An experimental study on timely activation of smoke alarms and their effective notification in typical residential buildings

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Abstract: The volume of smoke alarm sound in rooms (other than room of sound origin) in real houses and smoke alarm activation time in rooms in full-scale model houses using ionization, photoelectric and dual detector smoke alarms were determined in this study. The alarm sound level measurements indicated that the sound level in many locations is likely to be too low to provide reliable notification, particularly for sleeping people, if smoke alarms are not installed in every room. In addition, changing to a lower frequency (520 Hz square wave) alarm would further aid effective notification of building occupants. The smoke alarm activation measurements showed that the time to detection (given a particular smoke source) was influenced by door position (open versus closed), the room in which the fire occurs, the location (room or hallway) of the detector, the type of detector and the smoke alarm manufacturer. Furthermore time to detection is also influenced by the type and form of the material that is burning. It was observed that photoelectric smoke alarms had the highest incidence of non-activation and when they did activate they, on average, took longer to activate than ionization and dual (ionization and photoelectric) smoke alarms over all smoke sources considered in this study. It is concluded that to achieve early detection and provide adequate notification, smoke alarms are necessary in every room and should be interconnected.

Keywords: smoke alarm; sound level; activation time; residential building; interconnection.

1. Introduction

Home fires are still a problem in our daily lives. From 2007 to 2011 United States fire departments responded to an average of 1,000 home structure fires every day, and home fires killed an average of seven people per day and caused roughly $28 in damage every second [1]. According to the statistics by Australasian Fire and Emergency Service Authorities Council (AFAC) [2], the residential deaths per 100,000 persons is between 0.1 and 0.7 during 1996-2004. According to The United States Fire Administration [3], the estimation of annual residential building fire deaths in United States is between 2385 and 3050 from 2003 to 2012. According to AFAC [4], the time period when most fire fatalities occurred was during the general sleeping times of 8pm-8am (72%) in Australia, and the figure increases to 78% in New Zealand with a peak occurring between midnight-4am (42%). The study of Xiong *et al.* [5] indicates that one out of four surviving occupants (24.2%) (of relatively minor household fires) were asleep at the time of ignition, while in fires that resulted in fatalities, four out of five fatally injured (80.5%) were asleep.

Home smoke alarm technology has been in use since the middle of the 20th century. According to estimates by the National Fire Protection Association (NFPA) and the U.S. Fire Administration, U.S. home usage of smoke alarms rose from less than 10% in 1975 to at least 95% in 2000, while the number of home fire deaths was cut nearly in half [6]. A working smoke alarm has been reported to reduce the risk of death from residential fires by from between 50% to 70% [7, 8]. The US Fire Administration reports that more than 88% of the homes in United States have at least 1 smoke alarm installed, but 60% of the residential fire deaths occur in homes without an operational alarm Analysis of data from the United States Fire Administration's National Fire Incident Reporting System (NFIRS) and the NFPA's fire department survey showed that from 2003 to 2006, no smoke alarms were present in 31% of reported home fires and 40% of home fire deaths [9]. Stated another way, smoke alarms were present in 60% of home fire deaths. Notwithstanding that some of these fatalities may have been caused by explosions or similar close physical encounters with fire, the presence of a smoke alarm is most useful if the smoke alarm is activated quickly by the presence of smoke and the alarm signal is such that people in the dwelling are notified as quickly as possible of the fire. There are basically three different types of residential smoke alarm: the ionisation alarm, the photoelectric alarm, and the dual alarm [7]. Ionization and photoelectric alarms operate via different mechanisms, detecting invisible/fine and visible products of combustion, respectively [10]. Photoelectric alarms use optical sensors and are more likely to respond to slow, smouldering conditions. The working principle of ionisation detectors is based on a modified theory which includes soot particle charge fraction functionality in addition to the generally accepted particle size and number density dependence [11]. Smoke alarms of either the ionisation type or the photoelectric type are designed to activate quickly and thus provide time for alerted occupants to escape from most residential fires, although in some cases the escape time provided can be short [6].

Many studies have been conducted to analyse the performance of different types of smoke alarms. The Consumers Union in the United States [12] tested ionisation and photoelectric alarms in 1994 and found that in a smouldering, smoky fire, the ionization alarms responded in 25 to 35 minutes, whereas the photoelectric models reacted in half that time. A statistical study was conducted to compare the performance of different residential smoke detector technologies when exposed to different fire types by Milarcik et al. [13]. The results showed that ionisation detectors, on average, respond faster to flaming fires, while photoelectric detectors, on average, respond faster to smouldering fires. They further determined that both technologies provide statistically equivalent warning to different types of fires for the next residential fire occurrence i.e. it cannot be determined with confidence which detector will be activated first to the next fire. Cleary [14] conducted a full-scale fire test series in a building mock-up designed to represent a portion of a small house or an apartment to examine smoke alarm sensitivity. Similar to other studies [12, 13], he found that in general the photoelectric alarm responded more quickly in a smouldering fire and the ionization alarm responded quicker in flaming fire configurations. One particular brand of dual alarm was found to register in a faster average time compared to other single and dual alarms. Milke and Zevotek [15], through a limited number of cooking fire tests, observed that an ionization alarm provided a faster response than the photoelectric alarm, but was more prone to nuisance alarm. Bukowski et al.

[6] performed comprehensive real-scale tests on the performance of different type of smoke alarms. They arrived at similar conclusion that ionisation type alarms provide somewhat better response to flaming fires than photoelectrical alarms, and photoelectric alarms provide (often) considerably faster response to smouldering fires than ionization type alarms. Su and Crampton [16] conducted a series of experimental studies in a residential dwelling as well as in a laboratory room to examine the effect of "dead air space" (i.e. a corner where smoke was thought unlikely to reach) on smoke response. The results showed that smoke can reach the "dead air space" under the experimental conditions and the smoke alarms installed in the "dead air space" can respond to the fire at times comparable to, and in many cases even earlier than, the smoke alarms installed at conventional locations.

Determination of the most appropriate locations for smoke alarms in residential buildings requires consideration of many factors. These include the likely smoke sources (particularly those that are involved in fires resulting in injury or death), detector type, alarm sound and the alarm brand (or manufacturer) because these factors affect either the time taken for smoke detection or the likelihood of the alarm signal alerting people. An alarm signal attenuates as it travels and encounters walls and closed doors. Halliwell and Sultan [17] proposed a simple expression to calculate attenuation of the alarm signal including the effects of floor area and closed doors. It is notable that, in the USA, the NFPA has required smoke alarms in bedrooms since 1993 and interconnection of smoke alarms for new homes only since 1989 [18, 19] but some countries, such as Australia, did not have these requirements until early 2014 [20]. Lee [21] examined the feasibility of applying modifications to residential smoke alarms or the addition of secondary devices to improve the sound effectiveness for smoke alarms. He also suggested that the use of interconnected smoke alarms and lower frequency alarm tones may result in improved audibility, especially for older adults. Furthermore, the Australian Standard for emergency notification [22] noted that the sound level of a smoke alarm should be at least 75 dBA at the pillow. It is also important to investigate whether a sound level of this can be achieved with the hallway placement of detectors as specified for houses by the Building Code of Australia (BCA) [20].

