

Analyzing Evacuation Versus Shelter-in-Place Strategies After a Terrorist Nuclear Detonation

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We superimpose a radiation fallout model onto a traffic flow model to assess the evacuation versus shelter-in-place decisions after the daytime ground-level detonation of a 10-kt improvised nuclear device in Washington, DC. In our model, $\approx 80\text{k}$ people are killed by the prompt effects of blast, burn, and radiation. Of the $\approx 360\text{k}$ survivors without access to a vehicle, 42.6k would die if they immediately self-evacuated on foot. Sheltering above ground would save several thousand of these lives and sheltering in a basement (or near the middle of a large building) would save $\approx \frac{1}{3}$ of them. Among survivors of the prompt effects with access to a vehicle, the number of deaths depends on the fraction of people who shelter in a basement rather than self-evacuate in their vehicle: 23.1k people die if 90% shelter in a basement and 54.6k die if 10% shelter. Sheltering above ground saves approximately half as many lives as sheltering in a basement. The details related to delayed (i.e., organized) evacuation, search and rescue, decontamination, and situational awareness (via, e.g., telecommunications) have very little impact on the number of casualties. Although antibiotics and transfusion support have the potential to save $\approx 10\text{k}$ lives (and the number of lives saved from medical care increases with the fraction of people who shelter in basements), the logistical challenge appears to be well beyond current response capabilities. Taken together, our results suggest that the government should initiate an aggressive outreach program to educate citizens and the private sector about the importance of sheltering in place in a basement for at least 12 hours after a terrorist nuclear detonation.

KEY WORDS: Evacuation models; nuclear radiation; terrorism.

1. INTRODUCTION

The U.S. Department of Homeland Security has developed 15 national planning scenarios for use in preparedness activities, and we consider the first of these scenarios: a surface blast of a 10-kt improvised nuclear device (IND) in the Washington, DC

Mall at 10 a.m. on a weekday.⁽¹⁾ In contrast to the Cold War scenario of simultaneous 1-mt airblasts over 100 cities,⁽²⁾ this terrorist scenario allows for some consequence management. Although⁽¹⁾ claims that “by far, the greatest factor impacting the reduction of the effects of the detonation on the general population” is the speed and appropriateness of the shelter/evacuation-in-place protective action decisions that are made in the first 24 hours, no analysis was performed to suggest what an optimal shelter/evacuation strategy might be.

We formulate and analyze a mathematical model of this scenario to investigate the impact of various shelter/evacuation strategies. The mathematical model first calculates the number of deaths and

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Table I. Casualty Count (Deaths and Injuries Broken Out by Prompt Casualties, Pedestrian Casualties, and Casualties Among People with Access to a Vehicle) for Various Key Scenarios (Defined by the Shelter Location, the Evacuation Rate, and Whether or Not Basic Medical Care is Available)

Scenario			Deaths				Injuries			
Shelter location	Evacuation Rate (%)	Medical Care	Prompt	Pedestrian	Vehicle	Total	Prompt	Pedestrian	Vehicle	Total
Above ground	10	No	76.8k	42.5k	42.1k	161.4k	10.0k	15.2k	16.2k	41.4k
Above ground	50	No	76.8k	43.0k	49.5k	169.3k	10.0k	16.7k	13.6k	40.3k
Above ground	90	No	76.8k	43.6k	56.7k	177.1k	10.0k	18.2k	18.0k	46.2k
Basement	10	No	76.8k	30.4k	23.1k	130.3k	10.0k	17.2k	18.0k	45.2k
Basement	50	No	76.8k	36.3k	38.8k	151.9k	10.0k	17.8k	14.5k	42.4k
Basement	90	No	76.8k	42.2k	54.6k	173.6k	10.0k	18.5k	18.2k	46.7k
Above ground	10	Yes	75.3k	36.8k	35.4k	147.5k	10.0k	14.7k	15.6k	40.4k
Above ground	50	Yes	75.3k	35.3k	45.8k	156.4k	10.0k	16.2k	13.3k	39.6k
Above ground	90	Yes	75.3k	36.9k	56.0k	168.2k	10.0k	17.5k	17.9k	45.4k
Basement	10	Yes	75.3k	23.8k	18.5k	117.6k	10.0k	17.7k	13.4k	41.1k
Basement	50	Yes	75.3k	28.1k	36.3k	139.7k	10.0k	17.9k	12.2k	40.1k
Basement	90	Yes	75.3k	35.5k	54.1k	164.9k	10.0k	17.8k	17.7k	45.6k

Note: All other aspects of the model use the base-case values in Fig. 2.

injuries caused by the initial effects of the detonation, which are from the blast, the heat (both direct heat and indirectly via burned buildings), and the prompt (i.e., emitted within the first minute) radiation. We then superimpose two spatiotemporal processes: the radiation fallout plume as it travels downwind in the subsequent days, and the pedestrians and vehicles evacuating the city, where the traffic flow of vehicles is modeled using a system of partial differential equations. We calculate the number of casualties from the fallout under a variety of behavioral responses regarding shelter versus evacuation.

