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Dynamic and Non-Linear Analysis of the Impact of Diurnal Temperature Range on Road Traffic Accidents

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Abstract: The diurnal temperature range (DTR) is a significant indicator of climate change, and a previous study has shown its impact on human health. However, research investigating the influence of DTR on road traffic accidents is scarce. Thus, this study aims to evaluate the impact of changes in DTR on road traffic accidents. The present study employs two methods to address the complexities of road accidents. Firstly, panel data from 20 cities and counties in Taiwan are utilized, and the autoregressive distributed lag (ARDL) model is employed for estimation. Secondly, distributed lag non-linear models (DLNMs) are used with quasi-Poisson regression analysis to assess the DTR's lagged and non-linear relationships with road accidents using time series data from six Taiwanese metropolitan cities. The study results indicate that a decrease of 1 °C in DTR raises long-term road traffic accidents by 17.1%. In the short term, the impact of declining DTR on road accidents is around 4%. Moreover, the effect of low DTR values differs in each city in Taiwan. Three cities had high levels of road accidents, as evidenced by an increase in the relative risk value; two cities had moderate responses; and one city had a relatively lower response compared to high DTR values. Finally, based on the cumulative relative risk estimations, the study found that a low diurnal temperature range is linked to a high road traffic accident rate, especially during the lag-specific 0–5 months. The findings of this study offer fresh evidence of the negative impact of climate factor on road traffic accidents.

Keywords: diurnal temperature range; climate factor; air pollution; road accident

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1. Introduction

As per the report by the World Health Organization (WHO) in 2018, road traffic accidents (RTA) are the foremost cause of mortality for children and young adults aged between 5 and 29 years, which surpasses deaths caused by HIV/AIDS, tuberculosis, and diarrheal diseases. The report further indicates that apart from the deaths, about 50 million people are subjected to non-fatal injuries and other health impacts due to road accidents [1]. In this scenario, achieving the Sustainable Development Goals (SDGs) target of reducing road accidents by half appears to be complex [2].

Numerous prior studies have endeavored to determine the factors that contribute to road traffic accidents (RTAs). A report from the World Health Organization (WHO) in 2018 estimates that one of the primary reasons for such accidents is the rising number of motorized vehicles. The number of vehicles globally has grown rapidly, from 0.85 billion in 2000 to 2.1 billion in 2016 [1]. Along with structural factors like the number of vehicles, road quality, and traffic flow, several studies have found that air pollution is also a contributing factor to RTA. Sager's seminal paper [3] demonstrated that air pollution, particularly $PM_{2.5}$, is strongly associated with RTAs in the United Kingdom. The study employed atmospheric temperature inversions as a source of plausibly exogenous variations in daily air pollution levels. Similarly, Ahmadi et al.'s [4] study in Tehran supported the earlier findings from Sager [3], using the same approach.

In addition to air pollution, weather-related factors are also linked to RTAs. Theofilatos and Yannis [5] discovered a strong association between precipitation and RTAs. A study conducted in Saudi Arabia using samples revealed that weather factors such as temperature, rainfall, and sandstorms have a significant effect on RTAs [6]. However, Hermans, et al. [7] have reported that weather factors such as wind speed, temperature changes, and humidity have a mixed impact on RTA.

As climate-related factors have not yet been extensively researched as one of the leading causes of road traffic accidents (RTAs), and since safe driving necessitates not just physical fitness but also cognitive and sensory skills [8,9], this study seeks to address this research gap. Within this context, the study explores the impact of diurnal temperature range (DTR) on the rise in road traffic accidents. Prior studies on the effects of temperature shock and DTR on the human body have proposed DTR as a factor influencing road traffic accidents [10–13].

The diurnal temperature range (DTR) is a crucial global climate change indicator. Easterling, et al. [14] define DTR as the daily difference between the maximum temperature (Tmax) and minimum temperature (Tmin). DTR has been suggested to provide more insight into climate change than solely global mean surface temperature [15]. In recent years, DTR has piqued the interest of scientists, with considerable attention paid to its effects on the human body. Liang, et al. [16] discovered a significant positive correlation between DTR and chronic obstructive pulmonary disease (COPD) in a seminal study. Previous research has also revealed a connection between DTR and hospitalizations for cardiovascular and respiratory ailments [17]. DTR is likewise associated with increased non-accident mortality, cardiovascular mortality, and cool season mortality from respiratory diseases in acute cases [18,19].

The motivation for this study is based on previous research that suggests a strong connection between the diurnal temperature range (DTR) and its impact on human health and cognition. This study aims to fill the gap in the literature by measuring the impact of DTR on road traffic accidents in Taiwan. To the authors' knowledge, no previous study has examined the impact of DTR on road accidents. The study is expected to contribute to the literature on the impact of climate factors on road traffic accidents in several ways. First, it will provide evidence that climate-related factors have a broader impact on human mobility risks beyond just human health. Second, the study will facilitate a broader discussion of the adverse effects of climate-related factors on human safety. Finally, the study results are expected to inform the government's implementation of road safety protocols that take into account the impact of climate-related factors, specifically DTR.

2. Literature Review

DTR is a significant parameter in the assessment of global climate change owing to its sensitivity towards changes in radiative energy balance. The sensitivity of DTR towards these changes makes it an appropriate measure, as stated by Makowski, et al. [20] and Sun, et al. [21]. Braganza, et al. [15] have observed a decline in DTR over the last five decades due to a more substantial increase in daily minimum temperature than daily maximum temperature. The reduction in DTR is attributed to an increase in temperature, leading to a decrease in DTR as per Adekanmbi and Sizmur [22]. They have further established that this decline in DTR is associated with a decrease in the duration of sunlight and an increase in the number of clouds. The aerosols, precipitation, and water vapor have been considered as some of the potential causes of such cloud formation.

The variability in DTR on a local scale has been an area of interest in the scientific community due to its potential implications for climate change and human health. While global trends suggest a decrease in DTR due to an increase in daily minimum temperature, local variations can be attributed to factors such as cloud cover, precipitation, and water vapor. The sensitivity of DTR to such factors has been demonstrated by various studies, including those conducted by Liu, et al. [23] and Shen, et al. [24]. Additionally, DTR variations on a local scale can also be influenced by seasonal characteristics and anthropogenic factors, as discussed by Easterling, et al. [14] and Shen, et al. [24].

The influence of the diurnal temperature range (DTR) on human health has been well-established in numerous studies. Cheng, et al. [25] conducted a systematic review that found a significant association between DTR and mortality and morbidity, particularly for cardiovascular and respiratory diseases. The study also revealed that parents and children are more susceptible to DTR changes. The correlation between DTR and respiratory mortality was further investigated by Kim, et al. [26], who found that DTR has a greater effect on parents, and that the impact varies depending on geographical factors. Furthermore, various studies using broader datasets have linked DTR with death rates in several countries, and show that the mortality burden due to DTR has been increasing for several decades [27]. This indicates that the negative effects of DTR on human health are persistent and likely to worsen in the future as global climate change continues to drive temperature variability. However, further research is necessary to fully understand the mechanisms underlying these associations and to develop effective strategies for mitigating the impact of DTR on human health.

When exploring the impact of temperature changes on human physiology, researchers have found that it is not just the physical body that is affected, but also the cognitive abilities of individuals. According to recent studies, neuro-behavioral performance tests can be influenced by variations in air temperature, leading to changes in response time and cognitive performance [28]. In a study conducted by Khan, et al. [29], word list learning and recall tests were utilized to examine the relationship between temperature changes and cognitive abilities. The results showed that cooler temperatures in traditionally warmer regions were associated with changes in cognitive skills. Furthermore, Zivin, et al. [30] analyzed data from China's National College Entrance Examination (NCEE) and discovered that a 2 °C increase in temperature resulted in a reduction of 0.68% in the total test score. These findings are further supported by a study conducted by Park, et al. [31], who tested 10 million students retaking the PSATs and found similar results. These studies demonstrate the impact of temperature changes on cognitive performance and highlight the need for further research in this area.