Any improvement in fire safety due to changes in building regulations requiring smoke alarms requires that people similar to those who are currently killed or injured in fires in dwellings be saved from death or injury in similar fires in the future. Thus improvement requires that people similar to those currently being killed or injured notice and act on smoke alarm warnings they currently do not notice, or if they do, they do not act on in such a way as to avoid death or injury. In order to help provide evidence about important aspects of smoke alarms, a comprehensive experimental investigation on smoke alarms in typical residential buildings was conducted in this study. It covers the five distinct aspects of (1) type of detector (ionisation/photoelectric/both) and time to activation, (2) location of the smoke alarm and time to activation, (3) fuel types and time to activation, (4) volume of the smoke alarm signal in different rooms and (5) comparison of the volume of different signals in different rooms. The first three aspects were studied in full-scale replica model houses using a range of fuels, while the latter two aspects were studied in real (occupied) homes. The information from this study can be used to inform an estimate of the changes in fatalities that would occur if smoke alarms in every room and/or interconnected[1] smoke alarms were required by revised building regulations. The paper is unique in combining both consideration of the measurement of sound levels and measurement of activation times of smoke alarms to smoke within dwellings of the same size and dimensions. This combination supports the idea of analysing the smoke alarm in a real world home setting as a single system. It is to be noted that to calculate escape times prior to reaching untenable conditions, there may be delays based on fuel, alarm type, room of origin, room of alarm, etc., beside activation times. Irrespective of whether those delays are short or large, this study is not intended to address whether the alarms are providing enough time for escape.

2. Methodology

2.1 Smoke alarm sound level tests

The houses used in the experimental investigations were intended to represent typical Australian houses. Three were single storey and one was of two storeys above ground. No houses had basements. Anecdotal evidence suggests that they represent typical Australian houses. Plans of the houses are included in Fig. 1. The houses are numbered from 1 to 4 to allow identification of particular houses, shown in Table 1. House 4 is a two storey house.

Table 1 A summary of the houses for smoke alarm sound level tests

ID	Storey	Room of sound origin (RSO)[a,b]	Number of RSOs
H1	1	Bedroom 1, Bedroom 2, Bedroom 3, Family area, Back hall, Front Hall, Lounge, Study room	8
H2	1	Bedroom 1, Bedroom 2, Bedroom 3, Family area, Back hall, Front hall, Kitchen, Lounge, Study room	9
H3	1	Bedroom 1, Bedroom 2, Family area, Back hall, Front hall, Kitchen, Lounge, Study room	8
H4	2	Bedroom 1, Bedroom 2, Bedroom 3, Back hall, Front hall, Kitchen, Living room, Lounge, Study room	9

Note: [a] Two sounds at set levels (85 and 105 dBA) were emitted from likely smoke alarm positions in each room (RSO), generally close to the middle of the ceiling, and in each hallway; and
[b] The sound levels in each room were measured in positions diagonally opposite the room doors at approximately pillow height to simulate the likely sound level that sleeping people would experience (as shown by the dots in rooms of Fig. 1).

The sound level in each room was measured with various combinations of doors open and closed in the four real furnished houses. Two sounds at set levels were emitted from likely smoke alarm positions in each room of sound origin (RSO), generally close to the middle of the ceiling, and in each hallway. The recorded smoke alarm sounds were emitted from a large speaker at 85 and 105 dBA sound levels measured 1 m from the speaker. Lower sound levels were measured at other locations in the RSO, but these measurements do not form part of this study. It is to be noted that AS 1670.1 [22] requires that the sound levels should not be less than 85 dBA and not more than 105 dBA. Similarly UL985 [23] has a requirement of 85 dB at

[1] Interconnection means all available smoke alarms are interconnected wirelessly (via RF module) or hard-wired and activation of one smoke alarm will cause activation of all interconnected smoke alarms.

10 feet for residential sounders which would be around 95 dB at 1 meter.

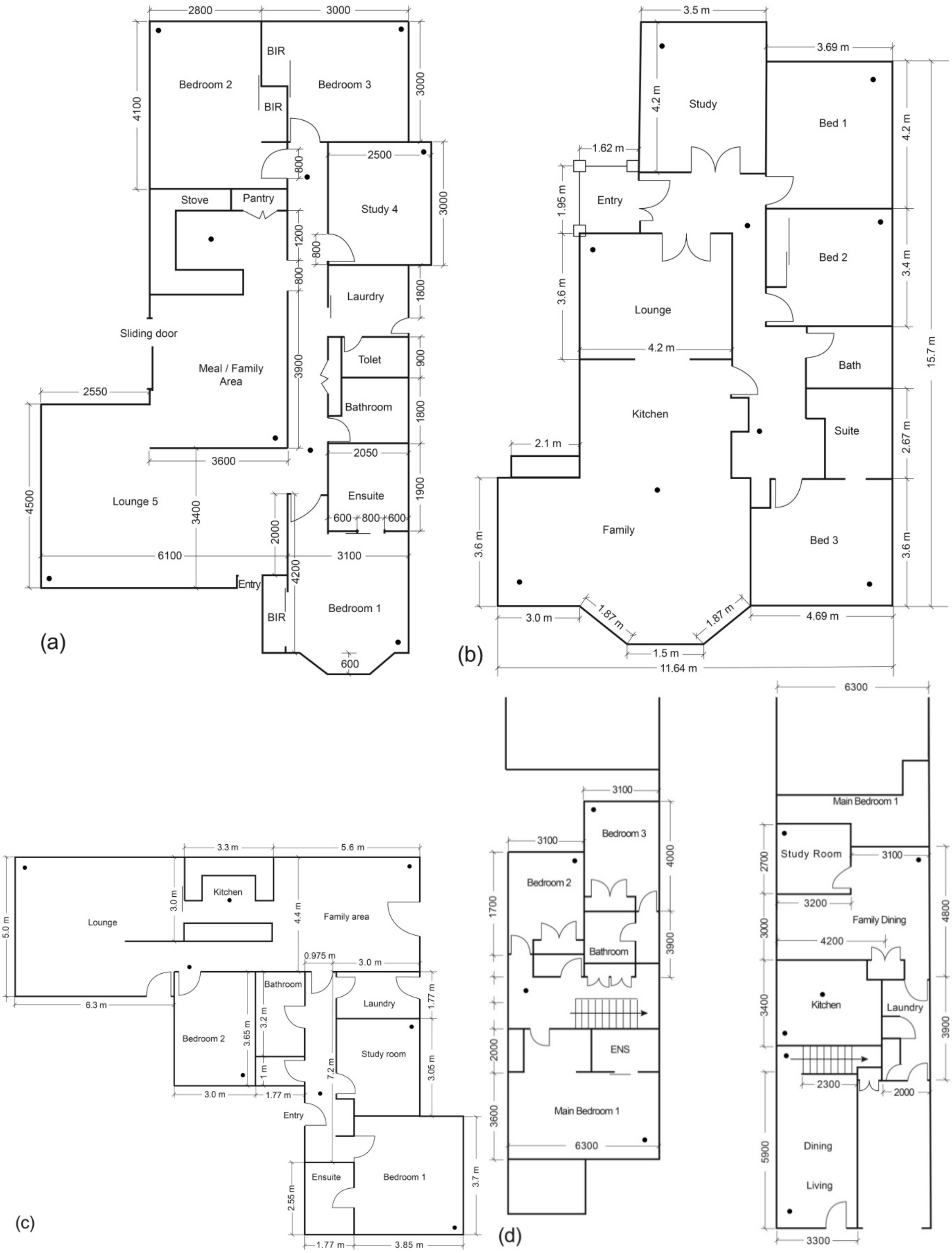

Fig. 1 Plan for four types of houses: (a) House 1; (b) House 2; (c) House 3; and (d) House 4. The dots in the rooms represent the positions where sound levels were measured at approximately pillow height and in the halls and kitchens represent smoke alarms.

