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ORIGINAL PAPER

Stochastic modeling of the impact of meteorological conditions on road traffic accidents

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Abstract Meteorological conditions have become one of the major factors that influence the frequency and severity of motor vehicle collisions in urban environments. In Kuwait, more than 60,000 accidents occur each year, and about 500 people are killed annually on the roads. This paper is intended to investigate the impact of meteorological conditions on traffic accidents in Kuwait. Stochastic models are developed to analyze and examine the influence of meteorological conditions on the level of road accidents. Normal and lognormal probability densities and their associated cumulative density functions are used to model the meteorological conditions in four different seasons. The results indicate that the most influential meteorological condition that causes accidents is temperature during the fall, spring, and winter seasons. In the summer, wind speed is identified as the most influential factor that accounts for the increased road accidents, with temperature as the second highest meteorological condition affecting accidents. Wind speed and humidity are also found to have significant influence on accident level, following temperature in the fall and winter seasons, respectively. Correlation analyses were also applied and supported the findings obtained using stochastic analyses. The results of this study may help local authorities to reduce the number of accidents and help save people lives.

Keywords Traffic accidents · Meteorological conditions · Stochastic models · Descriptive and correlation analyses

1 Introduction

The rates of road traffic accidents in metropolitan areas worldwide have risen substantially over at least the last two decades. Decreasing associated severe injuries and fatalities became one of foremost concerns among policy makers and academia. Economic losses from accidents can reach up to 2.5 % of GNP (Elvik 2000). According to the World Health Organization (WHO), 600,000 people die and 15 million are injured in road accidents each year. In the European Union, a total of 1.2 million accidents occur every year, leading to more than 40,000 fatalities. These figures are similar to those of the US, although slightly less. This high number of deaths and casualties is increasingly considered unacceptable. In accordance with the Kuwait ministry of health report, road accidents were the third highest cause of death between 1998 and 2002, which contributes to 7.14 % of the total deaths in Kuwait (Ministry of Health the State of Kuwait 2002). It is also noteworthy to mention that the current fatality-to-injury ratio in Kuwait is about 1:5; respectively, compared with 1:80 in the UK, for example. These statistics indeed show how road accidents have become a central issue in Kuwaiti society.

Many countries have implemented policies aiming to reduce the number of road fatalities. These include enacting seat belt laws, red light running or speeding tickets, and

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enhancement of police enforcement system (e.g., speed cameras). Violations of these policies have caused severe injuries and increased the mortality rate.

Uncontrolled conditions, such as meteorological conditions, have a dramatic influence on road safety. Poor weather varies by area, and the level of risk that poor weather poses for motor vehicle collisions (Cromley 2007) is determined by the road conditions and each driver's behavior. Meteorological conditions such as visibility, temperature, wind speed, and humidity are important factors that affect traffic accidents. In particular, the driver's behavior is often affected by changing meteorological conditions. For example, under different visibility conditions (e.g., dust, haze, rain, or fog), people generally drive slower and simultaneously keep a shorter distance between theirs and the vehicle in front of them. Gusts of wind can push relatively high vehicles, such as busses, delivery vans, camper vans, and caravans, off their path, and under extreme conditions, can even cause them to roll. In addition, high temperature has psychological and/or physiological effects on drivers.

There have been numerous studies regarding the influence of weather conditions as a cause of traffic accidents (e.g., Codling 1974; Palutikof 1991; Edwards 1996). Precipitation, and the resulting poor visibility, is the main cause of many weather-related incidents (Songchitruksa and Balke 2006; Koetse and Rietveld 2009). Keay and Simmonds (2006) investigated the impact of rainfall on daily road accidents in the metropolitan area of Melbourne, Australia, over the period of 1987–2002. Their analysis is performed from several viewpoints of the accident count, which has been normalized for variation in traffic volume, and indicated that the effect of rainfall is multifaceted. In another study (Cromley 2007), the influence of rain or snow conditions was significant on the rate of collisions, based on proportions. Britsy et al. (2008) study the effect of weather conditions on daily crash counts using a discrete time series model. The results show that several assumptions related to the effect of weather conditions on crash counts are found to be significant in the data and that if serial temporal correlation is not accounted for in the model, this may produce biased results. Lu and Tsai (2008) have evaluated the influence of climate on vessel accidents from a seafarer's perspective, specifically in the container shipping context. Factor analysis revealed six safety climate dimensions: management safety practices, supervisor safety practices, safety attitude, safety training, job safety, and coworkers' safety practices. Vinodkumar and Bhasi (2009) have determined safety climate factors and their relationship with accidents and personal attributes in the chemical industry. Jung et al. (2010) investigated the rainfall effect on single-vehicle crash severities using a polychotomous response model. Their study found that the backward sequential logistic regression model produced the best results for predicting crash severities in rainy weather where rainfall intensity, wind speed, roadway terrain, driver's gender, and use of safety belts were found to be statistically significant. Andersson and Chapman (2011) investigated the relationship between temperature and severe road accidents in the West Midlands, UK, using UKCIP climate change scenarios and a temporal analogue. It has been demonstrated that the predicted reduction in the number of frost days should in turn reduce the number of road accidents caused due to slipperiness by $\sim$50 %.

Traffic accidents due to meteorological conditions such as visibility, wind speed, temperature, and humidity are one of the reasons for morbidity and mortality in various parts of the world. To the best of our knowledge, the influence of meteorological conditions on the road traffic accidents in the State of Kuwait has not been systematically analyzed. Consequently, the purpose of this study is to gain better insight on the effect of changing meteorological conditions and their relationships to motor vehicle accidents. The latter is achieved by fitting appropriate probability and accumulative probability densities to the meteorological and accident data. A descriptive analysis using the parameters characterized the fitted models is further performed to draw a casual and meaningful conclusion.

The paper is organized as follows: the meteorological data and method are given in Sect. 2. Section 3 presents the results of the proposed methodology. A thorough discussion is given in Sect. 4, followed by conclusions in Sect. 5.