The objective of this study is to contribute to the existing literature regarding the effects of diurnal temperature range (DTR) on road traffic accidents. Although some studies have explored the impact of DTR on human health, a comprehensive investigation of its effect on road traffic accidents has yet to be conducted. Therefore, this study aims to address this gap in knowledge by providing additional insights into the relationship between DTR and road traffic accidents. Furthermore, this study will also expand the current understanding of road traffic accidents caused by environmental factors. Although past research has primarily focused on the impact of air pollution on road traffic accidents, this study will broaden the scope to include the impact of DTR, which is a critical environmental factor that may significantly influence road safety. As such, the findings of this study will be a valuable addition to the literature and can provide useful insights for policymakers and stakeholders to enhance road safety strategies and policies.

3. Data and Methodology

3.1. Data

The present research employs a monthly dataset spanning over a long period of time from 20 different regions in Taiwan, specifically from 2008 to 2021, to conduct a comprehensive panel analysis. In order to further enrich the investigation, the study also utilizes time series data gathered from six of Taiwan's major cities, namely Taipei, New Taipei, Taoyuan, Taichung, Tainan, and Kaohsiung. The data utilized in this study are sourced from various institutions, including the Ministry of Transportation's Taiwan's Road Traffic Safety Data, which provide the number of traffic accidents per day. The study also draws on climate data, including the diurnal temperature range, calculated using daily maximum and minimum temperatures from the Barkeley Earth Database and Taiwan's Central Weather Bureau. In addition, air pollution data are included in this study, which were gathered from a number of reliable sources such as Taiwan's Central Weather Bureau and the Taiwan air quality monitoring network from the Environmental Protection Administration. By utilizing this rich and diverse data, the study aims to provide a nuanced understanding of the relationship between road accidents, climate, and air pollution in Taiwan.

As indicated earlier, the focal point of this study is to identify the factors that influences road traffic accidents. The present investigation aims to enhance previous studies by exploring the relationship between road accidents and the daily temperature margin. To accomplish this objective, Table 1 provides a comprehensive account of the panel data descriptive statistics, which offers a detailed breakdown of the data utilized in the study.

Table 1. Descriptive statistics from panel data of 20 cities and counties.

Description	Variable	Mean	Std. Dev.	Min	Max	Sources
Accident rate (person/month)	*AC*	1155.99	1174.14	25	5606	Ministry of Transportation and Communication https://stat.motc.gov.tw (accessed on 12 February 2023)
Diurnal temperature range (°C)	*DTR*	5.20	0.97	1.94	7.75	Barkley Earth Database https://berkeleyearth.org/data (accessed on 26 January 2023) and Central Weather Bureau, Observation Data Inquiry System V7.2 (cwb.gov.tw) (accessed on 17 January 2023)
Wind speed (m/s)	*Wind*	2.61	1.76	0.1	13.9	Central Weather Bureau, Observation Data Inquiry System V7.2 (cwb.gov.tw) (accessed on 12 February 2023)
Precipitation (mm)	*Prec*	192.75	243.57	0	3346	Central Weather Bureau, Observation Data Inquiry System V7.2 (cwb.gov.tw) (accessed on 12 February 2023)
Cloud cover	*Cloud*	6.17	1.58	3.4	9.9	Central Weather Bureau, Observation Data Inquiry System V7.2 (cwb.gov.tw) (accessed on 12 February 2023)
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	44.66	19.94	11.3	125.7	Environmental Protection Administration https://statis91.epa.gov.tw/epanet/index.html (accessed on 15 February 2023)

Additionally, the descriptive statistics for each city, which are the subject of investigation within this paper, are outlined in detail in Appendix A. A comprehensive examination of these statistics yields insights into the specific characteristics of each city. Notably, when evaluating the frequency of road accidents, Taichung emerges as the city experiencing the highest incidence rate, with an average of 3704 cases per month. This suggests a significant road safety concern in Taichung. Following closely is Kaohsiung, reporting 3543 cases, also indicating a substantial occurrence of accidents. Similarly, Taoyuan registers 2462 cases, while New Taipei and Tainan report 2449 and 2016 cases, respectively. Taipei concludes the list with 1704 cases, reflecting relatively fewer accidents compared to the other cities under scrutiny.

Furthermore, on delving into the diurnal temperature range (DTR) data, also provided in Appendix A, interesting patterns emerge. Taoyuan displays the highest average DTR level at 5.86 °C. This suggests notable temperature fluctuations within the city, which could potentially contribute to variations in driving conditions. Taichung closely follows with a DTR of 5.84 °C, while New Taipei exhibits a slightly lower DTR of 5.24 °C. Tainan and Kaohsiung report DTRs of 4.78 °C and 4.62 °C, respectively, indicating relatively milder temperature fluctuations. Lastly, Taipei presents the lowest DTR at 3.11 °C. These variations in temperature fluctuations among the cities may offer insights into the potential impact of weather conditions on road safety and accident rates.

3.2. Methodology

The assessment of factors contributing to road traffic accidents presents a formidable challenge. The complexity of this issue stems from the interplay of structural and environmental factors, such as road conditions, population density, and environmental conditions, which collectively contribute to road traffic accidents [32]. Therefore, this study employs a comprehensive design that accounts for these complex interactions through a two-part analytical approach. Firstly, the study utilizes data from 20 Taiwanese cities and counties to examine the dynamic effect of diurnal temperature range (DTR) and road traffic accidents. To achieve this, the autoregressive distributed lag (ARDL) model proposed by Pesaran and Smith [33] and Pesaran, et al. [34] is employed for the first estimation. Secondly, the study focuses on time series data from six Taiwanese metropolitan cities to investigate the non-linear relationship between DTR-lag-road traffic accidents. This second analysis employs distributed lag non-linear models (DLNMs) proposed by Gasparrini, et al. [35], which allow for the capture of non-linear effects. Through this analytical approach, this study aims to provide a more nuanced understanding of the complex relationship between DTR and road traffic accidents in Taiwan.

This study employs panel data with a large T, allowing for a robust analysis of the data over an extended period. Fixed effects models are often utilized for this type of data analysis, as demonstrated in previous studies such as those conducted by Graham [36], Dzemski [37], Jochmans [38], and Adha, et al. [39]. Additionally, the autoregressive distributed lag (ARDL) model is a suitable statistical method for panel data analysis, particularly when T > N. This model can also be used to explore the effects of environmental factors on human behavior and human health, as noted by Adha, et al. [40] and Shiau, et al. [41]. The selection of the ARDL model in this study was based on various testing of the data, including the Hausman Test, the cross-sectional dependence test for panel data models [42], the unit root test [43,44], and the panel cointegration test developed by Pedroni [45], Pedroni [46], Kao [47], Westerlund [48], and Westerlund [49].

The present study has utilized a statistical model that has been previously developed and tested by previous researchers in the field, namely Lei, et al. [11] and Sager [3], to thoroughly investigate and examine the impact of diurnal temperature range (DTR) on the occurrence of road traffic accidents. The model, which has been expressed in a concise and systematic manner, seeks to capture and analyze the intricate relationship between DTR and road traffic accidents, and thereby provide valuable insights into this critical issue.

$$lnAC_{it} = \alpha + \beta_1 lnDTR_{it} + \beta_2 lnWind_{it} + \beta_3 lnPrec_{it} + \beta_4 lnCloud_{it} + \beta_5 lnPM10_{it} + \varepsilon_{it} \quad (1)$$

where AC_{it} is the natural logarithm of road traffic accidents in region i and month t. $lnDTR_{it}$ is the change in diurnal temperature range every month; $lnWind_{it}$ is wind speed rate; $lnPrec_{it}$ is precipitation; $lnCloud_{it}$ is cloud cover; and $lnPM10_{it}$ is particulate matter less than 10 micrometres. α is the constant value of the model proposed and ε_{it} is error terms.

