Taking Shelter: Estimating the Safety Benefits of Tornado Safe Rooms

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ABSTRACT

Over the past several decades, engineers have made significant progress in the design and construction of structures able to withstand tornadic winds and debris. The aftermath of the 3 May 1999 F5 tornado in Moore, Oklahoma, highlighted the modest market penetration of tornado shelters in metropolitan areas. The authors use historical data from Oklahoma to estimate the potential casualties that tornado shelters could prevent and calculate that the cost per fatality avoided in single-family homes is $29 million while the cost per fatality avoided for mobile homes is $2.6 million. The estimates are sensitive to the proportion of strong (F3 or stronger) tornadoes and the choice of an interest rate for present-value calculations. If the F-scale distribution of Oklahoma tornadoes resembled a reported national frequency distribution and fatalities per category storm are held constant, the permanent home cost per fatality avoided triples to $88 million.

1. Introduction

The past several decades have witnessed considerable progress in the design and construction of shelters able to withstand tornadic winds (FEMA 1999a). The technology now exists to build belowground shelters and aboveground safe rooms allowing occupants to survive even the most powerful tornadoes. Safe rooms designed at the Wind Research Center at Texas Tech University in Lubbock, Texas, can withstand 250 mi h^{-1} winds and wind-blown debris (FEMA 1999a). The Federal Emergency Management Agency (FEMA) is emphasizing safe rooms as a windstorm mitigation measure (FEMA 1999a). The 3 May 1999 F5 tornado in Moore, Oklahoma, and the ensuing Oklahoma Safe Room Initiative have publicized tornado shelters to the general population, and home buyers' reactions have been very positive.[1]

[1] A model home equipped with a safe room attracted the most attention among home buyers at the Tulsa (Oklahoma) Parade of Homes and a development in Tulsa will feature safe rooms in all the new homes (Fowler et al. 2000).

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The aftermath of the 3 May 1999 tornado illustrated the very low market penetration of shelters even in the heart of Tornado Alley. Safe room technology has existed for more than a decade, yet only after the 3 May tornado did safe rooms become available as an option in construction of new homes. Suburban homes in Oklahoma do not typically feature basements, and prior to the storm few homes were equipped with in-ground shelters, the modern equivalent to the storm cellars that had protected residents of the region for decades. Survey results following the 3 May tornado found only 16% were in some kind of shelter during the storm (Brown et al. 2000). Only one home in the path of the F5 tornado had a safe room (FEMA 1999b).

Most research has focused on shelter engineering and the potential to protect residents from tornadoes. In contrast, little research has been done on the economic value of shelters. Safety is a value, but we live in a world of scarcity in which we cannot have everything we value. Building shelters is costly, and it is only natural for economists to ask whether tornado shelters yield benefits commensurate with these costs. We investigate this question by estimating the number of fatalities and injuries tornado shelters might prevent in Oklahoma and the cost of equipping homes in the state with shelters. We also calculate a cost-per-fatality-avoided figure for tornado shelters to allow comparison with empirical estimates of the value of a statistical life and with other life-saving policies. Based on historical data for 1950–99, we estimate a cost per fatality avoided of about $29 million for single-family homes and $2.6 million for mobile homes.

This paper is organized as follows. Section 2 examines the economics of self-protection and reviews arguments concerning the inefficiency of such markets. Section 3 then calculates the cost per fatality avoided for shelters in permanent single-family homes. Section 4 calculates the cost per fatality avoided for mobile homes and discusses issues relating to community shelters and shelters for renters. Section 5 concludes with questions that economic analysis raises for future tornado-shelter research.

2. The economics of self-protection

Tornado shelters provide two kinds of benefits: protection of residents against injury when tornadoes strike occupied buildings, and peace of mind with the knowledge that one's family will be safe in the event of a tornado. Shelters provide a safe place for residents to avoid injury and are not intended to prevent damage to the rest of the structure. A safe room can protect important papers, valuables, and keepsake items, but we ignore property-damage savings in this paper. We do not attempt to quantify the nonpecuniary peace-of-mind benefits, because we are unaware of reliable estimates of these values. Also, instead of choosing values of life and injury and making explicit cost–benefit calculations, we present our results in the form of a cost per fatality avoided.