2 Materials and method

2.1 Data description

Meteorological data were collected daily by the weather station at the Kuwait International Airport, Kuwait. Meteorological data were obtained from March 2009 to March 2010 (1-year data span). The random variables (i.e., accident and meteorological conditions), are normalized by their corresponding mean, X/m, where X and m represent data and their mean, respectively. The variable X/m is created and included in the stochastic model. The choice of variables is based on previous research (studies in the Sect. 1), where they have demonstrated their importance/significance and hypothesized them as being influential toward predicting the number of accidents. The variables of meteorological conditions include temperature, wind speed, humidity, and visibility. Note that the data were daily averages and thus do not reflect instant meteorological conditions. The daily accidents numbers are obtained from the major roads covered by all cities in Kuwait. Information on daily traffic exposure from March 2009 to March 2010 is obtained from the Kuwaiti Ministry of

Table 1 The annual data from Ministry of Interior for the State of Kuwait

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Accident	27,696	31,028	37,650	45,375	54,878	56,235	60,410	63,323	55,78	61,298	62,330
Killed	331	300	315	372	398	451	460	447	410	470	374

Interior. More specifically, for each city region, daily vehicle counts are obtained for each road segment of the major road network based on loop detector data. Taking into account the length of the road segments, this enables us to calculate the day-to-day total amount of vehicle kilometers driven on the major road network of each city region. Table 1 indicates the annual data from the Ministry of Interior for the state of Kuwait from 2000 to 2010. It should be mentioned that 71–73 % of accidents took place during the work day due to high pedestrian and traffic volumes during these times compared to the same times during weekend days. The lowest number of the accidents was reported in the year 2000 and was estimated to be 27,696. The least number of those killed is reported in 2001 as 300, during which time the associated accident count was 31,028. On other hand, the highest numbers of accidents were 61,298 and 62,330 during the years 2009 and 2010, respectively. Therefore, it is of great importance that we investigate the factors that most influence the traffic accidents in Kuwait during the years 2009 and 2010.

2.2 Stochastic models

The traffic accident data randomly fluctuate due to changes in meteorological conditions. In stochastic models, the probability density function (PDF) is mostly used to model random distribution with various applications. For a continuous random variable, the PDF is the probability that the variable has a value x. Since the probability for continuous distributions at a single point is zero, it is often expressed in terms of an integral between two points.

The PDF, P(x), of a continuous distribution is defined as the derivative of the cumulative distribution function D(x),

$$D'(x) = [P(x)]_{-\infty}^{x} \tag{1}$$

$$= P(x) - P(-\infty) \tag{2}$$

$$= P(x), \tag{3}$$

so,

$$D(x) = P(X \leq x) \tag{4}$$

$$= \int_{-\infty}^{x} P(\xi) d\xi \tag{5}$$

a probability function satisfies

$$P(x \in B) = \int P(x) dx \tag{6}$$

and is constrained by the normalization condition,

$$P(-\infty < x < \infty) = \int_{-\infty}^{\infty} P(x) dx = 1 \tag{7}$$

the normal distribution of the PDF is commonly used in such studies, it is given as:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(x-u)^2/(2\sigma^2)} \tag{8}$$

the following is the normal distribution cumulative density function (CDF):

$$D(x) = \frac{1}{\sigma\sqrt{2\pi}} \int_{-\infty}^{x} e^{-(x'-u)^2/(2\sigma^2)} dx' \tag{9}$$

the Lognormal distribution is a function in which variables become logarithmic variables in the normal distribution. Thus, the lognormal distribution PDF and CDF are:

$$P(x) = \frac{1}{\sigma\sqrt{2\pi}x} e^{-(\ln x - \mu)^2/(2\sigma^2)} \tag{10}$$

and

$$D(x) = \frac{1}{2}\left[1 + erf\frac{(\ln x - \mu)}{\sigma\sqrt{2}}\right] \tag{11}$$

where conditions σ and μ can be determined conveniently by calculating the mean and standard deviations of the natural logarithms of the data. Two issues should be emphasized at this point. First, normal and lognormal have been chosen as the basis distributions in this study. The choice has not been made arbitrarily; instead, different distributions have been tested. It turns out that normal and lognormal distributions are those that give a satisfactory fitting of the accident and the metrological data. Second, it is well known that accident counts would be properly fitted using a Poisson distribution. However, since the normal distribution can serve as an approximation to the binomial, and the binomial and the Poisson distributions are closely connected, it seems reasonable that the normal distribution approximate the Poisson (Montgomery 1997). The above approximation is adopted in the current work.

3 Results

The main purpose of this section is to assess the predictive performance of the stochastic models that have been developed in the previous section. In order to investigate how traffic accidents will change under various meteorological conditions, descriptive, stochastic, and correlations analyses were used to study the relationship between the traffic accidents and each meteorological conditions (temperature, humidity, visibility, and wind speed) during four seasons: spring (March 21–July 20), summer (July 21–September 20), fall (September 21–December 20), and winter (December 21–March 20).

3.1 Descriptive analysis

Table 2 shows a descriptive analysis to highlight the influence of meteorological conditions on traffic accidents during the winter, spring, summer, and fall seasons. In the succeeding section, the effect of each meteorological condition on the traffic accidents was statistically evaluated during the four different seasons in attempts to establish a correlation between the different variables.

3.2 Temperature

Comparing the mean values for temperature and road accidents listed in Table 2 during the four seasons, it is clear that increase in the temperature induces a greater accident level. The mean temperatures for winter, fall, and spring were 15, 18.6, and 27.6 °C, respectively, and the corresponding mean accidents were 182.8, 206.2, and 210, respectively. This indicates that, with each incremental increase in the temperature, there was an increase in accident level accordingly. This shows a positive linear relationship between temperature and accident level during the winter, fall, and spring