Furthermore, the autoregressive distributed lag (ARDL) model with the PMG and MG estimators will be used for statistical estimation in this study. As shown below, the autoregressive distributed lag model in this study is based on the models proposed by Pesaran and Smith [33] and Pesaran, et al. [34]:

$$lnAC_{it} = \sum_{j=1}^{m} \lambda_{ij} lnAC_{i,t-j} + \sum_{j=0}^{n} \vartheta_{ij} X_{i,t-j} + \mu_i + e_{it} \quad (2)$$

where i denotes the location with i = 1, . . ., N; t represents the time with t = 1, . . ., T; and j denotes the number of time lag. X_{it} is the vector of the independent variable in the study. μ_i is the group-specific effect. From Equation (2), the next step is the re-parameterization that equation:

$$\Delta lnAC_{it} = \mu_i + \varphi_i lnAC_{i,t-1} + \beta_i' X_{it} + \sum_{j=1}^{m-1} \lambda_{ij} \Delta lnAC_{i,t-j} + \sum_{j=0}^{n-1} \vartheta_{ij} \Delta X_{i,t-j} + \mu_i + e_{it} \quad (3)$$

where

$$\varphi_i = -1\left(1 - \sum_{j=1}^{m} \lambda_{ij}\right), \beta_i = \sum_{j=0}^{m} \vartheta_{ij},$$

Thus, Equation (3) is rewritten as an error correction model:

$$\Delta lnAC_{it} = -\mu_i + \varphi_i \left(lnAC_{i,t-1} - \theta_i' X_{it}\right) + \sum_{j=1}^{m-1} \lambda_{ij*} \Delta lnAC_{i,t-j} + \sum_{j=0}^{n-1} \vartheta_{ij*} \Delta X_{i,t-j} + \mu_i + e_{it} \quad (4)$$

where $\theta_i = -\left(\frac{\beta_i}{\varphi_i}\right)$ is the long run relationship between accident rate and predictors X_{it}. In addition, λ_{ij*} and ϑ_{ij*} are short run coefficients regarding the increasing rate of road accidents and predictors, respectively.

In the subsequent phase of our investigation, we will be employing time series data that were culled from six major metropolitan centers in Taiwan. This selection was chosen based on the heightened mobility levels in urban environments, which have been consistently implicated as one of the key factors contributing to road traffic accidents. Our analysis will delve into the intricacies of the non-linear relationship between DTR-lag and road traffic accidents, with the aim of elucidating the underlying phenomenon that governs the interplay between environmental variations and mortality. The comprehensive nature of this study will enable us to capture the diverse array of responses that road traffic accidents exhibit with respect to changes in the diurnal temperature range across the six urban areas that are being analyzed. By harnessing the time series analysis, we aim to offer valuable insights that can inform targeted interventions to mitigate the deleterious effects of environmental changes on human health.

To accomplish the aims of the second stage of our inquiry, we have employed a sophisticated analytical framework that combines distributed lag non-linear models (DLNMs) with quasi-Poisson regression analysis to estimate both lagged and non-linear relationships between diurnal temperature range (DTR) and road traffic accidents. Drawing upon the ground-breaking work of Gasparrini, et al. [35], our model represents a cutting-edge advancement in the field of environmental research. This approach affords us the opportunity to comprehensively investigate the complex dynamics that underpin the relationship between DTR and road traffic accidents. This study's model is as follows:

$$lnAC_{it} = \alpha + \beta_1 DTR_t, m + ns(Wind_t, 3) + ns(Prec_t, 3) + ns(Cloud_t, 3) + ns(PM10_t, 3) + ns(Time, 3 \times 4) + \varphi MOY_t \quad (5)$$

where AC_t represents the monthly number of road traffic accidents in each major city in Taiwan. DTR_t is the time-series matrix for estimating the lag and non-linear effects of DTR on road traffic accidents in the current month. ns represents a natural cubic spline, $Wind_t, Prec_t, Cloud_t$ are climate factors, $PM10$ is fine particles, and 3 is the degree of freedom in this model. $Time$ represents long term trends and MOY_t is the month of the year that is used in the model proposed.

To provide a clearer understanding of the estimation procedure utilized in this study, refer to Figure 1.

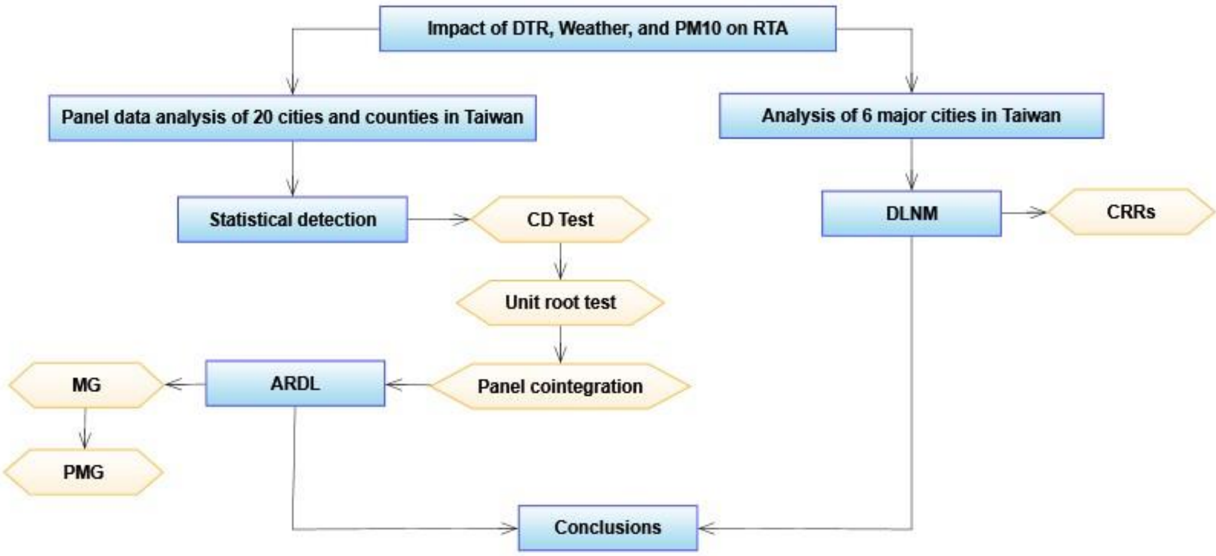

Figure 1. The illustrative outline of the estimations.

4. Results

4.1. ARDL Analysis

This section presents the findings of the empirical calculations derived from the first proposed method. To begin with, we performed a cross-sectional dependence test as shown in Table 2, which revealed that all three models employed—namely Pesaran, Frees, and Friedman—strongly rejected the hypothesis of cross-sectional independence, with statistical significance at the 1% level. This outcome indicates that the residual correlation value of the proposed model demonstrates a clear cross-sectional dependence under the fixed effect specification.

Table 2. Cross-sectional dependence test.

CD Test	Pesaran	Frees	Friedman
H_0	7.830 ***	5.876 ***	14.548 ***

Notes: *** denotes 1% levels of significance.

In order to further evaluate the validity of our proposed model, the current study conducted a stationary test, utilizing both the panel root test developed by Choi [50] and the IPS test proposed by Im, et al. [51]. As shown in Table 3, the results of the stationary test reveal that all variables employed in our analysis strongly reject the null hypothesis at a significance level of 1%.

Table 3. Unit root test.

Variable	Fisher Test				IPS Test
	Inverse Chi-Squared	Inverse Normal	Inverse Logit	Modified Inv. Chi-Sq	
AC	392.38 ***	−15.74 ***	−24.2 ***	39.39 ***	−16.78 ***
DTR	825.72 ***	−26.65 ***	−51.14 ***	87.84 ***	−30.5 ***
PM_{10}	548.47 ***	−20.96 ***	−33.97 ***	56.84 ***	−22.65 ***
Wind	723.49 ***	−24.51 ***	−44.81 ***	76.41 ***	−27.58 ***
Prec	807.13 ***	−26.23 ***	−49.99 ***	85.76 ***	−29.99 ***
Cloud	627.77 ***	−22.71 ***	−38.88 ***	65.71 ***	−24.95 ***

Notes: *** denotes 1% levels of significance; The lag lengths are selected using BIC, AIC, and QIC.

