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A Bayesian analysis of domestic fire response and fire injury

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ABSTRACT

In this article domestic fire response and fire injury was examined using a Bayesian analysis approach. A Bayesian model was developed to estimate the probability of non-fatal fire injury associated with a given fire response (escape, return to fire, fight the fire) under given circumstances of non-fatal fire injury (age band, gender, smoke alarm presence, type of domestic fire). The Bayesian model was developed using non-fatal fire injury data recorded by Merseyside Fire and Rescue Service between 2011 and 2022. Overall, more domestic fire injuries relating to attempting to fight the fire occurred in properties with a smoke detector (82 % of attempting to fight the fire injuries) compared to properties without a smoke detector (18 % of attempting to fight the fire injuries). Similarly, fire injuries sustained returning to the fire mainly occurred in properties with a smoke detector (75 % of returning to fire injuries) as opposed to properties without a smoke detector (25 % of returning to fire injuries).

1. Introduction

In England the advice from Fire and Rescue Services in the event of a domestic fire is to “Get out, stay out, call 999” [1,2]. However, householders do not always heed such advice [3], and may be injured in a domestic fire whilst returning to the fire or attempting to fight the fire. Human behaviour in response to a domestic fire can be affected by variations in the disposition of individuals such as psychological traits including temperament and risk-taking tendencies [4]. Understanding and quantifying domestic fire risk is important to enable informed decisions to be made by Fire and Rescue Services regarding the domestic fire risk in their community [5]. Residential fires pose a significant threat to life and property in urban and rural areas worldwide, with residential room fires being responsible for 73.0 % of fire injuries in the United States during 2014–2018, and 78.3 % of the fatalities during 2019 in mainland China [6]. Legislation can have an effect in reducing fire risk, for example, legislation concerning reduced ignition propensity cigarettes that was introduced in the UK in 2011 [7]. Clark et al [8] commented upon the need for further research into fire incidents and fire-related risk behaviour based on a study of fire injuries in England in 2011/12. In this article a Bayesian statistical approach [9] to the analysis of domestic fire response and fire injury based upon non-fatal fire injury data over the period 2011 to 2022 in Merseyside, a county in the North West of England is examined. The types of dwellings covered in the study included: Bungalows, Converted Flats/Maisonettes, Houses, Houses in Multiple Occupation, Purpose built flats/Maisonettes, and Self-contained sheltered housing. The type of fire injury recorded was determined by fire officers attending the fire, based upon the guidance provided for the UK Fire Incident Recording System [10], which includes the following injury categories: Overcome by gas, smoke of toxic fumes: asphyxiation; Burns – severe; Burns – slight; Combination of burns and overcome by gas/smoke amongst others.

The county of Merseyside includes 645 km^2 of land containing a mix of high density urban areas, suburbs, semi-rural and rural locations, but overwhelmingly the land use is urban [11]. The Bayesian statistical approach adopted is based upon knowledge of fire responses (the prior probabilities) and modifying that knowledge based upon analysis of relevant fire injury circumstances data to arrive at posterior probabilities, in this case the probability of different fire responses involving different age groups, genders, smoke detector presence, and type of domestic fire. Using a Bayesian statistical approach assists in determining outcomes with practical significance as well as statistical significance, to aid in drawing inferences from the fire injury data to support fire prevention activities. The research questions posed by this research were: How can domestic fire injuries associated with different fire responses be modelled?, What circumstances affect domestic fire

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injuries relating to fire response? This is an important area for research since domestic fire injuries have social and economic costs, and, therefore it is important for Fire and Rescue Services to better understand the nature of domestic fire response by householders in order to appropriately target fire prevention activities to those most at risk. In 2023 the estimated cost of fire injuries to the National Health Service in England was £23 million [12]. The research analyses the occupant response and not the fire fighter response to the fire incident. The originality of the research is the use of Bayesian analysis for modelling the different domestic fire responses associated with fire injury based upon actual fire injury data from Merseyside Fire and Rescue Service.