Table 2 Descriptive analysis during spring, summer, fall and winter seasons

	Descriptive statistic					
	Min.	Max.	Mean	Std.	Skews	Kurtosis
Season winter (December 21–March 20)						
Accident no.	87	290	182.8	53	−0.063	−0.97
Meteorological parameters						
Temperature (°C)	4.7	24.6	15	4.2	−0.15	0.044
Humidity (%)	18	95	57.3	22	0.072	−1.075
Visibility (km)	0.2	20	11.6	7	−0.1	−1.5
Wind speed (m/s)	0.3	16.5	4.5	2.6	1.41	4.7
Season spring (March 21–July 20)						
Accident no.	84	321	210	48.9	−0.59	−0.19
Meteorological parameters						
Temperature (°C)	14	40	27.6	5.97	−0.4	−0.71
Humidity (%)	8	97	27.7	21.8	1.7	2.04
Visibility (km)	0.9	20	11.5	6.17	0.02	−1.33
Wind speed (m/s)	0.7	13	5.5	2.46	0.51	0.45
Season summer (July 21–September 20)						
Accident no.	101	275	182.3	40.7	−0.23	−0.66
Meteorological parameters						
Temperature (°C)	25	49.7	32.3	2.4	−0.73	1.03
Humidity (%)	6	73	19.4	13.56	2.6	6.34
Visibility (km)	0.9	20	12.6	5.7	−0.27	−1.08
Wind speed (m/s)	1.4	9.7	6.2	1.82	−0.51	0.90
Season fall (September 21–December 20)						
Accident No.	101	332	206.2	56.9	−0.21	−0.93
Meteorological parameters						
Temperature (°C)	9.4	29	18.6	6	0.07	−1.55
Humidity (%)	12	100	60.3	29.8	−0.37	−1.47
Visibility (km)	0.1	20	11.3	6.9	−0.10	−1.44
Wind speed (m/s)	0.9	9.2	4.4	1.9	0.21	−0.33

seasons. In the summer season, although the mean temperature increased to 32.3 °C as shown in Table 2, the mean value for accidents declined to 182.3, which is inconsistent with the results observed during the other three seasons. This presents the possibility that temperature does not have a significant impact on accidents, but it is possibly related to traffic density. Summer in the State of Kuwait and also other parts of the world are characterized by less traffic volume due to annual educational institutes' and employees' holidays. Skewness (i.e., lack of symmetry) and kurtosis (i.e., data are peaked or flattened relative to a normal distribution) (see Table 2), are also supported the trend observed above. Note that the excess kurtosis is being followed in this work; i.e., for normal distribution, excess kurtosis equal to zero. As the mean temperature increases, the accidents skewness decreases (skews to the left) and accidents kurtosis increases, which indicates that the distribution becomes less flat (negative kurtosis value) relative to a normal distribution during winter, fall, and spring seasons, respectively. Again, there was discrepancy in the skewness and kurtosis analysis during the summer season, which is consistent with the previously observed trend. This is again likely due to the lower traffic density in the summer compared to that of other seasons.

3.3 Wind speed, humidity, and visibility

According to the statistical results listed in Table 2, there was no direct relationship between the accident level and changes in wind speed, humidity, and visibility. For example, with increased wind speed from 4.4 (m/s) in the fall to 4.5 and 5.5 (m/s) in winter and spring, respectively, the associated mean accidents were 206.2, 182, and 210, respectively. With an increase in wind speed to 4.5 (m/s), the mean accident decreased, but with the next step of increase, the accidents increased again. Humidity and visibility show similar trends to those observed with wind speed. These discrepancies indicate that there is no consistent relationship between the accident levels and the changes in wind speed, humidity, and visibility. This is possibly due to the dominant effect of temperature on other meteorological conditions, which makes the determination of their correlation type with accidents difficult to identify. This indeed increased the interest to identify such relationships between accident level and meteorological conditions or at least to identify the significance of each meteorological condition during each season, which will be investigated in the next section (stochastic analysis).

3.4 Stochastic analysis

The variable of the accident and meteorological conditions were normalized by its mean, X/m, in order to illustrate the change in the shape of the PDF and CDF of the accidents with changing meteorological conditions. Figures 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 show the normal and lognormal PDF and CDF of the traffic accidents and meteorological conditions during the four seasons. The features of the normal and lognormal PDF and CDF for the traffic accidents and meteorological conditions during the four different seasons are as follows.

3.5 For the spring season

Figures 1 and 2 show the normal and lognormal PDF of both traffic accidents and metrological conditions. It is clear from Fig. 1 that the normal PDF of the traffic accidents and temperature demonstrate a symmetrical sharp and narrow curve. With wind speed and visibility, the normal PDF has a symmetrical but wide curve. With humidity, the normal PDF shape was wide with a right-hand skew. The highest value