The main finding is that sheltering in place (and especially in basements) is greatly preferred to evacuation when the goal is to save lives; numerical results supporting this conclusion are summarized in Table I and Fig. 2, but are difficult to follow without first reading the main body of the article. For example, sheltering in basements would save about one-third of the lives that would be lost if everyone without access to a vehicle who survived the immediate detonation attempted to flee on foot. Similarly dramatic results pertain when comparing lives lost among those with access to a vehicle between those who attempt to flee and those who shelter in place. The intuition is simple: while one would think that escaping the fallout zone is the best way to avoid injury or death, when even a small fraction of people attempts to do so, such creates traffic queues that in effect cause much greater exposure to radiation than would occur if people stayed inside and below ground. Combining this logistical

observation with the facts that means of communications between the government and its citizens will be limited after the detonation, situational awareness of both the plume location and travel times will be low, and shelter/evacuation compliance has been low in past events⁽³⁾ and in recent surveys,⁽⁴⁾ we conclude that the only robust strategy is to advise everyone to shelter in place. Consequently, our policy proposal is that the government should be educating the public to shelter in place below ground for at least 12 hours after a terrorist nuclear attack.

2. THE MODEL

2.1. Prompt Effects

The mathematical model (Fig. 1) is formulated in detail in the Supporting Information; while the model focuses on the first national planning scenario, it could be applied much more broadly (e.g., to other cities, other weather conditions, and other detonation sizes). The initial effects of the detonation are due to the blast overpressure, the thermal energy, and the prompt radiation, all of which are emitted in a radially symmetric manner. For each of these three prompt effects, we calculate the probability of death and the probability of serious injury (i.e., requiring hospitalization) for the effect in isolation, as a function of the radial distance r from the location of the detonation.

To compute the blast casualty probabilities, we assume that 85% of people are inside at the time of

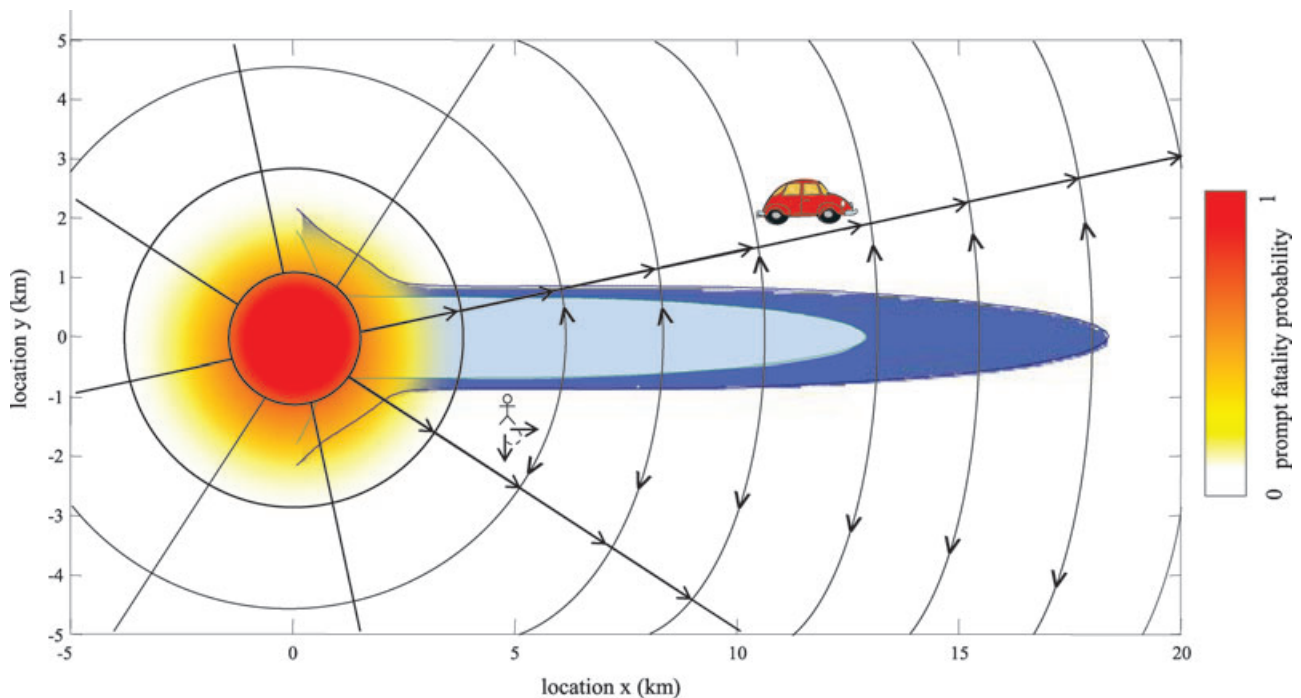


Fig. 1. A graphical description of the model. Fatality probabilities from blast, burns, or prompt radiation are spatially symmetric and color-coded. There are many pedestrians at $r < 7.1$ km who evacuate by foot at a random outward angle with a 90° range. Vehicle evacuation is from the closest point on the closest arc (arcs are located every 3 km starting at $r = 1.5$ km) and then to either the closest of eight rays (after some family consolidation) for shortest-route evacuation (used for self-evacuation) or to the adjacent ray that is farther away from the fallout plume for avoidance evacuation (used for delayed evacuation). The radiation fallout plume moves in the direction of the wind and decays with time according to $t^{-1.2}$. The fallout contours are 24-hour integrated doses for 500 rem (dark) and 250 rem (light); the median lethal radiation dose is 385 rem.

