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Estimating Smoke Alarm Effectiveness in Homes

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Abstract. This paper sets out to answer two questions. What effect does installing smoke alarms have on reported fires and casualties for the "average" household? How much of an effect would increasing smoke alarm utilization have on the total number of fires and casualties in the United States? The installation of smoke alarms in homes without them will reduce the expected number of fires reported from a (formerly) non-smoke-alarm residence by a factor of 3.5 to 5 (a 70 to 80% reduction) and reduces the number of expected casualties by a factor of 2.5 to 3.5 (a 60 to 70% reduction). Unexpectedly, the number of casualties per reported fire is lower for non-smoke-alarm households compared to smoke-alarm households. This could be due to changes in people's behavior when they have a smoke alarm in the home or because the less dangerous fires are preferentially extinguished when smoke alarms are present. If smoke alarms were installed in all residences, the number of fires reported to the fire department could be reduced by 25% or more. More realistically, each percent increase in smoke alarm penetration reduces reported fires by more than 2.6%. There is evidence that the number of homes with smoke alarms are lower than current estimates that rely on telephone-only survey interviews. The actual smoke alarm usage is probably below 92%. It seems likely that this is due to a correlation between phone presence and smoke alarm utilization.

Keywords: Smoke detectors, Smoke alarms, Home, Fires, Effectiveness

1. Introduction

Between 2009 and 2013, an average of 2470 people per year lost their lives in home structure fires ('home fires'), and an additional 13 300 were injured [1]. Home fires represented 27% of all reported fires, yet constituted 84% of all fire fatalities and 77% of all fire injuries, respectively. Smoke alarms have been in general use since the early 1970's, and "provide a critical early warning of fire, allowing additional time to escape" [2]. Moreover, "mounting evidence suggests that smoke alarms play a key role in reducing the number of deaths and injuries associated with household fires each year." [3] Some 96% of homes are reported to have smoke alarms, but more than 25% of reported fires occur in homes without smoke alarms. [2] That suggests that installing smoke alarms can have a large

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effect on the fire problem. It also suggests that the small number of residences without smoke alarms produce a large percentage of the reported fires.

This report sets out to answer the following questions:

- What effect does installing smoke alarms have on reported fires and casualties for the "average" household?
- How much of an effect would increasing smoke alarm utilization have on the total number of fires and casualties in the United States?

In this study smoke alarms are considered to be present without regard to their functional status. Identifying the impact of functional versus non-functional alarms is beyond the scope of this study.

This report differs from previous research in providing better estimates of the impact of installing smoke alarms on reported fires and casualties for the average household.

1.1. Literature Review

Several studies e.g., [3–5] that evaluated the impact of smoke alarms found that their presence was important for reducing fire risk. A higher percentage of fires are reported to the fire department in homes without smoke alarms than in homes with them. Ahrens [2] reports that more than 25 % of reported home fires occur in homes where there are no smoke alarms or no working smoke detectors. It is worth noting that these studies relate to reported fires. Ahrens suggests that while smoke alarms are traditionally considered tools for fire protection rather than prevention, they may in many situations activate before a full fire develops, a condition the report calls "almost-fires," thus serving to prevent some ignitions.

Fires in homes without smoke alarms are deadlier than fires in homes with them. Ahrens reports that three out of five home fire deaths are in homes without a smoke alarm. For comparison, only one fourth of reported fires occur in homes without working smoke alarms. This resulted in a death rate per reported fire that was twice as high in homes without a working smoke alarm than in home fires with working smoke alarms.

Runyan et al. [5] studied fatal fires that occurred in North Carolina between January 1988 and January 1989. They compared households where a fatal fire had occurred to a random sample of control households where a non-fatal fire had occurred. In their study the absence of a smoke alarm was a risk factor for fatality. The risk ratio for that death rate was approximately 1.5.

Istre et al. [4] studied the occurrence of fires in relation to smoke alarms in a section of Dallas between 1991 and 1997. They found that 30% of reported house fires had smoke alarms present. The rate of injuries per house fire was higher for house fires without a functioning smoke alarm than in those with one. Overall (accounting for both the occurrence of fire and the likelihood of injury conditional on occurrence of a fire), people living in houses without functioning smoke alarms were more than eight times as likely to suffer an injury.

In 2005 the US Consumer Product Safety Commission (CPSC) sponsored a survey to study smoke alarm use in the United States [6]. It had the additional objectives of identifying how many fires occur in the United States and determining what percentage of those fires are reported to the fire department. They found that 96.7% of households reported having smoke alarms. They estimated that there are 6.6 fires (reported and unreported) per hundred households per year in the United States. Of these only about 3.4% are reported to the fire department. They found a statistically significant difference in the number of households with smoke alarms between fire households and non-fire households. That implies that households without smoke alarms have more fire ignitions than households with smoke alarms.

The American Housing Survey (AHS) asked about the presence of working smoke alarms in its 2007, 2009 and 2011 surveys. It found smoke alarm utilization rates ranging from 91.7% in 2007 to 94.6% in 2011. These results are different, and lower, than results reported either in the CPSC report or by the NFPA. The other surveys simply asked about "installed" alarms, which may account for the difference. However, considering how well the AHS numbers line up with those from previous surveys, either virtually all installed smoke alarms are working or most people answered as if "working" meant "installed."

The main data on smoke alarm utilization in the United States comes from Ahrens [2] who reports the results of a series of surveys between 1977 and 2011, most of which were conducted by the National Fire Protection Association (NFPA), of the presence of smoke alarms in US households. In 1977, some 22% of US households surveyed reported having smoke alarms. That increased steadily until 2000 when some 95% of US households surveyed reported having smoke alarms. From 2001 to 2011, reported smoke alarm presence from surveyed households remained essentially constant between 95 and 97%. While there is no reason to doubt the trends, evidence suggests that the survey methods used, which relied on telephone interviews, may overestimate the utilization rate for all homes.