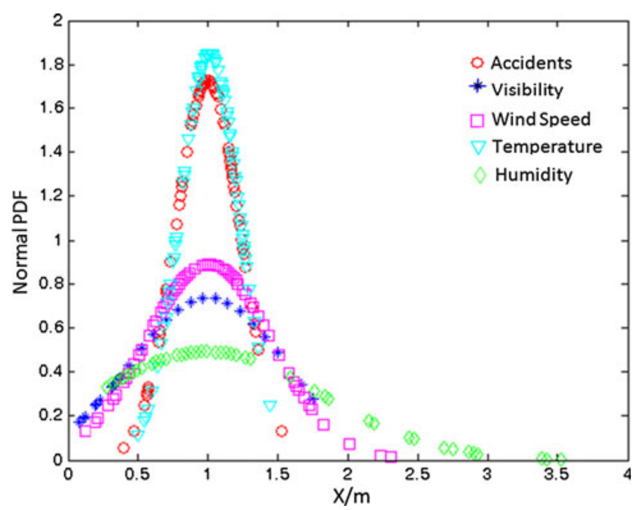

Fig. 1 Normal PDF during spring season

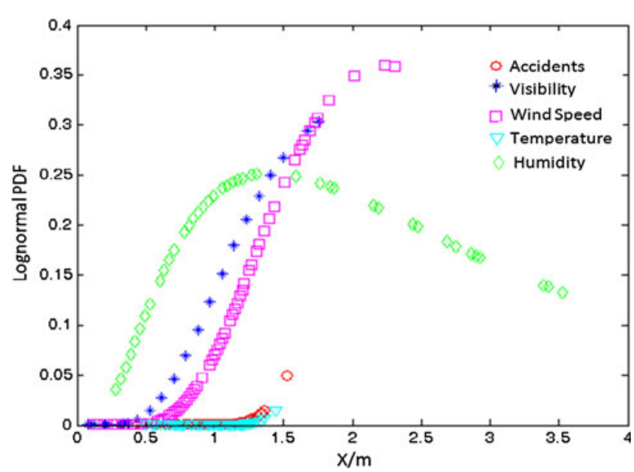

Fig. 2 Lognormal PDF during spring season

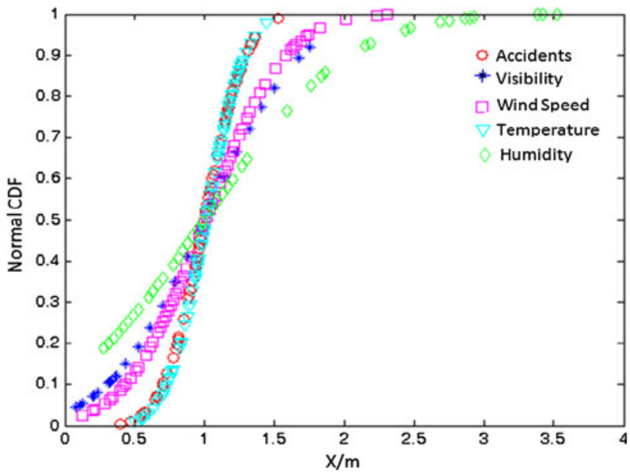

Fig. 3 Normal CDF during spring season

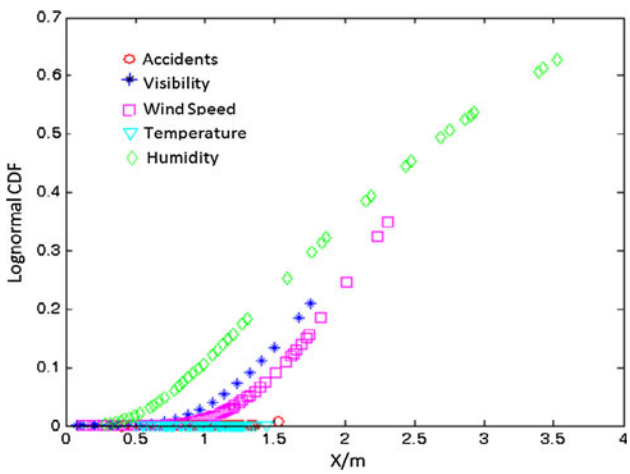

Fig. 4 Lognormal CDF during spring season

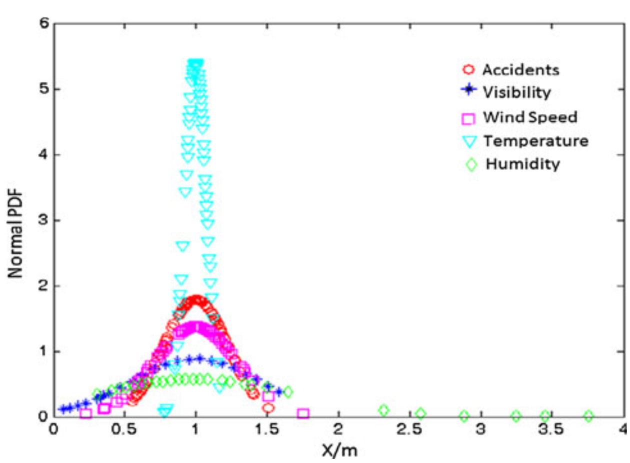

Fig. 5 Normal PDF during summer season

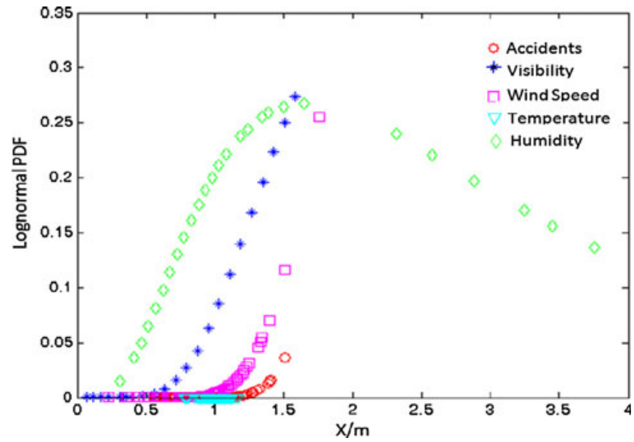

Fig. 6 Lognormal CDF during summer season

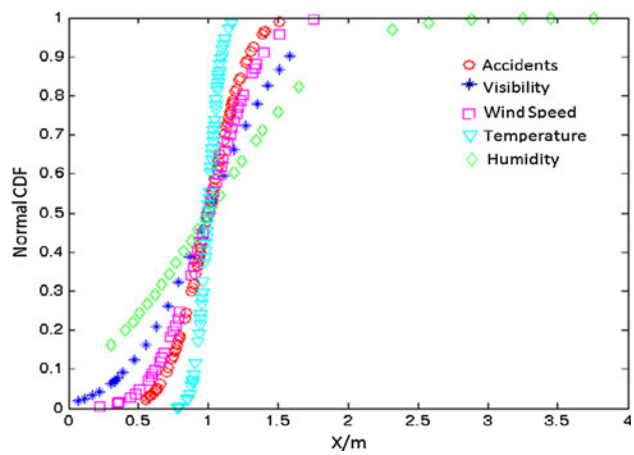

Fig. 7 Normal CDF during summer season

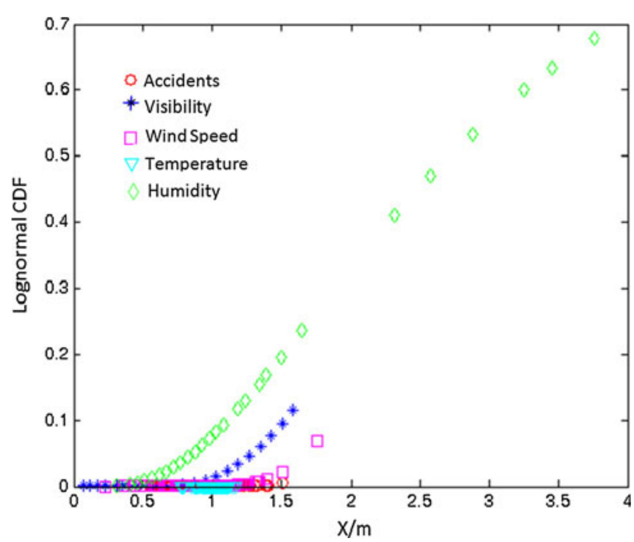

Fig. 8 Lognormal CDF during summer season

the normal PDF reached was 1.9 and appeared with temperature, while the lowest value was 0.5 and appeared with humidity. According to lognormal PDF (Fig. 2), the low values of the lognormal PDF appeared with accidents and temperature. It should be highlighted that the normal and lognormal PDF of the traffic accidents were very close to