The sounds used were the ~3100 Hz sound currently used in Australia in domestic smoke alarms and the 520 Hz square wave sound, which has been used in the testing of arousability of various groups of sleeping people [24-29] from deep sleep. These sounds are discussed in details in those articles. The latter sound is now required by the NFPA for smoke alarms in certain circumstances [19]. The smoke alarms were located exactly in the middle of the RSO and 0.5m below the ceiling (in Fig 1 these are shown by dots in kitchens and hallways).

The sound levels in each room were measured in positions diagonally opposite the room doors at approximately pillow height to simulate the likely sound level that sleeping people would experience. The sound levels were measured using Lutron SI-4001 sound meters with the settings on “slow response” to minimise sound meter fluctuations and “maximum hold” because maximum levels were most appropriate for alerting as described in [30]. All measurements were conducted during the day with the houses unoccupied, and in most cases the ambient sound level was in the range 35-40 dBA with occasional higher excursions when, for example, an aeroplane passed overhead or a truck passed by.

Table 2 A summary of fuels used in the tests

ID	Fuel	Description
BE	Burning ethanol	In preliminary tests that none of the smoke alarms were activated (even in the room of origin) by the burning ethanol, and consequently this fuel was not used in subsequent testing.
BW	Braided wick	90 strands of braided wick (cotton) 800 mm long which smouldered producing voluminous whitish smoke
HF	Heptane	burning n- heptane (plain heptane rather than the 96 wt.% heptane plus 4 wt.% toluene specified in [31]) rapidly produced very black smoke
DF	Decalin	burning decalin very rapidly produced a great quantity of very black smoke
SW	Smouldering wood	the rapidly smouldering wood consisted of ten dried sticks (again pinus radiata rather than the beechwood specified in [31]) placed on a hotplate with the temperature of the hotplate raised to 600°C over eleven minutes as specified in [31]) produced a greater quantity of light grey smoke
WC	Wood crib	the wood crib fire used a small crib of seven layers of sticks (pinus radiata instead of the beechwood specified in [31]) and burned as a flaming fire with light grey to white smoke
ST	Smouldering towel	cotton towel smouldering due to an electric heating element, the light grey smoke produced built up quite slowly
PF	Polyurethane foam	three sheets (each about 500 mm × 500 mm × 20 mm) of soft polyurethane foam without flame-retardant additives of density about 20 kg/m^3 were ignited as specified [31] producing much black sooty smoke

2.2 Smoke alarm activation tests

As it is risky and costly to conduct fire and smoke tests in real houses, full scale models of the four houses used for the sound measurement were constructed and the time of activation of the domestic smoke alarms in each room and hallway was recorded. The full scale model houses were constructed of cardboard with the doors and windows cut out and opened and shut as required for each case tested. It is assumed that for smoke movement, properly sealed cardboard model houses would have a similar influence as real houses primarily constructed of light weight plasterboard walls. The smoke sources tested are as set out in Table 2. These materials and the form of combustion were based on those specified in ISO/TS 7240-9 (2006) “Test fires for fire detectors” [31] for the testing of smoke detectors. One can also use standard fire tests as per UL 217 [32]. It is to be noted that standard fire tests are not a perfect representation of real fires. While they aren't perfect, they are designed to bracket most/all scenarios. Furthermore they provide some level of measurable performance and are easily replicable by other researchers. With the restrictions of conducting hazardous testing of full room fires due to occupational hazard and safety regulations as well as ethical consideration, tests were restricted in this regard. This is a limitation of this study. It was found in preliminary tests that none of the smoke alarms were activated (even in the room of origin) by the burning ethanol, and consequently this fuel was not used in subsequent testing. Minor adjustments were made to the smoke sources due to difficulty in exactly matching the materials specified, shown in Table 2.

Analysis of preliminary experimental results showed that the activation time (if activation occurred: in many tests some alarms did not activate) was very strongly influenced by whether interconnecting doors were open. However, under the controlled (very still) environmental conditions used for these tests (housed within 70m L x 40m W and 30m H Large Scale Fire Testing Facility) there was little influence of whether windows were open or closed. Consequently all of the results reported here, unless noted otherwise, were for tests with the windows closed. Each room of fire origin (RFO) is listed in Table 3.

The smoke alarms used in this project were purchased from retail outlets. They were battery powered units and were sold under two brand names. They are referred to in this paper as Brand 1 and Brand 2.

Table 3 A summary of the houses for smoke alarm activation tests

ID	Storey	Room of fire origin (RFO)[a,b]	Number of RFOs
H1	1	Bedroom 1, Bedroom 2, Bedroom 3, Kitchen, Lounge, Study room	6
H2	1	Bedroom 1, Bedroom 2, Bedroom 3, Kitchen/Family room, Lounge, Study room	6
H3	1	Bedroom 1, Bedroom 2, Kitchen, Lounge, Study room	5
H4	2	Bedroom 1, Bedroom 2, Bedroom 3, Kitchen, Lounge, Study room	6

Note: [a] The smoke alarms were fitted on the ceiling at the centre of the room with approximately equal distance from the doorway to each alarm; and

[b] The fire sources were located at the centre of each floor of the rooms.

Despite the fact that there was a small gap at the top, bottom and on one side of each door, initial testing indicated that even when the room of fire origin was full of dense smoke, virtually no smoke was emitted through the closed door into the adjacent room or hallway and that there was no detection of this smoke by alarms in these locations. On this basis it was decided not to continue with tests with the RFO door closed. The movement of smoke through a closed door was checked using a real door in a model building (it was not considered acceptable to severely smoke log rooms in occupied houses) and the situation described above for the model building was found to be reproduced in these situations: unless there was some pressure difference induced between the two rooms by mechanical ventilation or external wind there was very little smoke movement from one room to another with the door closed. Therefore all of the results reported here for smoke travel and alarm activation are for the case with all room doors open.

In each of the model houses smoke was produced using each of the fuels in Table 2 set alight in the RFO and the time to activation of the smoke alarms fitted in each room and hallway was recorded. The smoke alarms were fitted on the ceiling at the centre of the room with approximately equal distance from the doorway to each alarm. Each room was fitted with two ionization alarms, two photoelectric alarms and one dual (ionization and photoelectric) alarm. In hallways the dual alarm was omitted. The response time (or activation time) of the alarms of each type and from each manufacturer were compared and found to be very similar. That is, there was consistency in the results obtained when comparing alarms of the same type and brand. The smoke alarms were cleaned regularly and batteries changed and through repeat testing it was established that there was no trend towards greater activation or shorter activation times though one may expect that alarms to become more sensitive from repeated use.

3. Results and analysis

In this section, sound level and smoke alarm response time results are presented and analysed. In the sound level experiments, described in Section 3.1, four real houses were used to test the sound level in RSO and the "other" room (i.e. not the RSO) using two kinds of sound sources (85 and 105 dBA) with two different frequencies (520 Hz square wave and 3100 Hz). Several parameters were analysed, including the door position, sound frequency, room of sound measured and speaker installation location. In Section 3.2, the performance of three types of smoke alarms (ionization, photoelectric and dual alarms) using eight fire sources were summarized. Activation times of these smoke alarms were obtained from the experiments. Section 3.3 provides a statistical analysis of the performance of smoke alarms.