Douglas et al. [7] surveyed smoke alarm prevalence in portions of Oklahoma City in 1990 using both a phone survey and an in-person survey. They found that the telephone survey overestimated overall smoke alarm usage when compared to the in-person survey. Their conclusion was that telephone surveys may overestimate the presence of functioning smoke alarms in some populations because populations without telephones are more likely not to have smoke alarms.

There have been two studies that evaluated the impact of smoke-alarm give-away programs on fire outcomes. The first study [8] looked at a program in Oklahoma City between 1990 and 1994. They identified a section of the city where fires and fire casualties were high relative to the rest of the city. Their initial survey indicated that 34% of homes in the target area did not have smoke alarms. They distributed 10 100 smoke alarms to 9 291 homes. They found that the overall hospitalization rates for burn injuries declined by 80% in the target area and the rate per fire decreased by 74%. The rest of the city experienced a small increase in both values. In the target area, the rate of reported fires decreased by 25%, while in the rest of the city it decreased by 18%.

The second study [9] looked at a program in Dallas between 2001 and 2011. They installed alarms in homes in at-risk census tracts, with different census tracts targeted at different times. The control population was households in the target tracts that were not provided with smoke alarms. They found that the rate of fire casualties (defined as people transported or hospitalized for burn injuries or who died as a result of burn injuries) was lower for the program population compared to the non-program population (casualty rate per 100,000 population: 3.5 vs. 9.5, respectively).The effect declined significantly the second five years. They speculate that this is due to non-functioning of the alarms over time.

1.2. Fire Risk Model

Here a (statistical) fire risk model is developed to evaluate the impact smoke alarms have on deaths and injuries. Figure 1 shows a conceptual model. The model starts with the probability of ignition and concludes with life-safety outcomes.

A natural assumption for modeling ignition is to assume that the probability of ignition (π) is independent of the presence of smoke alarms (where $\Delta \in \{present, absent\}$ indicates whether smoke alarms are present or absent) since smoke alarms *per se* are incapable of preventing ignitions. However, the results by the Consumer Product Safety Commission do not support that assumption. Ahrens [2] suggests that smoke alarms may alert to conditions before they become full-blown fires (a condition the report terms "almost-fires") making it possible for the occupants to prevent some fires before they fully develop.[1]

This study looks exclusively at whether smoke alarms are present. It does not consider how many smoke alarms are installed, where they are installed, how close they are to the fire or whether they are functioning. While all of those factors undoubtedly impact the effectiveness of smoke alarms, most of that data is not captured in NFIRS. This study is necessarily based on NFIRS, and without that data thosed factors cannot be effectively accounted for. While smoke-alarm functioning is captured in NFIRS, there is little data on the percent of installed smoke alarms that are functioning. Further the data on functionality of smoke alarms in NFIRS has a substantially higher missingness rate. Therefore this study focusses simply on the presence of smoke alarms.

Detection time (t) is a random variable that depends on the presence of smoke alarms. A reasonable assumption is that holding household factors constant, installation of a smoke alarm will reduce the detection time. That is, if a smoke alarm is exogenously installed (or removed) from a house (taking homeowner/occupant choice out of the equation), the presence of a smoke alarm will on average reduce the detection time.

"Unreported" Fires are assumed to either self-extinguish or be extinguished by the occupants. The vast majority of fires are not reported to the fire department, and (presumably) are extinguished by the occupants. It is expected that the probability that a fire is reported to the fire department ($p_0(s)$) will depend on its size at

[1] Thanks to an anonymous reviewer for pointing this out.

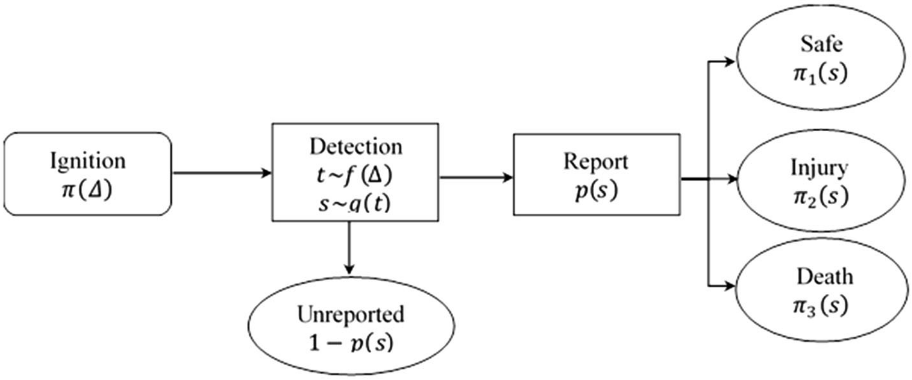

Figure 1. Model of detection time and home fires.

the time of detection (where s is fire size at the time of detection). Fire size at the time of detection will in turn be a random variable that depends on the time to detect. It is assumed for this model that fires that are not reported to the fire department result in no casualties. Otherwise, casualties will depend on the size of the fire at the time of detection.

As mentioned, it is tempting to assume that the presence of smoke alarms is independent of all these steps except for detection. However, there is good reason to believe that this is not true of ignition (likely a result of the endogeneity), so it may not be true of fire size or outcome either.

2. Data

Data are drawn from the National Fire Incident Reporting System (NFIRS). It is a reporting system used by fire departments nationwide to report on their activities. The system is maintained by the US Department of Homeland Security and is designed to capture all activities engaged in by a fire department, including fires, EMS and community outreach. The system is voluntary at the national level, so some departments do not use the system or report data to it. Data is obtainable from the US Fire Administration.

The NFIRS system records the time, date and location of all incidents, the type of the incident (e.g., fire, EMS call, hazardous materials incident, service call, etc.), property use, equipment and personnel on the call, number type and severity of casualties, actions taken, and a host of other data. For fires specifically, NFIRS collects information on the size of the fire, room of origin, heat source, item first ignited, human and other factors contributing to ignition, presence and effectiveness of alarms and automatic suppression equipment among other data.