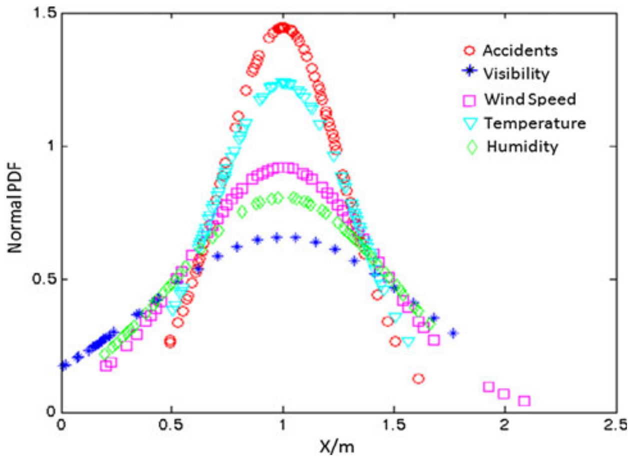

Fig. 9 Normal PDF during fall season

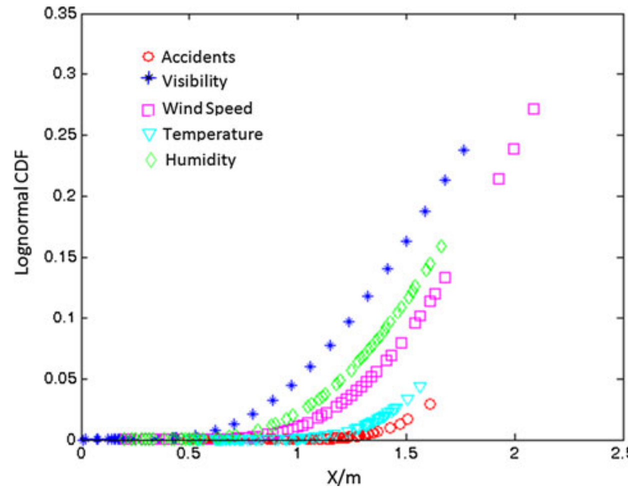

Fig. 12 Lognormal CDF during fall season

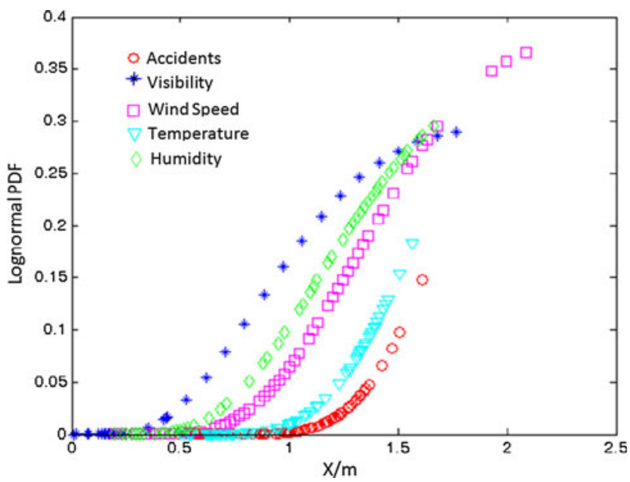

Fig. 10 Lognormal PDF during fall season

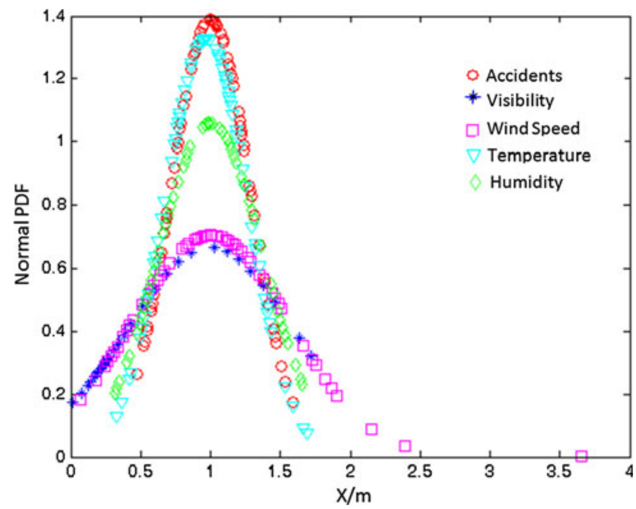

Fig. 13 Normal PDF during winter season

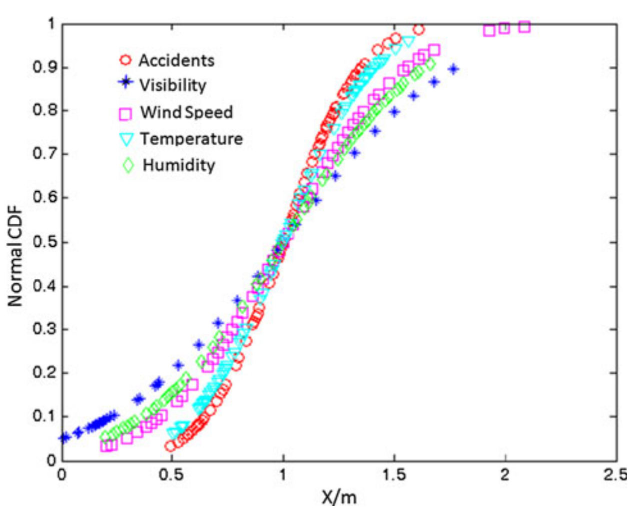

Fig. 11 Normal CDF during fall season

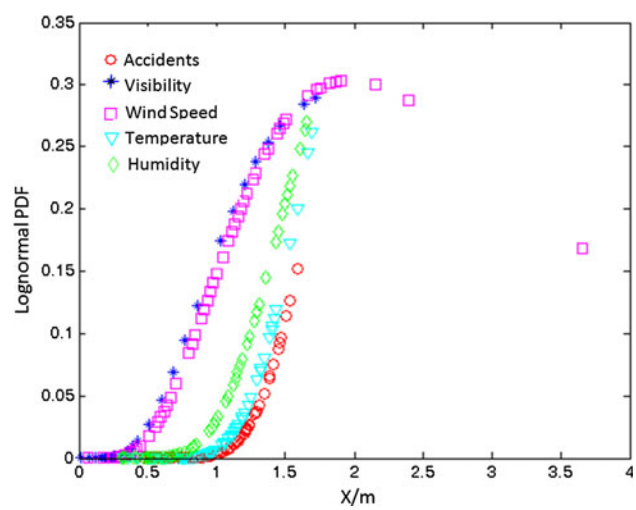

Fig. 14 Lognormal PDF during winter season

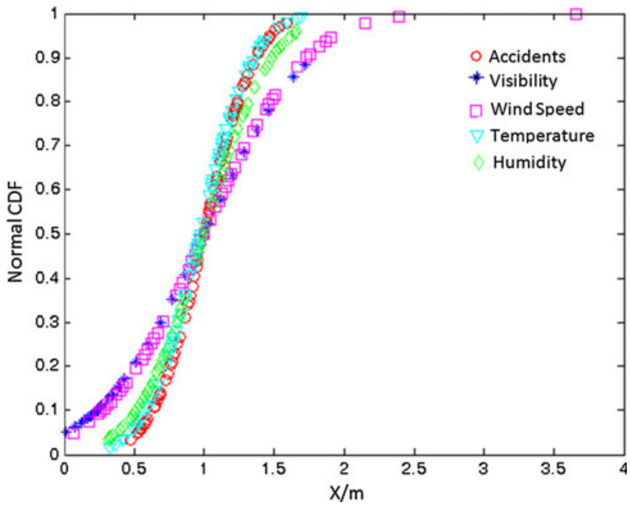

Fig. 15 Normal CDF during winter season

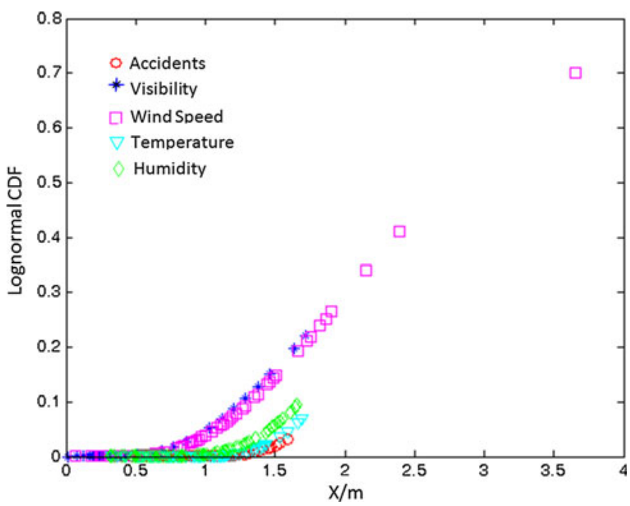

Fig. 16 Lognormal CDF during winter season

temperature in the sense of shape and values, as shown in Figs. 1 and 2. These similarities indeed show that temperature had a strong effect on the road accidents. The normal and lognormal CDF of traffic accidents as well as metrological conditions are shown in Figs. 3 and 4. As shown in Figs. 1 and 3, the normal PDF and CDF of the traffic accidents were far from wind speed, visibility, and humidity. This would in turn lead to the fact that wind speed, visibility, and humidity have a low effect on road accidents during the spring season. One main interesting feature is that the value and shape of the normal and lognormal CDF of the accidents was again similar to that of temperature, which is consistent with the previous observation (Figs. 1, 2). It is also important to mention that the normal and lognormal CDF of the accidents and temperature (Figs. 3, 4) were observed as higher than that of the wind speed, visibility, and humidity at 0.5< CDF <1. Conversely, the normal and lognormal CDF of the accidents and temperature was lower than that of the wind speed, visibility, and humidity at 0.0< CDF <0.5.

3.6 For the summer season

The normal and lognormal PDF of accidents and metrological conditions during the summer season are reported in Figs. 5 and 6. Again, the normal PDF of temperature (Fig. 5) was sharp and narrow, similar to the trend observed in the spring season (previous section). As shown in Fig. 5, the shape of the normal PDF of accidents was also narrow but wider than that with temperature. The value of normal PDF of accidents was also less than that observed with temperature. With visibility and humidity, the shape of normal PDF was symmetrical and wide. It is also noteworthy to mention that the high value of the normal PDF and the lowest value of the