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Ambient temperature and risk of motor vehicle crashes: A countrywide analysis in Spain

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ABSTRACT

Background: Some studies have documented that cold or hot ambient temperatures increase the risk of motor vehicle crashes. However, the number of existing studies is still limited, especially for the effects of cold.
Objectives: To estimate the relationship between ambient temperatures and risk of motor vehicle crashes in Spain, and to estimate the same association when restricting to those crashes with driver performance–associated factors (namely distraction, fatigue, sleepiness or disease).
Methods: We used data for the period 1993–2013. We conducted a time series analysis controlling for seasonality and trends and using the distributed lag nonlinear model framework to estimate nonlinear and delayed effects of up to 7 days. Analyses were conducted at the province level and combined using multivariate meta-analysis.
Results: The study included 1,908,460 motor vehicle crashes, 37% of them with associated driver performance factors. The overall analysis showed that the risk of crashes increased almost linearly with temperature. The estimates of the cumulative effect of lags 0–7 when comparing the 99th percentile and the first percentile of temperature produced a relative risk (RR) of 1.15 (95% confidence interval (CI): 1.11, 1.20). The estimates were slightly higher when analyses were restricted to crashes with driver performance–associated factors (RR: 1.23, 95% CI: 1.17, 1.30). In some provinces that reached temperatures below 0 °C, an increased risk with cold temperatures was also observed. An added effect of both cold spell and heat wave periods was found only in the analysis of crashes with driver performance–associated factors (cold spells, RR: 1.029, 95% CI: 1.005, 1.053; heat waves, RR: 1.020, 95% CI: 1.002, 1.039).
Conclusions: The increase of temperature increased the risk of motor vehicle crashes in Spain. Measures aimed at reducing the influence of heat on the risk of motor vehicle crashes can have important benefits for public health.

1. Introduction

Ambient temperature influences human health. Many studies have shown that both cold and hot temperatures increase the risk of mortality and of being hospitalized for different health problems (Gasparrini et al., 2015; Song et al., 2017). In recent years, several other studies have documented that ambient temperature can also increase the risk of intentional or unintentional injuries (Basagana et al., 2011; Parks et al., 2020), including occupational injuries (Fatima et al., 2021; Martínez-Solanas et al., 2018; Spector et al., 2019) and motor vehicle crashes (Basagaña et al., 2015; Liang et al., 2022).

The hypothesized mechanisms leading from ambient temperature to changes in the risk of motor vehicle crashes include decreased performance (mainly associated with heat) and bad car or road conditions (e.g. frost leading to slipperiness with cold weather or heat increasing the risk of flat tires). There are experimental studies that showed that, under hot conditions, drivers commit more technical errors, tend to drift out of the lane more often, miss more signals, report more fatigue and have a lower overall driving performance (Daanen et al., 2003; Mackie and O'Hanlon, 1977; Walker et al., 2001; Wyon et al., 1996). The association between temperature and actual crashes can only be assessed in observational studies. Several of them have documented an increased risk of crashes with heat (Ali et al., 2020; Gariazzo et al., 2021; Hou et al., 2022; Lee et al., 2020; Liang et al., 2021; Liu et al., 2017; Nazif-Munoz et al., 2021; Park et al., 2021; Wu et al., 2018; Zare Sakhvidi et al., 2022), and a few of them with cold

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temperatures (Gariazzo et al., 2021; Hou et al., 2022; Lee et al., 2020; Liang et al., 2021; Zare Sakhvidi et al., 2022).

In the past, we conducted an analysis linking heat and risk of motor vehicle crashes in one region of Spain (Basagaña et al., 2015). The study found that the risk of motor vehicle crashes increased with temperature in summer, and that the increase in risk was stronger during heat wave days. Results were even stronger when we restricted to crashes with driver performance–associated factors, which was in line with the hypothesis that decreased performance under hot conditions can be behind the increased risk of motor vehicle crashes. Here, we extended our previous study to the whole country, including data for more years and months of the year. The aims of the study were to try to replicate the findings with a bigger dataset and to study all ranges of temperature, including cold temperatures.

