as the perceived value of acquiring information is often limited (Chorus et al., 2006b; Lyons, 2006). The success of information provision is contingent on the characteristics of the information itself, such as its quality, accuracy, usefulness, timeliness, cost, and communication mode (Zhang and Levinson, 2008). Moreover, socio-economic and contextual variables significantly influence the impact of the information provision (Joh et al., 2011; Chorus et al., 2006a; Ben-Elia et al., 2008).

The published literature regarding the impact of information (weather forecasts) on activity-travel behavior is ambiguous. Khattak and de Palma (1997) reported that forecasted weather information did not significantly affect the probabilities of adapting mode and departure time. In contrast, the studies by Hagens (2005), Sihvola (2009), and Kilpeläinen and Summala (2007) demonstrated significant impacts. Thus, a fundamental question is whether forecasted weather information triggers changes in activity-travel behavior. This paper focuses on the impact of weather forecasts on activity-travel behavior.

An important issue in the cross-national transferability of findings is the fact that activity-travel behavior varies across spatial and temporal contexts (Khattak and de Palma, 1997). Consequently, published results and discussions are not always applicable to specific regional context(s), such as Flanders, the northern part of Belgium, which is the regional context considered in the present paper. Take, for example, the results of de Palma and Rochat (1999) and Kilpeläinen and Summala (2007), which were obtained in Switzerland and Finland, respectively. Adverse weather conditions such as snow and hail occur more frequently in these countries than in Flanders. It can be assumed that because of habituation, people in these countries experience these weather phenomena differently and, therefore, adapt their activity-travel behaviors differently.

In addition, most weather-related studies make no differentiation based on the particular activity. This is a shortcoming in the literature because people are less likely to change their regular commuting behavior due to weather forecasts than they are to alter trips for non-work/school-related purposes. Moreover, the majority of these studies only focus on a subset of weather types, mostly rain and snow.

Given the above considerations, the main objective of this paper is to accurately assess how weather forecasts change Flemish activity-travel behaviors, taking into account the full context of behavioral adaptations, activity purposes and weather types to clarify the ambiguities in published results and to verify the transferability of the results of previous studies to the context of Flanders.

2. Data

2.1. Stated adaptation experiment

Data regarding the impact of weather forecasts on Flemish activity-travel behaviors were collected by means of a stated adaptation experiment, which was carried out in March and April of 2009. Respondents, who were recruited by means of convenience sampling, were asked to indicate if and how they would change their activity-travel behaviors considering various experimental attribute profiles corresponding to different weather conditions.

In total, 586 respondents completed the stated adaptation survey, which was administered both on the Internet (86.7%) and via traditional paper-and-pencil questionnaires (13.3%). As documented by Cools et al. (2010a), this dual-mode administration was chosen to remedy the sample bias that can be introduced when only internet-based data collection is conducted. In total, 90 behavioral adaptations in response to different weather conditions were queried; the frequencies of 5 travel behavior changes in response to 6 weather conditions were determined, and this was repeated for 3 types of trips. These 90 behavioral adaptations were assayed for both actual weather and forecast weather conditions, resulting in a final total of 180 potential behavioral adjustments.

The three types of trips considered correspond to the categories of most commonly performed trips according to the Flemish travel behavior survey (Cools et al., 2010b): commuting (work/school), shopping and leisure trips. For each of these types of trips, the respondents indicated how often (never, in 1-25% of the cases, in 26-50% of the cases, or in more than 50% of the cases) they would make a certain change in activity-travel behavior. The following changes in travel behavior were queried: (i) changing the transport mode, (ii) changing the timing of the trip (postponing or advancing the trip to a later/earlier time on the same day), (iii) changing the location of the activity (work/school, shopping or leisure), (iv) canceling the trip altogether, and (v) changing the route of the trip.

In accordance with Cools et al. (2010c), who identified the weather conditions that had significant impacts on the daily traffic intensities of Belgian highways, the following weather conditions were considered: cold temperatures (defined as temperatures below freezing (0°C, 32°F), abbreviated as 'cold'), warm temperatures (defined as temperatures above 28°C (82.4°F), abbreviated as 'warm'), snow/freezing rain, heavy rain/thunderstorms (abbreviated as 'rain'), fog and storms/heavy wind. The question format is illustrated in Figure 1.

In addition to the stated adaptation questions, the survey also explicitly queried information concerning the average exposure of respondents to weather forecasts in their daily lives. In particular, the frequency of this exposure was ascertained as well as the media source(s) involved and the perceived reliabilities of the weather conditions forecast (measured on a 10-point scale). Furthermore, the survey collected information concerning the

Do you <u>postpone</u> or <u>advance</u> your work/school-related trip to a later/earlier moment the same day due to any of the following <u>forecasted</u> weather conditions?