3.1 Sound levels in other rooms

The sound level measured in the other rooms was decreasing as the distance from the RSO increases as expected. Taking House 4 as an example, the sound levels were measured in each room and hallway with Bedroom 1 as the RSO. As shown in the house plan in Fig. 1(d), House 4 is a two storey house having the living/dining (lounge) room, kitchen, laundry, family/dining (living) room and study on the lower floor and bedrooms 1, 2 and 3 and bathroom on the second level. It was observed that the sound level in bedrooms 2 and 3 (56.5 and 51.7 dBA respectively) were substantially lower than the sound emitted in the RSO (bedroom 1, 85 dBA measured 1 m directly in front of the speaker) and that the level in the rooms on the lower floor were lower again (44.1, 43.9 and 41.3 dBA for the lounge, kitchen and study respectively) with the sounds on each level falling marginally as the rooms become more distant from the RSO (bedroom 1).

Experimental studies [33] have shown that even at 75 dBA, between 18% and 44% of certain groups within the population (e.g., older adults, children, young adults, hard of hearing) will sleep through a ~3100 Hz smoke alarm. A sample of Australian adults with mild to moderate hearing impairment was found to have a mean awaking threshold for the ~3100 Hz signal of 75 dBA (standard deviation =15.2) [34, 35]. In the present study, the awaking threshold of 75 dBA was used as a comparative benchmark to analyse the effectiveness of smoke alarms under various situation. This decibel level is also the recommended Australian standard for smoke alarm volumes in bedrooms [22].

Categorical data analysis of the measured sound levels was undertaken to obtain an overall perspective on the results. This analysis produced very consistent results in the four houses and revealed the average decibel levels. The influence of sound frequency on sound level in other rooms can be seen in Fig. 2. The X axis shows the status of the door. In "Open-Close" for example, the "Open" represents when the door of the RSO was open and the "Close" means the measurement in other rooms were taken when the doors were closed. The Y axis is the average (arithmetic mean) sound level in other rooms apart from the RSO. The error bars on the top column are the range variability of four houses, showing that there is not much variability among four types of houses. It should be noticed that the variation is the obtained average sound level among four houses, so it does not necessarily mean that the measurement in each test is within these ranges.

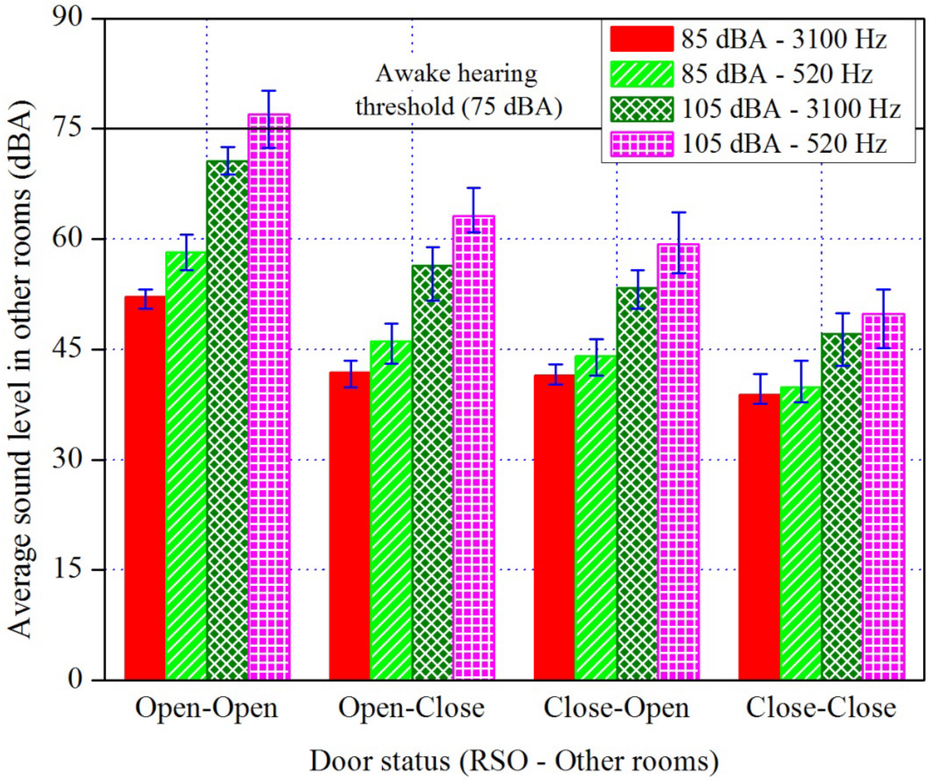

Fig. 2 Average sound levels in 'other' (non-Room of Sound Origin, RSO) rooms as a function of door open/close status, alarm volume and alarm frequency.

It can be seen that the low frequency sound source (520 Hz square wave) resulted in a relatively high sound level in other rooms. It is observed that the 520 Hz signal added 1-7 dBA to the sound level – for both 85 and 105 dBA alarm. Likewise, the 520 Hz square wave sound has consistently been found to be more likely to awake sleeping people in the event of a fire than other signals tested [36].

In Figure 2 the horizontal line at 75 dBA is the awaking threshold. It can be seen that only one situation could achieve the 75 dBA sound level for awaking sleeping people, which is the situation with all doors open with the 105 dBA, 520 Hz sound source. However the sound levels in certain 'other rooms' might be above the awaking threshold but are not shown in the figure as averages across all 'other rooms' as shown. Figure 2 shows that as soon as *any* doors are closed the average measured sound level in other rooms is much lower (by at least 12 dBA) than the awaking threshold.

There is little difference in average sound level whether the RSO or other rooms have a closed door, (i.e. between "Open-Close" and "Close-Open"). Not surprisingly, the situation with all the doors closed produces the average lowest sound level with the 85 dBA alarms (39.4 dBA average across alarms of both frequencies). The pattern of differences is the same for sound sources of both 85 dBA and 105 dBA, with the latter average sound level being about at least 20 dBA higher under different scenarios.

In the practice, it is impossible to keep all the doors in a home open all the time. Even if all doors are open with the most effective sound source there is no guarantee that a sound level of at least 75 dBA can be achieved in any particular room. However, if smoke alarms are installed in every room, the awaking threshold for sleeping people may be achieved when there is a fire, depending on the RSO and whether there is interconnection or not.