Economists distinguish between self-protection, which reduces the probability of loss, and self-insurance, which reduces the magnitude of loss but not the probability (Ehrlich and Becker 1972). Shelters provide a form of self-insurance: shelters do not affect the annual probability of a tornado strike at a given location but reduce the magnitude of loss. Economists assume residents maximize expected utility in making decisions under uncertainty (Kreps 1990). The expected value of a shelter is equal to the perceived probability of a tornado at the residence multiplied by the value of losses prevented by a shelter, plus peace-of-mind benefits (which do not depend on the residence being struck by a tornado). The value of a shelter depends on peoples' income (higher income generally increases the value of safety) and their attitudes toward risk and will vary across households.[2] The probability of a tornado and cost of a shelter are the main elements of the decision to acquire a shelter. Residents, according to expected-utility theory, purchase a shelter if the expected value exceeds the cost. Efficiency in this market involves purchase of shelters by all residents for whom the expected value exceeds the cost.

Several problems plague self-insurance markets and lead to residents failing to take protective measures that appear to be cost effective. A first set of problems involve the interaction between the ability to insure against loss and the incentive to undertake mitigation. The existence of market insurance can eliminate the incentive to self-insure. The availability of full insurance at an actuarially fair price shifts the benefits from residents' purchase of shelters to their insurance company. Residents will not incur costs to reduce the insurance company's liability unless purchase of protection lowers insurance rates. Insurance companies may not offer discounts if they cannot verify that policy holders are taking precautions. The prospect of public-sector relief for disaster costs may also weaken a resident's incentive to undertake costly hazard mitigation. A second set of problems involves the applicability of expected-utility theory to low-probability, high-consequence events such as tornadoes, hurricanes, and earthquakes. A number of studies present evidence that suggests that expected-utility theory does not accurately describe peoples' decisions in the face of small risks (Kunreuther 1978; Camerer and Kunreuther 1989; Kunreuther and Roth 1998). People act as if such rare events ''could not happen to me'' and consequently treat a small probability of a catastrophic loss as a zero probability. An example of such behavior is the failure of at-risk residents to buy flood insurance even when available at subsidized rates. The expected value of a shelter is zero if residents treat the probability of a tornado as zero.

Insurance and disaster relief seemingly will not pose severe problems for the tornado-shelter market. Shelters are designed to avoid casualties, and full insurance against or a relief payment in compensation for loss of life or limb (a payment that would leave the victim as well off as if the injury had not occurred) is not generally possible. As a consequence, residents capture the benefits of mitigation in this case, not insurance companies. In addition, insurance companies could offer lower premiums to homeowners if shelters reduced insured expected property damage by more than their cost. Some economists have found evidence supporting the applicability of expected-utility theory to low-probability events. A prominent study by Brookshire et al. (1985) finds evidence of earthquake risk premiums in house prices in California consistent with the theory; that is, houses in higher-seismic-risk zones sell at a discount. Although people might treat some low-probability events as zero-probability events, people also overestimate some risks with dramatic consequences, such as airplane crashes; they may similarly overestimate tor-

[2] Another factor in a household's demand for a shelter is the sturdiness of their home. A particularly well engineered home, or a home with a basement, provides extra protection for residents and reduces the value of a shelter. We consider permanent homes as a group and make no allowance for this factor, but the cost per fatality avoided will not be uniform for all homes exposed to the same tornado risk.

nado risk. To be specific, O. Ozdemir and J. B. Kruse (1999, unpublished manuscript) find that survey respondents overestimated the annual U.S. tornado death rate per million by several orders of magnitude.

The efficiency of the market for tornado shelters is consequently an empirical question. Quantification of the safety benefits of shelters provides important evidence in this regard. If shelters yield significant safety benefits at a very low cost, nonpurchase by residents might indicate a remediable market failure. If consumers fail to purchase shelters that provide cost-effective protection, a role might exist for policies to encourage their purchase—such as subsidies, low-interest loans, or building-code requirements.