the detonation⁽¹⁾ and are in either a concrete building or a multistory wall-bearing building (e.g., a three-story brick apartment), calculate the probability of severe or moderate damage as a function of r for these two building types (the damage probability is a function of the peak overpressure from the blast, which itself is a function of r),⁽¹⁾ and the probability of death or serious injury from being in a severely or moderately damaged building of each type or being outdoors.^(5,6) All dose-response functions in our model, whether for human death, human injury, or building damage, are fit to either lognormal cumulative distribution functions (cdf) or lognormal complementary cdfs.

To assess thermal effects, we divide the population into four groups: those who are in a burned building, in an unburned moderately damaged building, in an unburned undamaged building, or outside. We compute the probability of a building at location r being burned (this probability is a function of the thermal fluence, which in turn is a function

of r),⁽⁷⁾ and use⁽⁵⁾ to estimate the probability of dying or being injured in a burned building. Casualties in unburned moderately damaged buildings and outside are due directly to the thermal energy. We estimate the outside shielding factor from data in References 2, 5, and 7 and assume that unburned buildings provide 80% thermal shielding. We assume that unburned undamaged buildings provide 100% thermal shielding. The dose-response data for burn fatalities and injuries are taken from References 5 and 8.

Prompt radiation, which by definition is emitted within the first minute, consists of neutrons, secondary gamma rays, and fission product gamma rays. We use models and data for each of these components⁽⁶⁾ to compute the total prompt radiation at location r . To account for the heterogeneity in shielding protection for various types of buildings,^(5,9) we assume that the radiation transmission factor for people who are inside is a uniform random variable ranging between 0.1 and 0.5 in undamaged buildings (Equation (27) in Supporting Information),

which represents sheltering in small buildings above ground; later, we consider sheltering in basements or near the middle of large buildings. Dose-response data (in the absence of medical care) for radiation fatalities and injuries are taken from References 1 and 6.

We compute the total prompt probability of death and of serious injury as a function of r by accounting for the facts that many people receive fatal doses of more than one effect, and that combined serious injuries can be fatal (e.g., the fatal radiation dose is significantly smaller for someone who has a serious burn or blast injury⁽⁸⁾). Multiplying these probabilities times the spatial daytime population yields the total number of prompt fatalities and injuries in each location. We use LandScan USA⁽¹⁰⁾ to construct the spatial nighttime population of Washington, DC, and its surrounding areas, and (following Ref. (1)) obtain the daytime population by adding 481k people uniformly to the region $r < 5$ km and adding 220k uniformly to the annulus between $r = 5$ and 11 km.

2.2. Radiation Fallout

Turning to the temporal part of the model, we compute the fallout dose rate at each location and each point in time assuming a wind speed of 10 mph, using a relatively simple model⁽¹¹⁾ that has been calibrated against the more complicated NARAC model.⁽¹²⁾ For ease of exposition, we assume that the coordinate system is such that the wind direction is along the positive x -axis (Fig. 1). In the base case, the wind direction is 11.25° N of east.

2.3. Self-Evacuation

We consider two types of evacuation: self-evacuation, in which people evacuate by vehicle or on foot (if they have no access to a vehicle) soon after the detonation, and delayed evacuation, in which people evacuate (again, by vehicle or on foot) only after sheltering in place for a significant amount of time (hours or days). While sheltering in place, people experience the same random indoor shielding factor that was used during our prompt radiation calculations. We assume that no one has access to a vehicle for $r < 1.5$ km because the roads are not passable due to blast and burn damage, and that 38% of people in $r \in [1.5, 7.1]$ km do not have access to a vehicle because they are commuters⁽¹³⁾ or are residents who do not own one.⁽¹⁴⁾

The detonation occurs at time $t = 0$ and the loading time is the time at which the self-evacuation is initiated, and consists of a diffusion time plus a preparation time. We assume the preparation time (which occurs indoors) is 15 minutes for everyone.⁽¹⁵⁾ The diffusion time (85% of people are inside during this interval) depends upon personal and interpersonal situational awareness. We assume the diffusion time is 0 for $r < r_p$, where r_p represents the distance within which people are directly aware of a nuclear detonation. We consider two different values: $r_p = 4$ km is the value at which windows break in our model and represents low personal situational awareness, and $r_p = 17$ km is the visibility distance on a clear day (the mushroom cloud is visible for 1 hour⁽⁵⁾) and represents high personal situational awareness. We assume that the diffusion time is 1 hour for $r > r_i$ (consistent with diffusion times from nearby industrial accidents^(16,17)), where r_i is the minimum distance at which electronic communications (phones, television, Internet) are intact; we ignore the fact that even in areas where the telephone system is operational, it is likely to be overloaded.⁽¹⁸⁾ We consider two values, $r_i = 17$ and 320 km (Table 1–15 of Ref. (1)), which correspond to high and low interpersonal situational awareness, respectively. Hence, we consider four scenarios in total, with two values of r_i and two values of r_p , although we focus on the case where $r_p = 4$ km, $r_i = 17$ km. People located in $[r_p, r_i]$ have to rely on battery-powered radios, face-to-face contact with neighbors, nonelectronic communications with the government (e.g., loudspeakers atop vehicles⁽¹⁾), or family members driving home with the news. We assume that the mean diffusion time in this range is 3 hours.