Data for NFIRS is filled out by firefighters at the scene, so the information it contains is typically limited to the information a firefighter at the scene would have. For example, fire deaths are defined as any fire casualties resulting in death within one year. However, it is unclear how often follow-up on casualties is revised. Often data that is not required is left unentered. Other systematic problems can occur. For example, a number of large departments report in excess of 80% of the fires they respond to are confined fires (the nationwide average is less than 40%). Nevertheless, while NFIRS has known reporting problems, it is still the best data set available for understanding the nature and extent of the fire problem in the United States.

Fires selected for this analysis were structure fires in one- and two-family dwellings (NFIRS property-use code ‘419’), including both confined and unconfined fires, for the years 2009 to 2016. For each incident, the NFIRS data on smoke alarm activation is recorded. Data are categorized based on whether an alarm was present or absent (or unknown). Note that for many confined fires presence of smoke detectors was not collected and is thus considered unknown in this analysis. The 50 departments with the most single-family-residence fires were used. Four departments were excluded *ex ante*: the New York Fire Department (FDNY), Detroit, Baltimore, and Gwinnett County Georgia. The FDNY was excluded because its reporting rate for smoke alarm utilization was below the 30% limit set below. Detroit was excluded because it was expected based on previous experience to be highly unrepresentative of the rest of the country. Baltimore and Gwinnett County were excluded because they reported no fires where there were no smoke alarms. The analysis below assumes that reporting of smoke alarm status at fires is independent of whether smoke alarms are present, and that assumption was clearly violated for Baltimore and Gwinnett County.

After the top 50 departments were selected, any department with an average reporting rate of smoke alarm usage of less than 30% across all years of the sample was dropped because it was judged that they would not have enough observations for reliable results. That left 44 departments in the sample. Figure 2 shows the locations of those departments.

The data selection has the potential to bias the results if the impact of smoke alarms is different for areas served by large departments as compared to smaller departments, or if reporting rate correlates with impact. It was judged that the gains in terms of analytical tractability and reliability outweighed the risk of bias.

For the 44 departments in this study, for each year between 2009 and 2016, the number of fires reported to NFIRS in each of the following six categories were counted:

- Smoke alarms present, no casualties;
- Smoke alarms absent, no casualties;
- Smoke alarm state unknown, no casualties;
- Smoke alarms present, casualties present;
- Smoke alarms absent, casualties present; and
- Smoke alarm state unknown, casualties present.

This analysis looks at total casualties. It is understood that deaths and injuries are different, applying to different people under different circumstances [10, 11]. It was decided to look at total casualties for this study, rather than specifically deaths, because there were not enough deaths for reliable analysis. Since fire injuries far

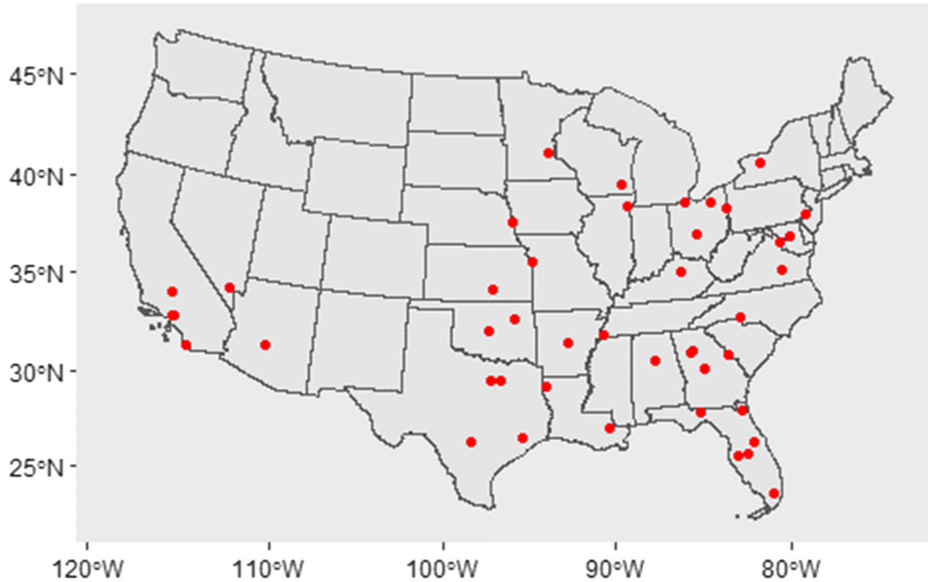

Figure 2. Locations of the departments used in this study.

outnumber deaths, to the extent that the results differ for deaths and injuries, these results will most closely resemble the results for injuries.

3. Estimated Model

The model estimated is a simplified version of the conceptual model set out above. It is assumed that the ignition rates for homes with smoke alarms and those without are the numbers identified in CPSC report (analyzed below). Those numbers are assumed to be constant across all 44 departments and all 7 years of the study. The smoke-alarm utilization rate, which is discussed in more detail below, is also assumed to be known and constant across all departments and years. The model assumes that the reporting rate on smoke-alarm activation for a particular department depends only on whether a casualty occurred. While reporting rate may vary between departments, within a department it only depends on whether a casualty occurred.

There are six independent variables evaluated here determined by alarm state and presence of casualties. Mathematically, the model is:

$$\mathrm{E}\left[F_{dt}^{pf}\right] = pop_{dt}\alpha fr^{p}\delta^{p}\rho_{d}^{f} \tag{1}$$

$$\mathrm{E}\left[F_{dt}^{pn}\right] = pop_{dt}\alpha fr^{p}(1-\delta^{p})\rho_{d}^{n} \tag{2}$$

$$\mathrm{E}\left[F_{dt}^{af}\right] = pop_{dt}(1-\alpha)f\lambda r^{a}\delta^{a}\rho_{d}^{f} \tag{3}$$

$$\mathrm{E}\left[F_{dt}^{an}\right] = pop_{dt}(1-\alpha)f\lambda r^{a}(1-\delta^{a})\rho_{d}^{n} \tag{4}$$

$$\mathrm{E}\left[F_{dt}^{uf}\right] = pop_{dt}[\alpha f r^{p}\delta^{p} + (1-\alpha)f\lambda r^{a}\delta^{a}]\left(1-\rho_{d}^{f}\right) \tag{5}$$

$$\mathrm{E}\left[F_{dt}^{un}\right] = pop_{dt}[\alpha f r^{p}(1-\delta^{p}) + (1-\alpha)f\lambda r^{a}(1-\delta^{a})]\left(1-\rho_{d}^{n}\right) \tag{6}$$

In this, $F_{dt}^{\Delta k}$ is the number of fires reported to fire department d and year t for alarm status Δ and casualty status k. Here Δ is one of ‘p’ (indicated that smoke alarms were present), ‘a’ (indicating that smoke alarms were absent), and ‘u’ (indicating that the alarm state was unknown). The casualty status, k, is one of ‘f’ (indicating that a casualty occurred during the fire) and ‘n’ (indicating that no casualty occurred). The variable pop_{dt} is the number of housing units for department d and year t, and α is the proportion of households with smoke alarms.