3. Casualty/cost trade-offs

In this section we calculate the number of casualties shelters could prevent and the cost of shelters. We consider the hypothetical experiment of equipping all permanent homes in Oklahoma with shelters and assume that shelters prevent all in-home tornado casualties.

We make the casualty calculations using historical data from Oklahoma from between 1950 and 1999.[3] During these 50 yr, the state experienced 260 tornado fatalities and 3895 injuries for averages of 5.2 fatalities and 77.9 injuries per year. Not all of the state's residents live in permanent homes, and residents will not always be home when a tornado strikes, so in-home shelters will not eliminate all of these casualties. For the United States as a whole between 1985 and 1999, 28.59% (237 of 829) tornado deaths occurred in permanent homes (Storm Prediction Center 2000). Applying this fraction to the total annual tornado fatalities yields an estimate of 1.487 Oklahoma tornado deaths per year in permanent homes. We assume this number of fatalities will occur without shelters and that shelters in all homes prevent all of these deaths. We could not find similar statistics on the circumstances for tornado injuries. The percentage of injuries in homes is likely higher than the percentage of fatalities given that homes provide better protection than mobile homes, resulting in fewer fatal injuries. Indeed, 63% of injuries in the 3 May 1999 tornadoes occurred in permanent homes while only 50% of fatalities that day occurred in permanent homes (Brown et al. 2000). The proportion of permanent home fatalities is generally higher in violent tornadoes, so both these figures are higher than the 28.6% figure for permanent homes for all tornadoes nationally. Applying the national fatality percentage to injuries produces an estimated 22.27 injuries per year in permanent homes, which is likely a lower bound. Again we assume shelters will prevent all of these injuries.

We calculate cost on a flow basis assuming a 50-yr useful life of a shelter. Calculation of costs on an annual basis allows comparison with annual casualties avoided with 100% of homes equipped with shelters. Expressing both costs and casualties on an annual basis avoids complications related to the choice of a discount rate and corresponds to a steady-state equilibrium in the housing market in which all houses have shelters and 1/50 of homes must be replaced each year. There were 1 004 747 occupied single-family homes in Oklahoma in the 1990 U.S. Census. Assuming that the number of homes per capita remains constant, population growth in the state since 1990 produces an estimated 1 072 613 occupied homes in 1999. We will use $2000 as the approximate cost of an underground shelter (FEMA 1999a). We ignore maintenance expenditures on the shelter, which are small. Aboveground safe rooms cost $4000–$6000, but because we assume that underground shelters provide 100% protection, we only make cost calculations using the $2000 figure. Hence our estimate of cost per fatality avoided is a lower bound. The annual cost of providing shelters for each permanent home in Oklahoma is $42.905 million, and this would prevent an estimated 1.487 fatalities and at least 22.27 injuries per year. Thus, the cost per fatality avoided for shelters in permanent homes in Oklahoma is $28.85 million (=42.905/1.487).

Evaluating shelters as a safety investment involves comparing this figure with the monetary value of fatal risks and injuries. The prospect of valuing life troubles many people, but both individuals in their daily lives and policy makers trade off risk and money every day. The choices individuals make to purchase smoke detectors or speed while driving or engage in dangerous activities such as mountain climbing reveal preferences toward risk of death. Choices involving risk and money—to take a risky job, for instance—implicitly reveal a monetary value the person places on a probability of death, assuming the objective risk can be estimated. Economists call this money trade-off for a probability of death the value of a statistical life. For example, a labor-market study might determine that jobs with a 0.001 mean annual fatality risk have a wage premium of $5000 per year. The implicit value of a statistical life in this case is $5 million (=5000/0.001). The cost per fatality avoided for shelters would indicate the minimum value residents would need to place on a statistical life to justify purchase solely on the grounds of preventing tornado fatalities. Many empirical studies have estimated the value of a statistical life, and they typically produce values in the range of $1–$10 million, with an average of about $5 million.[4] The Environmental Protection Agency's (EPA) study of the benefits and costs of the Clean Air Act prior to the 1990 amendments, for instance, used a value per fatality avoided of $4.8 million in 1990 dollars (EPA 1997), which adjusted for inflation would be $6.1 million in 1999 dollars. As a consequence, fatalities prevented alone will not

[3] All tornado figures from Oklahoma used in this paper are taken from Storm Prediction Center records.