2. Material and methods

2.1. Design and setting

We conducted a time series study that linked the daily counts of number of vehicle crashes in Spain for the period 1993–2013 with the daily ambient temperatures. We included the 50 provinces of Spain and excluded the autonomous cities of Ceuta and Melilla, located in North Africa. The main climate in Spain is Mediterranean, with dry, hot summers and mild winters and low rainfall, but other climates are also present, e.g. oceanic in the Northwest, arid and semi-arid in the Southwest, subtropical in the Canary Islands, and continental in the mountain ranges.

2.2. Motor vehicle crashes data

We obtained individual data from all crashes with victims (dead or injured) reported during the study period from the General Direction of Traffic (*Dirección General de Tráfico*, DGT). These data came from the official forms filled by those involved in the crash and by the police officers attending the crash. Therefore, crashes for which a form was not filled were not included in the present study. These forms are used by the insurance companies and we expect that most crashes with injuries or vehicle damage are included.

The official form has a field for concurrent factors assigned to the crash by the traffic authorities. These include use of alcohol or drugs, speeding, traffic violation or bad road conditions, among others. This field reflects the opinion of the agent attending the crash in reference to factors that the agent believes that have been important for its occurrence. Those crashes for which at least one of the boxes "distraction" or "fatigue, sleepiness or disease" were ticked were classified as crashes with driver performance–associated factors. We also used the information of those crashes for which the box "adverse meteorology" was ticked in the concurrent factors field, as well as those with any of the following boxes ticked in the field "atmospheric factors": intense fog, light mist, drizzle, heavy rain, hail, snow, strong wind or "other".

From the same source, we also obtained data on the average fleet age at municipal level for year 2013. This was converted to province-level data by computing averages weighted by the size of the fleet in each municipality.

2.3. Temperature data

Daily data on average temperature for the province capitals of Spain were obtained from official meteorological stations through the ECA&D database (European Climate Assessment and Dataset, 2016). Missing values of temperature (0.01% of the data) were replaced by the mean of the temperature of the preceding and subsequent day, when both were available, or by the temperature registered on that particular date in the most correlated station otherwise. We defined cold spells and heat waves as those days belonging to a period with $\geq$2 consecutive days with temperatures below the province-specific historic 5th percentile or exceeding the province-specific historic 95th percentile, respectively (Basagaña et al., 2015).

2.4. Statistical analysis

Data on crashes was aggregated by province and date to obtain daily counts. Daily counts for each province were linked with the temperature registered in the province capital by date.

We fitted quasi-Poisson regression models linking the number of crashes with temperature, separately for each province. We used the distributed lag nonlinear model (DLNM) framework, which allows modelling nonlinear and delayed effects of temperature (Gasparrini, 2011; Gasparrini et al., 2010). The maximum lag investigated was 7, with the assumption that temperature could have cumulative effects over several days, for example, through fatigue. In particular, we used the penalized version of DLNMs, which facilitates model selection (Gasparrini et al., 2017). We built a crossbasis using P-splines with 9 degrees of freedom for the exposure-response function, and P-splines with 7 degrees of freedom for the lag-response function. These values were chosen as they were large enough to capture complex curves. The crossbasis was penalized using a second-order difference penalty. We calculated the overall exposure response function by cumulating the estimates over all lags, and combined the results of all provinces using multivariate meta-analysis (Gasparrini and Armstrong, 2013). We centered the curves at the temperature of minimum risk of accidents within the interval between the 1st and 99th percentile of temperature. We also estimated the best linear unbiased predictions (BLUPs) to obtain province-specific exposure response functions (Gasparrini et al., 2012).

The number of motor vehicle crashes depends, among other things, on the number of circulating vehicles per day and the distance driven. This information was not available but it is known to have temporal patterns (Brijs et al., 2008). In order to account for these variations, we included several terms in the models, for each of the provinces. First, we included a temporal trend in the models, using a natural spline with 12 degrees of freedom per year. This high number of degrees of freedom was chosen to be able to capture complex annual patterns. In a sensitivity analysis, we fitted all models using 8 degrees of freedom per year. Second, we included interaction terms for day of the week and four-year periods, to allow for a varying effect of day of the week over time. Day of the week can influence car use and driving patterns, as well as other patterns that influence crash risk, such as alcohol consumption. Third, we included separate dummy variables for bank holidays, and possibly days immediately prior or after a holiday, using the following process. For each province, we summed all accidents by day and month, thus having a series of 366 days that included all accidents occurred on January 1st, January 2nd and so on. This series reflected the seasonal pattern in the province across all years. We fitted a linear generalized additive model to this series, including as predictor a thin plate regression spline of time with dimension 25 to make sure the seasonal pattern was well captured. Then, we calculated the standardized residuals from the model. We decided to include dummy variables for a specific day in the model if i) the standardized residual for that day was greater than 2 or smaller than -2; and ii) the day could be identified as a holiday, or a day immediately prior or after a holiday. The chosen terms for each province were included as adjustment variables in the main models. This procedure is illustrated in the Appendix, section A.1.