The variable f is the reported fire production rate for homes with smoke alarms. It is defined as:

$$f = \mathrm{E}\left\{\frac{\#Fires}{\#Homes} \mid Alarm\ Present\right\}$$

The variable λ is the multiple by which the fire production rate for homes without smoke alarms differs from that for homes with smoke alarms. That is:

$$f\lambda = \mathrm{E}\left\{\frac{\#Fires}{\#Homes} \mid No\ Alarm\ Present\right\}$$

The variable r^{p} is the “pass-through rate” for homes with smoke alarms: that is, it is the proportion of fires which are reported to the fire department for homes with smoke alarms. The variable r^{a} is the pass-through rate for homes where smoke alarms are absent.

The variable δ^{p} is the probability that a fire produces at least one casualty conditional on there being an alarm present. That is:

$$\delta^{p} = \mathrm{P}\{Casualties > 0 \mid Fire\ \&\ Alarm\ Present\}$$

The variable δ^{a} is the probability that a fire produces at least one casualty conditional on there being no alarm present:

$$\delta^{a} = \delta^{p}\theta = \mathrm{P}\{Casualties > 0 \mid Fire\ \&No\ Alarm\ Present\}$$

The convenience variable θ is defined as ratio of δ^a and δ^p.

The variable ρ_d^f is the probability that the smoke alarm state is reported for department d conditional on a casualty occurring. That is:

$$\rho_d^f = \mathrm{P}\{\text{Alarm State Reported} \mid \text{Fire} \,\&\, \text{Casualty} \,\&\, \text{Department} = \mathrm{d}\}$$

Finally, ρ_d^n is the probability that the smoke alarm state is reported for department d conditional on no casualty occurring. That is:

$$\rho_d^n = \mathrm{P}\{\text{Alarm State Reported} \mid \text{Fire} \,\&\, \text{No Casualty} \,\&\, \text{Department} = \mathrm{d}\}$$

Of these, pop_{dt}, the $F_{dt}^{\Delta k}$, α, λ, and f terms are data. The remainder are parameters to be estimated.

The casualty ratio is defined as the ratio of the probability that a casualty will occur if there is no smoke alarm to the probability that a casualty will occur if there is a smoke alarm. That is:

$$k = \frac{\delta^a}{\delta^p}.$$

It represents the additional risk of casualties from not having a smoke alarm conditional on there being a fire. Ahrens [2] computes the casualty ratio as:

$$k_A = \frac{\frac{F^{af}}{F^{an}+F^{af}}}{\frac{F^{pf}}{F^{pn}+F^{pf}}}$$

(where department and year notation is suppressed for clarity), which is different from what is used here. Substituting for the variables above, that becomes:

$$k_A = \frac{\frac{pop(1-\alpha)f\lambda r^a\delta^a\rho^f}{pop(1-\alpha)f\lambda r^a(1-\delta^a)\rho^n+pop(1-\alpha)f\lambda r^a\delta^a\rho^f}}{\frac{pop\alpha fr^p\delta^p\rho^f}{pop\alpha fr^p(1-\delta^p)\rho^n+pop\alpha fr^p\delta^p\rho^f}}$$

Cancelling common terms and rearranging, this becomes:

$$k_A = k\frac{(1-\delta^p)\rho^n + \delta^p\rho^f}{(1-\delta^a)\rho^n + \delta^a\rho^f}$$

This expression reduces to the form used in this report if and only if $\rho^n = \rho^f$ or $\delta^a = \delta^p$. That is, the two numbers are identical if and only if the casualty rates are the same regardless of alarm presence or the reporting rate for smoke alarms is the same for fires when there are casualties as when there are not. The probabilities that $\rho^n = \rho^f$ or $\delta^a = \delta^p$ are estimated below.

The random variables $F_{dt}^{\Delta k}$ are assumed to be distributed as Poisson variables. The model is estimated in STAN [12] as a Bayesian model.

3.1. Reanalysis of the CPSC Results

In 2005, the Consumer Product Safety Commission (CPSC) funded a survey to determine the characteristics of fire households versus non-fire households and to estimate the number of fires occurring annually [6]. They asked people about occurrence of any fires that may have occurred in their household, regardless of whether those fires were reported to the fire department. They also asked about a number of personal and household characteristics.

They found that there were 6.6 fires per hundred households per year in the United States. Of these, only about 3.4% were attended by the fire department. The fire production rate was estimated using a sophisticated weighting model, accounting for the weights from the stratified survey and the time since the fire occurred (to account for variable recall ability).

Among other characteristics, they asked about the presence of smoke alarms in the house. They estimated that 96.7% of households reported having at least one smoke alarm in the house. When they compared fire households to non-fire households they found (among other things) that "92.7 percent of fire households and 96.8 percent of non-fire households had at least one smoke alarm," a difference that they reported as being statistically significant (95% confidence level).

There are two objectives in reanalyzing the CPSC results. First, is to understand how much higher the ignition rate is for non-smoke-alarm households compared to smoke-alarm households. Second, needed are estimates of confidence intervals for the ratio above as well as the percent of smoke alarm households.

To do that, the number of survey responses is estimated in each of the four categories defined by whether the household had a fire (yes/no) and whether it had smoke alarms (yes/no; see Table 1). The survey was designed so that non-fire households were sampled at a rate of 1:40, so the non-fire households were given a weight of 40.