lognormal PDF of the meteorological conditions appeared with temperature, which is consistent with the trend observed in the spring season (previous section). Another interesting observation is that wind speed became the most influential meteorological conditions on road accidents, as shown in Figs. 5 and 6, as the shape and values of the normal and lognormal PDF are very close. Temperature has become the second influential factor affecting the road accidents after wind speed. Figures 7 and 8 show the normal and lognormal CDF of road accidents and metrological conditions during the summer season. As shown in Figs. 7 and 8, the normal and lognormal CDF of road accidents and wind speed are almost identical, which indicates a strong direct correlation between the two. The temperature effect on road accident was also found to be significant after wind speed, as shown in Figs. 5, 6, 7 and 8. According to the normal and lognormal PDF and CDF (Figs. 5, 6, 7, 8), the rate of road accidents was largely affected by wind speed and then by temperature.

3.7 For the fall season

Figures 9, 10, 11 and 12 show similar stochastic analysis to those reported in previous sections. Interestingly, the shape of the normal PDF of both traffic accidents and meteorological conditions (Fig. 9) were symmetrical but with different sharpness. The shape of the normal PDF of both accidents and temperature were narrower than that of the other metrological conditions, and the shape of the normal PDF of visibility was the widest. The highest value of the normal PDF was found with the accidents, whereas the lowest normal PDF value was that of visibility. Figure 10 shows the lognormal PDF for road accidents and meteorological conditions. The highest values of the lognormal PDF were found with visibility while the lowest values were found with accidents. In line with Figs. 9 and 10, it is obvious that the normal and lognormal PDF of road accidents were similar to those with temperature. The normal and lognormal CDF analysis, which are shown in Figs. 11 and 12, are also similar and consistent with normal and lognormal PDF analysis, which shows that the temperature effect is greatest on road accidents, compared with other meteorological conditions. According the stochastic analysis shown in Figs. 9, 10, 11 and 12, wind speed became the second most influential condition after temperature, and visibility was found to be the least condition affecting road accidents.