*Mark the answer that corresponds mostly to your situation. Only **one** answer is possible for **each forecasted weather condition**.*

	No, never	Yes, occasionally (<25% of the cases)	Yes, sometimes (<50% of the cases)	Yes, usually (>50% of the cases)
Cold temperature	O	O	O	O
Snow/freezing rain	O	O	O	O
Heavy rain/thunderstorm	O	O	O	O
Fog	O	O	O	O
Warm temperature	O	O	O	O
Storm/heavy wind	O	O	O	O

Figure 1: Stated adaptation question concerning postponing/advancing work/school-related trips

respondents' socio-demographic profiles and queried different activities and trip-related attributes. Although a convenience sample was used for this study, the respondents' age, gender and marital state were used as the basis for calculating weights that guarantee optimal correspondence between the survey sample composition and the Flemish population. The weights were calculated by matching the relative frequencies of the three-way cross-tabulations of the sample with those of the total population. Because all the cross-tabulations were known, such that the multivariate correlations were taking into account, the weights ensured that the relative frequencies of the weighted sample corresponded exactly to those of the total population. It is worth noting that all the tables and figures presented in this paper are based on the weighted results.

2.2. Data description

Recall that the main goal of this paper is to investigate how weather forecasts trigger changes in Flemish activity-travel behavior. The study was based on the following five specific research questions:

1. Do changes in activity-travel behavior depend on forecasted weather conditions?
2. Do changes in activity-travel behavior depend on degrees of exposure to weather forecasts?
3. Do changes in activity-travel behavior depend on the media sources of weather forecasts?
4. Do changes in activity-travel behavior depend on the perceived reliability of weather forecasts?
5. Which factors trigger changes in activity-travel behavior in the presence of adverse weather conditions, and, in particular, what roles are played by the weather-forecast characteristics (exposure, media source, perceived reliability) considered herein?

The dependent variables required to tackle the first four questions are the changes in activity-travel behavior in response to the forecasted weather conditions. As mentioned in the previous subsection, 90 behavioral changes were queried with regard to weather forecasts. These changes in activity-travel behavior are displayed in Figure 2. Note that the original response categories (never, in 1-25% of the cases, in 26-50% of the cases, or in more than 50% of the cases) have been dichotomized to increase the interpretability of the graph as well as for the methodological reasons discussed in Section 3. From Figure 2, one can clearly see that travelers do adapt their activity-travel patterns in response to forecasted weather conditions. This is especially the case for trips with non-mandatory activity-trip purposes (i.e., shopping and leisure trips). The forecasted weather condition that appears to trigger the most changes is snow, while cold weather had the least impact. The remarkably strong behavioral reactions to forecasted storms are in line with the published literature regarding actual weather effects (e.g., Cools et al. (2010a) and Cools et al. (2010c)).

To address the fifth research question, we have investigated behavioral changes in response to 'actual' weather forecasts, taking into account the different features of weather forecasts. Because respondents could indicate multiple changes in activity-travel behavior simultaneously, it was necessary

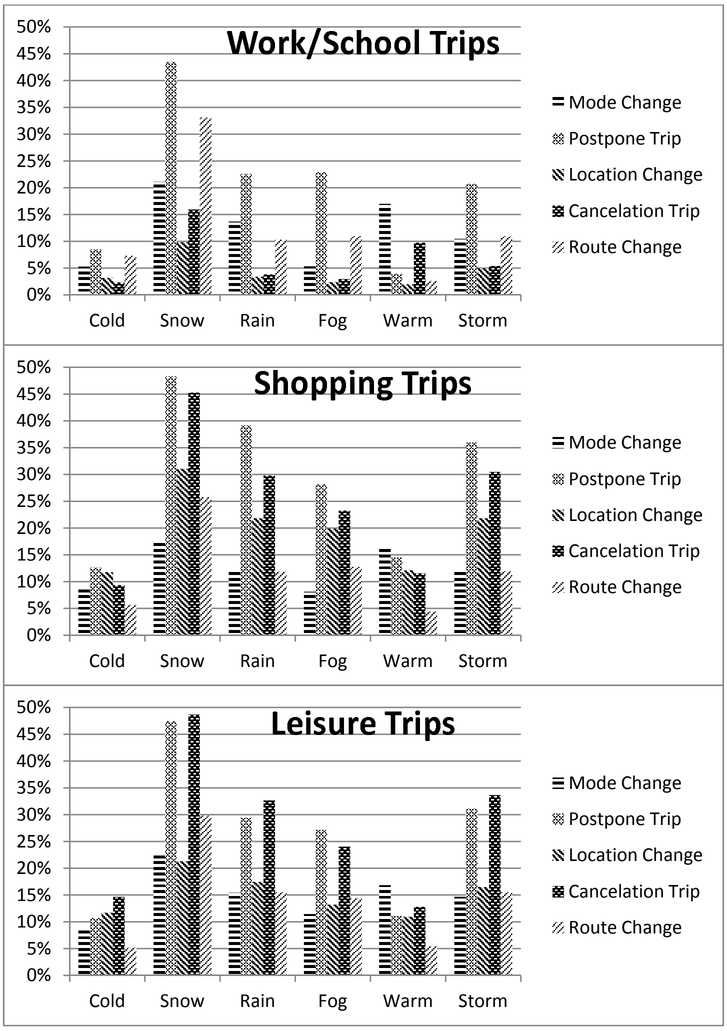

Figure 2: Behavioral changes in response to different forecasted weather conditions

to prioritize the different changes. The main selection criterion behind this prioritization is the overall impact of a given change on the activity-travel behavior from an environmental perspective. Note that a comparable approach was followed by Cools et al. (2011) in their assessment of the impact of road pricing on changes in activity-travel behavior. The prioritization scheme is displayed in Table 1.