People who self-evacuate on foot from location (x, y) (where the detonation is at $(0,0)$) are assumed to travel at 1 mph in a random direction that is uniformly distributed in $[\arctan(\frac{y}{x}) - \frac{\pi}{4}, \arctan(\frac{y}{x}) + \frac{\pi}{4}]$ (i.e., with a range of 90°); the slow speed and random direction account for initial confusion, movement around buildings, injuries, and the need to carry things (or children). We assume that there are no congestion effects among evacuating pedestrians or between pedestrians and vehicles.

We assume that there are 2.5 people per evacuating vehicle.⁽¹⁹⁾ Vehicles evacuate (Fig. 1) the city via arcs (paths of constant radius from the detonation location, each of which has two lanes of traffic moving in each direction, and interference due to cross-traffic) that exist every 3 km starting at $r = 1.5$ km, and eight⁽²⁰⁾ outgoing rays (paths emanating from the

detonation location, each of which has four lanes of traffic). The angle between the wind direction and the closest ray is set equal to the median value of $\frac{\pi}{16} = 11.25^\circ$ (Fig. 1).

In our model, evacuating vehicles instantaneously move in the radial direction to the closest arc. In shortest-route evacuation (which is appropriate for self-evacuation), to account for the 50% increase in local traffic due to family consolidation,⁽²¹⁾ we assume that $\frac{3}{4}$ of the vehicles travel on the arc to the closest ray and $\frac{1}{4}$ travel to the other adjacent arc. For avoidance evacuation (which may be more appropriate for modeling delayed evacuation—this is referred to as lateral evacuation in Ref. (22)), all vehicles travel on arcs in the direction away from the centerline of the fallout plume, and hence there is only one direction of traffic flow on the arcs in this case.

Traffic flow along rays and along each direction of the arcs is modeled according to the classic kinematic wave model,⁽²³⁾ incorporating traffic engineering data that quantify the relationship between traffic flow and traffic density.⁽²⁴⁾ These partial differential equations are coupled together, so that exits from arcs correspond to entrances on rays. Flow at the arc-ray intersections is restricted by the spare capacity in the right lane of the ray and the capacity out of the single-lane exit ramp of the arc, and hence a traffic jam on a ray can cause traffic buildups on the arcs. In addition, vehicles wait in a queue to enter the arc at each location if there is no spare arc capacity at this location.

2.4. Delayed Evacuation

People (pedestrians or those with vehicles) who do not self-evacuate are assumed to shelter in place until the delayed evacuation, which begins at time τ_e . We consider two extreme policies for the delayed evacuation of vehicles: a high-dose-first policy, which gives evacuation priority to people in areas with high fallout doses, and a low-dose-first policy, which gives priority to people in areas with low fallout doses. Delayed vehicle evacuation uses avoidance evacuation, and evacuation is optimized under both extreme policies so as to evacuate as quickly as possible while maintaining the congestion below a specified level: the density on the arcs and rays never exceeds the level that achieves maximum flow, there are no backups at the arc-ray intersections, and no queue buildups for vehicles trying to enter the arcs. We also

impose an outer limit (r_e , which is 50 km) on allowable ray evacuation; that is, vehicles are not allowed to enter a ray at location $r > r_e$.

To model delayed pedestrian evacuation, we define the evacuation region to be the intersection of the region $r > 1.5$ km (because evacuation stations need to be outside of the blast and burn zones) and the region where the fallout dose rate at time τ_e is greater than or equal to 10 rem/hour (where rem is the standard unit of measurement for the biologically equivalent dose), which allows emergency workers to perform lifesaving activities for 5 hours.⁽²⁵⁾ Pedestrians walk (at 1 mph in a random direction with a 22.5° range) to the perimeter of the evacuation region, at which point they are assumed to be at an evacuation station. Pedestrians who are outside of the evacuation region at time τ_e are assumed to be immediately evacuated without incurring additional fallout. We assume that pedestrians are not exposed to any radiation fallout after they arrive at the perimeter of the evacuation region, which essentially assumes that people are either well sheltered from fallout at the evacuation station or that there are ample vehicles (e.g., buses) and hence no waiting at the evacuation station, and that these vehicles incur very little traffic congestion (e.g., some of the inbound lanes on the rays are devoted to these vehicles and other emergency vehicles). Hence, our casualty estimates for delayed pedestrian evacuations should be viewed as lower bounds.