2. Literature review

2.1. Bayesian statistics

Bayesian statistics [9] which is named after the British mathematician Thomas Bayes, uses conditional probabilities which concern the likelihood of an outcome based upon a previous outcome having occurred in similar circumstances [13]. Bayesian statistical approaches can use point estimates of input parameters or probability distributions of input parameters. Such probability distributions contain uncertainty information about the input parameters and can be propagated through statistical models to obtain uncertainty information about predicted quantities of interest [14]. Bayesian statistics has been utilized in healthcare to determine the accuracy of medical test results by consideration of how likely an individual is to have a given medical condition and the general accuracy of the test results [15]. A Bayesian approach has also been used for financial analysis [16] and policing [17] to estimate and update risk evaluations, and for emergency management modelling [18], and nuclear safety [19]. Rhode et al [20] used Bayesian statistics to generate disaggregate spatial forecasts of residential household fires across metropolitan South-East Queensland in Australia. A Bayesian approach has been used in the modelling of fire development and fire forensics [21].

2.2. Domestic fire response

The presence of active smoke alarms and other fire safety measures such as sprinkler systems have been identified as residential fire-related injury protective factors [22]. In the UK, residential sprinkler systems are only required in blocks of flats with a top storey more than 11 m above ground level [23]. Tannous et al [24] had identified in a study in Australia that smoke detectors in dwellings may not be operational (due to missing or dead batteries, being removed from the ceiling and on shelves, or in some cases still in the package and unopened). Matellini et al. (2103) and Ramli et al [25] had developed models for dwelling fire development and occupancy escape; however, these were based mainly upon expert opinion and scenarios rather than detailed analysis of actual Fire and Rescue Service data. In addition, the models did not include householders returning to the fire. Song and Lovreglio [26] had investigated personalized exit choice behaviour in fire accidents, but had not included fighting the fire or returning to the fire as fire responses. In addition, the analysis undertaken was based upon an online survey in which participants were asked to choose an exit by considering different hypothetical scenarios, rather than actual fire incidence data. Taylor et al [3] examined fire injuries sustained by householders attempting to fight a domestic fire using classical frequentist statistics, but did not examine fire injuries associated with escaping the fire, or returning to the fire. Clark et al [8] commented that fire prevention strategies need to better understand how different factors heighten fire risk in combination based on a study of fire injuries in England in 2011/12. Beaulieu et al [27] advocated the promotion of safe ways to deal with a dwelling fire in fire safety campaigns. Thompson and Wales [28] stated that there has been only limited research into human behaviour in dwelling fires.

The research presented in this article extends previous research by examining the Bayesian modelling of fire injury associated with the domestic fire responses of escape, return to fire, and attempting to fight the fire, based upon the fire injury circumstances of age band, gender, smoke alarm presence, and type of fire from actual fire injury incidents recorded by Merseyside Fire and Rescue Service.

3. Research method

The research method adopted for the research reported in this article was the Bayesian modelling of domestic fire response and fire injury. Based upon previous research concerning domestic fire injury circumstances relating to age, gender, whether a smoke detector was present in the property, and the type of domestic fire being factors influencing a given domestic fire response and likelihood of fire injury [3,29] a model of the circumstances of domestic fire response and fire injury was developed which was then examined using Bayesian statistical analysis. The analysis was conducted using non-fatal fire injury data recorded in the English fire incident recording system by Merseyside Fire and Rescue Service over the period 2011 to 2022. This time period included periods of household restrictions due to COVID-19 which impacted the behaviours of residents and also Fire and Rescue Services. Residents were working/studying more from home and thereby less likely to leave things unattended. In addition, it was also a period when Fire and Rescue Services reduced home safety visits and education programs. In Merseyside the number of accidental dwelling fire injuries, and the percentage of accidental dwelling fires resulting in injury had shown a slightly larger decrease during COVID-19 restrictions compared to the typical decrease between the preceding years [30].