The following example clarifies this scheme. A respondent indicated that, in response to heavy rain, he/she never changes the travel route, changes the activity location or makes trip changes in 1-25% of the cases, and alters his/her transport mode or the timing of the trip 26-50% of the time. For this respondent, the ranks for a mode change, time-of-day change, location change, trip cancelation and route change are 8, 13, 7, 6 and 16, respectively. The action corresponding to the lowest rank – in this case, trip cancelation (which has a rank value of 6) – is the adaptation considered for the modeling process because this adaptation is likely to have the largest impact from an environmental point of view. If the respondent did not consider any change(s), then all changes have a rank value of 6 and, correspondingly, 'No change' would be the respondent's choice option. Table 2 displays the overall percentages of this prioritized adaptation variable. In agreement with results related to weather forecasts (Figure 2), more behavioral changes are made when discretionary trips are involved.

Table 1: Prioritization of the behavioral adaptation

	Mode Change	Time of Day Change	Location Change	Trip Cancelation	Route Change
Never			16		
0-25%	9	15	7	6	14
26-50%	8	13	4	3	12
>50%	5	11	2	1	10

In addition to dependent variables, different explanatory variables are used to investigate the impact of weather forecasts. For the continuous predictors, mean and standard deviation values are provided, while, for categorical variables, the percentages of each class are tabulated and the reference category is highlighted. These categorical variables are internally coded as $(k-1)$ dummy (0-1) variables, where k is the number of classes.

The first group of explanatory variables corresponds to the key variables in this study, which are the following weather-forecast-related variables: forecasted weather conditions, average exposure to weather forecasts, media source and perceived reliability of the weather forecast. As shown in Table 2, approximately 60% of the respondents absorb weather information on a daily basis. The most important media sources for weather information are television and, to a lesser extent, radio. The internet and newspapers clearly play smaller roles. In general, the respondents appear to be satisfied with the reliability of forecasted weather information.

Table 2: Descriptive statistics

Variable name	Description
Dependent variables: Prioritized behavioral adaptation	
Work/school	Mode: 10.2%, Time-of-day: 10.0%, Location: 3.4%, Cancelation: 8.5%, Route: 8.2%, No change[1]: 59.7%
Shopping	Mode: 5.5%, Time-of-day: 5.5%, Location: 9.5%, Cancelation: 33.1%, Route: 1.2%, No change[1]: 45.2%
Leisure	Mode: 5.4%, Time-of-day: 4.2%, Location: 8.2%, Cancelation: 33.8%, Route: 1.8%, No change[1]: 46.6%
Independent variables	
Weather forecast characteristics	
Weather type[2]	Cold: 16.7%, Snow: 16.7%, Rain: 16.7%, Fog: 16.7%, Warm[1]:16.7%, Storm:16.7%
Exposure	Daily[1]: 59.3%, Weekly: 33.2%, Occasionally: 7.5%
Media source[3]	Television[1]: 81.2%, Radio: 63.4%, Internet: 23.1%, Newspaper: 22.9%
Perceived reliability	Low (1-5): 15.4%, High[1] (6-10): 84.6%
Socio-demographic characteristics	
Age	Mean: 43.3, Standard Deviation: 15.1
Gender	Female: 49.0%, Male[1]: 51.0%
Children	No[1]: 35.3%, Yes: 64.7%
Degree	No secondary: 12.9%, Secondary: 36.3%, College: 30.5%, University[1]: 20.2%
Income	Low[1] ($\leq$ 1250€): 20.2%, Medium-High ($>$ 1250€): 70.0%, Unspecified: 9.7%
Marital state	Single[1]: 36.7%, Married: 63.3%
Profession	Professionally active: 73.3%, Students[1]: 11.3%, Inactive: 15.4%
Urbanization	Metropolitan: 16.5%, Strong: 11.3%, Moderate: 50.8%, Weak[1]: 21.5%
Transport-related characteristics	
Bicycle ownership	No: 6.5%, Yes[1]: 93.5%
Car ownership	No: 3.1%, Yes[1]: 96.9%
Driving license	No: 11.6%, Yes[1]: 88.4%
Season ticket	No: 60.9%, Yes[1]: 39.1%
Work/school trips	Mean: 4.4, Standard Deviation: 3.7
Shopping trips	Mean: 2.1, Standard Deviation: 1.7
Leisure trips	Mean: 3.7, Standard Deviation: 2.7

1: Reference category

2: The percentages are equal because of the experimental design

3: The percentages do not sum to 100% because the 4 media sources were queried separately

In addition to weather-forecast-related variables, the explanatory variables include different descriptors of the socio-demographic profiles of respondents. Recall that the results in this paper are based on weighted results, which is also the case for the descriptive statistics displayed in Table 2. The following variables were considered: age, gender; children, degree, income, marital state, profession and urbanization. In addition, transport-related variables were considered; in particular, bicycle and car ownership within the household as well as possession of a driving license and/or a public transport season ticket were envisaged. In addition to variables related to the availabilities of transport options, actual travel behavior was surveyed by recording the weekly frequency of work/school trips, shopping trips and leisure trips.

3. Methodology

To address the main research question of this paper, two statistical techniques were adopted. The first technique, the Pearson chi-square independence test, was used to test the first four research questions. This technique was adopted to assess the (univariate) relationship between weather forecast attributes (i.e., exposure, media source and perceived reliability) and changes in response(s) to forecasted weather conditions.