A Bayesian model (STAN [12]) is used to estimate (1) the fire production rate for homes with smoke alarms, (2) the ratio of the fire production rate for homes without smoke alarms to those with smoke alarms, and (3) the percent of homes with smoke alarms. Input data is the response numbers from Table 1 (modified by the response weight given to non-fire households). The Bayesian model then found best-fit parameters for f, α, and λ.

Table 2 reports the results from this reanalysis. The results for the fire production rate are simply copied from the CPSC report. This analysis was able to

Table 1
Response Weights

		Smoke alarms	
		Yes	No
Fire	Yes	849	67
	No	2046	68

Table 2
Reanalysis Results for the CPSC Report

	Mean	SD	Confidence limits		Beta distribution parameters		Gamma distribution parameters	
			2.5 (%)	97.5 (%)	Alpha	Beta	Shape	Scale
f	0.0656		0.0546	0.0764			126.0	5.2×10^{-4}
α	0.9673	6.06×10^{-4}	0.9661	0.9685	83,045	2800		
λ	2.3773	2.96×10^{-1}	1.8368	2.9934			64.66	3.68×10^{-2}

Here f is the fire production rate per household, α is the percent of households with smoke alarms, and λ is the ratio of ignitions for non-smoke-alarm households to smoke-alarm households

reproduce the results from the CPSC report for smoke alarm utilization. In addition, it was determined that the average house without a smoke alarm had an average of 2.4 fire ignitions for every one ignition in a house with smoke alarms.

The table also includes best-fit parameters for probability distributions for the respective parameters. Results for the smoke-alarm utilization results were fit to a beta distribution, and the other two values were fit to gamma distributions. Those parameters were used in the subsequent analysis.

4. Results

As discussed above, it seems likely that the proportion of homes with smoke alarms is overestimated when based on a telephone survey. For that reason, this model is estimated with five different numbers for smoke alarm utilization. Input parameters used for those models is listed in Table 3.

Results of this analysis are shown in Table 3, except for the department-by-department estimated reporting rates (which are available from the author on

Table 3
Model Parameters and Results Here α is the Percent of Households with Smoke Alarms, f is the Fire Production Rate Per Household, and λ is the Ratio of Ignitions for Non-Smoke-Alarms Households to Smoke-Alarm Households

	α (%)	f	λ	Pass through rate			Casualties (%)		
				Alarms	No Det.	Ratio	Alarms	No Det.	Ratio
Model1	96.7	0.0645	2.34	0.0103	0.1250	12.09	3.00	2.06	0.686
Model2	94.0	0.0645	2.34	0.0106	0.0677	6.38	3.00	2.06	0.686
Model3	92.0	0.0645	2.34	0.0108	0.0508	4.69	3.00	2.06	0.686
Model4	90.0	0.0645	2.34	0.0111	0.0406	3.67	3.00	2.06	0.686
Model5	87.5	0.0645	2.34	0.0114	0.0325	2.85	3.00	2.06	0.686

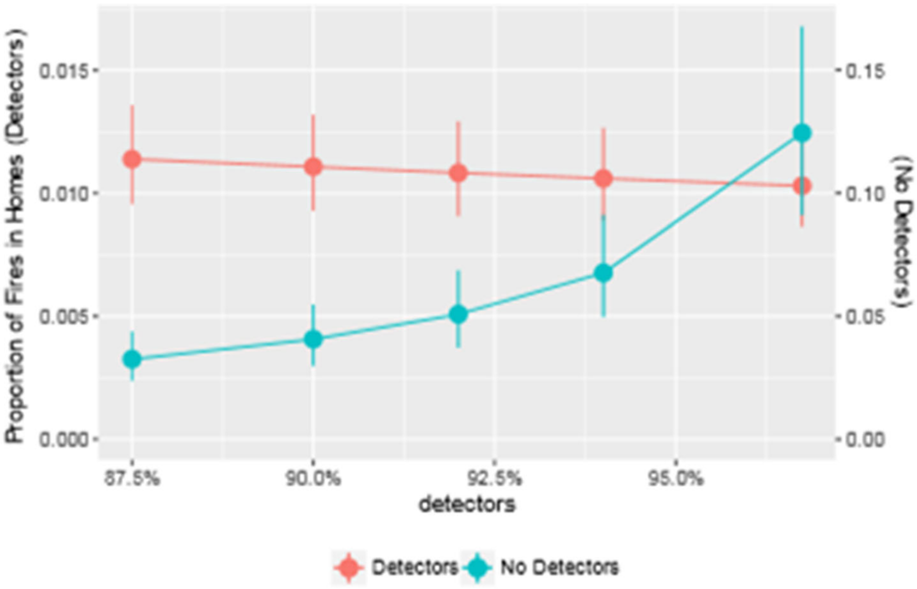

Figure 3. Pass-Through rate for fires. Error bars are 95% confidence limits.

request). The 44 departments in the study have widely varying rates at which they reported smoke alarm state at fires. Reporting rates varied from 29.1 to 87.9% for fires at which no casualties occurred, with the "average" department having about a 53% reporting rate. In addition, seven departments (including the FDNY) were excluded from this study for having reporting rates less than 30%, and the City of Baltimore (excluded for other reasons) has a reporting rate less than 10%.

Some 34 out of 44 departments have higher reporting rates when there are casualties compared to when there are none. Of these 18 are statistically significantly higher at the 95% confidence level. None of the 44 departments have statistically significantly lower reporting rates for casualties.

The r variable above can be thought of as a "pass-through rate" for fires (i.e., the rate at which ignitions "pass through" and are reported to the fire department). Estimates for its value vary depending on the value attributed to smoke-alarm usage and based on whether smoke alarms are present. As can be seen in Fig. 3, estimates for homes with smoke alarms vary from 0.011 for the case where smoke alarms are in 87.5% of houses to 0.010 when smoke alarms are in 96.7% of houses. Estimates of the pass-through rate vary much more dramatically for homes without smoke alarms. Those estimates vary from 0.032 for the case where smoke alarms are in 87.5% of houses to 0.122 when smoke alarms are in 96.7% of houses.