The subsequent analysis involved the cointegration test panel aimed at establishing the long-term association among variables. To achieve this objective, the study employed a set of models developed by Kao [47], Westerlund [48], Westerlund [49], Pedroni [45], and Pedroni [46]. As presented in Table 4, the findings indicate that all the statistical tests used achieved a significant level of 1%. In this regard, it is evident that all the models rejected the null hypothesis, which postulates that the data series were not related in the long term. To determine the optimal lag lengths, this test used three different criteria: Bayesian, Akaike, and Quinn. By applying these widely accepted criteria, we were able to select the most appropriate lag lengths for our model, providing a more accurate and comprehensive analysis of the underlying patterns and dynamics in our data. Hence, the results provide empirical evidence that the data in the current research exhibit a cointegrated behavior. The outcomes of this study, therefore, indicate that the proposed models are suitable for testing the cointegration of panel data.

Table 4. Panel cointegration test.

Pedroni		Kao		Westerlund	
Test	**Statistic**	**Test**	**Statistic**	**Test**	**Statistic**
Panel v	−1.920 ***	Modified DF	−7.170 ***	Gt	−2.228 ***
Panel rho	−16.548 ***	DF	−7.072 ***	Ga	−9.023 ***
Panel t	−14.799 ***	ADF	−1.973 ***	Pt	−9.874 ***
Panel ADF	−16.956 ***	UMDF	−61.947 ***	Pa	−7.697 ***
Group rho	−19.173 ***	UDF	−20.646 ***		
Group t	−18.003 ***				
Group ADF	−20.366 ***				

Notes: *** denote 1% levels of significance; The lag lengths are selected using BIC, AIC, and QIC.

After conducting thorough examinations, the findings suggest that the data used in this research are appropriate for analysis utilizing the panel autoregressive distributed lag (ARDL) model. The estimation results of the DTR effect are presented in Table 5. The estimation results in Table 5 shows two distinguished estimators used in this study, MG and PMG.

Table 5. Estimation results.

	MG		PMG	
	Coefficient	**Std. Error**	**Coefficient**	**Std. Error**
DTR	−0.171 ***	0.206	−0.199 ***	0.161
PM_{10}	0.368 ***	0.096	0.246 ***	0.042
Wind	−0.510 ***	0.196	−0.436 ***	0.066
Prec	−0.028 **	0.027	−0.051 **	0.014
Cloud	0.242 **	0.135	0.164 **	0.078
Δ *DTR*	−0.040 *	0.037	−0.026 *	0.020
Δ PM_{10}	0.029 *	0.020	0.014 *	0.015
Δ *Wind*	0.076 ***	0.016	0.087 ***	0.014
Δ *Prec*	−0.005	0.002	0.003	0.002
Δ *Cloud*	−0.122 ***	0.018	−0.115 ***	0.019
ECT	−0.224 ***	0.027	−0.165 ***	0.020
Constant	1.707 ***	0.208	1.216 ***	0.130
Observations	3273		3273	
Hausman test	23.20 ***			

Note: *, ** and *** denote 10%, 5%, and 1% levels of significance, respectively.

In this research, the pooled mean group (PMG) and mean group (MG) estimators were compared to obtain the best estimation results. The Hausman test was used to determine the best and most efficient model, which was found to be the MG estimator. According to the MG calculations, a 1 °C decrease in the DTR over the long term was associated with a

17.1% increase in the risk of an RTA. Interestingly, the effect of DTR on RTAs was observed to be smaller in the short term, as the MG model's estimation indicated a 4% increase in RTAs with a decrease in DTR. In comparison to the effect of air pollution, specifically particulate matter, the magnitude of the DTR effect on RTAs was found to be smaller. However, it should be noted that estimating results using air pollution variables such as PM_{10} can lead to bias if calculated directly [3]. Therefore, when compared to estimates from other studies utilizing air pollution variables, such as the study by Sager [3], the effect of DTR on RTAs was observed to be larger, particularly in Taiwan. These findings suggest that DTR may play a significant role in the incidence of RTAs in certain regions and should be taken into consideration when implementing measures to reduce the incidence of these accidents.

The present study's findings corroborate previous research that has reported a positive correlation between air pollution and traffic accidents [3,4,52]. Specifically, the estimation outcomes derived from the ARDL model reveal that PM_{10} exert a positive influence on road traffic accidents. This phenomenon is observed across both short-term and long-term estimates. In fact, long-term estimates indicate that PM_{10} possess a significant effect on road traffic accidents. Evidently, over the long term, the deleterious effects of air pollution are set to be exacerbated. It is worth noting that previous studies have uncovered a close association between air pollution and human cognitive performance [53].

4.2. DLNM Analysis

The subsequent phase of this investigation delves into the non-linear association between DTR-lag-road traffic accident via the utilization of distributed lag non-linear models (DLNMs). The examination encompasses six major cities in Taiwan, specifically Taipei, New Taipei, Taoyuan, Taichung, Tainan, and Kaohsiung.

The lag time plays a crucial role in understanding the temporal dynamics of the relationship between DTR and road traffic accidents. In previous research, lag effects of DTR on health outcomes have often been observed in the order of days [11,12]. These shorter lag periods are appropriate when studying the immediate health impacts of temperature fluctuations on individuals. However, in this study, the lag effects in the order of months is driven by the recognition that certain consequences of DTR variations may have a delayed and cumulative nature, akin to the lag effects observed in relation to broader climate phenomena. We extended the lag time to encompass several months to capture the potential lagged and cumulative effects of DTR on road traffic accidents. This approach is deemed necessary because while DTR and driving are indeed experienced on a shorter timescale, the influence of DTR on road safety may manifest over more extended periods due to factors such as gradual changes in road conditions, driver behavior adaptations, and the cumulative impact of temperature variations on road infrastructure.

Figures 2 and 3 illustrate the non-linear and lagged relationship between the diurnal temperature range (DTR) and road traffic accidents in six major metropolitan areas in Taiwan. The purpose of presenting two types of figures is to help readers better understand the findings in cases where one figure may not be clear. These figures reveal how the urban areas in Taiwan respond differently to changes in DTR with regards to road traffic accidents. The results indicate that a lower DTR effect tends to increase road traffic accidents in New Taipei, particularly at lags of 0–10 months. However, at higher DTRs ($\geq$4.6 °C), the relationship between DTR and road traffic accidents is relatively lower at lags of 0–25 months. This trend becomes more prominent at higher DTR levels, where it reinforces the association between DTR and road traffic accidents. The maximum lag of 30 months in these figures provides a comprehensive understanding of the temporal relationship between DTR and road traffic accidents.