3.8 For the winter season

The normal and lognormal PDF and CDF of accidents and metrological conditions during the winter season are plotted in Figs. 13, 14, 15 and 16. The shape of the normal PDF of accidents, temperature, and humidity was symmetrical and narrow, while with visibility and wind speed, the normal PDF shape was symmetrical and wide, as shown in Figs. 13 and 14. The high values of the normal PDF were observed with the accidents, and low values were with visibility. The high values of the lognormal PDF were observed with visibility, and wind speed and low values were with accidents. The closed values of the normal and lognormal PDF of the accident were found with temperature. The second meteorological condition close to accidents was found to be humidity. Similar observations were observed with normal and lognormal CDF analysis (Figs. 15, 16), where again temperature was found most influential on road accidents and then humidity. Conversely, the least affecting condition found was visibility, which is consistent with the normal and lognormal PDF analysis. This finding is in line with previous studies, where temperature has found to be significant on road accidents, especially in combination with humidity or rain (Branas and Knudson 2001; Brown and Baass 1997; Fridstrom et al. 1995; Fridstrom and Ingebrigtsen 1991). The data reported in Figs. 13, 15 and 16 indicate that temperature was the most influencing factor, then humidity, whereas visibility was the least affecting factor on road accidents.

3.9 Correlation analysis

Spearman rank order and Pearson product moment correlations are applied to further investigate the relationship between metrological conditions and the number of accidents over all four seasons. Results obtained are shown in Fig. 17a–d. As shown in Fig. 17, there was a significant positive correlation between temperature and the number of accidents in spring, fall, and winter. The correlation coefficients (R) vary between 0.77 and 0.84 and with p value <0.05. Such results confirm the strong impact of temperature on accidents, which is indeed expected in such an arid-dry county like Kuwait. In the summer, as shown in Fig. 17b, the correlation between wind speed and the number of accidents was significant with the correlation coefficients of 0.81 and p value <0.05, which indeed demonstrate the influence of wind speed on accidents in summer. These obtained results using a correlation analysis are consistent with the descriptive and stochastic analyses applied in the previous sections.

4 Discussions

In terms of seasons, the majority of road accidents in this study were reported during the spring and fall seasons. These findings appear to agree with previous studies, which reported that most accidents occur during early July and September (Rashed 1982). These high accident numbers could be attributed to the increased numbers of daylight hours during the months of May, June, and July, which eventually leads to greater traffic volume. Satterthwatte (1976) report that sunlight can make the driver's task more difficult due to greater dazzlement. In September, the increased number of accident could be ascribed to the beginning of the academic year and return from public holidays in Kuwait, leading to increased traffic density. Conversely, the lowest accident average reported in this study was during summer. The lowest accident average in summer could be due to the decreased traffic volume, as summer is characterized by annual educational institutes' and employee holidays.

The results of this study have illustrated the importance effect of temperature on traffic accident numbers during all seasons except summer, during which wind speed was shown to have a stronger influence than other metrological conditions, although temperature ranks as the second most influential factor affecting accident number. These findings are consistent with previous studies, which present a significant positive correlation between the number of accidents and temperature over a wide range of months (Rashed 1982; Satterthwatte 1976). The influence of temperature on number of accidents can be interpreted by several possible reasons. First, exposure to heat radiation (temperature) is likely a major source of drivers' discomfort. Previous studies have reported that drivers' performance is likely to deteriorate within a few degrees above the optimum temperature, when drivers tend to be irritable and drowsy (McDonald 1984). Additionally, a driver will experience fatigue on a trip under intense sunlight exposure, which can adversely affect drivers' performance. Secondly, the prolonged exposure to heat stress (temperature) can deteriorate drivers' health conditions, which