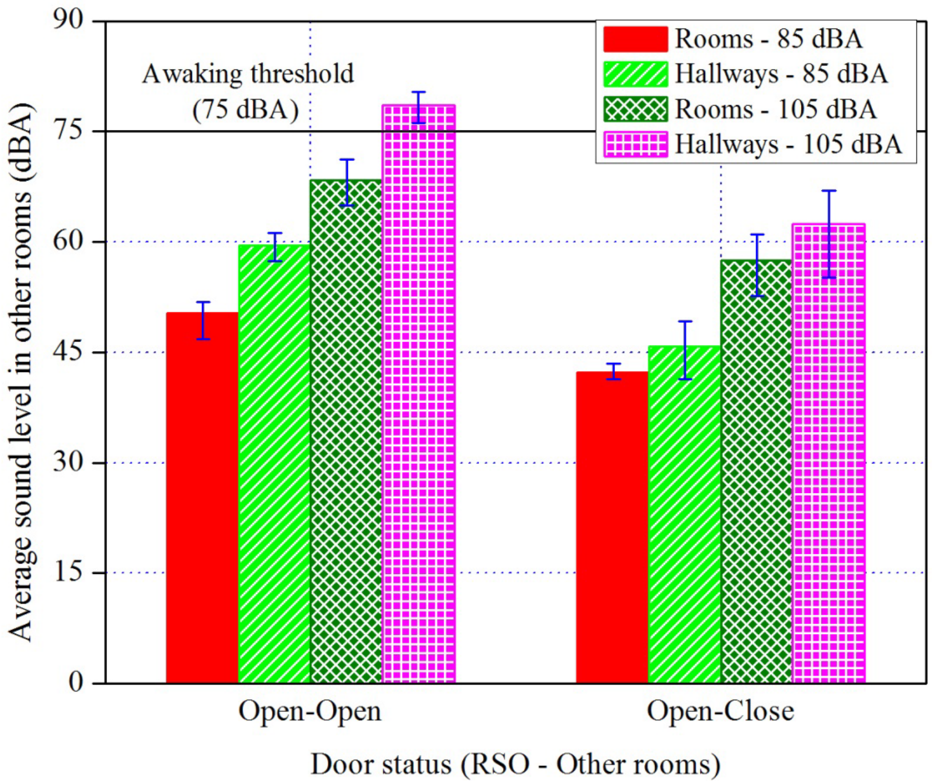

Fig. 3 Influence of alarm installation location (room or hallway) on sound level in other rooms (not the RSO); the average values included both 3100 and 520 Hz sound sources.

Figure 3 shows the difference between placing smoke alarms in hallways compared to in rooms. The results indicate that hallway smoke alarms can result in higher sound levels in other rooms, compared to alarm placement in rooms. For example, under the "Open-Open" situation for 85 dBA sound source, the average sound level in other rooms shows an increase of about

10 dBA when the alarm was installed in hallways compared to an alarm installation in a room. When a door of an other room is closed, the increase is not so obvious, yielding an increase of about 4 dBA. Figure 3 also shows that the only situation to achieve a threshold of 75 dBA is with all doors open and a 105 dBA sound source in the hallway.

The door status, sound frequency and RSO have an influence on the achievement of awaking threshold. Fig 4 (a) shows the combination of different factors on the achievement of awaking threshold. It is shown that it is not possible to achieve the 75 dBA waking threshold with a 85 dBA sound source located in the hallway or in other rooms, no matter what the door open or closed status is or the alarm frequency. Using 105 dBA will increase the possibility of passing the awaking threshold, seen in Figure 4 (b). However, this only applies for one scenario. A low frequency sound source (520 Hz square wave), a loud (105 dBA) smoke alarm located in the hallway with all doors open was found to exceed the awaking threshold. For the situation where one door is closed no combination meets the awakening threshold.

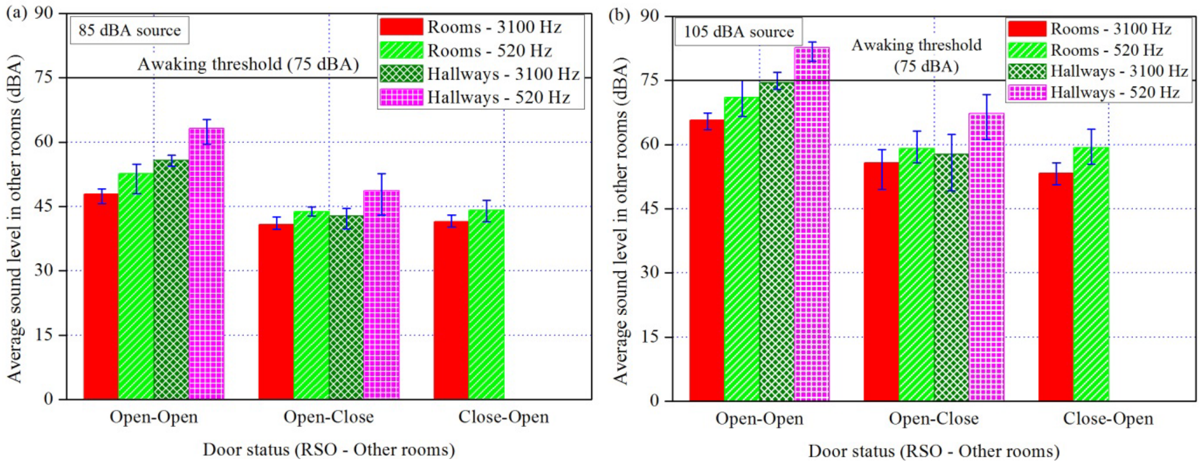

Fig. 4 Threshold under the combination of influencing factors for sound source of: (a) 85 dBA; and (b) 105 dBA

Since the average in all other rooms was generally under 75 dBA, this supports more alarms being installed and that interconnection is necessary. Although it does not necessarily mean that unless we have an alarm in every room (i.e. every room is a RSO) we will not get a loud enough notification, it is likely to be true in many places. Unless the sound level is analysed for each newly designed house, it is safer to be prescriptive by having an alarm in every room and requiring interconnection.

3.2 Smoke alarm response time

A sample of the results of smoke alarm response time for Model House 2 is presented in Table 4. These results are for three fuels: braided wick (BW), rapidly smouldering wood (SW) and heptane (HP). In Table 4 and subsequent tables the alarm type is signified: *I* is the ionization smoke alarm; *P* is photoelectric smoke alarm; and *D* represents dual ionization and photoelectric alarm, with the numerical suffix signifying the brand of alarm.

Table 4 Smoke alarm activation time in seconds with Bedroom 3 as the RFO, all doors open and all windows closed in Model House 2

Room	I1	I2	D1	P2	P1
			Fuel = BW		
Bedroom 3	14	5	9	95	110
Front hall	330	320	-	340	374
Kitchen	-	-	1851	2004	1617
Bedroom 2	560	687	566	531	568
Lounge	1143	558	511	502	576
Back hall	-	1761	1167	1621	-
Bedroom 1	1829	1829	805	896	813
Study	-	773	614	582	587
			Fuel = SW		
Bedroom 3	304	240	296	214	252
Front hall	425	386	-	358	365
Kitchen	-	-	1949	2053	2013
Bedroom 2	815	882	635	546	570
Lounge	995	815	478	495	632
Back hall	836	852	763	934	-
Bedroom 1	1043	1043	790	834	804
Study	1178	842	747	770	715
			Fuel = HF		
Bedroom 3	13	13	19	212	72
Front hall	52	45	-	504	225
Kitchen	303	300	-	-	-
Bedroom 2	172	193	273	-	927
Lounge	201	159	230	-	-
Back hall	79	69	235	-	-
Bedroom 1	169	159	233	-	-
Study	212	127	244	-	-

A number of observations may be made regarding the results presented in Table 4:

- there are many instances where some smoke alarms do not activate even though other smoke alarms in the same room do activate;
- the activation times in the room of fire origin (RFO) are generally much shorter than those in the hallways and other rooms;
- in general, for each alarm type and manufacturer, the activation time increases with greater distance from the smoke source;
- an exception to the above was for the smoke alarms in the kitchen where there were generally much longer delays in activation time than other rooms even though the distance from RFO to the kitchen was shorter than to most other rooms (this delay may be attributed to the much larger combined space of the kitchen and family room compared to other rooms);
- in many cases (for the same fuel and room) there are significant differences in the activation times for smoke alarms of different types and brands; and
- there are major differences in the activation times with the different fuels and these differences appear to vary with smoke alarm type and brand.