The Bayesian statistical analysis approach adopted applied the logic of conditional probabilities to point estimates of the categorical variable fire response, based upon the categorical variables gender, smoke detector presence and type of domestic fire, and the ordinal (ordered categories) variable age band. The rationale for using Bayesian statistics rather than classical statistics is the ability of Bayesian statistics to estimate the likelihood of outcomes under different sets of circumstances. Classical statistics can examine distributions of fire injuries relating to a given circumstance or pairs of circumstances, or predict the value of a variable, or classify an outcome over the range of a number of predictor variables [31,32]. However, using Bayesian statistics it is possible to examine the likelihood of a given outcome for each individual set of circumstances [31]. This involves more effort, but can yield a more detailed view of the likelihood of a domestic fire injury associated with different fire responses based upon different specific sets of fire injury circumstances. A naïve Bayes approach was adopted that assumed independence between the variables, however there could be dependence between some variables, for example, younger people might be less likely to smoke, and the likelihood of injury whilst escaping might be higher for the elderly.

The Bayesian modelling was undertaken using the MS Excel spreadsheet package and involved estimation of the likelihood of domestic fire injury associated with escape, attempting to fight the fire, and returning to the fire, given different combinations of fire injury circumstances relating to age band, gender, whether a smoke detector was present in the property, and the type of fire.

4. Results

4.1. Domestic fire response and fire injury modelling

Previous research had identified that age, gender, whether a smoke detector was present in the property, and the type of domestic fire were factors influencing a given domestic fire response and likelihood of fire injury [3,29]. In this research, domestic fire injury circumstances were used to model the likelihood of a given fire response. In Bayesian analysis terms this involved modelling the likelihood of a given domestic fire response based upon age, gender, smoke detector presence and the

type of fire.

Fig. 1 shows the proportion of domestic non-fatal fire injuries relating to escaping the fire, fighting the fire and returning to the fire between 2011 and 2022 in Merseyside. There were 1041 domestic fire injuries recorded by Merseyside Fire and Rescue Service in the period 2011 to 2022, of which 80.3 % were associated with escaping the fire, 17.4 % were associated with attempting to fight the fire, and 2.3 % were associated with returning to the fire. A Chi-square test of the frequency of the different fire responses gave a Chi-square value of 1069.18 with a p value < 0.001 indicating that the pattern of fire response was unlikely to be due to chance.

In terms of a smoke detector being in the property, 76.2 % of the recorded fire injuries occurred in a property with a smoke detector, and 23.8 % of the recorded fire injuries occurred in a property without a smoke detector. In terms of the overall distribution of fire injuries by gender, 55.2 % of those injured in a domestic fire were male, and 44.8 % were female.

In terms of the type of domestic fire in which the fire injury occurred, 50.2 % were cooking fires, 13.9 % were fires related to smoker's materials, 8.1 % were related to candle use, 7.7 % were related to electrical supply/appliances, 5.9 % were related to heater use, and 14.2 % were due to a variety of other causes.

Over the period studied there was an overall decrease of 34.3 % in the number of domestic fire injuries; however there was an increase of 23.1 % in the number of domestic fire injuries associated with attempting to fight the fire. The number of domestic fire injuries associated with returning to the fire was very small, ranging between 0 and 4 per year over the period studied.

Fig. 2 shows the distribution of the percentages of domestic fire injuries by age band in Merseyside between 2011 and 2022 and indicated that those in the 20–24, 50–54 and 85+ age groups accounted for the highest percentages of domestic fire injuries by age band over the period studied. In terms of the number of fire injuries per 10,000 of age band population [33], the 20–24, 40–44, 50–54, and 75+ age bands were the most at risk groups for domestic fire injury. This indicated that there was a wide diversity of age ranges at risk of domestic fire injury, and that fire injury prevention approaches need to take into account the variety of individuals that can be injured in a domestic fire.

Bayes theorem (1) [9] concerns conditional probability:

$$P(A|B) = P(A \cap B) / P(B) \quad (1)$$

The Probability of A given B = Probability and A and B/Probability of B.

In terms of the probability of fire response associated with domestic fire injury (2):

$$P(\text{response} \mid \text{circumstances}) = P(\text{response} \cap \text{circumstances}) / P(\text{circumstances}) \quad (2)$$

The domestic fire injury circumstances can be considered as a four dimensional vector (age, gender, smoke detector presence, type of fire).