3. RESULTS

3.1. Prompt Casualties

Prompt effects are dominated primarily by burns and to a lesser extent by prompt radiation (Fig. 1 in Supporting Information): blast fatalities drop rapidly from near 50% to $< 10\%$ at $r = 0.5$ km and blast injuries are rare for $r > 1.5$ km, prompt radiation is 100% fatal for $r < 1$ km but drops off rapidly with no injuries for $r > 1.2$ km, and burns are $> 80\%$ fatal for $r < 0.8$ km, but thermal fatalities and injuries drop off more slowly and can occur out to several km. Overall, there are 76.8k fatalities and 10.0k serious injuries due to the prompt effects of the detonation.

3.2. Sensitivity Analysis for Prompt Casualties

The prompt casualty results are qualitatively similar to those in References 1 and 26. Our model produces somewhat fewer blast injuries than References 1 and 26, but many of those injured by

blast are subsequently victims of burns, which was not explicitly considered in Reference 1. Our model appears to have fewer blast injuries and more burn injuries than in References 27 and 28 (they do not provide details), which is probably due to their explicit modeling of the urban terrain and either their possible omission of the fire data in Reference 7 or their assumption that not all people in burned buildings die. Because blast effects are dominated by the other two effects, our model is insensitive to two parameters that are quite uncertain in our model: the fraction of concrete and brick buildings, and the fraction of outside blast casualties that are fatal. Finally, changing the inside thermal shielding factor from 80% to 50% increases the number of prompt fatalities and prompt injuries by only 0.1k each.

3.3. Pedestrian Evacuation

Among the survivors of the prompt effects, 358.6k are pedestrians (i.e., have no access to a vehicle). The casualty rates are independent of the interpersonal awareness parameter r_i because all pedestrians are located at $r < 17$ km. If the shelter/evacuation decision is made independently of location then among pedestrians who self-evacuate, 12.4% die and 5.1% are injured from radiation fallout when personal awareness is low ($r_p = 4$ km); the casualty rates change to 12.2% and 5.4% with improved personal awareness ($r_p = 17$ km). For delayed evacuators, the casualty probabilities increase with the time of delayed evacuation (τ_e), with the death rate ranging from 11.5% when $\tau_e = 12$ hours to 12.0% when $\tau_e = 96$ hours in the low personal awareness case ($r_p = 4$ km), and decreasing by 0.5–1.0% when personal awareness is high ($r_p = 17$ km) (Fig. 2 in Supporting Information). Pedestrians located near the centerline of the fallout zone (i.e., near $y = 0$) are better off self-evacuating (but the difference is very small because nearly all of them die in either case), as are pedestrians near $x = 0$ but just behind the fallout (for a total of 16% of pedestrians), while pedestrians located elsewhere in—and around the periphery of—the fallout zone (19% of pedestrians) are better off delaying their evacuation (Fig. 3 of Supporting Information); the remaining 65% of pedestrians survive regardless of their shelter/evacuation decision. If we assume that delayed evacuation does not offer improved situational awareness (via a narrower range of walking angles) or less fallout exposure (via the evacuation stations), then the optimal time to evacuate for those in the periphery of the fallout zone

varies between 6 and 80 hours (Fig. 4 in Supporting Information).

3.4. Vehicle Evacuation

Among survivors of the prompt effects, 8.4M people in our study region (within 117 km of the blast) have access to a vehicle. We consider vehicle self-evacuation strategies that are location-dependent and location-independent; the location-dependent strategy represents a best-case scenario (and hence a lower bound on the number of casualties), while the location-independent strategy is somewhat more realistic in the immediate aftermath of a detonation. The location-independent strategy is characterized by P_{ev} , which is the fraction of people with access to a vehicle that self-evacuate, regardless of location (x, y) . Let $D_f(x, y)$ be the total unprotected fallout dose over the first 24 hours at location (x, y) , using Equation (42) in Supporting Information. We consider a three-parameter location-dependent self-evacuation strategy, where the fraction of people with access to a vehicle in location (x, y) who self-evacuate is $1 - f_n$ if $D_f(x, y) > \bar{D}_e$, and is f_p if $D_f(x, y) \leq \bar{D}_e$; here \bar{D}_e is the dose threshold, f_n is the false negative probability, and f_p is the false positive probability. Delayed vehicle evacuation begins at time τ_e , and hence vehicle evacuation strategies are defined by four parameters if self-evacuation is location-dependent and two parameters if self-evacuation is location-independent.

Until we get to the sensitivity analysis, we assume that delayed evacuation uses the high-dose-first policy and the situational awareness parameters are $r_p = 4$ km, $r_i = 17$ km. We first investigate three variants of the location-dependent strategy. In the first two of these variants, we set $f_n = f_p = 0$ to represent the best-case scenario. Setting $\bar{D}_e = \infty$ (i.e., all people with access to a vehicle initially shelter), we find that the optimal (i.e., death-minimizing) time to begin delayed vehicle evacuation is $\tau_e^* = 4.4$ hr, which results in 35.9k deaths among prompt survivors with access to a vehicle (Fig. 5 in Supporting Information). Next we jointly optimize \bar{D}_e and τ_e . Defining $n(\bar{D}_e)$ to be the total population of prompt survivors with access to a vehicle who live in locations (x, y) that have $D_f(x, y) > \bar{D}_e$ (i.e., the number of people who self-evacuate in a vehicle if $f_p = f_n = 0$), we find that the optimal values satisfy $n(\bar{D}_e^*) = 35.8$ k (which involves a 6.2 km² region just downwind from the blast) and $\tau_e^* = 4.4$ hours, with 31.1k deaths. Finally, using more practical values, we set the false