The Pearson statistic Q_p is defined by Equation 1:

$$Q_p = \sum_{i=1}^{k} \sum_{j=1}^{l} \frac{(n_{ij} - \hat{\mu}_{ij})^2}{\hat{\mu}_{ij}}, \tag{1}$$

where n_{ij} is the observed frequency in cell (i, j), which is calculated by multiplying the observed chance by the sample size, and $\hat{\mu}_{ij}$ is the expected frequency for table cell (i, j). When the row and column variables are independent, Q_p has an asymptotic chi-square distribution with $(k-1)(l-1)$ degrees of freedom (Agresti, 2002). The test assumes that at least 80% of the cells have expected frequencies of 5 or more. When this assumption is not met, modifications of the answer categories are required to ensure that this criterion is satisfied. This is operationalized in the present study by reducing the original response categories (never, in 1-25% of the cases, in 26-50% of the cases, or in more than 50% of the cases) to the dichotomous answer possibilities 'Change' and 'No change'.

Secondly, to investigate the fifth research question (the identification of factors that trigger changes in activity-travel behavior in the presence of adverse weather conditions and the determination of the role of weather-forecast characteristics), a GEE-MNL-model was constructed. The GEE-MNL model extends the classical multinomial logit (MNL) model by explicitly taking into account the correlated responses by means of a marginal effect model that is estimated using generalized estimating equations (GEE). In marginal models, the mean function is modeled directly, and the correlation structure is regarded as a nuisance parameter. It is important to consider this correlation structure, as behavioral adaptations in response to different weather conditions are most likely correlated. In other words, a certain behavioral adaptation in response to one weather condition is likely to be correlated to the behavioral adaptation in response to another weather condition.

To estimate the GEE-MNL model, the procedure suggested by Kuss and McLerran (2007) was followed: the GEE-MNL model was specified as a marginal model by reorganizing the response vector in a way that enables it to be fitted as a multivariate binary model. The original variable Y_{ij}, corresponding to behavioral adaptations in response to certain weather variables, is now written as an $((R-1)\times 1)$-vector $Y_{ij}^{\star}$ of binary variables $Y_{ijr}^{\star}$, such that $Y_{ij} = 2, ..., R$ results in $Y_{ij}^{\star} = 1$ in column r and 0 anywhere else.

In the case of $Y_{ij} = 1$ (reference category), $Y_{ij}^{\star} = 0$ in all $R-1$ columns. In the present paper, R equals 6 (5 behavioral changes + the no-change alternative in cases where no change was made), and the no-change alternative is defined as the reference category.

Let $Y_i^{\star} = (Y_{i1}^{\star'}, ..., Y_{in_1}^{\star'})$ denote the $(n_i(R-1)\times 1)$ response vector for the i-th cluster with expectation $\pi_i^{\star}$ and covariance matrix $V_i^{\star}$. This covariance $V_i^{\star}$ is a 'double-block' diagonal matrix, where the $(R-1)\times(R-1)$-block for (r,r') on the 'inner' block of the main diagonal of $V_i^{\star}$ is a multinomial covariance matrix for the j-th observation in the i-th cluster. Furthermore, it is noteworthy that the remaining elements on the 'outer' block specify the covariance between two different observations (j,j') in the i-th cluster. Formally, this amounts to

$$V_i^{*} = \mathrm{cov}(\mathrm{Y}^{*}_{\mathrm{ijr}}, \mathrm{Y}^{*}_{\mathrm{ij'r'}}) = \begin{cases} \pi^{*}_{ijr}(1-\pi^{*}_{ijr}) & \text{if} \quad \mathrm{j}=\mathrm{j'}, \mathrm{r}=\mathrm{r'} \\ -\pi^{*}_{ijr}\pi^{*}_{ijr'} & \text{if} \quad \mathrm{j}=\mathrm{j'}, \mathrm{r}\neq\mathrm{r'} \\ \frac{\mathrm{corr}(\mathrm{Y}^{*}_{\mathrm{ijr}}, \mathrm{Y}^{*}_{\mathrm{ij'r'}})}{\sqrt{\pi^{*}_{ijr}(1-\pi^{*}_{ijr})\pi^{*}_{ij'r'}(1-\pi^{*}_{ij'r'})}} & \text{if} \quad \mathrm{j}\neq\mathrm{j'} \end{cases}, \qquad (2)$$

where the first two lines of Equation 2 correspond to the 'inner' block of $V_i^{\star}$, the third line corresponds to the 'outer' block, and $\pi^{*}_{ijr} = E[Y^{*}_{ijr} = 1]$. It should be noted that the third line does not constitute a circular definition. Instead, $\mathrm{corr}(Y^{*}_{ijr}, Y^{*}_{ij'r'})$ must be given a working correlation pattern in the analyses (Miller et al., 1993). The resulting model is given via the following equation:

$$\log(\frac{\pi_{ir}^{\star}}{1-\pi_{ir}^{\star}}) = \theta_r^{\star} + X_{ij}'\beta_r^{\star}, \quad (3)$$

where $\pi_{ir}^{\star}$ denotes the expectation of all elements of $Y_i^{\star}$ belonging to response category r, $\theta_r^{\star}$ a vector of parameters to be estimated and X_{ij} the vector of explanatory variables. Note that there is no reference to a random effect in the model equation.