The fire response variable has the categories {escape, return, fight}, the age variable has the categories {0–4, 5–9, …. 80–84, 85+}, the gender variable has the categories {male, female}, the smoke detector presence variable has the categories {smoke detector, no smoke detector}, and the type of fire variable has the categories {cooking, smoking, candle, heater, other}.

The Bayesian analysis approach models the probability of a fire injury relating to escape, returning to the fire, fighting the fire given the fire injury circumstances. Bayes theorem provided a method for determining the conditional probability of different fire response events. By using a Bayesian approach it was possible to analyse the probability of the different fire response events that occurred over the time period studied, rather than events that conceivably could have happened but did not. The Bayesian logic of conditional probabilities was applied to point estimates representing the different combinations of fire response circumstances.

For example, for an age 20–24 male injured in a cooking fire in a property with a smoke detector, the probability of an injury associated with fighting the fire (3) would be:

$$P(\text{fight} \mid \text{20–24, male, smoke detector, cooking fire}) = P(\text{fight and 20–24, male, smoke detector, cooking fire}) / P(\text{20–24, male, smoke detector, cooking fire}) \quad (3)$$

Based upon the fire injury data from Merseyside Fire and Rescue

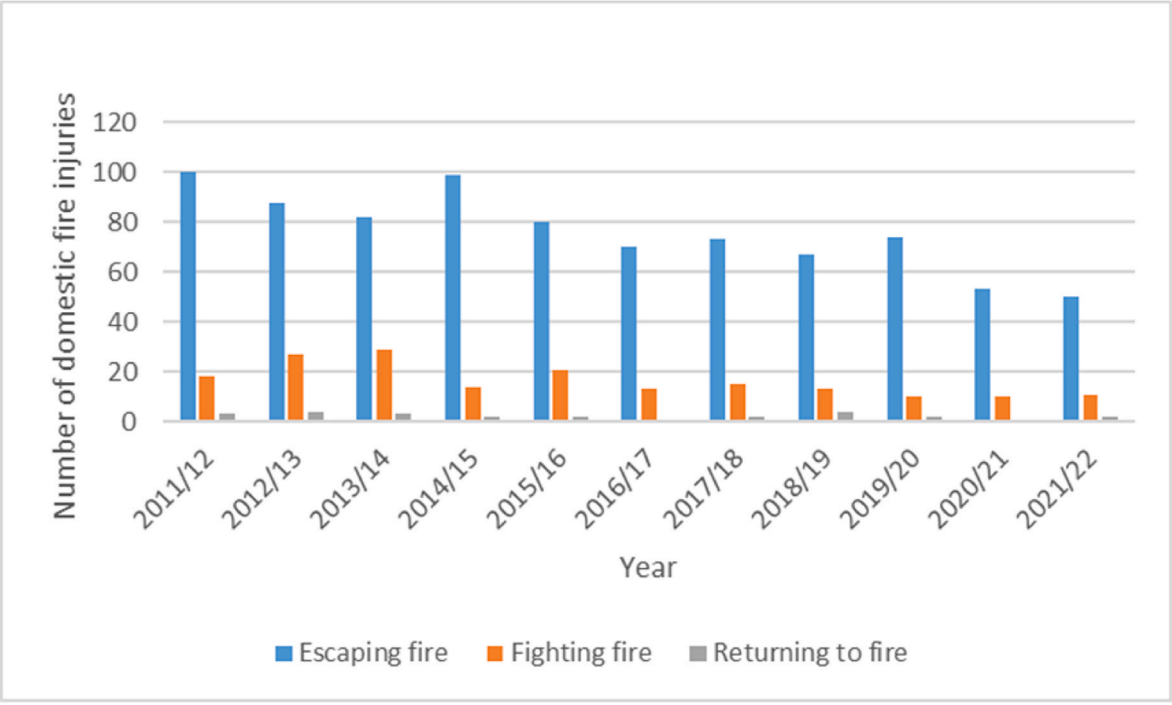

Fig. 1. Number of domestic non-fatal fire injuries per year by fire response in Merseyside 2011 to 2022.