Generally the smoke alarms that did not activate were those most remote from the RFO but this was also influenced by the fuel and other (some unidentified) factors. Table 5 shows the overall percentage of the non-response alarms from all four houses. It is to be noted that the experiments conducted in the current study were not reliability tests. The smoke environments to which the smoke alarms were exposed were not controlled nor were they measured. Therefore, the results presented in Table 5 cannot be used to verify the reliability of the smoke alarms.

Inspection of Table 5 reveals that there was a minor difference (1%-8%) between the manufacturers, but that the major difference was between the ionization (I) and photoelectric (P) alarms, with the photoelectric alarms not activating much more frequently. The other major difference was between the two storey house (House 4) and the other houses which were all single storey. This difference is principally due to the smoke alarms in the lower storey not activating when the room of fire origin was on the second storey.

Table 5 Proportion of smoke alarms of each type and manufacturer that did not activate

House	I1	I2	P1	P2	D1
H1	20%	15%	48%	40%	12%
H2	17%	20%	37%	30%	25%
H3	8%	5%	27%	29%	12%
H4	41%	40%	50%	46%	39%
Average	22%	21%	41%	36%	24%

It is obvious in Table 4 that when the smoke alarms did activate there was great variation in the time of activation for smoke alarms in different rooms and hallways and for different smoke alarms of different types and brands. However it is difficult, by inspection, to discern an overall pattern in this variation, though some systematic variation can be seen even in the small sample in Table 4 as noted above. For this reason a statistical analysis has been undertaken using all of the data to confirm these initial observations and to attempt to identify more subtle effects.

3.3 Statistical analysis of smoke alarm response time

In the following analysis the smoke alarm non-activations have been ignored entirely, the analysis is of actual activation times.

As the houses differed quite considerably in geometry (shape, number of rooms, size, etc.) a categorical least squares regression analysis [37] has been used to investigate the importance of various factors in determining the smoke alarm activation time and to enable the results for the houses to be compared. This analysis has been conducted separately for each house and the results combined to consider the overall situation (see Figure 5). Figure 5 represents the comparison of activation time between different alarms with respect to one type of ionization smoke alarm (I1) under the fire scenario of polyurethane foam. The ratio was obtained by comparison between two types of smoke alarms using regression.

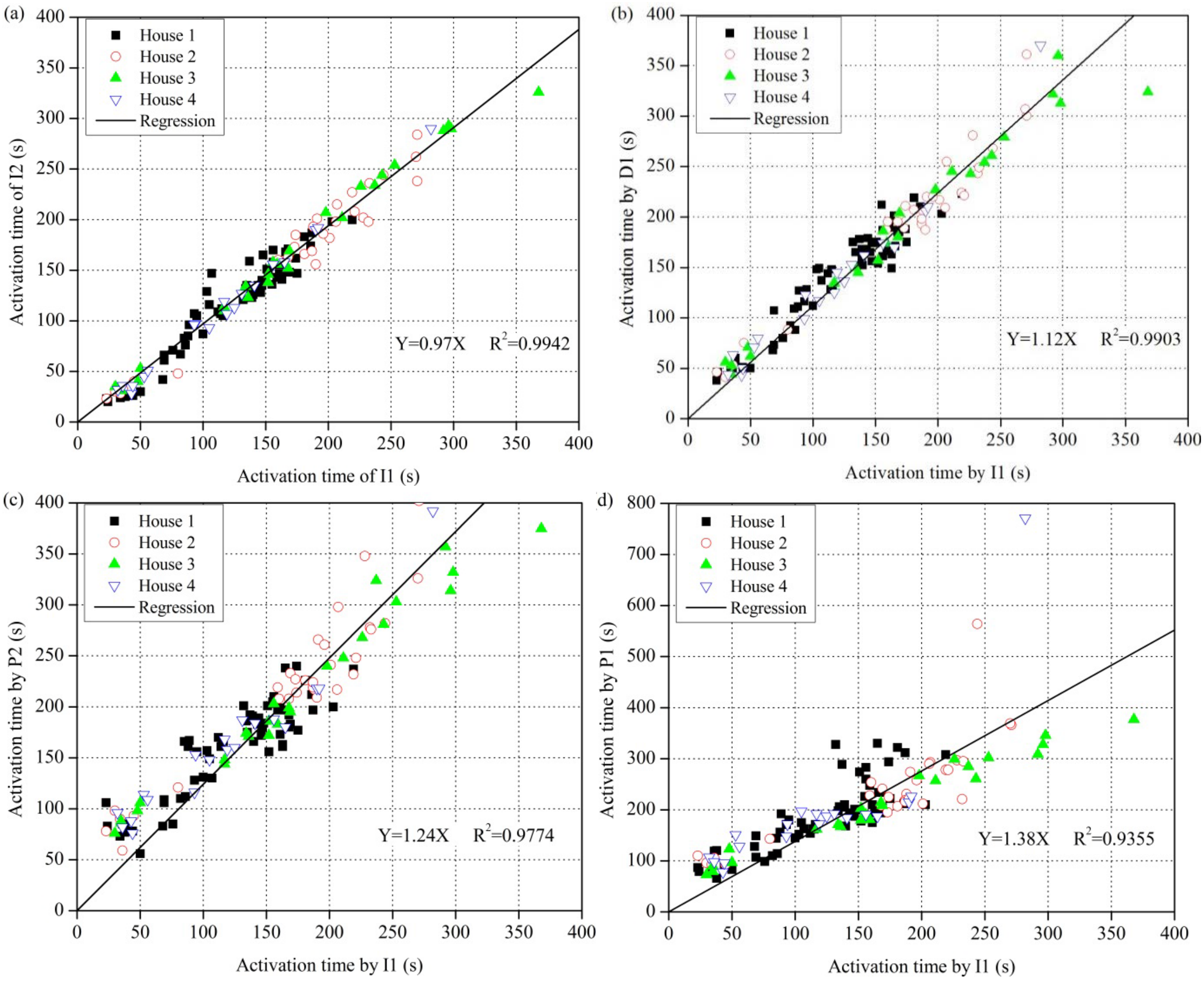

Fig. 5 Comparison of activation time between different alarms under the fire scenario of polyurethane foam using regression analyses

Table 6 The comparison of activation time ratio among different alarms

Fuel		I2	D1	P2	P1
BW	I1	0.93	0.77	0.78	0.83
DC	I1	0.89	1.15	1.33	1.45
PF	I1	0.97	1.12	1.24	1.38
HP	I1	0.90	1.34	2.58	2.65
SW	I1	0.95	0.81	0.78	0.84
ST	I1	0.93	0.88	0.85	0.89
WC	I1	0.92	1.14	-	-

The responses of various alarms in relation to the various fuel types are shown in Table 6. It is noted that these alarms respond differently according to the fuel types. For fuel types such as braided wick (BW), smouldering wood (SW) and smouldering towel (ST), the activation times of photoelectrical smoke alarms (P1 & P2) and the dual alarm (D1) are shorter than those of an ionization alarm. But for other fuel sources, such as decalin (DC), polyurethane foam (PF), heptane (HP) and wood crib (WC), the ionization alarms respond faster than the photoelectrical and dual alarms.