4. Results

4.1. Impact of forecasted weather conditions and weather forecast characteristics

Remember that, to address the first four research questions, the different behavioral changes (displayed in Figure 2) were analyzed using independence tests. Thus, for the first four research questions the 5 behavioral changes were all taken into account and not prioritized as is the case for the fifth research question. Table 3 displays the results of the statistical tests assessing the dependence of behavioral changes on the type of forecasted weather. This table indicates that all behavioral changes depend (with statistical significance) on the type of forecasted weather. In other words, across the three different types of trips and across the six behavioral changes, the type of forecasted weather clearly influences the changes in travelers' activity patterns. Take, for example, the dependence of mode changes in work/school trips on the type of forecasted weather. The chi^2-value for this test equals 108.95, and the degrees of freedom equal 15 (=(6 weather conditions - 1)× (4 response levels - 1), which yields a p-value that is smaller than 0.001 and, thus, smaller than the typical level of significance ($\alpha = 0.05$). Consequently, the null hypothesis of this test, that mode changes in work/school trips are independent of the type of forecasted weather, should be rejected. Furthermore, it can be concluded that the type of forecasted weather significantly influences mode changes in work/school trips. Similar conclusions can be drawn for all the other tests presented in Table 3.

With regard to the effect of the travelers' average exposure to weather forecasts, one can discern from Table 4 that the exposure level to weather forecasts has only limited influence on the changes in activity-travel behavior. With regard to work/school trips, the chi^2-tests indicate that, regardless of the weather condition considered, the behavioral changes in response to weather forecasts do not significantly depend on the exposure level(s) to

Table 3: Dependence of behavioral changes on the type of forecasted weather

Behavioral Change	Work/School		Shopping		Leisure	
	Chi^2	DF	Chi^2	DF	Chi^2	DF
Mode Change	108.95	15	57.58	15	80.03	15
Postpone Trip	353.43	15	290.50	15	311.48	15
Location Change	51.51	5	101.01	15	42.55	15
Cancelation Trip	111.28	5	291.51	15	269.80	15
Route Change	260.03	15	162.49	15	192.80	15

The p-values for all independence tests are less than 0.001

these forecasts. A similar result can be depicted for leisure trips, although the behavioral changes in response to warm weather forecasts do depend significantly on exposure levels. In contrast, behavioral changes in relation to shopping trips are more likely to be impacted by exposure levels. In the case of forecasts predicting rain, snow or fog, the behavioral changes are significantly affected by weather forecasts.

Concerning the impact of media sources of weather forecasts on changes in activity-travel behavior, Table 4 shows that the results indicate that behavioral adaptations do not depend on the media source. Irrespective of the type of trips and the type of forecasted weather, the likelihood that travelers will change their activity-travel behavior is not influenced by the media source. Thus, in contrast to the effect of exposure, the media source of the weather forecast does not significantly affect activity-travel behavior.

The final weather-forecast aspect that was investigated in this study is the perceived reliability of the weather forecast, which was measured on a 10 point scale. A dichotomization of the perceived reliability into low perceived reliability (1-5) and high perceived reliability (6-10) was performed to investigate the impact of perceived reliability on the probability that travelers will adjust their activity-travel behaviors. From Table 4, one can see that, in accordance with the results regarding the media source, the perceived reliability of the weather forecast does not affect the travelers' frequencies of making changes in their activity-travel behavior. This is true for every trip type and weather condition considered in this study.

Table 4: Dependence of behavioral changes on the characteristics of the weather forecast

Activity Type	Weather Type	Exposure[1]		Media Source[2]		Reliability[3]	
		Chi	P-value	Chi	P-value	Chi	P-value
Work/School	Cold	6.19	0.995	12.71	0.991	2.10	0.990
	Snow	14.67	0.685	10.35	0.998	12.25	0.199
	Rain	7.79	0.982	18.40	0.891	2.72	0.974
	Fog	13.71	0.748	18.26	0.896	6.39	0.700
	Warm	11.84	0.855	11.56	0.996	3.87	0.919
	Storm	13.30	0.773	20.51	0.809	6.79	0.659
Shopping	Cold	21.10	0.274	9.97	0.999	7.84	0.551
	Snow	***43.52***	***0.001***	13.64	0.984	6.94	0.643
	Rain	***31.52***	***0.025***	10.64	0.998	10.63	0.302
	Fog	***46.91***	***<0.001***	21.02	0.785	5.09	0.827
	Warm	25.10	0.122	17.34	0.922	4.14	0.902
	Storm	22.82	0.198	9.47	0.999	8.51	0.484
Leisure	Cold	6.58	0.993	17.55	0.917	7.81	0.554
	Snow	20.65	0.298	8.75	0.999	10.51	0.311
	Rain	20.85	0.287	7.17	0.999	5.21	0.816
	Fog	17.44	0.493	11.77	0.995	4.17	0.900
	Warm	***31.04***	***0.028***	22.25	0.724	7.56	0.579
	Storm	18.06	0.452	13.53	0.985	9.24	0.415

Bold italic *values indicate a significant effect of the weather forecast characteristic*
Degrees of freedom:
1: *18 ((3 levels of exposure - 1) × (5 behavioral changes x 2 answers (Yes/No) - 1))*
2: *27 ((4 media sources - 1) × (5 behavioral changes x 2 answers (Yes/No) - 1))*
3: *9 ((2 levels of reliability - 1) × (5 behavioral changes x 2 answers (Yes/No) - 1))*

4.2. Determinants of changes in activity travel behavior and the role of weather forecast characteristics

To determine the factors that trigger changes in activity-travel behavior in the presence of adverse weather conditions, and particularly, to determine the role of the characteristics (exposure, media source, perceived reliability) of the weather forecasts, a GEE-MNL-model was constructed. It should be noted that the prioritization of the different changes in activity-travel behavior was required, as respondents could indicate multiple changes simultaneously (see Table 1). After prioritizing the changes in activity-travel behavior, the transformed (prioritized) response variables were then analyzed using the proposed GEE-MNL modeling framework.