[4] For more on the concept of the value of a statistical life and empirical estimates see Viscusi et. al. (2000).

be sufficient to justify purchase for most residents of permanent homes.

The cost per fatality avoided does not include all shelter benefits, so it does not follow that shelters are a poor investment simply because the $29 million figure exceeds estimates of the value of a statistical life. Values for injuries prevented and for peace of mind would need to be added to the value of lives saved for a complete cost–benefit analysis. A value for injuries prevented depends on the severity of the injuries; only 23% of injuries from the 3 May tornado, for instance, required hospitalization (Brown et al. 2000). Consequently adding a value for injuries avoided would not greatly affect the cost-per-fatality-avoided figure.[5] The kinds of tradeoffs used to estimate the value of a statistical life also add some qualifications to the cost per fatality avoided (Viscusi 1993). Studies that estimate the value of a statistical life typically use voluntarily assumed risks that involve only the decision maker, such as the added wage premium needed to induce a worker to take a dangerous job. Residents may view an involuntary risk such as tornadoes very differently from voluntarily assumed risks. Furthermore, the wage differentials used in estimation depend on the wealth and attitudes toward risk of workers who actually take dangerous jobs; individuals who place the highest values on safety will not take risky jobs at market wage differentials. In other words, some people place a value on life in excess of even the upper range of the values reported above. In addition, the value of statistical life revealed by an adult accepting a personal risk may not be indicative of the value parents place on protecting their children.

The peace-of-mind benefits should figure prominently in households' decision to purchase a storm shelter. Casualties prevented by a shelter necessarily depend on the probability a home will be struck by a tornado, which is low even in Tornado Alley, and the small probability of a tornado strike diminishes even a large value placed on casualties. Anxiety exists, however, even if a tornado never comes within 5 mi of a home, so the small probability of a tornado strike does not diminish this component of shelter benefits. Parents may place a great value on providing peace of mind for their children. We have not tried to quantify peace-of-mind benefits, because, in the absence of an accepted valuation method, any number we would assign would be arbitrary.

The cost-per-fatality-avoided calculation allows evaluation of whether a low market penetration rate of shelters might signal a market failure and a role for public policies to encourage or subsidize purchase of shelters. Economics attempts to understand the behavior of people, not to prescribe that behavior. Benefits are subjective and preferences differ, so economists would be uncomfortable prescribing a household's private, personal decision to purchase a tornado shelter. A low cost per fatality avoided in the presence of a low market penetration rate, though, would indicate a possible market failure and a possible role for policy. The value calculated here suggests that while some households will consider shelters a worthwhile investment other fully informed households will probably decide they are not worth the cost. The cost per fatality avoided is sufficiently high that a low market penetration rate cannot be considered indicative of market failure.

Several assumptions we have made affect the analysis, and we discuss how plausible alternatives affect our calculations. If shelters are not 100% effective or if people do not use shelters, the cost per fatality avoided will be higher than calculated above. We have assumed every home would need a shelter to provide full protection, but two families might be able to share a shelter, which would reduce the cost per fatality avoided. If, for instance, each shelter could protect two families, only one-half of the single-family homes would need to be equipped with shelters, and the cost per fatality avoided would be one-half of the figure reported. Inclusion of maintenance costs for shelters would raise the cost per life saved.

The figure of $28.85 million per fatality avoided is calculated on a flow basis, which corresponds to the value of shelters in steady-state equilibrium in the real estate market. This figure reflects costs once the market adjusts and avoids potential controversy in choosing a discount rate. Because few homes currently have shelters, providing all homes in the state would require a capital investment now, whereas safety benefits would begin now and continue into the future. A public policy decision to encourage purchase of shelters would need to discount the safety benefits.[6] To illustrate the effect of discounting, we calculate a cost per fatality avoided employing 3% and 6% discount rates to future values. The cost of equipping all homes in Oklahoma with a shelter, based on the figure of $2000 per home, would be $2145 million, incurred now as a current capital investment.[7] With no discounting, shelters would prevent 74.35 fatalities over 50 yr. Discounting future fatalities