In separate analyses, we fitted the same models described above but with additional terms, namely indicator variables for cold spell and heat wave periods (i.e. both those indicator variables and the crossbasis of temperature were included in the same model). This model estimated the added effect of cold spells and heat waves (Gasparrini and Armstrong, 2011). The province-level estimates for the added effect of cold spells and heat waves was combined using univariate meta-analysis.

As sensitivity analyses, we conducted stratified analyses by grouping provinces by quartiles of average age of the fleet and of average temperature. In addition, we repeated the analyses by 5-year periods. We also conducted an analysis excluding all accidents for which adverse meteorology was marked as a concurrent factor or the above-mentioned atmospheric conditions were marked in the form.

3. Results

The study included data on 1,908,460 motor vehicle crashes, 696,500 (36.5%) of them with driver performance–associated factors. Fig. 1 shows the evolution by year, with an increase in the total number of crashes in the middle period followed by a subsequent decrease to baseline numbers. The average number of motor vehicle crashes per year was 90,879, and the daily average was 249 (90 for those with driver performance–associated factors). The months with highest number of crashes were June and July (Fig. 1). The day of the week pattern changed by year period (Figure A.1). This could possibly be due to a reduction in drunk driving over years, especially during weekends (Pulido et al., 2014). In the earliest period, the highest number of crashes was registered on the weekend, while in the latest period the pattern was completely reversed and weekends registered the lowest number of crashes. Figures A.2 and A.3 show the distribution of crashes by province, which reflected the population in each province (the Pearson correlation coefficient between number of crashes and population was 0.94).

Annual average temperatures in Spain ranged from 11 °C to 21 °C, with a North to South gradient (Fig. 2). The first percentiles of temperatures ranged from −2.6 °C to 16.2 °C and the 99th percentiles ranged from 21.8 °C to 32.4 °C, respectively, across provinces.

Fig. 3 (left panel) shows the pooled cumulative (over 7 days) association between the number of motor vehicle crashes and average temperature. Results showed a monotone increasing risk of motor vehicle crashes as temperature increased. The relative risk (RR) comparing the 1st and the 99th percentiles of temperature was RR = 1.15 (95% confidence interval (CI): 1.11, 1.20). This association was stronger on the same day (lag 0), and decreased with increasing lags, although all associations were statistically significant up to lag 7 (Figure A.4). The meta-analysis showed little heterogeneity between provinces (I^2 = 1%). Figure A.5 shows the estimated province-level curves. In some provinces that reached temperatures below 0 °C, an increased risk with cold temperatures was also observed. However, it only reached statistical significance for the Madrid province. Fig. 4 shows the results when stratifying provinces by average temperature. There was an indication for an increased crash risk with cold temperatures in the coldest provinces, along with somewhat smaller associations with heat.

Fig. 3 (right panel) shows the relationship when crashes were restricted to those with driver performance–associated factors. Results showed an increasing linear relationship between temperature and risk

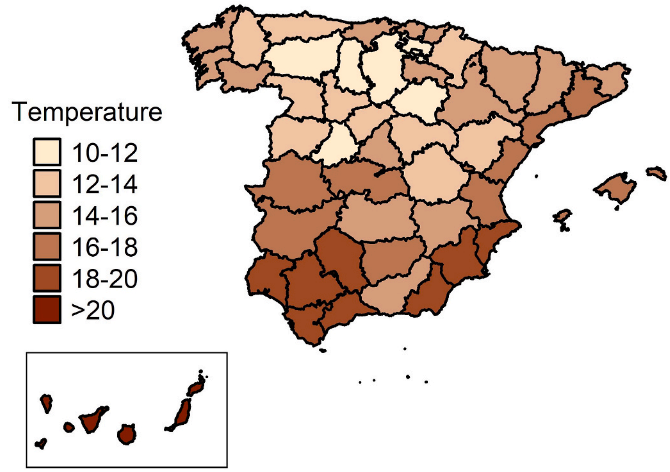

Fig. 2. Map of the average temperature (in °C) by province, 1993–2013.