The explanatory variables that were considered for the analysis are listed in Table 2. Three groups of explanatory variables were taken into consideration. The first group of explanatory variables includes the key variables in this study, namely the weather-forecast-related variables: the forecasted weather condition, the exposure to the weather forecasts, the media source and the perceived reliability of the weather forecast. In addition to these weather-forecast-related variables, the explanatory variables included different descriptors of the socio-demographic profile of the respondents. Finally, different transport-related variables were envisaged.

Separate models were estimated for each type of activity purpose. Only the significant factors (assuming a level of significance of 5%) were retained in the final models. The level of significance was determined by examining the type III score statistics. These statistics provide insight into the overall effect of a variable. For instance, in the case of a categorical variable, these statistics are calculated based on the different dummy variables simultaneously. Take as an example the type of weather condition. Because there are 6 different weather conditions considered, the simultaneous effects of 5 dummy variables are assessed using this type III score. As noted in section 3, the formulation of the GEE-MNL was estimated as a multivariate binary model (5 binary outcomes). Therefore, the corresponding type III score statistic for this variable corresponds to 25 (5×5) degrees of freedom. It should be noted that the 'no-change'-alternative was used as the reference category in this MNL model.

From Table 5, one can note that the type of weather condition is the most predominant explanatory variable in all three models. The largest share of the variance in the behavioral changes is thus attributable to the type of weather. In addition, it should be mentioned that exposure to weather forecasts, media source, and perceived reliability of the weather forecast play no role. After all, only the significant factors are presented in Table 5, and these variables did not have a significant impact in any of the three models.

Table 5: Score statistics for Type III GEE-MNL analysis

Selected	Work/School			Shopping			Leisure		
Variables	Chi^2	DF	Sign.[1]	Chi^2	DF	Sign.[1]	Chi^2	DF	Sign.[1]
Weather Type	272.39	25	⋆⋆⋆	267.98	25	⋆⋆⋆	254.44	25	⋆⋆⋆
Age	42.06	5	⋆⋆⋆	−−−	−−	−−	47.55	5	⋆⋆⋆
Gender	−−−	−−	−−	17.66	5	⋆⋆	−−−	−−	−−
Children	12.32	5	⋆	−−−	−−	−−	−−−	−−	−−
Degree	−−−	−−	−−	−−−	−−	−−	27.54	15	⋆
Profession	−−−	−−	−−	20.82	10	⋆	−−−	−−	−−
Urbanization	40.45	15	⋆⋆⋆	−−−	−−	−−	−−−	−−	−−
Driving License	−−−	−−	−−	14.13	5	⋆	13.05	5	⋆
Season ticket	16.71	5	⋆⋆	−−−	−−	−−	−−−	−−	−−

−−− *indicates that this variable was not incorporated in the final model*

1 *Significance:* *n.s.: p-value ≥ 0.05, ⋆ p-value < 0.05,*
⋆⋆ p-value < 0.01, ⋆⋆⋆ p-value < 0.001

The interpretation of the individual parameters of weather effects, which are presented in Table 6, is not straightforward. On the one hand, these parameters are alternative, specific, and conditional upon the reference alternative (i.e., the no-change alternative). On the other hand, the parameters are conditional upon the reference category of the weather variable itself (i.e., extreme warm weather).

Concerning work- and school-related trips, it appears that fewer mode changes are made in the presence of fog and cold temperatures compared to snow and warm weather. The likelihood of changing the timing of the trip appears to be higher for all weather conditions in comparison to warm weather. Location changes appear to be least dependent on weather type; nonetheless, the probability of changing the work or school location is higher in the presence of snow and storms. Finally, trip cancelations and route changes are most likely to occur in the presence of snow.

Regarding shopping trips, one could observe that mode changes are more likely to be made in warm weather compared to other extreme weather conditions. Furthermore, it is noteworthy that the timing of shopping trips is most likely to be changed in the presence of rain and storms and that the probability of altering the shopping location is highest during periods of fog