[5] One way to demonstrate this would be to "add" injuries to the fatalities avoided and recalculate the cost per casualty avoided. Viscusi (1993) reports a range of estimates of $30 000–$50 000 for the value of an injury taken from labor-market studies. If we use $50 000 per statistical injury (which seems generous given the severity of tornado injuries) and the EPA figure of $4.8 million per statistical life, it implies a trade of 1 fatality = 96 injuries. The estimate of 22.27 annual injuries in permanent homes translates into an extra 0.232 fatalities, and the cost per casualty avoided becomes $24.96 million (=42.905/1.719). Even if one-half of the 77.9 injuries per year occur in permanent homes, the cost per casualty avoided is $22.67 million.

[6] Discounting captures the effect of impatience when benefits or costs are not realized at the same time. Most people are impatient and consider a dollar today to be worth more than a dollar a year from now. Gramlich (1990) discusses discounting in greater detail and the choice of an appropriate interest rate for discounting.

[7] If some homes in the state already have shelters, this would reduce the current capital cost. We could find no published estimate of the percentage of homes in Oklahoma that currently have a shelter, and so we make the calculations assuming all homes must be equipped.

TABLE 1. Effect of tornado strength on expected fatalities.

F-scale rating	Fatalities per tornado	OK tornado distribution	Annual average No. of storms	U.S. tornado distribution	Annual No. of storms
F0	0.0021	0.3326	19.30	0.5504	31.95
F1	0.0148	0.3337	19.37	0.3156	18.32
F2	0.0246	0.2289	13.29	0.1004	5.827
F3	0.236	0.0759	4.405	0.0259	1.503
F4	1.541	0.0260	1.509	0.0072	0.418
F5	7.875	0.0028	0.163	0.0005	0.029

at a 3% discount rate yields a present value of 39.41 fatalities, which generates a cost per fatality avoided of \$54.44 million (=2145/39.41). Applying a 6% discount rate yields a cost per fatality avoided of \$86.39 million (=2145/24.84).[8] A higher discount rate would produce a higher cost per life saved.

Tornado fatalities are almost exclusively a result of violent tornadoes. Analysis of the Storm Prediction Center tornado database reveals that less than 3% (2.86%) of Oklahoma tornadoes were very violent—F4 or F5—over the period, yet these tornadoes produced over two-thirds (68.1%) of fatalities. The fatalities per tornado in each category ranged from 0.002 for F0 and 0.015 for F1 storms to 1.54 and 7.88 for F4 and F5 storms. The value of a storm shelter depends critically on the intensity distribution of tornadoes. Differences in the distribution of the intensity of storms can significantly affect the value of shelters. To illustrate this point, we hold the number of tornadoes per year in Oklahoma constant at the 50-yr historical average of 58.04 but apply the strength distribution of storms based on a national sample reported in Thompson and Vescio (1998). Almost 11% of Oklahoma tornadoes between 1950 and 1999 were rated F3 or stronger while less than 3.5% of tornadoes in the national sample were this strong. Table 1 illustrates the calculation, with the frequency distributions of Oklahoma and national tornadoes and the Oklahoma figures for fatalities per storm for storms of different intensities. Substituting the national strength distribution yields 1.709 tornado fatalities per year, and given the fraction of deaths avoided by in-home shelters employed and the cost calculations employed above, the cost per fatality avoided without discounting approximately triples to \$87.82 million. The sensitivity also applies in the opposite direction: an increase in the proportion of strong tornadoes relative to the Oklahoma distribution would lower the cost per fatality avoided.

The use of historical data for the 50-yr period of 1950–99 assumes average tornado deaths throughout this period as a proxy for future fatalities in the absence of mitigation efforts. Yet tornado detection technology has improved over the period—significant improvements include National Weather Service tornado warnings beginning in 1953 and the acquisition of Doppler radar in the 1980s—so tornadoes at the end of the period would be likely to cause fewer fatalities than an equivalent storm at the beginning of the period. Average annual casualty totals over the 50-yr period consequently overstate the potential benefits of shelters. On the other hand, population growth in the state over the period indicates more individuals are currently at risk, and this factor would understate the potential benefits of shelters. D. Merrell et al. (2001, unpublished manuscript) estimate regression models of casualties produced by a given tornado event, with strength of the tornado on the Fujita scale, time of day, month of year, a time trend, and population density for the affected county as control variables. The time trend has a negative predicted impact on fatalities; population density increases both fatalities and injuries. The casualties models predict close to the historical annual average tornado deaths in Oklahoma and consequently have little impact on the cost per fatality avoided. Nonetheless, the adjustments for these factors are not large, so the cost-per-life-saved figure based on historical averages is a reasonable approximation of the value of shelters.