Figure 4 shows the inverse of the pass-through rate (here termed the 'extinguishment rate') and can be interpreted as the number of fires extinguished (by

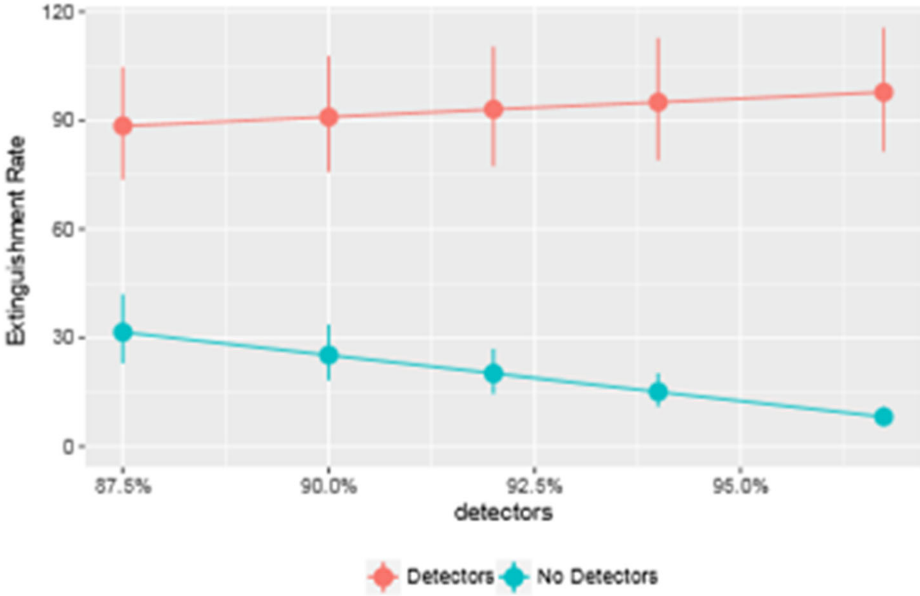

Figure 4. Extinguishment rate for fires. Error bars are 95% confidence limits.

someone other than the fire department or self-extinguish) for every fire that gets reported to the fire department.

Figure 5 is the ratio of the pass-through rates, with 95% confidence limits shown. If smoke alarm utilization is 87.5% then an ignition will be 2.9 times more likely to be reported to the fire department if it occurs in a home without a smoke alarm compared to one with a smoke alarm. That ratio rises to 12.2 when smoke alarm utilization is 96.7%.

On average, about 3% of reported fires in houses with smoke alarms produce casualties, a value which does not change with the smoke-alarm utilization rate. Reported fires in houses without smoke alarms are less likely to produce casualties than houses with smoke alarms, by a factor of about 0.7. This differs substantially from the results of Ahrens [2], although Ahrens focuses on deaths, which could be quite different from casualties where are analyzed here.

As shown in Table 4, reporting rate differs significantly between casualty and non-casualty fires. The hypothesis tested is that the reporting rate for each department is the same regardless of whether there are casualties, that is, for each department d, $\rho_d^n = \rho_d^f$, and uses the Wald test. Similarly, the results in Table 4 indicate that $\delta^a \neq \delta^p$. Therefore estimating the relative effect of alarms on casualties based on raw NFIRS data (i.e., without correcting for differential reporting rates) will be biased.

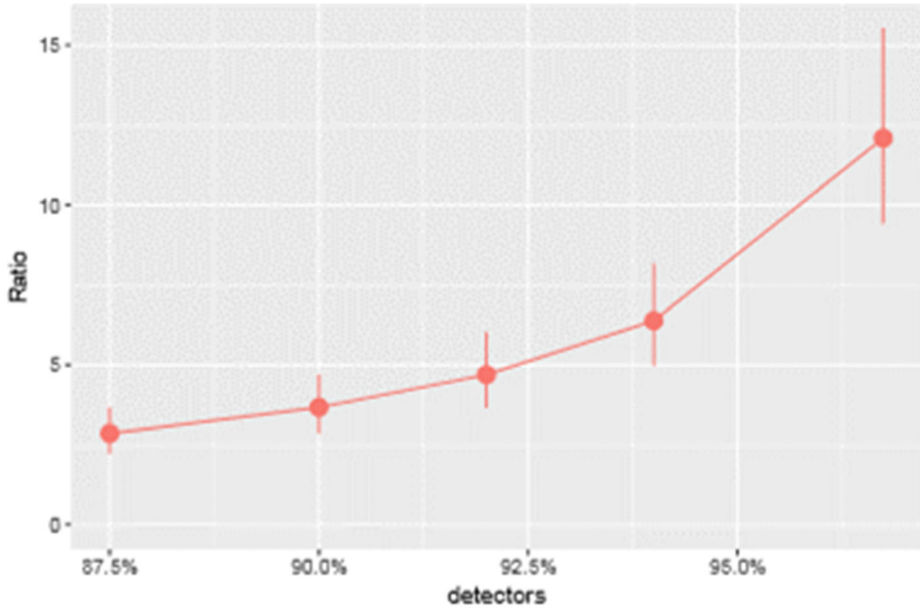

Figure 5. Ratio of pass-through rates for fires. Error bars are 95% confidence limits.