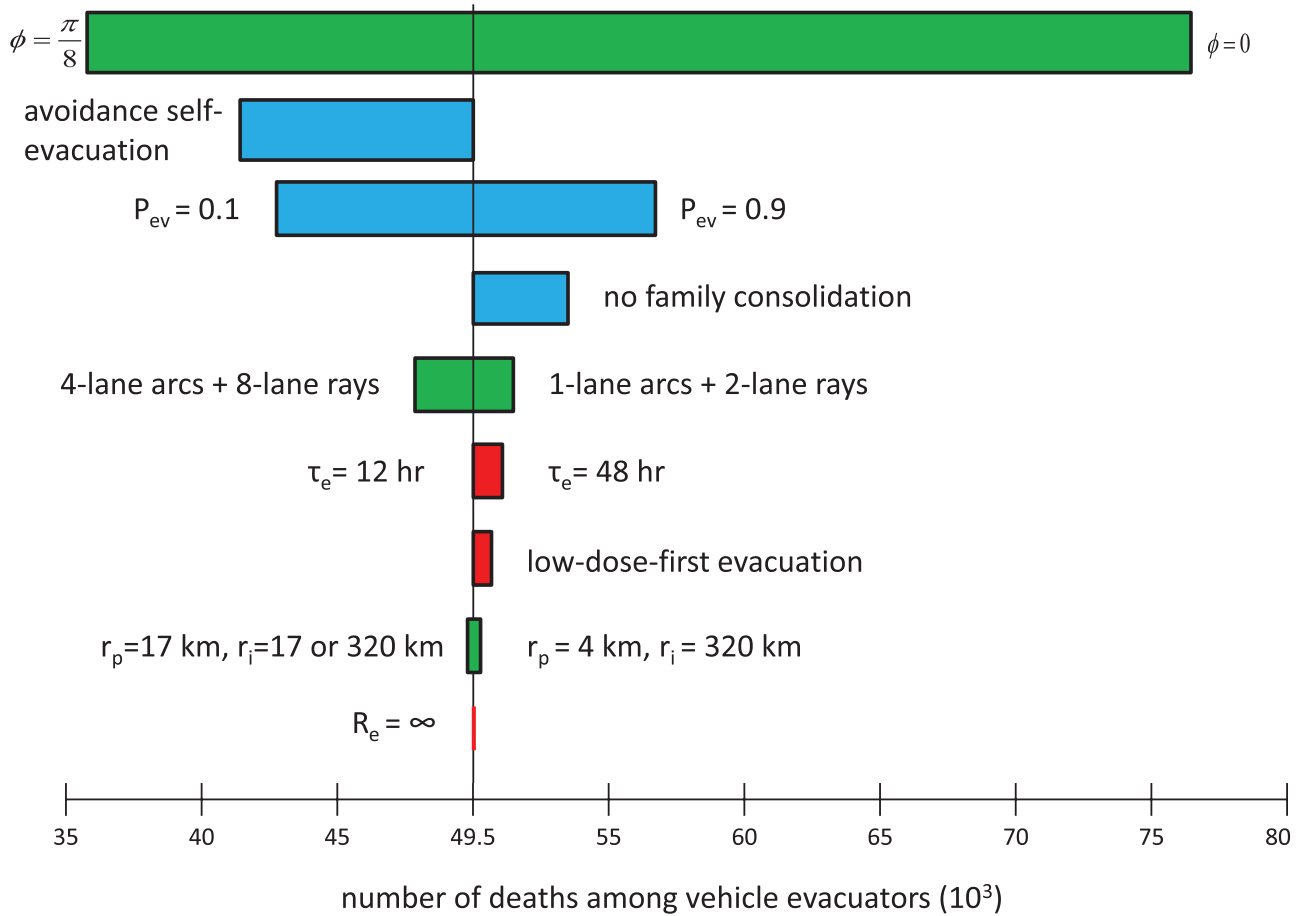


Fig. 2. A tornado diagram for the total number of deaths among vehicle evacuators with the base-case values: vehicle self-evacuation rate $P_{ev} = 0.5$, high-dose-first priority policy for delayed vehicle evacuation, delayed evacuation starts at $\tau_e = 24$ hours, ray arrivals are disallowed during delayed vehicle evacuation beyond $r_e = 50$ km, the angle ϕ between the wind direction and the closest ray is $\frac{\pi}{16} = 11.25^\circ$, shortest-route evacuation is used during vehicle self-evacuation; family consolidation occurs during vehicle self-evacuation; arcs have two lanes and rays have four lanes; and the situation awareness parameters are $r_p = 4$ km and $r_i = 17$ km. The colors (visible in the online version) red, blue, and green denote policy, behavioral and environmental variables, respectively.

negative probability $f_n = 0.05$ and the delayed evacuation time $\tau_e = 24$ hours, and find the optimal \bar{D}_e for each value of the false positive probability $f_p \in [0, 1]$. The number of fatalities increases roughly linearly from 32.8k when $f_p = 0$ to 57.6k when $f_p = 1$ (Fig. 6 in Supporting Information), and $n(\bar{D}_e^*)$ is 39.1k for all $f_p \leq 0.95$.