of crashes with associated driver performance–associated factors. The relative risk (RR) comparing the 1st and the 99th percentiles of temperature was RR = 1.23 (95% CI: 1.17, 1.30). This association was stronger on the same day (lag 0), and decreased with increasing lags, although all associations up to lag 7 were statistically significant (Figure A.6). The meta-analysis showed little heterogeneity between provinces (I^2 = 1%). Figure A.7 shows the estimated province-level curves. In this case, none of the provinces showed increased risks with cold temperatures. Stratifying provinces by average temperature did not reveal any trends (Figure A.8).

Figures A.9 and A.10 show the RRs comparing the 1st and the 99th percentiles of temperature by provinces. There seemed to be a certain North to South gradient, with higher relative risks in the South (the hotter regions), which was more evident for crashes with driver performance–associated factors.

For analyses with all crashes, the estimated added effect of cold spells was RR = 0.996 (95% CI: 0.984, 1.009), p-value = 0.50, with very low heterogeneity (I^2 = 0.07%). The estimated added effect of heat waves was RR = 1.010 (95% CI: 0.996, 1.026), p-value = 0.17, with moderate heterogeneity (I^2 = 25%). In the model for crashes with driver performance–associated factors, the estimated added effect of cold spells was RR = 1.029 (95% CI: 1.005, 1.053), p-value = 0.02, with low heterogeneity (I^2 = 16%). The estimated added effect of heat waves was RR = 1.020 (95% CI: 1.002, 1.039), p-value = 0.03, with very low heterogeneity (I^2 = 2%).

Results were very similar in a sensitivity analysis using 8 degrees of freedom per year to control for trend, e.g. the RR for heat for motor vehicle crashes was RR = 1.16 (95% CI: 1.12, 1.21) and the RR for

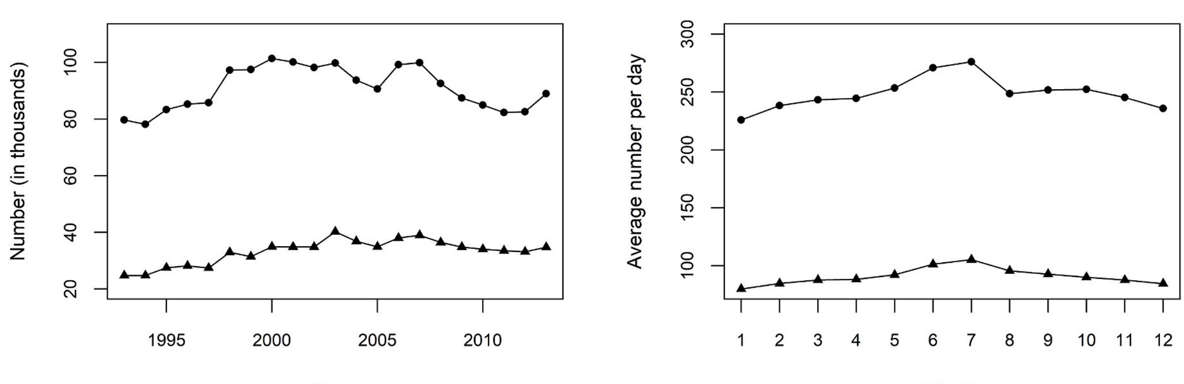

Fig. 1. Yearly (left panel) and monthly (right panel) evolution of the number of motor vehicle crashes (dot) and the number of motor vehicle crashes with driver performance–associated factors (triangle) in Spain, 1993–2013.