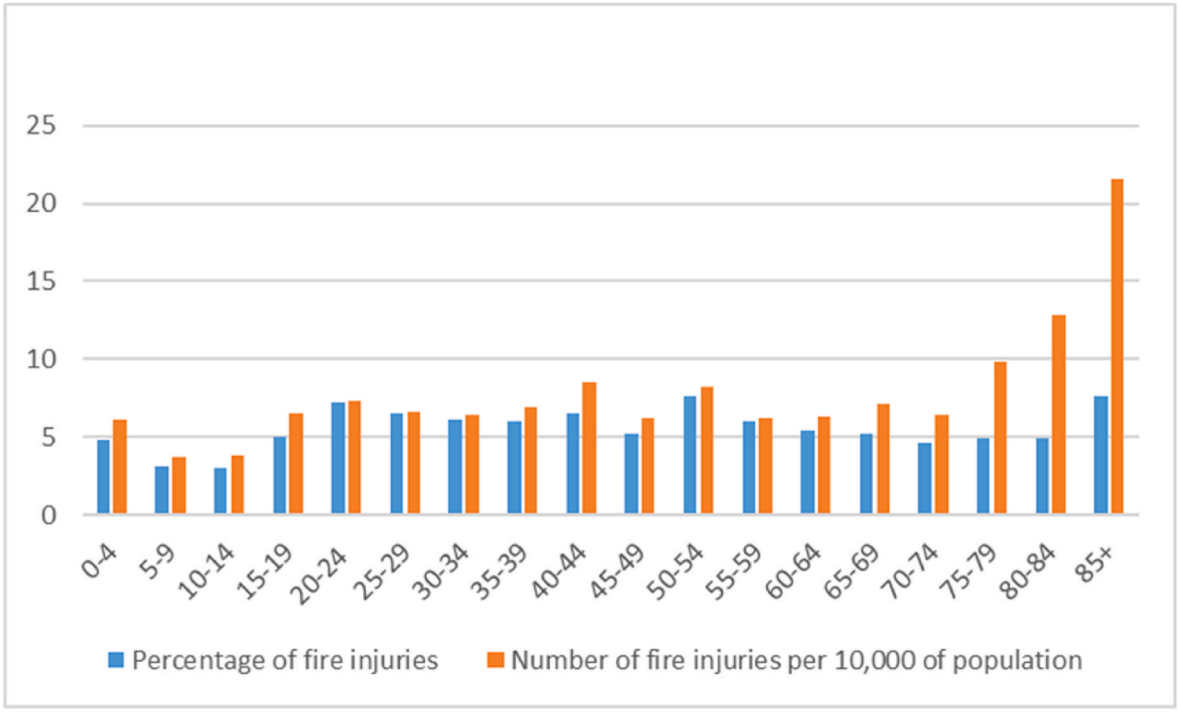

Fig. 2. Percentage of domestic fire injuries by age band in Merseyside 2011 to 2022.

Service over the period studied this equated to a probability of 45.45 %, with a 54.55 % probability of a fire injury being associated with escaping the fire.

In comparison, for an age 50–54 female injured in a cooking fire in a property with a smoke detector, the probability of an injury associated with fighting the fire (4) would be:

P (fight | 50–54, female, smoke detector, cooking fire) = P (fight and 50–54, female, smoke detector, cooking fire) / P (50–54, female, smoke detector, cooking fire) (4)

Based upon the fire injury data from Merseyside Fire and Rescue Service over the period studied this equated to a probability of 22.22 %, with a 66.67 % probability of a fire injury being associated with escaping the fire, and an 11.11 % probability of a fire injury being associated with returning to the fire.

4.2. Bayesian analysis of fire injury attempting to fight the fire circumstances

The following example conditional probabilities relating to fire injury attempting to fight the fire were identified as shown in Table 1.

In summary, over the period studied 17.4 % of domestic fire injuries were associated with attempting to fight the fire. The Bayesian analysis model indicated that there were differences in the circumstances of domestic fire response relating to injuries sustained attempting to fight the fire:

For cooking fire injuries (accounting for 50.2 % of domestic fire injuries in the period studied), males in the age bands 15–19, 20–24, 50–54, 65–69, and 85+ and females in the age band 85+ were more likely to be injured fighting such fires in comparison to the other age bands.