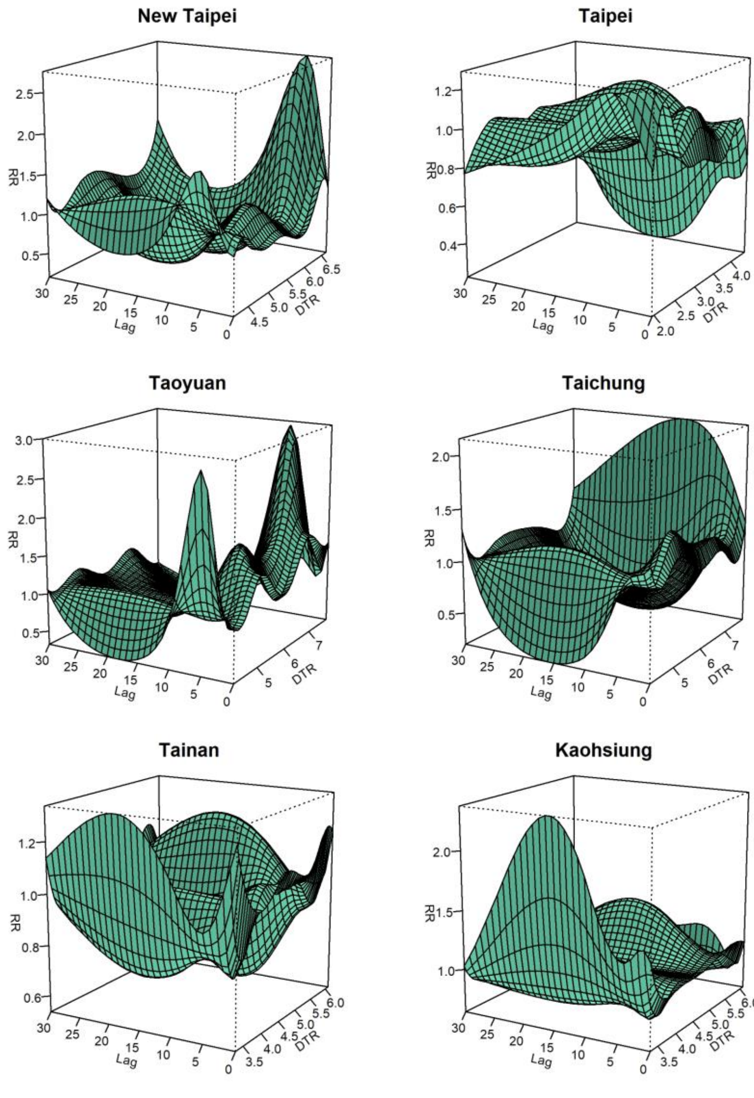

Figure 2. Effect of DTR on traffic accidents in the 6 metropolitan cities.

The results for Taipei are comparable to those obtained in New Taipei. A low diurnal temperature range has a higher association with road traffic accidents in Taipei, as revealed in Figure 2 and more comprehensively in Figure 3. The relative risk (RR) value is ≥1 at the DTR level of 2–2.5 °C and lag of 0–15 months, indicating an elevated risk of road traffic accidents. As the DTR value increases, the condition tends to improve, as evidenced by the lower RR value. The pattern observed in Taoyuan is quite similar to that observed in Taichung. At low DTR levels, road traffic accidents are moderate, and there is a positive correlation with an increase in DTR, particularly at lag 0–5 months. However, the relationship between road traffic accidents and DTR tends to improve at lag ≥ 10 month, as demonstrated by lower RR values.

Additionally, the study found that Tainan exhibits a unique pattern regarding the relationship between diurnal temperature range (DTR) and road traffic accidents (RTA). At a DTR level of 3.5 °C, the RTA response tends to be high at lag 0, indicating an immediate effect. However, conditions improve at lags of 1–30 months, indicating that the low level of DTR is not accompanied by an increase in road traffic accidents at lag ≥ 1 month. When the DTR level reaches 4.0–5.5 °C, the response to RTAs is high. On the other hand, the situation in Tainan is nearly identical to that in Kaohsiung, except for the fact that in Kaohsiung, a low DTR level is accompanied by a high RR rate of road traffic accidents, particularly at lags of 0–25 months with a DTR level <3.5 °C. This implies that the relationship between DTR and road traffic accidents in these two cities may be influenced by similar factors.

However, the magnitude and timing of the effect vary, indicating that local factors may also play a role in shaping this relationship.

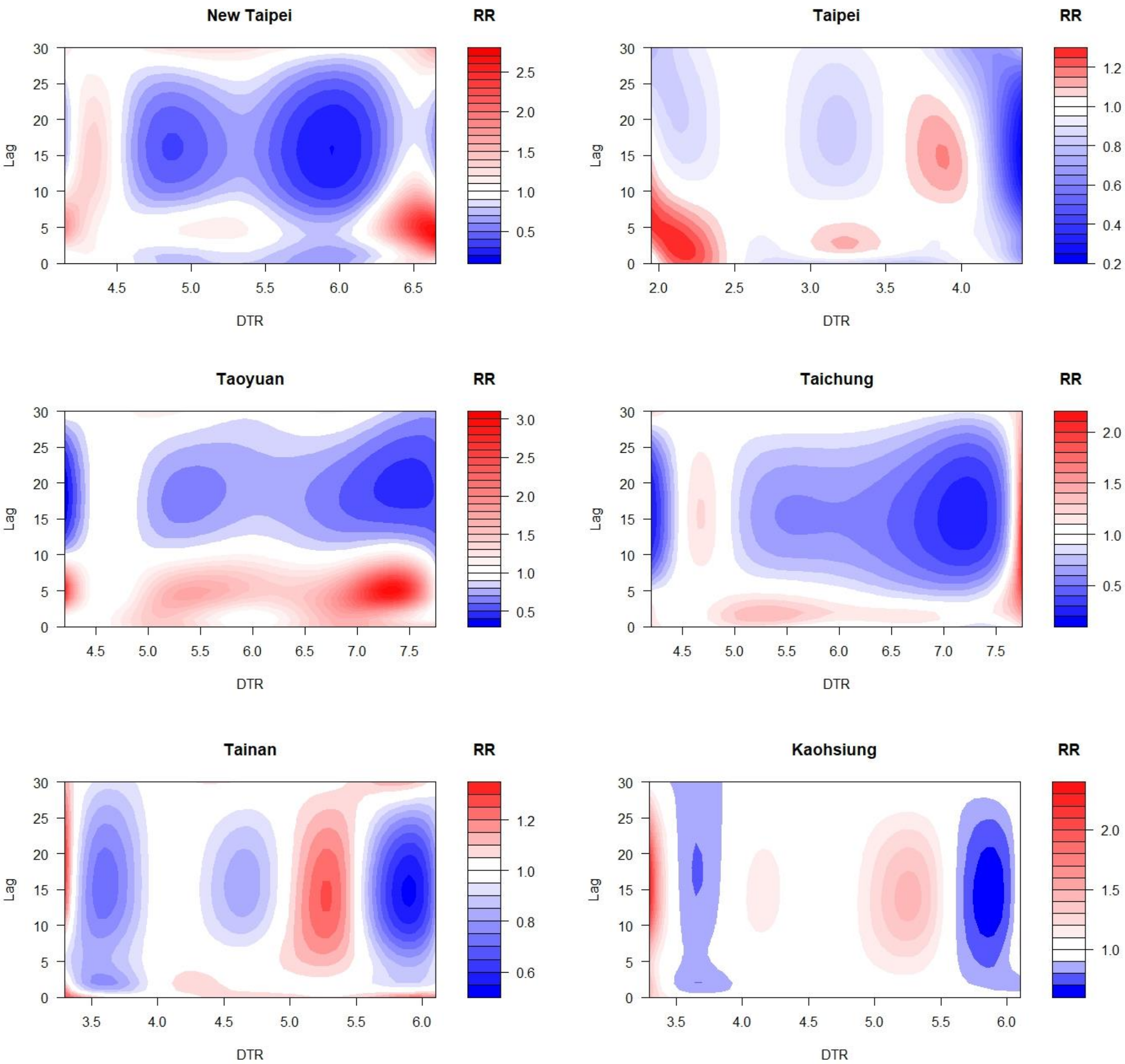

Figure 3. Contour plot of effect of DTR on road traffic accidents.

The present analysis investigates the response of road traffic accidents to specific DTR and lag values. As highlighted by Gasparrini, et al. [35] and Gasparrini [54], explaining the RTA response without specific DTR and lag values can be weak and is considered a limitation in the analysis shown in Figures 2 and 3. The inadequacy of the figures to explicate the impact of diurnal temperature range (DTR) on particular quantitative parameters, coupled with their constraining nature with regards to inferential objectives, is the root cause of this phenomenon. The insufficiency of these aforementioned visual representations to elucidate the nuanced effects of DTR on discrete variables and their incapacity to cater to inferences and conjectures concerning said variables are what underlie the observed trend.