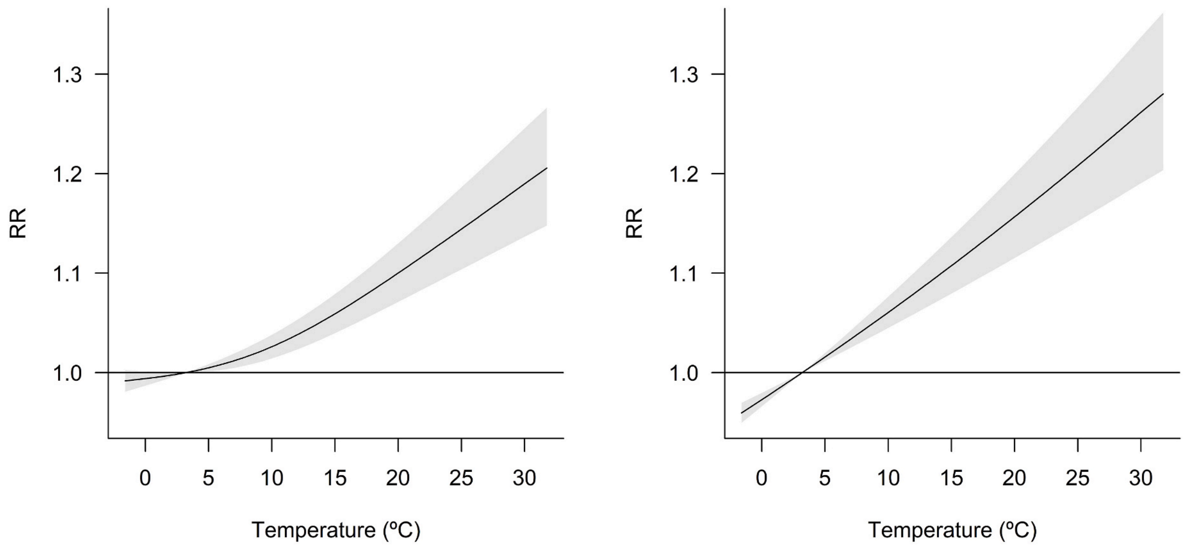

Fig. 3. Association (Relative Risk, RR and 95% confidence intervals) between ambient average temperature (in °C) and total number of motor vehicle crashes (left panel) and motor vehicle crashes with associated driver performance–associated factors (right panel). Associations were cumulated over 7 days. The resulting curves represent the RR obtained by combining province-level curves using multivariate meta-analysis. The reference temperature was 3 °C.

crashes with driver performance–associated factors was RR = 1.23 (95% CI: 1.17, 1.30). When stratifying provinces by average age of the fleet, there were no differences between groups (Figure A.11). When repeating the analyses by 5-year periods, we only observed small variations with no apparent trend (Figures A.12-A.13). When excluding crashes with adverse meteorology from the analyses, the association with heat became stronger for both all accidents and those with driver performance–associated factors (Figure A.14).

4. Discussion

In this countrywide analysis in Spain, we aimed to assess the short-term relationship between ambient temperature and risk of motor vehicle crashes, providing separate analyses for those crashes involving driver performance–associated factors and accounting for potentially nonlinear and delayed effects. Our results showed an almost linear association between average ambient temperature and the risk of motor vehicle crashes, with slightly higher estimates for crashes with driver performance–associated factors. Cold spell and heat wave periods were associated with an additional elevation of crash risk only in the analysis of crashes with driver performance–associated factors.

Our results confirmed those of our previous analysis in the Catalonia region (Basagaña et al., 2015), now with more years and a bigger sample. Despite the differences between the two studies (e.g. one included only the warm season and the other used data for the entire year, and the present one included more regions with different climates), results were remarkably similar. The previous study in the Catalonia region found a non-significant 0.4% increase in risk for each 1 °C increase in maximum temperature, which was a statistically significant 1.1% increase for crashes with driver performance–associated factors. The approximate increases for each 1 °C increase in the present analysis were a 0.6% increase for all motor vehicle crashes and a 1% increase for crashes with driver performance–associated factors. Thus, these results suggest that ambient temperature, and especially hot temperatures, have an influence in the risk of motor vehicle crashes in Spain. In addition, the previous study found an elevated risk during heat wave periods, especially for crashes with driver performance–associated factors. In the present study, we only estimated the added effect of heat waves, i.e., besides the effect of individual days' temperature, what extra risk is introduced by the fact that hot days occur consecutively. This added effect was only detected for crashes with driver performance–associated factors.