Turning to the more realistic location-independent self-evacuation strategy, we have 49.5k deaths using the base-case value of $P_{ev} = 0.5$. The three policy variables (i.e., primarily under governmental control)—the priority policy (i.e., high-dose-first vs. low-dose-first), the boundary condition (i.e., whether or not to allow ray arrivals

beyond 50 km), and the delayed evacuation time τ_e —have very little if any impact on the number of deaths (Fig. 2); indeed, the number of deaths is independent of τ_e for all values less than 28 hours, which is how long it takes to clear the highways of self-evacuators in the base case.

In contrast, the three behavioral variables (i.e., primarily under citizen control) have a considerable influence on the casualty count. The number of fatalities increases from 42.1k to 56.7k when the vehicle self-evacuation rate P_{ev} increases from 0.1 to 0.9 (Fig. 2). Disallowing family consolidation prior to evacuation (family consolidation was modeled by increasing the travel distance on arcs by 50%; note that

Washington, DC, public schools have a lock down plan, in which students cannot leave and parents cannot pick up their children⁽¹⁴⁾) increases the number of deaths by 4.6k because when all vehicles travel to the closest ray, half of the arc capacity remains unused. Avoidance self-evacuation of vehicles leads to a sizable drop in deaths, to 41.4k: the fallout-avoiding nature of the evacuation more than offsets the increased congestion caused by reducing the arc capacity in half.

Among environmental variables (i.e., largely out of everyone's control), the situational awareness parameters r_p and r_i have very little influence on the number of casualties, and halving or doubling the number of lanes on each ray and arc has a surprisingly small effect on the number of deaths because the congestion bottleneck shifts to the one-lane entrance and exit ramps. The parameter that has the biggest impact is the angle ϕ between the wind direction and the closest ray, which is assessed by changing the wind direction while keeping the roadway locations fixed. This effect is asymmetric and the number of deaths increases by $> 50\%$ when $\phi = 0$.

3.5. Sheltering in Basements

Until now, we have conservatively (with respect to our ultimate recommendation that everyone should shelter) assumed that people shelter above ground in small buildings. This assumption affects the survival of all delayed evacuees. To model sheltering in basements or near the middle of a large residential or office building, we change the indoor radiation transmission factor (after time τ_i) to a uniform random variable ranging between 0.05 and 0.1 (Fig. 2 in Ref. (9)) for $r > 0.5$ km. The death rate among delayed pedestrian evacuees drops from 11.7% to 8.0%, and to 6.3% when the personal situational awareness parameter increases from $r_p = 4$ to $r_p = 17$ km. When $\tau_e = 12$ hours, only 0.2% of pedestrians are better off self-evacuating than sheltering (compared to 16% when sheltering is above ground). Leaving all other vehicle evacuation parameters at their base-case values, the number of deaths among prompt survivors with access to a vehicle decreases from 49.5k to 38.8k when sheltering is in basements. The fatality count changes to 23.1k and 54.6k when $P_{ev} = 0.1$ and 0.9, respectively. The interpersonal situational parameter r_i still has no impact, but now improving r_p from 4 to 17 km reduces the number of deaths (under $P_{ev} = 0.5$) from 38.8k to 34.4k.

3.6. Medical Care

Although we do not model the detailed logistics of medical care delivery, we estimate the number of lives that could potentially be saved via antibiotics and transfusion support by increasing the median and 90th fractile radiation doses that cause death or injury by 30%, which is a compromise between the canine studies⁽⁸⁾ and the lower end of the range of the improvements claimed on page 508 of Reference 29. Using the base-case values in Fig. 2, and assuming that 50% of pedestrians self-evacuate, the total (due to prompt effects, and during pedestrian and vehicle evacuation) number of deaths decreases by 12.9k when the dose-response parameters are changed (Table I). Sheltering in place and medical care are somewhat synergistic mitigation schemes: medical care has the potential to save 8.9k lives when the self-evacuation rates are 90% and 13.9k lives when the self-evacuation rates are 10% (Table I).

4. DISCUSSION

4.1. Previous Studies

A consensus has not emerged on the evacuation versus shelter decision after a 10-kt nuclear detonation. Recommendations include evacuate unless a quick evacuation is not possible,⁽³⁰⁾ shelter in place,⁽³¹⁾ evacuate only people in the 24-hour dose-integrated median lethal dose range (a 5-mile-long oval),⁽³²⁾ and if the shelter transmission factor is 0.7, evacuate if the 24-hour integrated dose is > 100 rem (i.e., within 10 miles).⁽³³⁾ Two recent studies^(27,28) perform a more detailed analysis of shelter versus evacuation strategies. These models employ a more complicated effects and fallout model by accounting for urban terrain and non-Gaussian plumes generated by altitude-dependent wind direction (while these refinements would be very valuable for aiding in postevent situational awareness, they are not required for assessing shelter versus evacuation strategies prior to an event, as long as—as noted in Reference 28—the idealized Gaussian plume is not exploited for evacuation purposes). On the other hand, our analysis has a more detailed operational model by incorporating a traffic congestion model, distinguishing between pedestrians and people with vehicles, and considering imperfect plume knowledge, communications, and compliance with government recommendations. Both of these studies assess informed evacuation based on perfect plume