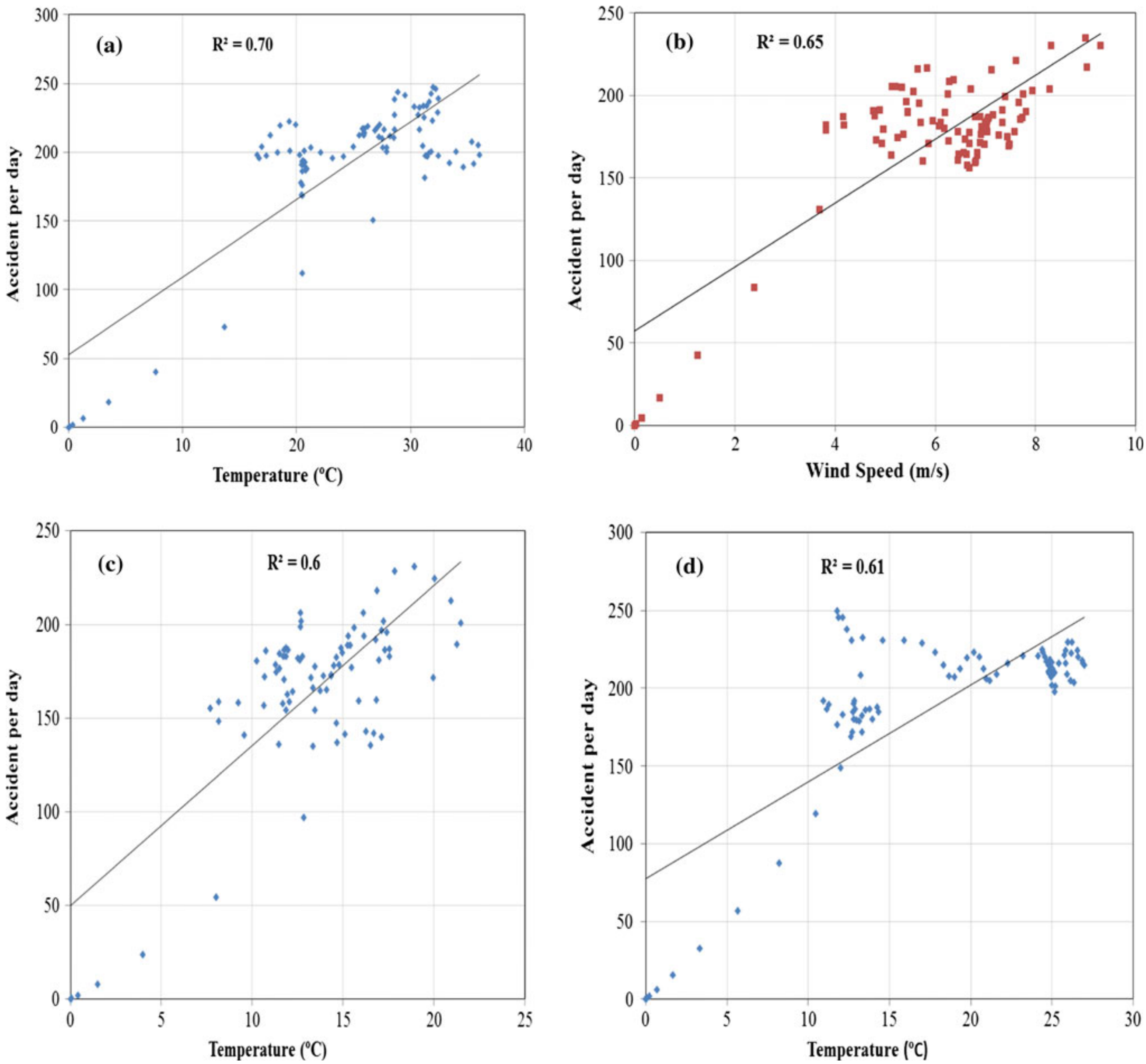

Fig. 17 Correlation analysis for **a** spring, **b** summer, **c** fall, and **d** winter

would affect his/her performance, which could eventually lead to road accidents (Mackie and O'Hanlon 1974; Fletcher et al. 1967; Vyazitskiy and Kumanichkin 1970; Honsbeen et al 1987; Hanson et al. 1995). In one study (Fletcher et al. 1967), it was reported that drivers' heart rate increased under heat stress conditions, while in another study it was found that heat stress can exacerbate existing pathologic conditions, such as heart disease and emphysema (Vyazitskiy and Kumanichkin 1970). Moreover, a severe loss of visual acuity was reported under exposure to thermal strain (Honsbeen et al. 1987). Similar observations were also reported in a previous study (Hanson et al. 1995). Despite the fact that a large number of new vehicles are equipped with air conditioning, numerous older vehicles are either not air conditioned or have poorly functioning air conditioning systems, particularly during exposure to hot temperatures. Other than drivers' discomfort and health conditions when exposed to heat stress, another possibility is burst tyres due to exposure to intense heat. Shanks et al. (1994), reported that burst tyres due to intense heat is recognized as a common cause of traffic accidents. Overall, all possibilities proposed above could explain the direct proportional effect of temperature on the number of road accidents.

In this study, in addition to temperature, wind speed was identified as the most influential factor account for increased road accidents in the summer season and the second most significant metrological conditions in the fall season. It is well known that the stability of a vehicle against wind speed depends on the vehicle's physical characteristics. Trucks and busses are more resistant to wind conditions due to their stronger physical characteristics as compared with passenger cars. The cross wind applied to the side of vehicle is typically as strong as the vehicle velocity induced air speed; the air pressure acting sideways can therefore be as great as the drag force in the driving direction. In the State of Kuwait, 77 % of vehicle accidents were identified in police reports as involving passenger cars in the year of 2000. Passenger cars are preferably used over public transport systems (busses) due to the long waiting period associated with bus travel duration, especially during months of hot temperature. Additionally, people prefer passenger cars (private cars) due to the low price of fuel in Kuwait. Therefore, since passenger cars are commonly used in the State of Kuwait, wind speed effects on road accidents is inevitable, which was indeed observed in this study, especially in the summer and fall seasons.

In the winter season, humidity has been found to be positively correlated with the number of road accidents in this study. This is possibly attributed to sweat evaporation and increased heart stress as a result of humidity. It should be mentioned that humid weather has been reported to have a great effect on accidents in California, USA (Satterthwatte 1976). In another study (Dhondt et al. 2011), it was reported that humidity also contributes to higher mortality rates in accidents, which is indeed consistent with our findings in winter. Furthermore, it should be emphasized that high humidity induces clouded windows and windscreens during rain, which would eventually lead to reduced visibility and thus increase the chance of accidents.

In summary, the influence of metrological conditions on road accidents has been examined. Our results show that an increase in temperature leads to increased accidents largely in all seasons, with the exception of the summer season, where wind speed was found to contribute slightly more than temperature. It is also found that wind speed has an influential effect during the fall season after temperature. In winter, humidity appeared to have a direct proportional effect on accidents succeeding temperature. These findings indeed show that intensive efforts are needed to improve driver education and awareness about the effect of weather conditions on driver health and performance. These efforts are of great importance in the State of Kuwait because of the massive increase in citizen and expatriate driver populations each year. Additionally, reducing the working hours during hot months or shifting of working hours to early morning times can help drivers avoid exposure to hot temperatures, which would contribute to a reduction in the road accident numbers. Finally, it is important to note that these suggestions are useful for any other countries that experience similar weather conditions.

5 Conclusion

The impact of meteorological conditions on road traffic accidents from several viewpoints were analyzed using stochastic modeling. The current study clearly indicates that there is a significant influence of meteorological conditions on accident rates. Temperature was found the most influential meteorological condition causing accidents during the fall, spring and winter seasons. During the summer season, wind speed was identified as the most influential factor that accounts for increased road accidents, and temperature appeared to be another meteorological condition affecting accidents. The second most influential metrological condition subsequent to temperature was humidity in the winter season and wind speed in the fall season. Correlation analyses were also performed and indeed supported the findings using stochastic analyses. These findings can help policy makers in the State of Kuwait to reduce the level of road accidents either through education programs or modification of working hours to reduce exposure to such severe metrological conditions found in this study.

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