For fire injuries relating to smoker's materials (accounting for 13.9 % of domestic fire injuries in the period studied), males in the age bands 15–19 were more likely to be injured fighting smoker's materials fires in comparison to the other age bands.

For fire injuries relating to candle use (accounting for 8.1 % of domestic fire injuries in the period studied) males in the age band 20–24, and females in the age bands 20–24, and 50–54, were more likely to be injured fighting candle fires compared to the other age bands.

Table 1
Example Bayesian analysis of fire injury attempting to fight the fire circumstances.

Age band	Gender	Fire Type	Smoke detector	Fight fire probability %	95 % confidence interval
5–9	Male	Cooking	Y	33.33	±2.86
10–14	Male	Cooking	Y	20.00	±2.43
15–19	Male	Cooking	Y	50.00	±3.04
20–24	Male	Cooking	Y	45.45	±3.02
25–29	Male	Cooking	Y	33.33	±2.86
30–34	Male	Cooking	Y	11.11	±1.91
35–39	Male	Cooking	Y	17.65	±2.32
45–49	Male	Cooking	Y	28.57	±2.74
50–54	Male	Cooking	Y	40.00	±2.98
55–59	Male	Cooking	Y	9.09	±1.75
60–64	Male	Cooking	Y	15.38	±2.19
65–69	Male	Cooking	Y	40.00	±2.98
70–74	Male	Cooking	Y	13.33	±2.07
75–79	Male	Cooking	Y	37.50	±2.94
80–84	Male	Cooking	Y	7.69	±1.62
85+	Male	Cooking	Y	48.08	±3.04

For fire injuries relating to electrical fires (accounting for 7.7 % of domestic fire injuries in the period studied) males in the age band 30–39, 45–54, and 60–69, and females in the age bands 20–24, 40–44, and 65–69 were more likely to be injured fighting electrical fires compared to the other age bands.

For fire injuries relating to heater use (accounting for 5.9 % of domestic fire injuries in the period studied) males in the age bands 50–69, 70–74, and 80–84 and females in the age bands 35–39, 55–59, and 65–69 were more likely to be injured fighting heating fires compared to the other age bands.

Overall, more domestic fire injuries relating to attempting to fight the fire occurred in properties with a smoke detector (82 % of attempting to fight the fire injuries) compared to properties without a smoke detector (18 % of attempting to fight the fire injuries).

4.3. Bayesian analysis of fire injury returning to the fire circumstances

The following example conditional probabilities relating to fire injury returning to the fire were identified as shown in Table 2.

In summary, over the period studied only 2.3 % of domestic fire injuries were associated with returning to the fire. With regard to householders being injured returning to the fire, this mainly occurred for cooking and smoker's materials fires.

For cooking fire injuries males in the age bands 45–49, 50–54, 80–84, and females in the age bands 15–19, 20–24, 50–54, 75–79, 85+ were more likely to be injured returning to such fires in comparison to the other age bands.

For fire injuries relating to smoker's materials males in the age bands 20–24, 50–54, 80–84, and females in the age bands 65–69, 85+ were more likely to be injured returning to smoker's materials fires in comparison to the other age bands.

Domestic fire injuries sustained returning to the fire mainly occurred in properties with a smoke detector (75 % of returning to fire injuries) as opposed to properties without a smoke detector (25 % of returning to fire injuries).

Table 2
Example Bayesian analysis of fire injury returning to the fire circumstances.