Table 4
Results of Tests Here α is the Percent of Households with Smoke Alarms, *W* is the Statistics from the Wald Test, *df* are the Degrees of Freedom Associated with the Wald Test, and *p* is the Significance Level for the Test

Test		$\rho^n = \rho^f$			$\delta^a = \delta^p$			
Model	α (%)	W	df	p	Estimate	Std. Error	t value	p
Model1	96.7	607.2	44	$< 10^{-16}$	− 0.0094	0.0012	− 8.114	4.89×10^{-16}
Model2	94.0	607.7	44	$< 10^{-16}$	− 0.0095	0.0012	− 8.125	4.47×10^{-16}
Model3	92.0	594.1	44	$< 10^{-16}$	− 0.0094	0.0012	− 8.121	4.63×10^{-16}
Model4	90.0	616.4	44	$< 10^{-16}$	− 0.0094	0.0012	− 8.133	4.16×10^{-16}
Model5	87.5	614.5	44	$< 10^{-16}$	− 0.0094	0.0011	− 8.246	1.64×10^{-16}

5. Analysis of Historic Data

One way of setting an upper bound on the impact of smoke alarms is to assume that all the gains in the fire problem since 1977 (when smoke-alarm data are first available) are from the installation of smoke alarms and to estimate what smoke-alarm impact would produce that level of result. Since it seems likely the installation of smoke alarms is only one of several processes and improvements at work to reduce reported fires and fire casualties, this serves as an upper bound on the impact of smoke alarms. The model estimated is:

$$F_t = pop_t f[\alpha_t + (1-\alpha_t)\lambda] \tag{7}$$

$$d_t = pop_t f \delta^d [\alpha_t + (1-\alpha_t)\lambda\theta] \tag{8}$$

where pop_t is the number of households in the country at time t, α_t is the smoke-alarm utilization rate at time t, f is the *reported* fire ignition rate for homes with smoke alarms, λ is the ratio of *reported* fire rates, δ^d is the *death* production rate for homes with smoke alarms, and θ is the ratio of *death* production rates (italics emphasize the differences from the previous model). The value for λ in this model will be roughly comparable to the λ in the previous model.

Data on number of single-family residential fires and casualties is from Haynes (2015) [1]. Data on number of households is from the US Census. Two versions of this analysis were run. In the first model, the smoke-alarm utilization data from Ahrens is used. In the second model, the smoke-alarm utilization data was rescaled by a factor of 0.9375. That implies that smoke alarm utilization stabilizes after the year 2000 at around 90% of households instead of 96%. Use of the two models made it possible to bracket the range in which smoke alarm utilization is expected to lie so these results could be compared to the earlier results. In both versions, Attention is limited to the time-period from 1980 – 1995. That was done because smoke alarm utilization stabilizes by 2000, and any changes in fire rates after that date will be due to other causes. Results are in Table 5.

Figure 6 shows actual and estimated fires and deaths from 1977 to 2011 for model 2 (based on the rescaled smoke alarm usage estimates). The graph for model 1 is similar.

While the model fits are good for the years 1980 to 1995, they are not very good outside those years. In particular, if smoke-alarm installation were the only contributor to reductions in reported fires and deaths, then fires and deaths would

Table 5
Results of Historical Analysis Here Textitf is the Reported Fire Production Rate Per Household, λ is the Ratio of Reported Fires for Non-Smoke-Alarms Households to Smoke-Alarm Households, δ^d is the Death Production Rate for Homes with Smoke Alarms, and θ is the Ratio of Deaths for for Non-Smoke-Alarms Households to Smoke-Alarm Households

	f (%)	λ	δ^d	θ
Model 1	0.0037	4.30	0.0091	0.769
Model 2	0.0028	5.56	0.0099	0.721

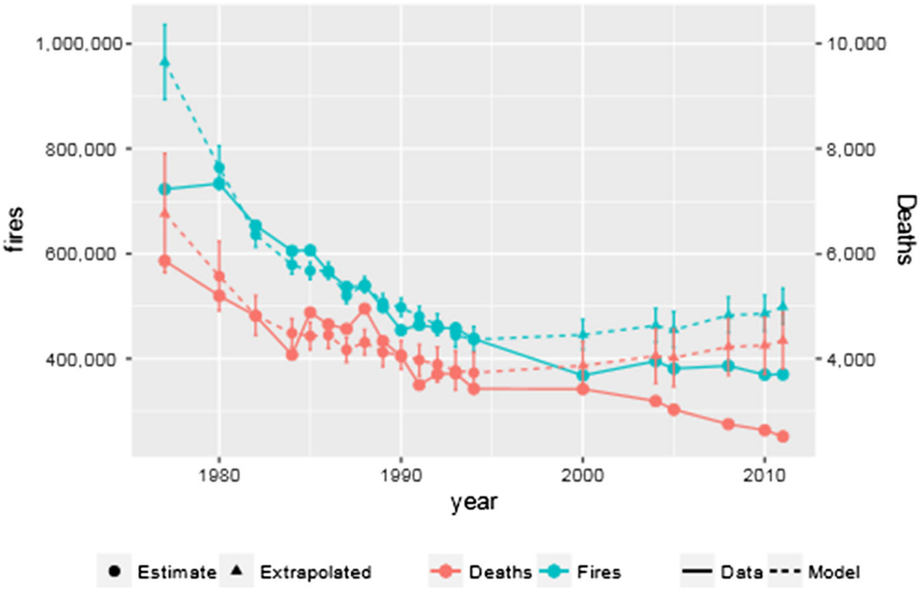

Figure 6. Modeled fires and deaths: historical Model 2. Error bars are 95% confidence limits.

have been increasing since 2000, and they have actually been stable or decreasing. That serves to emphasize that this model provides an upper bound rather than an actual estimate.

It is interesting that the results for ratio of deaths for homes without smoke alarms to homes with smoke alarms for both models are around 0.7, which is similar to the results obtained for casualties in the model above.

The ratio of fires for homes without smoke alarms to homes with smoke alarms ranges for these models between 4.2 (assuming smoke alarm utilization stabilizes at around 96%) and 5.6 (assuming smoke-alarm utilization stabilizes at around 90%). Figure 7 shows the ratio of pass-through rates estimated from the historical data superimposed on the pass-through rate ratio estimated above. The estimate based on the historical models should represent an upper bound on the pass-through ratio for any given value of smoke-alarm utilization, while the "NFIRS" line represents the best estimate of the pass-through ratio for any given value of smoke-alarm utilization. The historical estimate crosses the estimates based on the NFIRS data at about 92.5%, which suggests that actual smoke-alarm utilization is below 92%, and the pass-through ratio is below about 5.