A categorical data analysis was conducted to predict the time of smoke alarm activation. The categorical analysis uses a formula of the form:

$$t_A = C_1 + C_2(RFO) + C_3(ROOM) + C_4(FUEL) + C_5(ALARM) \qquad (1)$$

where t_A is the time of smoke alarm activation, s; C_1 is the constant, s; $C_2(RFO)$ is the constant dependent on room of fire origin, s; $C_3(ROOM)$ is the constant dependent on room in which the smoke alarm is located, s; $C_4(FUEL)$ is the constant dependent on smoke source, s; and $C_5(ALARM)$ is the value dependent on alarm type and manufacturer, s. Ci (i=1, 2, 3, 4, 5) are constants with respect to a particular test scenario.

The results of these regression analyses are summarised in Table 7. In Table 7 the maximum and minimum values of the constants C_2 to C_5 are shown. Thus, using the values from Table 7 in Eq. (1), the longest estimated activation time for a smoke alarm in House 1 is:

$$t_A = 493 + 109 + 187 + 419 + 55 = 1263 \text{ s}$$

Similarly, the shortest activation time for House 4 is:

$$t_A = 500 – 39 – 92 – 317 - 12 = 40 \text{ s}$$

It is observed from this table that the fire source (C_4) affects the activation time the most, followed by the location of smoke alarm (C_3), room of fire origin (C_2), and then the type of smoke alarm (C_5). The importance of each of the factors represented by the constants C_2 to C_5 is more easily appreciated from the range of each of these constants as shown in Table 8.

Table 7 Summary of activation time results of categorical regression analysis using Eq. (1) (shown as value of constants in seconds)

House	C_1	C_2 (RFO)		C_3 (ROOM)		C_4 (FUEL)		C_5 (ALARM)	
		max	min	max	min	max	min	max	min
1	493	109	-82	187	-88	419	-323	55	-45
2	425	74	-106	81	-63	406	-290	44	-37
3	509	105	-98	105	-51	350	-312	41	-45
4	500	35	-39	56	-92	379	-317	11	-12
Averages	482	81	-81	107	-74	389	-311	38	-35

Table 8 Range of values for constants C_2 to C_5 (as shown in Table 7) from regression analysis using Eq. (1)

House	C_1	C_2 (RFO)	C_3 (ROOM)	C_4 (FUEL)	C_5 (ALARM)
1	493	191	275	742	100
2	425	180	144	696	81
3	509	203	156	662	86
4	500	74	148	696	23
Average	482	162	181	699	73

It is apparent from Table 8 that the most important factor determining the activation time is the fuel and combustion type with an average contribution to activation time for the four houses of approximately 700 s. The room of fire origin and the room in which the smoke alarms are located are also important (with average contribution of about 160 and 180 s, respectively, about a quarter of the times for the fuel and combustion type). The least important factor is the type and brand of the smoke alarm with an average contribution of about 73 s (about one tenth of that combined for the fuel and combustion type).

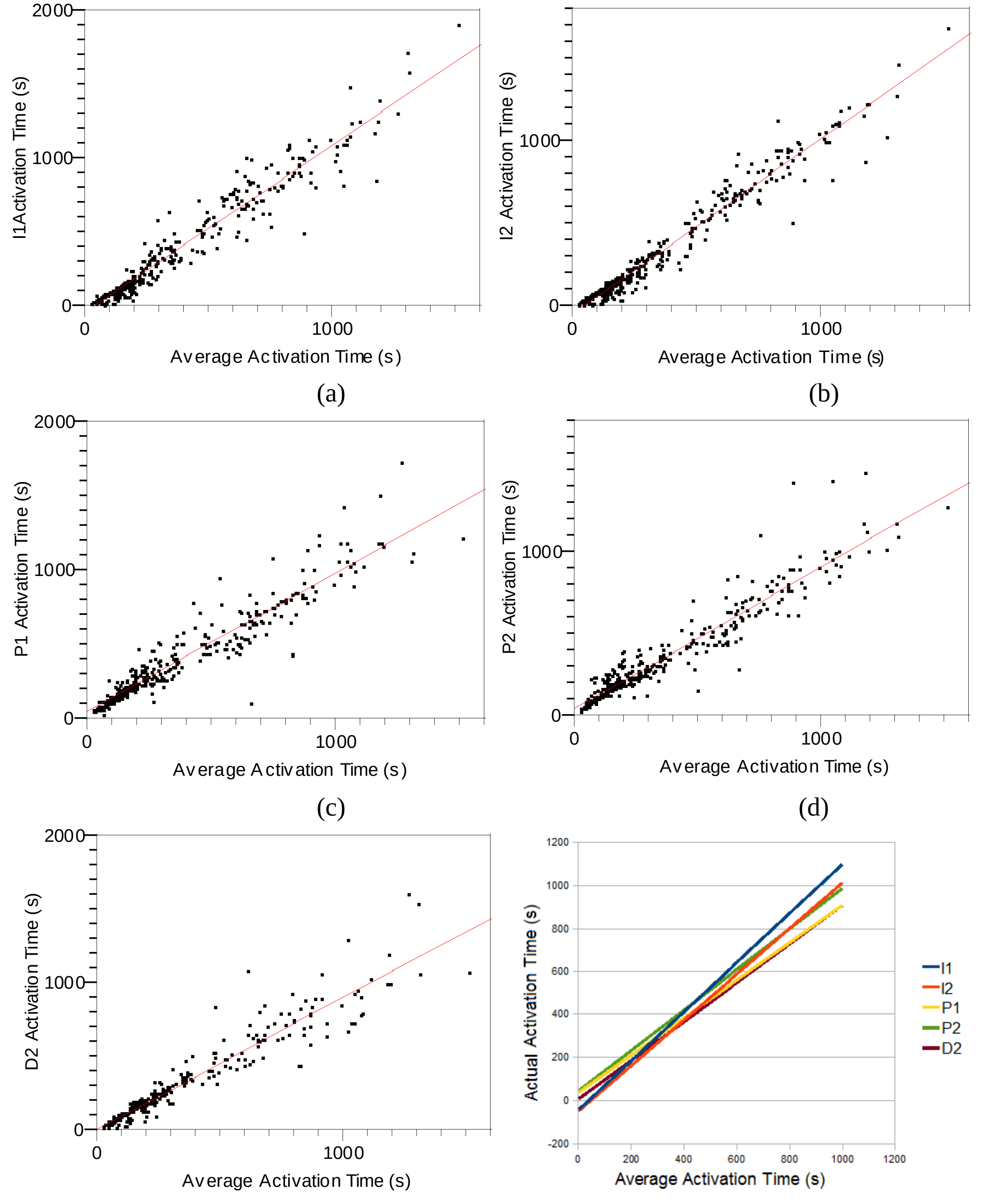

Fig. 6 Comparison of smoke alarm activation time with average activation time of all types of detectors in House 2: (a) I1; (b) I2; (c) P1; (d) P2; (e) D1; and (f) Lines of best fit for 5 alarm types

Fig. 6 shows the comparison of the response of the various types of smoke alarms (in the y-axis) for with average activation time of all types of detector (in the x-axis) for House. Fig

6(a)-(e) also show the least squares line of best fit and the scatter in data points for the smoke alarm types I1, I2, P1, P2 and D1. This is typical of the data for all of the houses and it is observed that there is great similarity in the response of the various types of smoke alarms. Fig. 6(f) allows comparisons to be made across the different alarms i.e. the lines of best fit from Fig. 6(a)-(e). It shows that at the shorter activation times the ionization alarms activate more quickly than the average, while at longer activation times it is the photoelectric alarms that activate more quickly. In general this is in accord with the observation that ionization alarms activate more quickly than photoelectric alarms to smoke from flaming fires, while photoelectric alarms activate more quickly to smoke from smouldering fires. The dual smoke alarm is generally activated at a time in between the ionization and photoelectric smoke alarms.