It is expected that the association with temperature varies by location as a function of the local climate or due to adaptation measures (e.g., air conditioning in vehicles). Still, several recent studies have reported similar increases in risk with increasing temperature. A study using fatal accidents for the whole continental US found an increase in risk during heat wave days (Wu et al., 2018), which was also found in our previous study (Basagaña et al., 2015). The increase in risk in the study in the US, which was around 3.4%, was found to be stronger on heat wave days without precipitation and with medium/high solar radiation. They were also able to identify obese and old drivers as those at higher risk. Other studies in the US have also documented increases in the risk of motor vehicle accidents with hot temperatures. For example, a study in the state of Maryland found an increase during heat events only if they occurred during spring or summer (Liu et al., 2017). A study in Boston found a non-significant 8% increase in the risk of traffic fatalities associated with warm nights, an association that was much stronger (around 31%) in Santo Domingo (Nazif-Munoz et al., 2021). Another study found increases with hot temperatures in Los Angeles, New York, Chicago and Seattle, although results did not always achieved statistical significance (Hou et al., 2022). A study in Alabama found an increase in traffic collisions during heat waves, but only when the heat wave days had no precipitation (Wu, 2022). Outside of the US, two studies in South Korea found increases in the risk of traffic crashes associated with heat. One found a 42% increase in the risk of injuries from motor vehicle crashes when comparing the temperature of minimum injuries with the 99th percentile of temperature and the effects were cumulated over 21 days (Lee et al., 2020). The other, restricted to summer, found that after exceeding a threshold of 30 °C, motor vehicle crashes increased by 0.6% per 1 °C increase in maximum temperature (Park et al., 2021). A study in northern China found a RR of 3 when comparing the temperature of minimum injuries with the 90th percentile of temperature after cumulating lags 0 to 7 (Liang et al., 2021). A study in Pakistan reported an increase in the risk of road fatalities of 3.6% for a 1% increase in temperature (Ali et al., 2020). A study in Iran focused specifically on motorcycle crashes and found a 20% increase in risk when comparing the 99th percentile of temperature with the temperature of minimum crashes (Zare Sakhvidi et al., 2022). Finally, a countrywide study in Italy found increases of 12% and of 6% when comparing the 75th and 99th percentiles of temperature for overall road crashes and work-related road crashes, respectively (Gariazzo et al.,