Table 6: Parameter Estimates for the GEE-MNL Models

	Mode		Time-of-day		Location		Cancelation		Route	
Parameter	Est.	Std.E.	Est.	Std.E.	Est.	Std.E.	Est.	Std.E.	Est.	Std.E.
Parameter Estimates for the Work/School Model										
Intercept	-1.831	0.531	-3.260	0.531	-1.499	1.375	-1.685	0.581	-5.269	0.657
Weather										
Cold	-1.204	0.241	1.255	0.356	0.382	0.390	-1.114	0.290	1.821	0.479
Snow	0.195	0.221	2.195	0.356	1.406	0.446	0.960	0.199	2.860	0.481
Rain	-0.122	0.249	2.149	0.348	0.699	0.479	-0.725	0.240	2.145	0.481
Fog	-1.238	0.324	2.233	0.353	0.314	0.583	-1.177	0.324	2.248	0.478
Storm	-0.395	0.234	1.861	0.358	0.994	0.345	-0.501	0.238	1.925	0.483
Age	-0.024	0.008	-0.024	0.006	-0.058	0.016	-0.016	0.008	-0.015	0.008
Children	0.686	0.274	0.322	0.261	-0.409	0.453	-0.302	0.294	-0.314	0.266
Urbanization										
Metropolitan	1.029	0.398	-0.762	0.367	-0.800	0.732	-0.178	0.443	0.781	0.427
Strong	-0.001	0.433	-0.339	0.359	-1.830	0.705	0.919	0.491	0.793	0.438
Medium	0.365	0.356	-0.511	0.281	-0.143	0.661	0.326	0.429	0.902	0.324
Season ticket	-0.129	0.229	0.381	0.234	0.004	0.352	-0.156	0.273	1.010	0.315
Parameter Estimates for the Shopping Model										
Intercept	-1.423	0.275	-2.660	0.385	-3.281	0.314	-2.675	0.247	-3.914	0.723
Weather										
Cold	-1.099	0.303	0.615	0.319	0.010	0.203	-0.303	0.186	0.127	0.291
Snow	-1.385	0.322	-0.006	0.302	0.595	0.248	2.202	0.159	1.062	0.847
Rain	-1.180	0.289	0.725	0.282	0.633	0.232	1.471	0.158	-0.435	0.971
Fog	-1.800	0.399	0.555	0.312	0.638	0.195	0.791	0.152	0.841	0.537
Storm	-1.290	0.305	0.785	0.285	0.338	0.206	1.335	0.151	-2.522	1.258
Gender	-0.623	0.306	-0.156	0.274	0.612	0.284	0.523	0.185	-0.801	0.590
Profession										
Active	-0.128	0.301	-0.704	0.278	0.190	0.275	0.591	0.217	-0.833	0.440
Inactive	-0.666	0.431	-0.930	0.634	0.666	0.458	0.826	0.382	0.425	0.836
Driving license	-1.466	0.435	-0.117	0.421	-0.061	0.391	0.775	0.393	-0.988	0.845
Parameter Estimates for the Leisure Model										
Intercept	-0.031	0.412	-3.120	0.518	-1.660	0.442	-2.677	0.382	-7.199	1.041
Weather										
Cold	-1.580	0.277	-0.542	0.587	-0.191	0.197	0.230	0.167	1.718	0.816
Snow	-1.603	0.262	0.408	0.476	-0.227	0.245	2.177	0.166	2.984	0.858
Rain	-1.612	0.269	1.117	0.402	0.011	0.227	1.321	0.148	2.762	0.853
Fog	-2.135	0.300	0.904	0.460	-0.036	0.216	0.904	0.150	2.853	0.802
Storm	-1.632	0.272	0.415	0.479	0.117	0.205	1.383	0.152	2.128	0.888
Age	-0.054	0.008	-0.009	0.011	-0.020	0.011	0.025	0.008	-0.020	0.012
Degree										
No secondary	1.832	0.524	0.091	0.685	0.401	0.647	-0.763	0.422	2.617	0.684
Secondary	0.367	0.354	0.041	0.446	0.309	0.374	-0.211	0.256	1.172	0.570
College	0.318	0.398	-0.561	0.455	-0.363	0.405	-0.109	0.263	2.124	0.595
Driving license	-0.550	0.346	-1.236	0.972	0.108	0.440	0.136	0.471	-2.155	0.787

or rain. Finally, in accordance with commuting trips, trip cancelations and route changes have the highest likelihood of occurring in the presence of snow.

The investigation of the parameter estimates relating to leisure trips shows that, in line with the results of the shopping trips, the likelihood of switching the transport mode is the highest in warm weather. In addition, one could observe that rain and fog are associated with the highest probability to make time-of-day changes. Changes in the leisure location do not to appear to be related to the type of weather. Finally, similar to commuting and shopping trips, trip cancelations and route changes are more likely to occur in the presence of snow.

With regard to the socio-demographic profile of the respondents, it is clear from Table 5 that various socio-demographic variables contribute to explaining the changes in activity-travel behavior. However, the contributions of these variables are limited to specific types of trips. Take age as an example. With the exception of cancelations of leisure trips, for which age has an increasing effect, age only has a significant effect on the likelihood of making changes in work/school and leisure trips. In particular (see Table 6), higher ages correspond to a lower likelihood of making behavioral adaptations in these types of trips. In contrast, the probability of adapting shopping trips is not influenced by age.