4. Shelters for mobile homes, apartments, and communities

Our analysis has focused on permanent homes, consistent with much public attention on tornado shelters. The Oklahoma Safe Room Initiative, for example, offered rebates to home owners. Yet not all Oklahomans own homes, and providing protection for renters and residents of mobile home parks raises different economic problems and different casualty/cost trade-offs. We provide a cost-per-fatality-avoided estimate for shelters for mobile homes and discuss apartments and community shelters in this section.

Renters will not necessarily be left out in the storm. Competition drives owners of rental property to offer potential residents a desirable place to live. Landlords seek to maximize profits, not to minimize costs, and thus offer amenities that increase the value of their units. Apartment complexes offer pools, saunas, and exercise facilities because residents will pay enough extra for them to make the provision of these amenities profitable. A tornado shelter is similar to other amenities, providing value to residents at a cost to the landlord. If residents will pay extra for access to a shelter in an apartment complex or on the grounds of a mobile home park, owners have an incentive to provide shelters. Whether enough renters will pay enough extra per month for a shelter to induce at least some landlords to provide shelters is an empirical question. In theory, the rental market should do no worse providing storm shelters than it does providing air conditioning or covered parking. Note that

[8] We discount the fatalities because we are not applying a specific value of a statistical life.

the cost per unit per month might be very small, probably no more than $10 per unit per month.[9]

We calculate the cost per fatality avoided on an annual (undiscounted) basis for mobile home residents for comparison with the permanent home figure in section 3. More tornado fatalities occur in mobile homes than in permanent homes; nationally 40.29% of fatalities between 1985 and 1999 occurred in mobile homes (Storm Prediction Center 2000), so full coverage of mobile homes in Oklahoma would save 2.095 fatalities per year. Oklahoma had 127 544 mobile homes/trailers in the 1990 census; allowing for population growth yields an estimated 136 159 mobile homes in 1999. We again assume each unit requires a $2000 underground shelter that lasts 50 yr and prevents all fatalities. The cost of providing shelters for 2% of mobile homes annually is $5.446 million, which yields a cost per fatality avoided of $2.60 million. Note that this figure is less than the typical estimate of the value of a statistical life. Again we caution the reader about inferring whether shelters are worth the cost solely from this figure. The cost for mobile homes relative to single-family homes is noteworthy; this value is an order of magnitude smaller than the cost per fatality avoided for single-family homes. Shelters for mobile homes consequently are a more cost-effective approach to preventing tornado fatalities. Mobile home residents, however, may not purchase shelters at the same rate as permanent home residents do because of differences in income or tolerance of risk.[10]

Community shelters offer a means of reducing the cost of protection, particularly if the shelter can be designed for multiple uses (FEMA 2000). Yet common shelters create problems of their own. Most notable, individuals must move from their homes to the shelter, and this movement can be dangerous. One fatality and 23 injuries occurred in the 3 May 1999 tornado as people tried to get to a shelter (Brown et al. 2000). Latecomers running to a community shelter may be caught outside when the storm strikes, facing greater risk than if they had remained within their homes. Last, community shelters would need to be closed before the tornado strikes, so residents inside unaware of exactly how close a tornado may be might face a dilemma of opening the door for latecomers and endangering all inside or keeping the door closed and possibly leaving those outside at the mercy of the storm. Although the cost savings may still make community shelters attractive, policy makers should recognize the trade-offs community shelters create.