In an attempt to circumvent this aforementioned constraint, Figures 4 and 5 have been introduced to portray the response of road traffic accidents at specific DTR and lag values, proffering an unparalleled advantage in comprehending the impact of DTR on RTAs, particularly where it is most pronounced. This critical analysis presents a unique opportunity to either validate or invalidate the findings of prior analyses, including those employing panel autoregressive distributed lag (ARDL) in all cities and counties in Taiwan. As such, the present inquiry endeavors to provide a more comprehensive and precise comprehension of the interplay between DTR, lag, and fatal traffic accidents, the outcome of which can have far-reaching implications for devising efficacious road safety strategies in Taiwan.

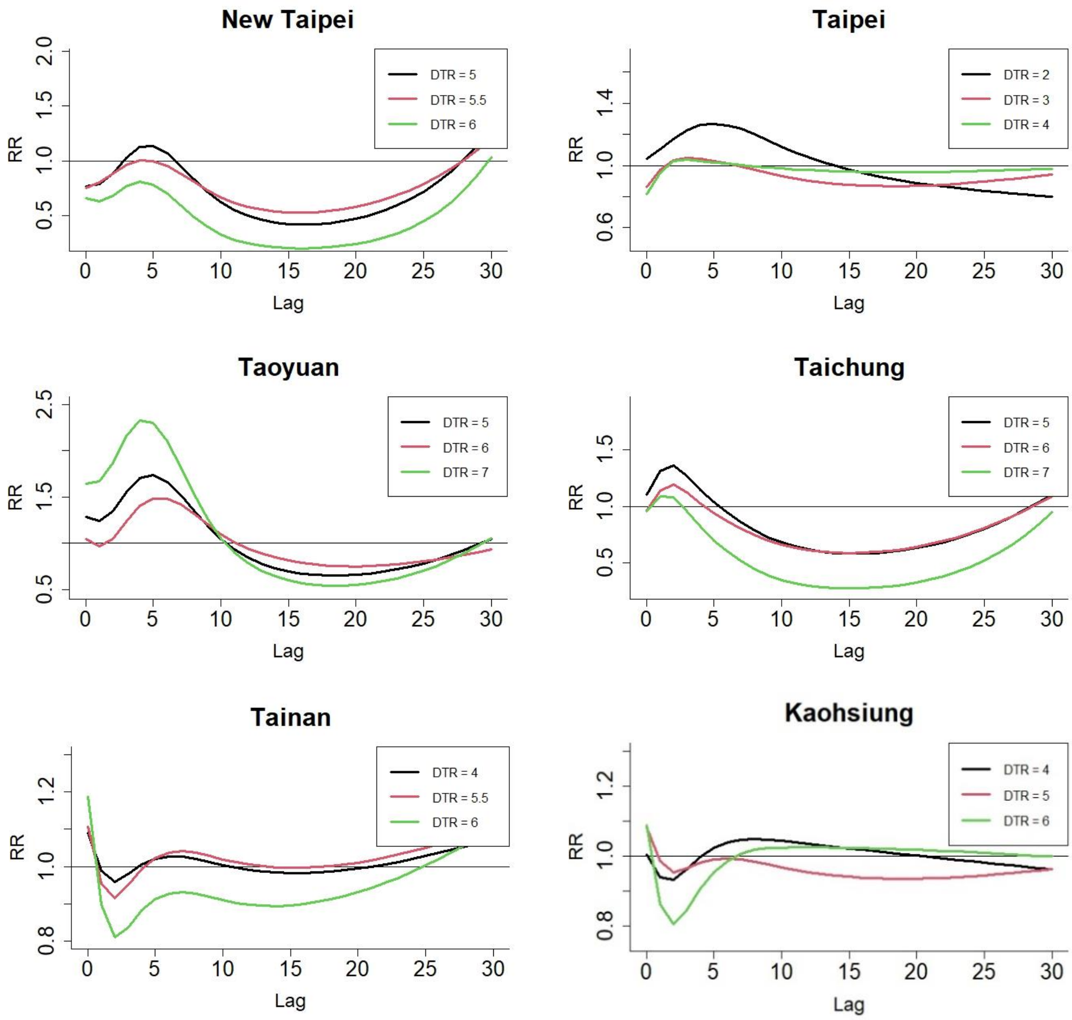

Figure 4. Lag-RTA curves for specific diurnal temperature ranges.

Upon evaluating the computational outcomes demonstrated in the graphical representation exhibited in Figure 4, it is discernible that divergent urban regions across Taiwan display unique responses. It is important to note that the DTR values depicted in Figure 4 have been adjusted to correspond to the DTR values for each respective city. As evinced by the aforementioned figure, a significant surge in the response to DTR levels from road traffic accidents occurred at the lag of 0–5 months in three metropolises, namely New Taipei, Taipei, and Taoyuan, while the escalation in Taichung, Tainan, and Kaohsiung was comparatively less pronounced. It is worth highlighting that with regard to road traffic accidents, the response exhibited to low and high DTR values is distinct. In the case of Taoyuan, high DTR rates were accompanied by an elevated number of road traffic accidents. On the contrary, in the cities of New Taipei, Taipei, and Taichung, a low DTR rate was found to be associated with a considerable surge in road traffic accidents. The responses in Tainan and Kaohsiung were similar, with moderate impacts of both low and high DTR levels in both cities. It is noteworthy that this study posits that with the exception of Taoyuan, low DTR rates were linked to a high response from rates of road traffic accidents across all the cities.

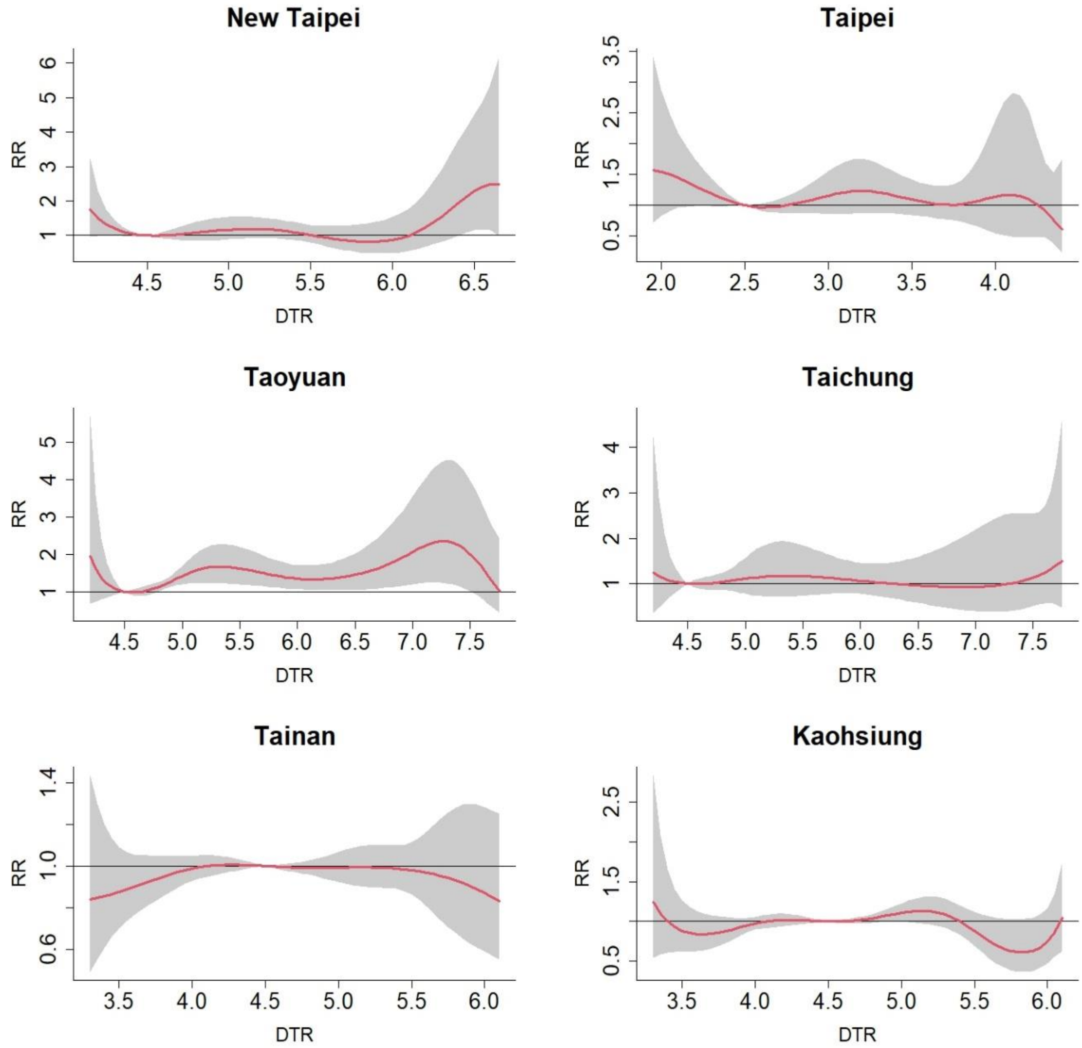

Figure 5. DTR-RTA curves for specific lag.