With respect to transport- and travel-related attributes, it may be that only the possession of a driving license and a season ticket for public transport play roles. The ownership of various transport modes and the frequency of making trips with a certain activity purpose are not influential. The possession of a season ticket appears to decrease the likelihood of route changes during commuting trips. Note that the sign of the estimate – the estimate corresponds to the respondents without season ticket – is positive. Therefore, the effect of having a season ticket is negatively associated with the probability of altering routes. Similarly, one could predict that the possession of a driving license increases the chance of changing transport modes in shopping trips and making route changes during leisure trips. In contrast, the likelihood of canceling shopping trips is lower for persons that possess a driving license

5. Discussion

The results presented in the previous section underscore the dual role of weather forecasts regarding changes in activity-travel behaviors. On the one hand, the results from both the independence tests (Table 3) and the GEE-MNL-model (Table 5) clearly illustrate the following significant effect of forecasted weather: the likelihood of making changes in activity-travel behavior depends significantly on the type of weather. On the other hand, the different methods of acquiring weather information (exposure, media sources, and perceived reliability) did not appear to impact the probability of behavioral adaptations.

This aforementioned duality is partially related to the difference(s) between weather forecasts and the true traffic and roadway conditions. It is more difficult for travelers to assess the effects of weather forecasts on road weather conditions, particularly with regard to their own observations of weather conditions. Often, behavioral alterations based on the travelers' own weather perceptions are limited to last-minute adaptations, such as changing the route or making time-of-day changes. Other adjustments, such as changing the activity location, changing transport mode or canceling the trip/activity, typically require longer times because these adaptations are generally planned more ahead of time and, thus, fall out of this last-minute range. This is the case for all three types of trips but is especially true for commuting trips. This observation is also underscored by the descriptive analysis (Figure 2), which showed that last minute alterations are, by far, more often chosen in response to adverse weather conditions than so-called 'planned' changes. To encourage 'planned' adaptations, the discrepancies between weather forecasts and the actual road conditions should be reduced. One possibility is to link road weather information systems to weather forecasts. Studies from Kilpeläinen and Summala (2007) and Sihvola (2009) showed that such road weather information services and, thus, weather forecasts have clear effects on trip schedulers. Nonetheless, the challenge lies in tailoring such a system for the specific context of Flanders and the Flemish weather.

A concern that is often raised with regard to stated adaptation experiments is the validity of the results. In this regard, it is important to stress that all the results presented in this paper were weighted such that there was an optimal correspondence between the true population and the respondents of the survey. Moreover, an internal validity check was performed to assess the quality of the data. Table 7 presents the independence tests of both the impact of actual weather and that of forecasted weather on the changes in activity-travel behavior. As expected, the effect of actual weather conditions is greater than the influence of forecasted weather conditions. This result can be observed by comparing the larger Chi^2-values for actual weather conditions with the values corresponding to forecasted weather conditions. Note that such comparisons of Chi^2-values can be made as long as both compared values correspond to the same number of degrees of freedom. The larger impact of actual weather, therefore, provides internal evidence that the stated adaptation experiment is valid.

Table 7: Significance of the type of weather: actual weather vs. forecasted weather[1]

Activity Type	Behavioral Change	Actual Weather Chi^2	Actual Weather DF	Forecasted Weather Chi^2	Forecasted Weather DF
Work/School	Mode Change	138.71	15	108.95	15
	Postpone Trip	409.05	15	353.43	15
	Location Change[2]	81.12	15	51.51	5
	Cancelation Trip[2]	174.79	5	111.28	5
	Route Change	362.56	15	260.03	15
Shopping	Mode Change	92.24	15	57.58	15
	Postpone Trip	542.97	15	290.50	15
	Location Change	235.69	15	101.01	15
	Cancelation Trip	555.65	15	291.51	15
	Route Change	302.34	15	162.49	15
Leisure	Mode Change	107.92	15	80.03	15
	Postpone Trip	522.45	15	311.48	15
	Location Change	62.85	15	42.55	15
	Cancelation Trip	405.26	15	269.80	15
	Route Change	357.76	15	192.80	15

[1] *All p-values < 0.001*

[2] *Estimated using reduced answer possibilities (Yes/No)*

6. Conclusions

This paper accurately assesses how weather forecasts induce changes in Flemish activity-travel behavior. The most important result is the dual role of weather forecasts with regard to activity-travel behavior. This duality provides insight into the ambiguity of the findings reported in the international literature. Moreover, the results validate the previously published findings of Khattak and de Palma (1997), who observed no significant effect of acquiring forecasted weather information on the likelihood of adapting mode choice and departure times.

The deeper understanding of how weather forecasts directly and indirectly affect traffic intensities provides insight for policy makers with regard to mitigating the negative impacts of forecasted adverse weather conditions. Therefore, the effect(s) of weather forecasts on travel behavior in weather-sensitive dynamic traffic models must be taken into consideration. These types of models will lead to more accurate traffic forecasts and can serve as important decision support tools for both long-term and short-term policy decisions. Take, for example, the case in which traffic managers attempt to reduce the negative impacts of inclement weather by intervening through various weather-related advisory and control measures; this practice is also referred to as weather responsive traffic management. A weather-sensitive traffic model could be a useful decision support tool for determining which measure is most applicable to a particular situation.

Furthermore, as noted in the discussion section, this study recommends the implementation of a road weather information system that is directly linked to weather forecasts in an attempt to address the discrepancy between the weather forecasts and the traffic and roadway conditions in Flanders.

Future research efforts should focus on the integration of the present findings into travel demand modeling frameworks. Moreover, models that directly link the effects of weather forecasts to the overall traffic observed on the network should be developed and further enhanced. Finally, data collection methods should attempt to survey both weather conditions and associated travel behavior with as much detail (both in space and time) as possible.

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