Journal of Transport Geography 28 (2013) 204–211

Contents lists available at SciVerse ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Impact of weather conditions on macroscopic urban travel times

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ARTICLE INFO

Keywords:
Weather conditions
Precipitation
Snow
Temperature
Macroscopic urban travel times

ABSTRACT

Weather conditions may significantly impact a series of everyday human decisions and activities. As a result, engineers seek to integrate weather-related data into traffic operations in order to improve the current state of practice. Travel times and speeds are two of the elements of a transportation system that may be greatly affected by the weather resulting in deterioration of roadway network performance. This study aims to investigate the impact of different intensities of rain, snow and temperature levels on macroscopic travel times in the Greater London area (UK) during the period 1 October–10 December 2009. The analysis was carried out for three 2-h periods on weekdays during the morning, afternoon and evening periods. Automatic Number Plate Recognition (ANPR) data obtained from more than 380 travel links are used in the analysis. The main finding is that the impact of rain and snow is a function of their intensity. Specifically, the ranges of the total travel time increase due to light, moderate and heavy rain are: 0.1–2.1%, 1.5–3.8%, and 4.0–6.0% respectively. Light snow results in travel time increases of 5.5–7.6%, whilst heavy snow causes the highest percentage delays spanning from 7.4% to 11.4%. Temperature has nearly negligible effects on travel times. It was also found that the longer links within outer London generally yield greater travel time decreases than those in inner London, and even higher decreases than the shortest links in central London. This research provides planners with additional information that can be used in traffic management to modify planning decisions and improve the transportation system control on a network scale under different weather conditions. In order to determine whether the weather effects are region-specific, continued research is needed to replicate this study in other areas that exhibit different characteristics.

1. Introduction

Travel times and speeds are two traffic parameters of a transportation system that may be greatly affected by the weather, resulting in deterioration of a network's performance (Koetse and Rietveld, 2007). Especially inclement weather conditions may result in substantial reductions of roadway capacities and thus, operating speeds (Martin et al., 2000; Koetse and Rietveld, 2009). Additionally, traffic demand may be largely affected by the weather, since the latter has a considerable impact on a series of human decisions such as transport modal choice, trip distribution, trip cancellation or postponement; altering roadway users' valuation of actual transport costs and travel times (Koetse and Rietveld, 2007, 2009).

Considering the significant impact of weather conditions on the transportation system and its performance, engineers are seeking to integrate weather-related data into traffic operations in order to improve the current state of practice. Agarwal et al. (2005) states in his report that "nearly all traffic engineering guidance and methods used to estimate highway capacity assume clear weather. However, for many northern states, inclement weather conditions occur during a significant portion of the year". For example, the Highway Capacity Manual (HCM) (TRB, 2000) suggests that free-flow speed on freeways is reduced by 9.7 km/h under light rainfall and by 19.3 km/h in heavy rain, without, nonetheless, explicitly defining rain intensity ranges. Potential incorporation of weather information into guidelines prerequisites a thorough understanding of how traffic conditions vary both spatially and temporally under different weather conditions. The separate analysis and exploration of the effects of different weather conditions on every urban or rural transport network is essential for local authorities to better understand the network's performance (Smith et al., 2004; Koetse and Rietveld, 2009). This task is of some importance taking into consideration the substantial variability among past research results that mainly depend on the target area, geometric, traffic and drivers' characteristics, socio-economic factors, the roadway functional class, the season of the year and the climate of the examined region (Smith et al., 2004; Wang et al., 2006; Koetse and Rietveld, 2007).

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http://dx.doi.org/10.1016/j.jtrangeo.2012.11.003

For example, the literature indicates that 'rain intensity matters' (TRB, 2000; Smith et al., 2004; Maze et al., 2005; Hranac et al., 2006; Wang et al., 2006) by affecting congestion and travel times; however, the reported speed reductions vary considerably. The estimated range of speed decrease due to light rain is roughly 2–10%. Ibrahim and Hall (1994) stated that light rain caused a drop in free-flow speeds of 5–10 km/h at two sites in Mississauga (Ontario), while Hranac et al. (2006) estimated free-flow speed and speed-at-capacity decreases of 2–3.6% and 8–10% respectively in Baltimore, Twin Cities, and Seattle. Unrau and Andrey (2006) found that speed dropped by approximately 10% on an urban expressway in Toronto (Canada) during daytime uncongested conditions and light rain.