If smoke alarms were placed in every room (particularly with interconnection), it is the knowledge of how the room characteristics, smoke source and smoke alarm type and brand affect the frequency of non-activation and the activation times of smoke alarms *in the RFO* that is important. Thus all data has been reanalysed, but using only the smoke alarm activation data from the RFO.

Inspection of the data (Table 4 and similar data for other rooms presented as Appendix C in [38]) has shown that in all there were 48 non-activations of alarms in the RFO (6% of possible activations). Of these 36 (75%) were photoelectric, 11 (23%) were duals and one (2%) was an ionization alarm. The non-activations were confined largely to one smoke source, the wood crib, which amounted to 70% of non-activations. The other non-activations were fairly uniformly spread among the other fuels. These non-activations were excluded from the remaining analysis.

Table 9 Summary of activation time results (shown as value of constants in seconds) of categorical regression analysis using Eq. (1) for the smoke alarms in the RFO only

House	C_1	C_2 (RFO)		C_3 (ROOM)		C_4 (FUEL)		C_5 (ALARM)	
		max	min	max	min	max	min	max	min
1	196	47	-49	0	0	284	-132	50	-45
2	212	160	-94	0	0	245	-146	88	-43
3	228	116	-99	0	0	251	-164	42	-36
4	197	54	-62	0	0	277	-136	39	-23
Average	208	94	-76	0	0	264	-144	55	-37

Eq. (1) was used to analyse the activation times for the smoke alarms in the RFO only (with C_3 (ROOM) zeroed). The results are summarised in Table 9. Comparison with the results in Table 7 shows that C_1 in Table 9 is about 43% of the value in Table 7, C_2 (RFO) and C_5 (ALARM) are reasonably similar in the two tables and C_4 (FUEL) in Table 9 is about 60% of the value in Table 7. This shows that a fire in most rooms would be detected earlier than by alarms fitted to the existing requirements of AS 1607.1 [22] and UL985 [23]. It is likely that people in the house, on average, would receive a louder alarm signal than under current standards, particularly if the doors inside the building were open. Secondly if all smoke alarms were interconnected, most fires would be detected earlier than by alarms fitted to the existing requirements and that most people in the building (or a person in most areas of the building) would receive an earlier and much louder alarm signal, even if the doors inside the building were closed.

Table 10 Value of constants (in seconds) of categorical regression analysis using Eq. (1) for the smoke alarms in the RFO only for each house

Constant	Type	House			
		1	2	3	4
	PF	-151	-146	-164	-128
	DF	-127	-129	-141	-136
	HF	-134	-109	-119	-120
	BW	-45	-39	-46	-41
	WC	19	14	54	11
	SW	107	164	166	137
	ST	331	245	251	277
	I2	-43	-41	-36	-16
	I1	4	-43	-26	-13
	D1	-26	-18	-11	-23
	P2	19	14	31	13
	P1	45	88	42	39

Table 9 also shows that if the smoke alarm and fire source are located in the same room, the alarm type has limited influence on their performance. However, under the same situation, the activation time of a smoke alarm is very dependent on fuel types. The constants derived for Eq. (1) for the smoke sources and the smoke alarms for each house are shown in Table 10. Inspection of Table 10 shows that each of the constants is reasonably consistent across the four houses. In Table 10 the fuel type is listed from top to bottom in the order of the smoke source that generally resulted in the fastest to the slowest activation. Similarly, the smoke alarm type is listed from top to bottom in the order of the type that generally resulted in the fastest to the slowest activation. It can be seen in the table that polyurethane foam (PF), decalin (DF) and heptanes (HF) resulted in comparatively fast activation and that the rapidly smouldering wood (SW) and smouldering towel (ST) resulted in comparatively slow activation.

4. Conclusions

Early (but reliable) detection of smoke and effective notification of building occupants are considered to be the basic requirements of smoke alarm systems. The smoke alarm sound level experiments show that the sound level in many rooms is likely to be well below the 75 dBA waking threshold sound level specified in AS 1670.1 [22], and even this level may not waken some at-risk populations [33]. Although it does not necessarily mean if we don't have an alarm in every room we won't get loud enough notification, it is likely to be true in many places. If smoke alarms are not installed in every room the sound level in many rooms is likely to be too low to provide reliable notification, particularly of sleeping people. Changing to a lower frequency (520 Hz square wave) alarm would alert more people, for two reasons: (1) the sound is transmitted through the dwelling slightly more effectively so sound volumes throughout the dwelling are slightly higher (supported by the current data) and (2) many people develop high frequency hearing loss as they age.

It was observed that even with all room doors open there is a substantial reduction of the sound level from room to room. Smoke alarms in hallways are very unlikely to produce loud enough sounds in all rooms, even with doors open, and will certainly not do so when doors are closed. The possibility of closed doors between the smoke alarm(s) and the fire is clearly an argument for smoke alarms in hallway and rooms where the adequate sound level may not reach. However analysis of which rooms will not receive adequate sound level will add another layer of complexity in designing each new house. Therefore it is safer to be prescriptive to have an alarm in every room. In addition if the smoke alarms of all rooms are interconnected, most people in the building (or a person in most areas of the building) would receive an earlier and much louder alarm signal, even if the doors inside the building were closed.

If smoke alarms in every room are adopted it is important to understand the relative importance of different factors. From the model house tests (the smoke alarm activation tests) it is observed that the time to detection (given a particular smoke source) is influenced by closed doors, the room in which the fire occurs, the location (room or hallway) of the detector, the type of detector and the smoke alarm manufacturer. Considering the results in the RFO, the smoke sources required in ISO 7240-14 [31], as used in this project, show that under these experimental conditions the photoelectric alarms appear to be activated more often than ionization and dual smoke alarms and ionization smoke alarms are generally activated sooner than the photoelectric smoke alarms. However it is not known if this finding is generalizable to smoke from other sources and travelling under other conditions. Notwithstanding that these ISO standard smoke sources may differ from fire and smoke sources in real house fires, our data suggests that the smoke source has a greater influence on activation time than the smoke alarm type. Smoke alarms in the room of fire origin generally activate more reliably than those elsewhere in the residential building and with shorter activation times. Replication of our study with a wider variety of smoke sources would be desirable to ascertain whether these conclusions hold across different fire source scenarios.

The findings of this study show the benefit of considering the smoke alarm as a system, where the possible implications of both smoke alarm activation and volume levels are considered in dwellings of the same size and design as in real houses. This study has led to changes in Australian regulations and from 1 May 2014, the BCA [20] has required that smoke alarms be interconnected where more than one alarm is required to be installed in the dwelling.

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