5. Conclusions: An economic perspective on future research

How do tornado shelters stack up against other life-saving policies? Viscusi et al. (2000) report the cost per life saved for 53 traffic, consumer-product, workplace-safety, and environmental regulations. The values range from $100 000 to almost $7 trillion (in 1995 dollars). Nineteen of the regulations listed had a cost per life saved that was higher than that for tornado shelters for permanent homes, whereas only 22 of the regulations saved lives at a lower cost than shelters for mobile homes.

Expected-utility theory indicates that the annual probability that a home will be struck by a tornado and the cost of a shelter are the major determinants of the cost per fatality avoided. Our calculations in this paper suggest that the cost-per-fatality calculations are in a range at which at least some residents of permanent homes and many residents of mobile homes will seriously consider purchase. Economists, engineers, and meteorologists can provide information to assist residents in their decision making. We offer a few concluding thoughts on additional information that the expected-utility model suggests would be of use for residents on the margin of purchasing shelters.

First, all shelters are not created equal, and residents must choose their desired level of protection. Options run from underground shelters for $2000 to above-ground safe rooms, which cost $6000 or more. We have assumed the low-end product prevents all tornado casualties, which reduces the cost per fatality avoided with shelters. If indeed a $2000 underground shelter yields full safety benefits, why should any resident wish to purchase a safe room? Engineering studies indicate that the safety potential of shelters depends on features such as the quality of the door, and higher-quality construction should increase the safety factor. In-home safe rooms certainly provide residents more convenient and faster access (which could be critical at night with only moments to seek shelter). We have not addressed whether the added safety and convenience is worth the cost. Engineers could provide information needed to calculate the marginal safety benefits of safe rooms versus underground shelters. Note that the cost per fatality avoided would be higher if low-end shelters do not prevent all tornado casualties.

Second, the annual probability of a tornado at a specific location will affect households' expected-benefits calculation. Residents will demand location-specific information on this score. Historical tornado frequencies for 1950–99 vary across Oklahoma. The annual tornado

[9] Shelters for mobile home parks able to protect up to 32 persons will soon be on the market for an estimated price of $15 000–$20 000 (T. Hope, Twister Pit, Inc., 2000, personal communication). The cost per unit if the price is $15 000 and 12 units use one shelter is $1250. A payment of $10 per month for 20 yr discounted with a real interest rate of 8% yields a present value greater than $1250. A payment of $15 per month with a 10% real interest rate yields a present value of $1500 in 15 yr. With sufficient market penetration of safe rooms, apartment dwellers may choose to go to a friend's or a relative's house in the event of a tornado instead of paying extra for a shelter in their apartment complex.

[10] As mentioned above in Footnote 9, the cost per unit may be lower than $2000 for mobile homes because of group shelters. If the cost per unit is $1250, the cost per fatality avoided for mobile homes falls to $1.63 million.

rate per 10 000 square miles for the state is 8.46, but this ranges from a low of 2.94 tornadoes per 10 000 square miles in Cimarron County to highs of 22.46 and 21.72 tornadoes per 10 000 square miles in Tulsa and Oklahoma Counties, respectively. The distribution of tornado strengths is also relevant, as the calculations in section 3 demonstrated. The value of a shelter depends critically on the annual probability of strong tornadoes at a location, which could vary significantly across the state. Meteorologists could provide extra information on this point. The above frequencies, for instance, are based on countywide averages. Can storm paths or parts of counties be identified in which tornadoes and especially strong tornadoes are particularly likely to strike?

We conclude with a cautionary note concerning our calculations. We have examined the safety benefits of shelters in isolation; we have not considered alternative actions that could reduce casualties and have assumed everyone takes shelter once shelters are installed. Even in Oklahoma, in which tornado awareness is very high, and even in the F5 storm of 3 May 1999 at which time residents received warning well in advance of the storm's approach, some deaths occurred because people failed to take the best available precautions (Brown et al. 2000). Also some tornado deaths occur overnight during which sleeping residents do not receive warning. Other policies that reduce casualties such as education concerning proper tornado precautions or greater use of National Oceanic and Atmospheric Administration weather radio to publicize tornado warnings would raise the cost per fatality avoided figure for shelters. In addition, making allowance for people who fail to use their shelters would also increase the cost per fatality avoided. Further research could explore the cost effectiveness of alternative policies relative to tornado shelters.

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