The corresponding drop in travel time attributed to heavy rain is generally higher and ranges between 4% and 20%. For instance, Stern et al. (2003) examined several roadway segments in Washington DC resulting in an average travel time increase of 14% during adverse weather conditions, while 17% of the examined cases yielded travel time increases greater than 20%. Agarwal et al. (2005) estimated freeway speed decreases of 4–7% during heavy rain (6.35 mm/h) for an area in the Twin Cities, Minnesota. Wang et al. (2006) examined an urban area in Nagoya City (Japan) concluding that an average speed decline of 6.03 km/h occurred during heavy rain and also the size of the weather effects was highly contingent with roadway characteristics, such as roadway class and number of lanes. Smith et al. (2004) indicated that light and heavy rain yield statistically different speeds when compared to 'no rain' conditions, but unlike other studies, there was no statistical evidence of that difference.

Likewise, a common finding on a global scale is that snow has the worst impact and diverse effects on travel times. Ibrahim and Hall (1994) estimated drops in free-flow speeds ranging 38–60 km/h, while Kyte et al. (2001) reported speed declines due to snow by up to 16 km/h. Agarwal et al. (2005) estimated speed decreases of 11–15% under heavy snow conditions (>12.7 mm/h) and Maze et al. (2005) corresponding decreases of 4–13%. In 2006, Hranac et al. showed that speed decreases during light snowfall from 5% to 16%, whilst heavy snow caused reductions spanning from 5% to 19%. Sabir et al. (2008) found that snow has a negative impact on speeds of approximately 7%. The previous findings explain the diversity in spatio-temporal weather effects on travel speeds. Although the estimates amongst studies are difficult to compare in magnitude, the impact of rain and especially snow on traffic speed at congested links during rush hours appear to be significant (Knapp et al., 2000; Sabir et al., 2008). Additional insights into the magnitude of weather impact on network travel times are necessary in order to make more accurate assessments and provide additional information to traffic managers (Agarwal et al., 2005; Koetse and Rietveld, 2009).

This task was particularly challenging in the past due to the lack of weather and traffic data of high spatial granularity (Sabir et al., 2008). Older studies (Botha and Kruse, 1992; Parsonson, 1992) were highly based on manual traffic counts and weather data that were obtained from a limited number of weather stations. Numerous subsequent studies utilised data from single or dual loop detectors and automatic traffic counters (Kyte et al., 2001; Smith et al., 2004; Hranac et al., 2006; Unrau and Andrey, 2006; Hablas, 2007). Presently, the technological advancements in data collection and management, infrastructure, software and hardware, as well as the extensive application of Intelligent Transportation Systems (ITS) can facilitate such analyses by broadening the target areas.

In addition to the above, the temporal resolution of the data has substantially improved in the last two decades. The review of past studies reveals that the granularity of both weather and traffic data typically ranges between 5 min to a few hours (Ibrahim and Hall, 1994; Hablas, 2007). Bluetooth, cell phone and GPS devices have attracted significant attention over the last years providing travel time and/or speed data on a per second interval or even less (Wang et al., 2006). Similarly, recent meteorological studies that examine weather satellite and radar technologies, have substantially improved the data granularity at the level of some seconds (Heinselman and Torres, 2011; Sutherland-Stacey et al., 2011); yet their utilisation in the transport field remains somewhat limited.

This paper attempts to address some of the shortcomings derived from the literature. One of the main limitations is that a large quantity of studies focuses on a limited number of routes or roadway segments, mainly due to a lack of data (Ibrahim and Hall, 1994). Limited research examines the performance of a transportation network at a state, city or even trip level (Sabir et al., 2008). Potential generalizations of the findings stemming from a roadway-level analysis would have to consider roadway characteristics and other contextual factors. On the contrary, transportation management agencies would benefit more from knowing the effects of the weather on the transportation network of greater geographical regions (e.g. central, inner and outer London). This may be better understood by reckoning that planning decisions and traffic control modifications are usually being applied within or on the periphery of large areas in urban systems (e.g. London) rather than on individual links.

Another drawback is that the majority of the research works engage with uncongested and/or rural freeways and expressways (Smith et al., 2004; Agarwal et al., 2005; Maze et al., 2005; Wang et al., 2006). It is worth stating that the quantification of weather effects on urban travel times poses many challenges. Urban links are usually shorter in length than rural roads, they exhibit lower operating speeds and carry more interrupted traffic due to pedestrian crossings and signalised intersections. However, the outcomes of a macroscopic study that focuses on a large urban area consisting of several travel links may offset the previous constraints. It may also provide valuable information to practitioners about the network's behaviour and not solely about links that carry a small percentage of the network's traffic. Furthermore, a large number of studies focus on extreme weather conditions (Botha and Kruse, 1992; Parsonson, 1992; Ibrahim and Hall, 1994; Bernardin et al., 1995, Hofmann and O'Mahony, 2005; Hablas, 2007; Martin et al., 2000; Koetse and Rietveld, 2009). This research differs from previous works on the consideration of different intensities of precipitation, snow and temperature levels, rather than simply examining the presence or absence of inclement weather conditions. Also, very few studies have looked at regional differences associated with inclement weather impacts on free-flow speeds (Hablas, 2007). Finally, the effects of weather variability on travel times or speeds have not been documented to a large extent, especially when compared to numerous studies dealing with the impact on traffic flows (Hanbali and Kuemmel, 1993; Al Hassan and Barker, 1999; Parry, 2000; Smith et al., 2004; Keay and Simmonds, 2005), and accidents' frequency and severity (Welch et al., 1970; McDonald, 1984; Stern and Zehavi, 1990; Maycock, 1995; Edwards, 1996; Andrey et al., 2003; Eisenberg, 2004; Shankar et al., 2004; Hermans et al., 2006).