6. Discussion

The results of Sect. 5 were intended to provide an upper bound on the impact of smoke alarms on the fire problem, and that allows us to derive an upper bound estimate on actual smoke alarm utilization of 92%. An upper bound on smoke-

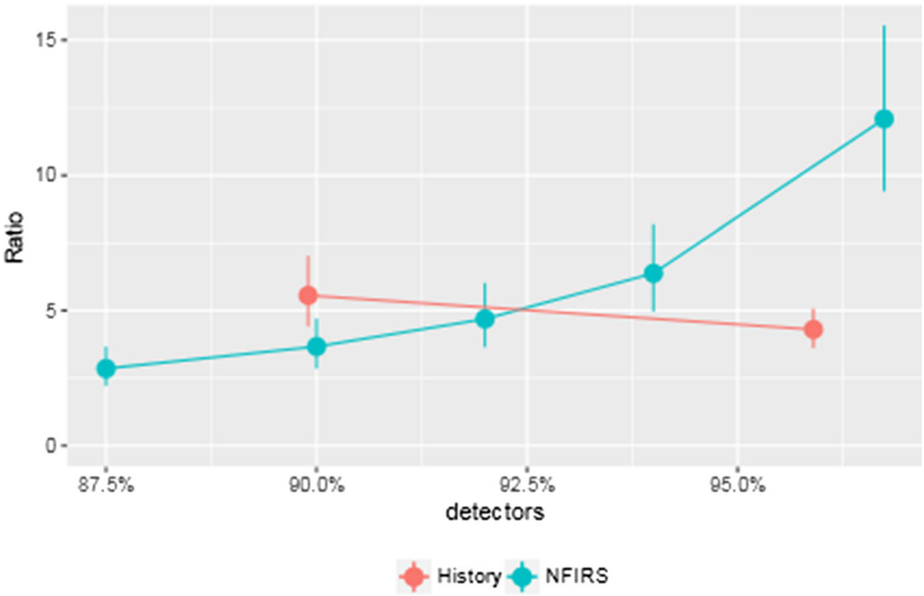

Figure 7. Comparison of ratios of pass-through rates. Error bars are 95% confidence limits.

alarm utilization of 92% means that the ratio of fires reported to the fire department in homes without detectors to reported fires in homes with detectors is less than 5 (see Table 3). The best estimate as to the lower bound on smoke-alarm utilization is between 87.5 and 90%. That corresponds to a lower bound on the ratio of reported fires in homes without detectors to those in homes with detectors of about 3.5. That implies that the installation of smoke alarms into a home without them would reduce the expected number of fires reported by a factor of 3.5 to 5.0. Installation of smoke alarms will reduce casualties as well. Casualties are reduced by a factor of 0.686 per reported fire independently of smoke-alarm utilization rate (see Table 3). That implies that casualties are reduced by a factor of 2.5 to 3.5.

To determine the effect of installing smoke alarms in the remaining households without them, the number of reported fires (resp. casualties) per 100 households were computed from the model for both households with smoke alarms and households without. Then the number of reported fire (resp. casualties) that would occur in households without smoke alarms if they were installed was computed from the model. The percent difference for each model is listed in Table 6. If smoke alarms utilization were 100%, the number of fires reported to the fire department could be reduced by 30% or more and casualties by 20% or more. More realistically, each percent increase in smoke alarm utilization reduces reported fires by more than 2.6% and casualties by more than 1.5%.

Table 6
Percent Decrease in Fires and Casualties from Installing Smoke Alarms in Households Without them

	% of Homes		Decrease in fire and casualty if			
			All homes have alarms		1 % increase in alarms	
Model	With alarms (%)	Without alarms (%)	Fires (%)	Casualties (%)	Fires (%)	Casualties (%)
Model1	96.7	3.3	45.2	35.2	13.7	10.7
Model2	94.0	6.0	41.2	30.6	6.9	5.1
Model3	92.0	8.0	38.5	27.4	4.8	3.4
Model4	90.0	10.0	35.4	23.8	3.5	2.4
Model5	87.5	12.5	31.7	19.3	2.5	1.5

Here α is the percent of households with smoke alarms

A number factors can influence these results. These include coding issues with NFIRS (see, for example, [13]) and the fact that in NFIRS data on detector status is not routinely collected for confined fires. As long as the issues are uncorrelated with detector presence these factors will not affect the results. However, that seems unlikely because fire size will likely correlate with detector presence. However, it is not expected that these factors will be large enough to change the results significantly.

7. Conclusion

The results of Sect. 5 make it possible to establish an upper bound estimate on actual smoke alarm utilization of 92%. This is lower than the CPSC or NFPA estimates and lower than some of the American Housing Survey estimates. There are at least two possible explanations for why previous surveys overestimate smoke alarm utilization. First, the CPSC and NFPA surveys were telephone surveys, and it seems likely that having a phone correlates with having smoke alarms installed in the house. Second is social desirability bias (see [14] for an example). People tend to answer polling questions in ways that (they perceive) make them look good to others. Since there is a social desirability associated with having smoke alarms, there would be a tendency to answer questions about the presence of smoke alarms in the affirmative.

The result that the number of casualties per reported fire is lower for non-smoke-alarm households compared to smoke-alarm households is unexpected. There are at least three possible (and non-exclusive) explanations for it. First, people, when they know that they do not have smoke alarms (and remember, these numbers come from surveys), could take actions that reduce the life-risk from fires that they do not take if they have smoke alarms installed. Secondly not all fires are created equal. It is possible that the fires which would be extinguished if smoke alarms were present (but were not) are on average the less dangerous ones. Third, it is possible that smoke alarms decrease deaths while increasing injuries. For example, earlier detection could prompt more people to attempt to fight the fire themselves, thus resulting in more injuries. If detectors have a different effect on injuries compared to deaths, then this study will track injuries rather than deaths due to the fact that there are far more injuries from fires than deaths.

Smoke alarms reduce the expected number of reported fires by a factor of 3.5 to 5.0 and reduce the number of expected casualties by a factor of 2.5 to 3.5. If smoke alarm utilization were 100%, the number of fires reported to the fire department could be reduced by 30% or more and casualties by 20% or more. More realistically, each percent increase in smoke alarm utilization reduces reported fires by more than 2.6% and casualties by more than 1.5%.

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