The estimation continues by scrutinizing the DTR-RTA response at a particular lag, as evidenced in Figure 5. Based on the evidence presented in this figure, it can be deduced that employing a specified lag of 5 month means that the response elicited from road traffic accidents at a low DTR level appears to be substantially amplified in virtually all cities, except for New Taipei. In addition, Figure 5 illustrates that in the context of Tainan, when the DTR level is low, the response observed from road traffic accidents is relatively subdued and tends to augment as the DTR level rises. Nevertheless, it is noteworthy that this trend undergoes a shift when the DTR level reaches 4 °C. At this threshold, the aforementioned condition is noted as ameliorating.

The variation in the effect of DTR on road traffic accidents between different cities with specific DTR values can be attributed to several factors. First, each city has its own unique local weather patterns influenced by its geographical location and proximity to bodies of water. Second, cities situated at higher elevations often encounter more drastic temperature swings between day and night. This can lead to increased expansion and contraction of road surfaces, contributing to DTR-related road hazards. Third, local precipitation patterns can interact with DTR to affect road conditions. In summary, differences in local weather, geographical characteristics, and climate-related factors can lead to varying effects of diurnal temperature range (DTR) on road traffic accidents (RTAs) between different cities. These factors influence the intensity and frequency of DTR, contributing to the diversity of road safety outcomes across urban areas.

5. Discussion

The results of this study provide valuable insights into the complex relationship between DTR, air pollution, and other meteorological factors on road traffic accidents (RTAs), shedding light on the varying effects of these factors over different time frames. The primary focus of our investigation is diurnal temperature range (DTR). In the extended time frame, we observed a considerable association between DTR and RTAs. A decrease in DTR was linked to a substantial increase in the risk of RTAs. This underscores the vital role of temperature fluctuations over extended periods in shaping road safety outcomes. It emphasizes the importance of considering temperature-related factors when devising road safety strategies, particularly from a long-term perspective.

Turning to other meteorological variables, our results indicate that the increase in wind speed and precipitation can have a protective effect against road traffic accidents over the long term. However, this relationship diverges significantly in the short term, where higher wind speed was associated with a noteworthy 1% increase in road traffic accidents. This temporal variation underscores the need for a nuanced approach when considering the time dimension of meteorological factors in road safety planning.

Furthermore, our analysis of cloud cover revealed intriguing patterns. Over the long term, the increase in cloud cover was associated with a rise in accident potential. In contrast, this effect did not manifest in the short term, where estimation results indicated the opposite trend. This nuanced interaction between cloud cover and road safety emphasizes the complexity of meteorological influences on RTAs and underscores the importance of accounting for temporal variations in safety planning.

To provide a more granular and nuanced analysis, the impact of the diurnal temperature range on road traffic accidents in six major metropolitan areas in Taiwan has been comprehensively summarized and presented in Table 6. The DTR rate, which reflects the specific characteristics of the diurnal temperature range in each of the respective cities, has been used as the basis for the analysis. The findings of the estimation reveal a strong and statistically significant correlation between low DTR levels and higher cumulative relative risks (CRRs) of road traffic accidents. This pattern is observed across all cities, with the exception of Taoyuan and Tainan. Specifically, among the cities with low DTR levels, at lag of 0–5 months, Taipei demonstrates the highest CRR level at 1.105 (95% CI: 0.664–1.521), followed closely by Taichung and Kaohsiung, which exhibit values of 1.082 (95% CI: 0.754–1.280) and 1.021 (95% CI: 0.870–1.383), respectively. These results underscore the importance of considering the impact of the diurnal temperature range when evaluating the risk of road traffic accidents in urban areas, and highlight the need for further research in this area.

Table 6. The cumulative relative risk of road traffic accidents in different DTR level.

City	Low DTR	Medium DTR	High DTR
New Taipei	0.888 (0.674–0.992)	0.840 (0.685–1.031)	0.855 (0.663–1.103)
Taipei	1.105 (0.664–1.521)	0.924 (0.768–1.111)	0.850 (0.604–1.197)
Taoyuan	1.016 (0.736–1.404)	1.022 (0.747–1.398)	1.033 (0.694–1.479)
Taichung	1.082 (0.754–1.280)	0.925 (0.716–1.193)	0.962 (0.701–1.322)
Tainan	0.956 (0.873–1.047)	0.899 (0.781–1.035)	1.101 (0.904–1.351)
Kaohsiung	1.021 (0.870–1.383)	0.924 (0.843–1.012)	0.917 (0.763–1.150)

Note: Low, medium, and high DTR represents 25th, 50th, and 75th percentile of DTR value from each city, with lag of 0–5 months together with its 95% confidence intervals.

The important aspect to discuss is also the monthly lag time used in this study. As mentioned before, driving is generally considered a short-term behavior, occurring on a daily basis. The decision to use longer lag times, such as 0–5 months or longer, in the context of DTR and road traffic accidents may seem counterintuitive when considering the immediate nature of driving. However, there are several reasons why longer lag times can be relevant:

1. While individual instances of driving occur on short timescales, the impact of environmental factors, like DTR, on road safety may accumulate over time [3,55]. For example, gradual changes in road surface conditions due to temperature fluctuations can affect safety outcomes over several months. Longer lag times allow us to capture these cumulative effects.
2. Roads and transportation infrastructure are not static. They undergo maintenance, repairs, and improvements that can take place over longer periods [56]. The influence of DTR on road conditions and infrastructure quality can affect road safety outcomes over time.
3. Drivers may adapt their behavior in response to changing weather conditions, including DTR [57–59]. These adaptations might not occur immediately but could develop over several months as individuals become more attuned to seasonal variations. Longer lag times account for the time it takes for these behavioral adjustments to manifest in safety outcomes.
4. The relationship between meteorological factors like DTR and road safety is multifaceted and may involve complex interactions [60,61]. Longer lag times allow for a more comprehensive exploration of these intricate relationships.

Based on this explanation, it appears that socio-economic aspects can also be one of the causes of road traffic accidents [62,63]. The socio-economic status of a city's population directly affects the number and types of vehicles on the road. Wealthier cities often have a higher rate of vehicle ownership, including a mix of cars, motorcycles, bicycles, and even public transportation systems [64]. The type of vehicles in use can impact the severity and frequency of accidents [65,66]. In addition, more densely populated cities tend to have higher traffic volumes and congestion, which can lead to a greater number of RTAs [67]. The risk of accidents involving pedestrians and cyclists in densely populated areas may also be higher due to increased interactions between road users.

The present study's findings corroborate previous research that has reported a positive correlation between air pollution and traffic accidents [3,4,52]. Specifically, the estimation outcomes derived from the ARDL model reveal that both $PM_{2.5}$ and PM_{10} exert a positive influence on road traffic accidents. This phenomenon is observed across both short-term and long-term estimates. In fact, long-term estimates indicate that $PM_{2.5}$ and PM_{10} possess a significant effect on road traffic accidents. Evidently, over the long haul, the deleterious effects of air pollution are set to be exacerbated. It is worth noting that previous studies have uncovered a close association between air pollution and human cognitive performance [53].