1.1. Purpose and objectives

The goal of this study is to investigate how precipitation, snow and temperature affect macroscopic urban travel times in the Greater London area, UK. The first objective is to examine spatio-temporal correlations of rainfall data. The results of this preliminary analysis serve as the basis for the selection of the examined travel links that form larger regions around each weather station. The second focus is to compare the effects of different intensities of rain, snow and temperature levels on travel times, during the morning, noon and evening period. The exploration of how the above impact varies among central, inner and outer London constitutes the third target. Finally, the results of the preceding analysis are compared against those of past research works within the last objective of the study.

The remainder of the paper is organised as follows. The study data (traffic and weather data) are presented in the second section, while the methodology of the study, including the results of the preliminary analysis and the performance measurements used, are provided in Section 3. The results of the analysis are presented and discussed in the fourth section, while conclusions are drawn in Section 5.

2. Study data

2.1. Traffic DATA

The traffic data used in the study are provided by the Transport for London (TfL) and were collected from Automatic Number Plate Recognition (ANPR) cameras that cover a significant part of London's transportation network (Fig. 1). The study period spans from 1 October 2009 to 10 December 2009.

The individual travel time of a vehicle within a link is estimated using two ANPR cameras that are installed on the start and the end node of the link. The cameras record the entrance and the exit time of a vehicle by matching its number plates at the two nodes. An average Link Travel Time[3] ($LTT_{i,t}$) is then calculated for every link i and 5-min interval t, as a simple average of the individual travel times of those vehicles that travelled along the link i during the examined time interval t:

$$LTT_{i,t} = \frac{1}{m_{i,t}} \sum_{r=1}^{m_{i,t}} (TT_{r,i,t}) \tag{1}$$

where $LTT_{i,t}$ = link travel time (s) of link i during the time interval t; $TT_{r,i,t}$ = individual travel time (s) of vehicle r along the link i (from the start to the end node) during the time interval t; $m_{i,t}$ = number of vehicles that travelled along the link i during the examined time interval t.

The initial data set includes more than 950 links allowing not only for examination of a limited number of roadways, but of large areas of the network that consist of multiple links.

2.2. Meteorological data

Hourly weather data, collected during the aforementioned study period from seven weather stations in the Greater London Area (Fig. 1), were obtained from the Met Office through the British Atmospheric Data Centre (BADC). Two of the stations are located in central London, one in inner, and four stations in outer London. The data set includes three variables: precipitation, snow, and temperature. Holidays (e.g. Christmas period) or days with unusual travel patterns due to special events were excluded from the analysis. The ANPR weekday data were properly aggregated so as to match the hourly intervals of the weather data set.

3. Methodology

3.1. Selection of links

The first step of the study includes a correlation analysis that aims to investigate how precipitation levels vary over distance, as well as for different aggregations of the data. The rationale behind this preliminary analysis relies on the assumption that rainfall is a local phenomenon in London that may significantly vary between two adjacent regions. A correlation coefficient is calculated for every pair of stations located at different distances (D) for four data aggregation levels: 1 h, 12 h, 24 h and 1 month. Fig. 2 shows the results of the analysis along with the R^2 of four linear lines, fitted to the data points of each aggregation level.

It is apparent from Fig. 2 that the longer the distance between two stations, the weaker the relationship of their precipitation data. However, the rate of the correlation decrease is substantial for the hourly data set ($\rho < 0.5$ for $D > 35$ km) but non-significant for the aggregated data ($\rho > 0.8$ for $0 < D < 35$ km). This can be also interpreted through the decrease in R^2 as the data is further aggregated.