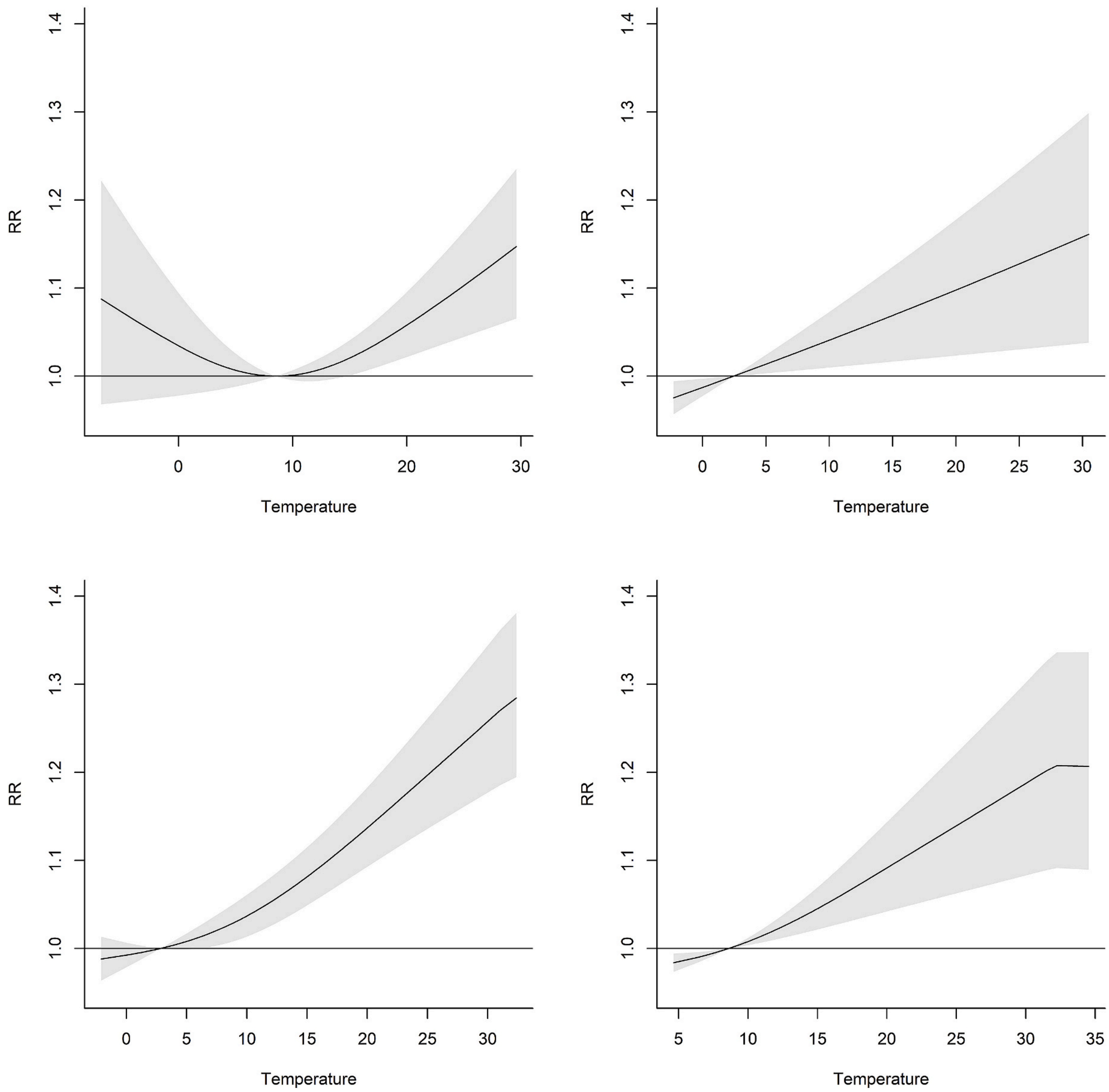

Fig. 4. Association (Relative Risk, RR and 95% confidence intervals) between ambient average temperature (in °C) and total number of motor vehicle crashes stratified by quartiles of province average temperature (top left: average temperature<13.34 °C; top right: average temperature between 13.34 °C and 15.08 °C; bottom left: average temperature between 15.08 °C and 17.21 °C; bottom right: average temperature greater than 17.21 °C). Associations were cumulated over 7 days. The resulting curves represent the RR obtained by combining province-level curves using multivariate meta-analysis within each group of provinces.

2021). The study was able to investigate different characteristics of the crashes, and found that the presence of motorcycles or the use of a vehicle on duty produced higher risks. Other studies can be found in a recent systematic review, which reported a statistically significant meta-analyzed RRs of 1.025 for road traffic accidents and of 1.073 for traffic accident injuries (Liang et al., 2022), although the different exposure metrics used in the different studies do not allow a proper interpretation of those pooled estimates.

The risk of motor vehicle crashes had a monotone increase with temperature in our study, and therefore, we did not detect an increase of the risk with cold temperatures, except for the effect of cold spell periods for crashes with driver performance–associated factors. Icy roads are a known risk factor for motor vehicle crashes. One of the reasons why we did not find an association with cold temperatures might be the fact that many provinces had a very small number of days with temperatures below 0 °C. When we looked at province-level curves, we found several provinces that showed an indication for higher risk for cold, and all of them had those elevated risks in the range of temperatures below 0 °C. The province curves were based on BLUPs, and therefore were shrunk towards the global curve, especially when the number of crashes in the province was small (Gasparrini et al., 2012). Only in Madrid the numbers were large enough to show a statistically significant association for cold temperatures. When we stratified the analyses by province temperature, we also found an indication of an effect of cold in increasing crash risk in the coldest provinces. Other studies have reported such increase for cold temperatures. Studies in South Korea and China reported increases that were in the range below 0 °C (Lee et al., 2020; Liang et al., 2021). The increase with cold temperatures observed in New York and Chicago was also mainly restricted to temperatures below 0 °C (Hou et al., 2022). A study in Italy found an increased risk of crashes of around 10% only when restricting to work-related crashes (Gariazzo et al., 2021). They reported results comparing the 25th and first percentiles of temperature, and the first percentile was below 0 °C for many parts of Italy. The study in Iran, that was restricted to motorcycle crashes, reported effects of cold for temperatures above 0 °C (Zare Sakhvidi et al., 2022). The mechanisms leading to increased risk of crashes involving motorcycles may be different than those of drivers of closed vehicles, as motorcycles are directly exposed to ambient temperature.