Finally, after analyzing the estimates of the first and second models, it is evident that a decline in the diurnal temperature range (DTR) is correlated with an increase in the incidence of road traffic accidents. The outcomes of the two models used in this investigation support the estimation results. The decline in the DTR represents that the difference between the maximum and minimum temperatures is decreasing over time, it can be an indicator of changes in the Earth's climate. A smaller DTR often suggests that the daily temperature range is becoming more uniform, with warmer nights and cooler days or vice versa. As the Earth's average temperature rises due to increased greenhouse gas emissions, it can affect the daily temperature patterns, which bolsters the evidence of the harmful impacts of global warming [15]. The relationship between cognitive ability and temperature exposure can be utilized to link the DTR and road traffic accidents [29]. As a result of this study, it is conceivable that the temperature change is one of the causes of road traffic accidents. These findings lay the groundwork for further research into the correlation between driving safety and climate change in the long term. Moreover, the study's findings expand the existing literature on the critical consequences of temperature variations. In essence, this research suggests that the negative effects of DTR extend beyond environmental concerns to encompass serious impacts on human safety and well-being. Therefore, it is imperative that effective measures be implemented to mitigate the effects of climate-related factors on driving safety.

6. Conclusions

The present study endeavors to scrutinize the association between diurnal temperature range and traffic accidents, specifically in Taiwan. The absence of any prior research examining the nexus between diurnal temperature range and road traffic accidents renders this study significant. The present study employs two analytical models to grasp the intricate nature of factors contributing to road traffic accidents. The first model is the autoregressive distributed lag (ARDL) panel, which relies on panel data from 20 Taiwanese cities and counties to generate an initial estimate. Subsequently, the second model is constructed using time series data collected from six major cities across Taiwan and analyzed using distributed lag non-linear models (DLNMs). The utilization of these two models allows for a more comprehensive understanding of the relationship between diurnal temperature range and road traffic accidents.

The primary objective of this study is to estimate the impact of climate factors, specifically diurnal temperature range and air pollution on road traffic accident in Taiwan. To achieve this, we utilized both PMG and MG ARDL models in the current investigation. The efficiency and effectiveness of these models were evaluated using the Hausman test, and the MG estimator was identified as the most appropriate method for explaining the proposed model. Based on our findings, a decrease in the diurnal temperature range has a significant impact on the likelihood of road traffic accidents. Our estimates reveal that, in the long term, a decrease of 1 °C in the diurnal temperature range leads to a 17.1% increase in the risk of road traffic accidents, with a significance level of 1% alpha. Besides, the short-term effect of DTR on RTAs was found to be smaller, with the MG model estimating a 4% increase in RTAs with a decrease in DTR. It is worth noting that the decrease in the diurnal temperature range, as revealed in this study, is associated with certain adverse effects. Specifically, our estimation results indicate an increase in road traffic accidents linked to this temperature range variation. Therefore, this study contributes to a better understanding of the relationship between diurnal temperature range and road traffic accidents, emphasizing the need for measures to enhance public safety in light of these temperature fluctuations.

As a follow-up to the first study, this research aims to capture the non-linear impact of DTR-lag on road traffic accidents. To achieve this, data were gathered from six major metropolitan cities across Taiwan, and distributed lag non-linear models (DLNMs) were used for the analysis. The results of the estimates indicate that a low DTR is closely linked to a high number of road traffic accidents. Notably, the estimation results for three cities, namely New Taipei, Taipei, and Taichung, were found to be statistically significant. Conversely, in the cases of Tainan and Kaohsiung, low DTR levels exhibited only a moderate effect on road traffic accidents, whereas for Taoyuan, high DTR levels were found to be associated with high rates of road traffic accidents. These findings align with those of the initial study, which suggested that the increase in mortality rates due to road traffic accidents is among the adverse consequences associated with shifting environmental conditions. These results underscore the necessity for interventions aimed at mitigating the detrimental impacts of evolving climatic factors on public safety, especially within the transportation sector.

The outcomes of this study offer fresh insights into the adverse effects of climate-related factors, particularly concerning variations in the diurnal temperature range. Consequently, it becomes imperative to introduce adjustments in both behavior and policies to counteract the repercussions of these changing environmental conditions, particularly as they pertain to road safety. Nevertheless, it is crucial to acknowledge that this study is subject to certain limitations. For instance, the utilization of monthly data imposes constraints on the precision of our estimations. Consequently, there exists the possibility that our findings may have underestimated the actual impact. To address this limitation, future research endeavors should aim to enhance the precision of estimations by incorporating daily data. This approach would facilitate a more nuanced comprehension of the connection between diurnal temperature range and road traffic accidents. Furthermore, the discoveries from this study can serve as a valuable resource for policymakers and stakeholders, underscoring the urgency of implementing immediate measures to prevent and alleviate the adverse effects of shifting climate-related factors on public safety, particularly within the transportation sector.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Descriptive statistics of six major cities:

A. New Taipei

Description	Variable	Mean	Std. Dev.	Min	Max
Road accident (person/month)	*AC*	2449.7	763.23	1226	4491
Diurnal temperature range (°C)	*DTR*	5.24	0.46	4.10	6.67
Wind speed (m/s)	*Wind*	2.06	0.45	1.1	3.1
Precipitation (mm)	*Prec*	187.85	152.58	14.5	965.8
Cloud cover	*Cloud*	7.18	1.06	4.7	9.6
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	37.43	11.19	18	82.5

B. Taipei

Description	Variable	Mean	Std. Dev.	Min	Max
Road accident (person/month)	*AC*	1704.2	319.9	708	2562
Diurnal temperature range (°C)	*DTR*	3.11	0.41	1.94	4.44
Wind speed (m/s)	*Wind*	2.40	0.48	1.3	3.5
Precipitation (mm)	*Prec*	185.51	155.19	13.8	957.1
Cloud cover	*Cloud*	7.35	0.96	5.1	9.5
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	38.99	13.03	15.5	99.3

C. Taoyuan

Description	Variable	Mean	Std. Dev.	Min	Max
Road accident (person/month)	*AC*	2461.96	907.47	912	4846
Diurnal temperature range (°C)	*DTR*	5.86	0.59	4.16	7.75
Wind speed (m/s)	*Wind*	1.01	0.45	0.3	2.6
Precipitation (mm)	*Prec*	158.76	133.33	0	738
Cloud cover	*Cloud*	7.15	0.92	4.8	8
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	43.41	13.60	17.5	97.8

D. Taichung

Description	Variable	Mean	Std. Dev.	Min	Max
Road accident (person/month)	*AC*	3704.39	857.02	1803	5606
Diurnal temperature range (°C)	*DTR*	5.84	0.46	4.11	6.68
Wind speed (m/s)	*Wind*	1.43	0.21	1.1	2.2
Precipitation (mm)	*Prec*	149.98	204.63	0	907.6
Cloud cover	*Cloud*	5.96	1.17	2.8	8.6
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	46.63	15.88	15.7	100.4

E. Tainan

Description	Variable	Mean	Std. Dev.	Min	Max
Road accident (person/month)	*AC*	2015.77	866.16	751	4343
Diurnal temperature range (°C)	*DTR*	4.78	0.53	3.86	6.34
Wind speed (m/s)	*Wind*	2.98	0.51	2	4.6
Precipitation (mm)	*Prec*	151.75	239.29	0	1301
Cloud cover	*Cloud*	5.28	1.07	1.8	7.6
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	60.67	24.73	14.7	123.6

F. Kaohsiung

Description	Variable	Mean	Std. Dev.	Min	Max
Road accident (person/month)	*AC*	3542.91	706.81	2192	5218
Diurnal temperature range (°C)	*DTR*	4.62	0.58	3.28	6.13
Wind speed (m/s)	*Wind*	2.06	0.26	1.4	2.8
Precipitation (mm)	*Prec*	178.03	277.17	0	1600.5
Cloud cover	*Cloud*	5.12	1.03	1.9	7.4
Suspended particles/PM_{10} (μg/m^3)	PM_{10}	61.06	25.11	16.8	116

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