Taking into account previous research findings (Smith et al., 2004; Maze et al., 2005; Hranac et al., 2006; Koetse and Rietveld, 2007), which indicate that precipitation is one of the most influential weather factors on traffic speeds, the results from Fig. 2 can be used to define areas for examination around each station. In order to better understand how rainfall affects network travel times, the hourly data set is used to conduct the main analysis. Aggregated data sets will not provide an insight into the impact of such short-term phenomena on travel times, since the latter may considerably vary within a short-period of time. Based on the above statements and in sake of precision, a distance D of 3 km is selected as the radius of the buffer area to be examined around each station. This distance is in line with past research (Agarwal et al., 2005) and corresponds to a 'strong' correlation coefficient that ranges from 0.8 to 1.0. Table 1 presents the characteristics of the selected travel links per station and Fig. 1 illustrates them on London's transportation network.

The links with a length of 50% or more falling within a buffer region are considered for examination. Station 726, located in the Kenley Airfield area, is excluded from the analysis, since none of the network links fall within its buffer area. It is worth noting that central London has, on average, the shortest links, followed by inner and outer London (Table 1).

3.2. Performance measurements

In contrast to past studies (Ibrahim and Hall, 1994; Martin et al., 2000; Kyte et al., 2001; Hranac et al., 2006; Unrau and Andrey, 2006; Tu et al., 2007), the target area is not focused on specific links; hence, there is a need to develop measurements that express the roadway performance at the network level. The total travel time (TTT) of each examined area is estimated as a weighted sum of individual link travel times, as shown in the following equation:

$$TTT = \frac{\sum_{i=1}^{n}(LTT_i \times l_i \times ADT_i)}{\sum_{i=1}^{n}(l_i \times ADT_i)} \tag{2}$$

where TTT = total travel time, LTT_i = link travel time of link i, l_i = length of link i, ADT_i = average daily traffic flow, and n = number of links.

The length and the average daily traffic (ADT) of each link are used as weights to adjust the links' contribution to the total travel time. Manual daily counts conducted by the Department for Transportation (DfT) are used to represent the ADT of each link. The analysis is carried out only for weekdays due to their bimodal travel patterns that are substantially different than the single-peak weekend trends.

In order to determine the effects of the weather conditions on the transportation system, the TTTs under base conditions are compared against the corresponding travel times during different intensities of rain, snow and low temperatures. The base conditions represent 'dry pavement' resulting from good weather conditions and occur when there is no rain or snow, and the temperature is greater than 10 °C.

[3] The analysis was also conducted using average Link Travel Speeds ($LTS_{i,t}$) or space-mean speeds; however, the results remain approximately the same.

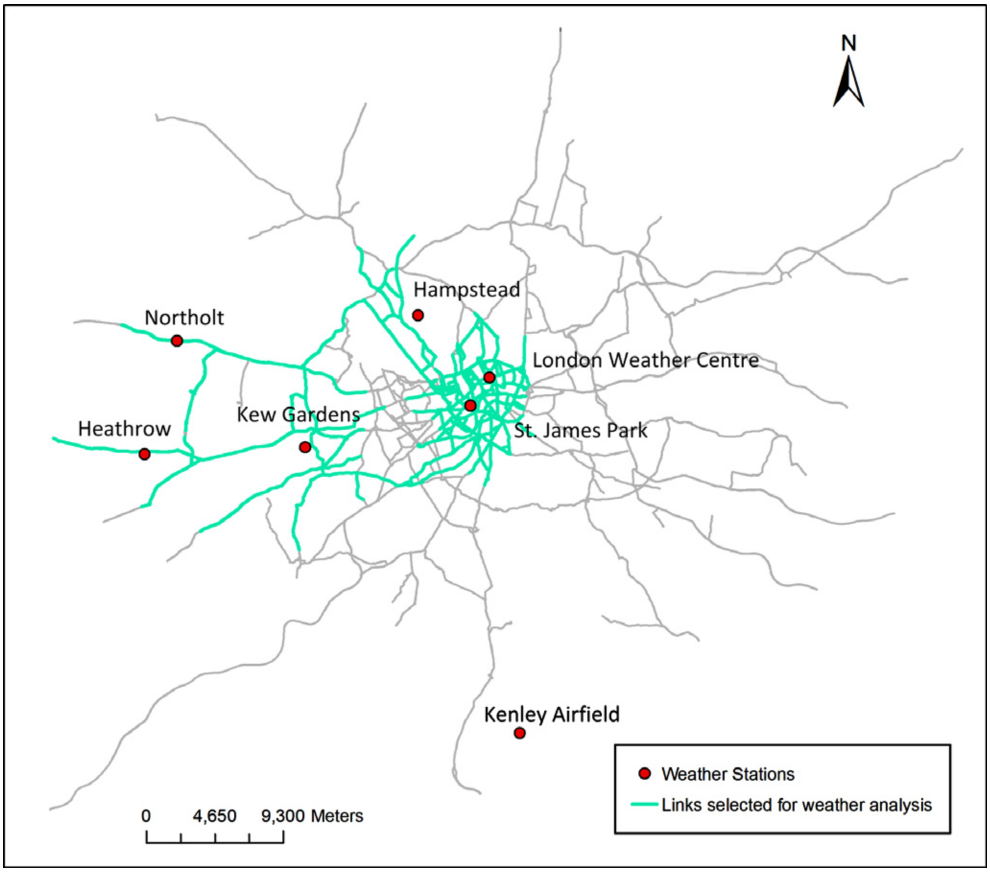

Fig. 1. Weather stations and travel links selected for the main analysis.