Age band	Gender	Fire Type	Smoke detector	Return to fire probability %	95 % confidence interval
45–49	Male	Cooking	Y	7.14	±1.56
80–84	Male	Cooking	Y	7.69	±1.62
20–24	Female	Cooking	Y	7.69	±1.62
50–54	Female	Cooking	Y	11.11	±1.91
75–79	Female	Cooking	Y	12.50	±2.01
85+	Female	Cooking	Y	6.67	±1.52
50–54	Male	Cooking	N	50.00	±3.04
15–19	Female	Cooking	N	16.67	±2.26
20–24	Male	Smoking	Y	12.50	±2.01
50–54	Male	Smoking	Y	25.00	±2.63
80–84	Male	Smoking	Y	33.33	±2.86
65–69	Female	Smoking	Y	50.00	±3.04

5. Discussion

Using a Bayesian analysis approach it is only possible to take account of the probability of events that have actually taken place and were recorded in the Great Britain fire incident recording system, and not of events that conceivably could have happened but were not reported to the Fire and Rescue Service concerned and therefore were not recorded in the Great Britain fire incident recording system. It was estimated in the English Housing Survey: Fire and Fire Safety, 2016–17 conducted by the UK Ministry of Housing, Communities and Local Government [34] that only a quarter of domestic fires were attended by a Fire and Rescue Service, implying that three quarters of domestic fires in England are not reported to a Fire and Rescue Service. The level of non-reporting of residential fire incidents implies that any statistical analyses of reported fire incidents must be considered in the light of such reported incidents being in the minority of cases, and that fire injuries could still occur in instances when the householder has successfully extinguished the fire and not called the local Fire and Rescue Service. Tannous and Agho [35] had noted the unwillingness of householders to call the fire service in a study in New South Wales, Australia. The Bayesian model used for the research was based on Naïve Bayes (independence between all the features/variables); however there could be dependence between some variables, for example in the area studied, younger people are typically less likely to smoke, but more likely to vape. Other sources of uncertainty in the analyses include the reliability of the classification of the different variables used in the analyses by the fire officers attending the fire. For example, there are twenty five different categories for the type of fire injury, and an individual could have injuries that cover more than one of these categories, in addition there are twenty one categories of dwelling. Overall, it appeared that there was a wide diversity of probabilities associated with fire injury relating to different fire responses corresponding to the different sets of fire circumstances.

6. Conclusions

The research reported in this article concerned Bayesian modelling of domestic fire injuries associated with fire responses relating to different domestic fire injury circumstances. This research enabled profiling of different age bands and genders in the different circumstances of smoke detector presence and type of domestic fire to model the likelihood of different fire responses based upon actual fire injury data recorded by Merseyside Fire and Rescue Service over the period 2011 to 2022. This is an important area of research since in order to attempt to reduce domestic fire injuries it is important to understand the different combinations of circumstances in which householders are injured going against fire safety advice and attempting to fight the fire themselves, or returning to the fire. It appeared that across most age bands and type of fire, and smoke detector presence, males were more likely to be injured attempting to fight the fire or returning to the fire compared to females.

Those aged less than 15 were unlikely to attempt to fight a domestic fire or return to the fire based upon the available data. There were different patterns with regard to being injured attempting to fight the fire by age band and gender across the different types of fires, indicating that householders of certain age bands and gender might be more likely to attempt to fight some types of domestic fires than others. Overall, more domestic fire injuries occurred in properties with a smoke detector (76 % of fire injuries) compared to properties without a smoke detector (24 % of fire injuries). Although smoke alarms should notify occupants and potentially lead to fewer fire injuries, it appeared that attempting to fight the fire and returning to the fire against the standard advice provided by UK Fire and Rescue Services to "get out, stay out, call 999" could be a factor in such fire injuries.

With regard to being injured returning to the fire, this mainly occurred for cooking and smoker's materials domestic fires, and showed different age band patterns for males and females.

In terms of practical implications, using a Bayesian statistical approach it is possible to estimate the probability of fire injury associated with a given domestic fire response (escape, attempt to fight the fire, return to the fire) relating to given fire injury circumstances. This is useful for fire prevention in terms of understanding the circumstances in which an individual may be likely to exhibit riskier fire behaviours such as returning to a fire or attempting to fight the fire.

CRediT authorship contribution statement

M. Taylor: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **J. Fielding:** Writing – review & editing, Methodology, Data curation. **D. Reilly:** Writing – review & editing, Methodology, Formal analysis, Conceptualization. **V. Kwasnica:** Writing – review & editing, Methodology, Formal analysis.

Declaration of competing interest

The authors report there are no competing interests to declare.

Data availability

Data will be made available on request.

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