In our study, we found elevated risks not only on the same day, but also delayed effects of up to a week. Other studies have also found delayed effects (Hou et al., 2022; Lee et al., 2020; Liang et al., 2021; Zare Sakhvidi et al., 2022). This suggests that the mechanisms leading to those increases in risk are not restricted only to the direct effect of temperature at the time of the crash. The direct and immediate effects could be mediated by reduced driver performance at extreme temperatures, as shown in experimental studies (Daanen et al., 2003; Mackie and O'Hanlon, 1977; Walker et al., 2001; Wyon et al., 1996). The delayed effects, however, could be mediated by other pathways, such as cumulative fatigue caused by warm nights that difficult sleeping (Radun and Radun, 2006), or cumulative dehydration, that leads to lower performance (Grandjean and Grandjean, 2007; Watson et al., 2015). Thus, protective measures such as air conditioning in cars may not fully protect against the increased risk of crashes with heat.

The present study had several limitations. First, we used temperature from the province capital instead of more localized temperature closer to the crash. However, daily temperature variations tend to be homogeneous within a province. In a previous study, we found that the within-province correlation between meteorological stations ranged from 0.87 to 1 (Martínez-Solanas et al., 2018). Second, we did not use other meteorological variables such as rain, wind or humidity, which may be related to the risk of motor vehicle crashes. In some studies, the effect of heat waves was stronger when restricting to days without precipitation (Wu, 2022; Wu et al., 2018), so our results for heat might be underestimated. In a previous study in the Catalonia region, we also found stronger associations when excluding days with precipitation (Basagaña et al., 2015). Although this approach can have some caveats, when we repeated our analyses excluding those crashes that were affected by adverse meteorology, the associations for heat increased. As days affected by other adverse meteorological conditions tend to register low temperatures, removing those crashes leads to a reduction in the estimated crash risk at low temperatures. This further expands the difference in crash risk between cold and hot days. Third, we did not have traffic volume data. These data are essential to estimate correct relative risks, but other studies have shown that, by appropriately controlling for temporal trends, one can obtain good estimates (Brijs et al., 2008). Fourth, our study was observational and therefore there may be unobserved confounders that, if considered, change the obtained estimations. Fifth, the data used came from registries and, especially the information on driver-performance factors associated with the crash, can be quite subjective, as the information is reported by the police officers attending the crash. We believe this information bias is not related to ambient temperature, and therefore it is not expected to bias the results, although estimates will be less precise.

Our study had several strengths. It was a countrywide study based on official registries and therefore it included all registered motor vehicle crashes. The study period was long and it included almost 2 million crashes. We also used state-of-the-art statistical methods to be able to capture potential nonlinear and delayed effects, and used a penalized method to facilitate model selection. Finally, the study was well-grounded on previous research and in particular it was inspired by a previous study with the aim of confirming the previous results with a bigger sample and more sophisticated analysis. The use of the information on driver performance-associated factors is also an original contribution of the study, as this information has rarely been used.

5. Conclusions

This countrywide analysis in Spain confirmed that there was an increased risk of motor vehicle crashes with high temperatures. This increase in risk was slightly larger for those crashes with associated driver performance factors, suggesting that the effect of heat on reducing driver performance may be an important factor. Still, some of the associations were delayed by several days, suggesting that other mechanisms may play a role. Measures aimed at reducing the influence of heat on the risk of motor vehicle crashes can have important benefits for public health.

Credit author statement

Xavier Basagaña: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization, Supervision, **Carlos de la Peña-Ramirez**: Formal analysis, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.114599.

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