Prior research highlights the importance of designating different intensities of rain, snow, and temperature levels. For instance, Maze et al. (2005) stated that 'clearly, intensity of precipitation matters', Smith et al. (2004) reports that 'the impact of rainfall is a function of its intensity', while the HCM (TRB, 2000) recommends the use of different free-flow speed values for different weather conditions. Considering the consistency of the results among past studies (Kyte et al., 2001; Bennartz et al., 2002; Smith et al., 2004; Agarwal et al., 2005; Maze et al., 2005; Hranac et al., 2006) that examined this topic and adopted similar methodologies, the intensities/categories of precipitation, snow and temperature are established and listed in Table 2.

A data set was developed for each of the six areas, for each category, as well as for the following time periods: AM (7:00–09:00), INTER (12:00–14:00), and PM (16:00–18:00). Each of these periods lasts 2 h, so as to avoid high variations of travel times that would result from longer periods within a day. Similar to previous research work, the night period (18:00–07:00) was excluded from the analysis (Smith et al., 2004). Afterwards, the percentage difference in total travel time (*DTT*) was calculated between base and non-base conditions as follows:

$$DTT = \frac{TTT^{Non\text{-}BaseCond.} - TTT^{BaseCond.}}{TTT^{BaseCond.}} \times 100\% \quad (3)$$

where DTT = difference of total travel time (%) between base and non-base conditions; $TTT^{Non\text{-}BaseCond.}$ = total travel time during non-base conditions, and $TTT^{BaseCond.}$ = total travel time during base conditions.

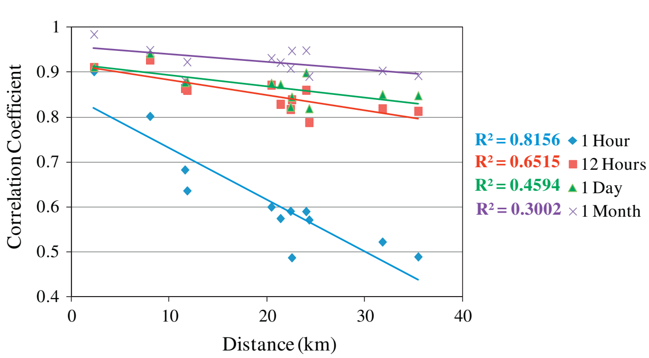

Fig. 2. Correlation coefficient of precipitation data versus distance of weather stations.

Table 1
Description of selected travel links per weather station.

Station ID	Area	Donut	Number of links	Total length (km)	Avg. length (km)
695	Hampstead	Inner	26	97.1	3.7
697	St. James Park	Central	172	455.8	2.6
708	Heathrow	Outer	16	64.2	4.0
709	Northolt	Outer	9	68.9	7.6
723	Kew Gardens	Outer	41	183.6	4.5
726	Kenley Airfield	Outer	–	–	–
19144	London Weather Centre	Central	87	112.8	1.3
Total	–	–	361	982.4	2.7

Table 2
Categories examined per weather variable.

Precipitation (mm/h)	Snow (mm/h)	Temperature (°C)
0–0.25	0–2.5	10–0
0.25–6.35	>2.5	<0
>6.35		

The statistical significance between the $TTT^{Non\text{-}BaseCond.}$ and the $TTT^{BaseCond.}$ is checked at a 95% confidence interval conducting Analysis of Variance (ANOVA) tests. The results of the study are presented in the following section.

4. Results and discussion

Tables 3–5 present the *DTT* for the examined categories of precipitation, snow and temperature respectively. The *DTT* of the statistically different population means are indicated with bold letters. It is worth noting that similar to previous research (Smith et al., 2004), in cases of rare weather phenomena (i.e., heavy snow) the sample sizes are small affecting the inherent variability of traffic data; thereby, the statistical significance of the results. Finally, a comparison of results with findings from other research works is conducted in Section 4.4.

4.1. Rain

Several comparisons can be made from the following tables. It is clearly shown in Table 3 that light rain has the smallest impact on travel times in all six areas and time periods. The smallest increase occurs in central London (Station ID 19144) for all time periods and ranges from 0.12% to 0.35%. On the contrary, the highest *DTT*s are observed in outer London. Station 708 yielded a *DTT* of 2.01% during the morning peak, while station 723 resulted in the greatest average delays; 2.07% and 2.11% during the INTER and the evening period respectively.

Compared to light rain, moderate rain causes, on average, a higher *DTT* that ranges between 1.45% and 3.81%. One similarity between these two categories is that outer London experienced the greatest *DTT*s (2.35–3.81%) on average, followed by inner (2.68–3.01%) and then central London (1.45–2.03%). A potential explanation behind this finding is that the areas examined in central London primarily consist of urban short links (Table 1), whose operational speeds are lower compared to the longer links in inner or outer London. Consequently, the travel times are not affected to the same extent. It is also worth noting that 12 out of 18 *DTT*s are statistically significant.

Table 3
DTT for different intensities of rainfall.

Precipitation (mm/h)	Time period	Difference in total travel time (%)					
		697 Central	19144 Central	695 Inner	708 Outer	709 Outer	723 Outer
0–0.25	AM	0.63 (32)	0.35 (31)	1.44 (31)	2.01 (33)	1.94 (28)	1.31 (30)
0.25–6.35		1.45 (28)	1.78 (28)	2.97 (26)	3.55 (22)	2.35 (23)	2.76 (22)
>6.35		**3.98** (20)	**3.57** (19)	**4.21** (22)	**5.17** (22)	4.39 (21)	**4.04** (21)
0–0.25	INTER	0.32 (30)	0.15 (29)	1.94 (29)	1.85 (28)	1.02 (25)	**2.07** (26)
0.25–6.35		1.59 (28)	**1.32** (31)	**3.01** (32)	3.25 (26)	**3.79** (30)	**3.22** (29)
>6.35		**5.34** (25)	**4.88** (26)	**5.11** (20)	**5.73** (24)	5.62 (15)	**6.01** (26)
0–0.25	PM	0.55 (23)	0.12 (33)	0.96 (20)	1.72 (21)	1.35 (24)	**2.11** (33)
0.25–6.35		**1.98** (27)	**2.03** (28)	**2.68** (30)	**3.81** (28)	2.66 (22)	**3.16** (32)
>6.35		**4.28** (22)	**3.75** (20)	**5.02** (24)	**5.31** (24)	5.25 (16)	4.93 (15)

Note: The numbers in parentheses denote the sample sizes expressed in hours and the values in bold represent the statistical significant *DTT*s at a 95% confidence interval.

Table 4
DTT for different intensities of snow.

Snow (mm/h)	Time period	Difference in total travel time (%)					
		697 Central	19144 Central	695 Inner	708 Outer	709 Outer	723 Outer
0–2.5	AM	**5.54** (8)	**6.03** (6)	6.88 (4)	6.39 (6)	6.21 (5)	**7.12** (7)
>2.5		8.23 (2)	**7.82** (4)	9.14 (4)	9.21 (3)	10.45 (3)	8.93 (2)
0–2.5	INTER	6.33 (5)	**5.86** (7)	**7.12** (6)	6.89 (4)	7.11 (4)	7.54 (4)
>2.5		**9.00** (4)	7.43 (2)	10.02 (2)	10.56 (2)	**11.44** (4)	10.23 (4)
0–2.5	PM	**6.01** (6)	6.41 (5)	**6.18** (7)	7.12 (4)	7.59 (5)	**7.31** (5)
>2.5		9.04 (3)	**8.41** (4)	9.11 (2)	9.72 (3)	10.01 (3)	9.56 (4)

Note: The numbers in parentheses denote the sample sizes expressed in hours and the values in bold represent the statistical significant *DTT*s at a 95% confidence interval.

Table 5
DTT for different temperatures.

Temperature (°C)	Time period	Difference in total travel time (%)					
		697 Central	19144 Central	695 Inner	708 Outer	709 Outer	723 Outer
10–0	AM	−1.15 (62)	0.43 (61)	**0.80** (62)	1.01 (64)	−0.84 (65)	**0.82** (63)
<0		1.54 (12)	0.41 (13)	0.22 (13)	−0.91 (10)	**1.54** (12)	1.02 (10)
10–0	INTER	0.02 (67)	−0.32 (68)	0.17 (69)	−0.43 (70)	−0.09 (68)	0.87 (69)
<0		0.36 (10)	0.25 (12)	−0.65 (9)	1.39 (8)	1.02 (11)	**1.11** (8)
10–0	PM	−0.32 (65)	−0.52 (62)	**1.43** (61)	**1.91** (65)	0.76 (65)	0.93 (67)
<0		**2.18** (12)	0.85 (14)	1.98 (14)	3.18 (13)	**2.07** (14)	−0.38 (13)

Note: The numbers in parentheses denote the sample sizes expressed in hours and the values in bold represent the statistical significant *DTT*s at a 95% confidence interval.

In accordance with prior research findings (Smith et al., 2004; Maze et al., 2005), heavy rain has the most significant effects on travel times. Similar to the other two intensities, outer London yielded the highest *DTT*s (4.04–6.01%), inner London slightly lower (4.21–5.02%) and central London the smallest (3.98–5.34%). Furthermore, 14 out of 18 travel times were found to be statistically different from the corresponding *TTT*s under base conditions.

4.2. Snow

Table 4 presents the percentage difference in total travel time caused by light and heavy snow. One can notice the small number of the statistically significant *DTT*s. This may be attributed to the limited number of snow days during the examined period, which yields small sample sizes. Nevertheless, the *TTT* increases are generally high in all cases and similar in range for the three time periods examined. Specifically, the percentage delays in *TTT* caused by light snow span from 5.54% (central London) to 7.59% (outer London).

Heavy snow consistently results in higher *DTT*s that range between 7.43% (central London) and 11.44% (outer London) confirming the trends previously revealed. The fact that only four *DTT*s are statistically significant may be attributed to the small size of the 'heavy snow' data sets, in contrast to the eight significant *DTT*s derived from the larger data sets developed for light snow conditions.

4.3. Temperature

The significant number of small negative *DTT* values, presented in Table 5, indicates that temperature has a small impact on travel times. Specifically, the first category (0–10 °C) yields *DTT*s that span from −1.15% (central London, AM peak) to +1.43% (inner London, PM peak). Seven *DTT* estimates are negative; nonetheless, the inconsistency of the results over time and across regions, does not allow for the drawing of explicit conclusions on the improvement of travel times. On the contrary, the large data sets in combination with the small number (specifically 4) of statistically significant estimates signify negligible effects on the road network performance.

On average, cold temperatures (<0 °C) cause higher percentage delays; however, similar to the first category, the results vary temporally and geographically, while their contribution is not as pronounced, since they are often accompanied with snowfall. The *DTT*s range from −0.91% (outer London, AM period) to +3.18% (outer London, PM peak). Six cases exhibit lower travel times during cold than higher temperatures, a fact which is contradictory to the consistent results presented in Tables 3–5. All three significant values are positive and greater than 1%, suggesting that cold temperatures may be associated with snow conditions that largely affect travel times, as it was previously shown.

4.4. Comparison with other study results

Table 6 summarises the results of seven studies, produced for different intensities of rain, snow, and temperature. One may notice the variation in the reductions of the speeds across the studies, which may be primarily attributed to different weather, traffic, and socioeconomic characteristics amongst the study areas. For example, Kyte et al. (2001) and Smith et al. (2004) found similar speed reductions for different intensities of rain and snow. This finding is contradictory to the results of the majority of the studies, which suggest that 'intensity matters' (Agarwal et al., 2005; Maze et al., 2005; Wang et al., 2006).

In accordance with most of the studies (Ibrahim and Hall, 1994; Martin et al., 2000; Kyte et al., 2001; Agarwal et al., 2005; Maze et al., 2005; Hranac et al., 2006; Unrau and Andrey, 2006; Wang et al., 2006; Sabir et al., 2008), light rain has the smallest impact on travel times (reduction of 0.1–3.8%). Heavy rain causes greater delays, which are generally lower than those described in HCM, but close in range than those reported by Agarwal et al. (2005) and Maze et al. (2005). These two studies report similar speed reductions due to light snow, but greater delays in case of heavy snow. On the contrary, the speed decreases estimated by Hranac et al. (2006) due to heavy snow (5–19%) are only slightly higher than those caused by light snow (5–16%). Note that the wide ranges reported by Hranac et al. derive from the examination of three areas that experience completely different annual snow precipitation, thus it is very likely that the drivers' behaviour differs on snowed pavement. These findings need to be further investigated, because adverse weather conditions are expected to cause substantial delays in cities where travellers are not used to driving under snow conditions (e.g. London). On the contrary, snowfall may discourage road users from travelling, decreasing traffic demand. A combined examination of traffic volume with travel time data is necessary to uncover more trends behind this finding.

Similar to other studies, temperature has nearly a negligible impact on vehicle speeds (Agarwal et al., 2005; Sabir et al., 2008; Koetse and Rietveld, 2009), as opposed to cyclists, who highly depend on it (Koetse and Rietveld, 2007). Cold temperatures yield small increases in travel times; nonetheless, their contribution is not as pronounced, since they are often accompanied with snowfall. Future research that distinguishes cold temperatures from snow conditions may provide more insights into this topic.

The decreases in travel times of this study are generally lower than the corresponding values reported by HCM (TRB, 2000) and some of the studies. This may be attributed to several reasons. First, by the large number of urban links examined that are associated with lower operational speeds, as opposed to those of American or Canadian rural freeways and expressways. A second explanation is that the majority of the other studies estimate time-mean-speeds (derived from loop-detector data) that are always lower than the more accurate space-mean speeds, on which this analysis is based. A third explanation may stem from the

Table 6
Algebraic and percentage changes in operating speeds from several studies.

Variable	Range	Categories derived from HCM (2000)	Reduction in operating speeds						
			HCM (2000)	Ibrahim and Hall (1994) Mississauga, Ontario (km/h)	Kyte et al. (2001) Idaho (km/h)	Smith et al. (2004) Hampton Roads, Virginia (%)	Agarwal et al. (2005) Twin Cities, Minnesota (%)	Maze et al. (2005) I-35, Northern Iowa (%)	This Study (2010) London, UK (%)
Rain (mm/h)	0–0.2	Light	2–14	0–13	9.5	3–5	1–2.5	2	0.1–2.1
	0.2–6	Light	2–14	0–13	9.5	3–5	2–5	4	1.3–3.8
	>6	Heavy	5–17	5–10	9.5	3–5	4–7	6	3.6–6
Snow (mm/h)	⩽1	Light	8–10	0–8	16.4	N/A	3–5	4	5.5–7.6
	1–2	Light	8–10	0–8	16.4	N/A	7–9	8	5.5–7.6
	2–12	Light	8–10	0–8	16.4	N/A	8–10	9	7.4–11.4
	>12	Heavy	30–40	38–60	16.4	N/A	11–15	13	7.4–11.4
Temperature (°C)	1–10	N/A	N/A	N/A	N/A	N/A	1–1.5	1	−1.2 to 1.9
	0 to (−20)	N/A	N/A	N/A	N/A	N/A	1–2	1	−0.9 to 3.2
	<−20	N/A	N/A	N/A	N/A	N/A	0–3.6	2	−0.9 to 3.2

N/A: Not Available.

trends presented in Tables 3–5, according to which, the longer links within outer London yield higher travel time decreases than inner London, and even greater than the shortest links in central London. In other words, short in length urban links are expected to have lower operating speeds than rural roads or urban freeways, consequently, to experience shorter travel time delays. Based upon the previous statement, the results are comparable with those generated by Agarwal et al. (2005), who used data from a metro region around the Twin Cities. Additionally, they are of similar range with those of Wang et al. (2006), who also examined a signalised urban area in Japan resulting in an average speed decline of 6.03 km/h during heavy rain.

5. Conclusions

Given the lack of detailed guidance on the quantification of speed decreases due to different categories of weather variables, the results of this study may be used to better understand how different intensities of rain, snow, and temperature levels affect macroscopic travel times in the transport network of London. The most important finding of the current study is that the impact of rain and snow is a function of their intensity. Specifically, the ranges of the total travel time increase due to light, moderate and heavy rain are 0.1–2.1%, 1.5–3.8% and 4.0–6.0% respectively. Light snow results in travel time increases of 5.5–7.6%, whilst heavy snow causes the highest percentage delays spanning from 7.4% to 11.4%. Temperature has nearly negligible effects on travel times. It was also found that the longer links within outer London generally yield higher travel time decreases than those in inner London, and even greater than the shortest links in central London. From the comparison of the results with those of past studies it can be concluded that the weather effects on speeds and travel times vary considerably, depending on the target area, geometric, traffic and drivers' characteristics, socioeconomic factors, the roadway functional class, the season of the year and the climate of the examined region.

This research provides planners with additional information, presently not available in the Highway Capacity Manual (TRB, 2000) that can be used in traffic management to modify planning decisions and improve the transportation system control on a network scale under different weather conditions. A macroscopic analysis that combines travel time, traffic flow, and density data is currently undertaken, aiming to explore the relationships of these parameters, overcome limitations, and address questions arose herein. Furthermore, there is a need to use larger data sets in cases of rare weather phenomena, in order to minimise potential effects of the inherent variability of traffic data. Continued research is also needed to replicate this study in other areas that exhibit different characteristics, in order to determine whether the weather effects are region-specific.

Acknowledgments

The authors of the paper would like to thank Transport for London (TfL), Met Office and BADC for providing the data used in the study. This work was completed as part of the STANDARD project (EP/G023212/1), funded by EPSRC and in partnership with Transport for London. The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or polices of TfL or Met Office.

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