knowledge and perfect communications; while informed evacuation is recommended in Reference 28 in some cases (transmission factor of 0.25, good situational awareness, and rapid evacuation route), this strategy is viewed as risky in Reference 27, due to their assumption of perfect plume knowledge and perfect communications. As explained later, after explicitly accounting for traffic congestion and imperfect citizen compliance (in addition to limited plume knowledge and communications), we recommend against informed evacuation, and believe that the most robust strategy is to advise everyone to shelter.

4.2. Pedestrian Evacuation

Approximately two-thirds of pedestrians who survive the prompt effects are safe from the fallout, regardless of their protective actions. Improved personal situational awareness reduces the death rate less among self-evacuators than among delayed evacuators because self-evacuators who are initially inside remain there for an additional 3 hours (which can reduce exposure) while delayed evacuators who are initially outside move inside 3 hours earlier. The shelter versus evacuation decision among pedestrians trades off better protection, improved situational awareness, and shorter walking distance to the fallout-free zone (via evacuation stations) versus longer exposure time, albeit with a dose rate that is proportional to $t^{-1.2}$. On average, pedestrians are slightly better off sheltering, especially if personal awareness is high. Although 8.4% of pedestrians (near $x = 0$ and just behind the fallout) are better off self-evacuating, pedestrians will not know where they are with respect to the fallout zone when this decision needs to be made, and so the best response in the absence of accurate spatiotemporal information (e.g., that neighboring buildings are on fire) is to shelter in place. Although the casualty rate increases with the time at which delayed evacuation is initiated (τ_e), our model of delayed evacuation is somewhat optimistic: it is assumed to improve situational awareness via a narrower range of walking angles and there is no fallout exposure after a pedestrian reaches an evacuation station. That is, our delayed evacuation model implicitly assumes that first responders with personal dosimeters⁽²⁵⁾ set up evacuation stations by time τ_e , but in fact these resources may not be ready until 12–48 hours after an attack; for example, according to plans,⁽²²⁾ there will be no significant federal response for 24 hours and

full federal response will not be achieved until 72 hours. To the extent that our assumptions are violated and consequently that delayed evacuation does not offer improved situational awareness or evacuation stations, the optimal value of τ_e may increase (Fig. 4 of Supporting Information). However, the assumptions regarding improved situational awareness and evacuation stations do not affect the ultimate shelter versus evacuation decision because sheltering is still optimal (under either set of assumptions) even for large values of τ_e , when little fallout is occurring.

4.3. Vehicle Evacuation

Although the pedestrian shelter/evacuation decision can be viewed as individuals optimizing in isolation without affecting the outcomes of other people's decisions,⁽³⁴⁾ the negative externalities (in the form of traffic congestion) imposed during vehicle evacuation greatly complicate the shelter/evacuation decision for vehicles. In the best-case scenario where (1) there is perfect understanding of the present and future location and magnitude of the fallout, (2) every citizen's shelter/evacuation decision can be dictated, and (3) the infrastructure for delayed vehicle evacuation can be stood up very quickly, then our model predicts a lower bound of 31.1k deaths among people with access to a vehicle, which is achieved by self-evacuating 35.8k (i.e., everyone in a 6.2 km² region just downwind from the blast) and evacuating everyone else starting at $\tau_e = 4.4$ hours. Even if (1) and (3) were to hold, if 30% of people outside of the 6.2 km² region decided to self-evacuate, the number of deaths would exceed the case in which everyone sheltered.

Of course, in an actual event, (i) the fallout details will not be known precisely, (ii) communications between citizens and the response community will be very limited and people will make their own shelter/evacuation decision, and (iii) the infrastructure for delayed vehicle evacuation will not be ready for ≈ 24 hours.⁽²²⁾ In this more realistic situation, our model predicts that the number of deaths is largely dictated by the fraction of people who self-evacuate, increasing from 42.1k when 10% self-evacuate to 56.7k when 90% self-evacuate. The policy variables, the situational awareness parameters, and the highway capacities have little or no impact on the number of casualties (Fig. 2). Although the avoidance self-evacuation of vehicles reduces the number of deaths significantly (although not to the point where self-evacuation dominates sheltering), we do not view

this assumption as realistic. The shortest-route and avoidance self-evacuation schemes deviate in two geographical regions: a small group of people who are not in the fallout plume and a larger group who are in the plume. At the time of self-evacuation, with perhaps human visibility as the only guide, it may be possible for the former group to assess the situation; but it would be much more difficult for the latter group, particularly if the plume is not Gaussian-shaped.⁽²⁸⁾ That is, we do not believe that most of the benefits of evacuation avoidance in Fig. 2 could be realized in practice. Similarly, self-evacuation would fare better among pedestrians if we increased the walking speed and narrowed the range of walking angles, but we do not believe that large changes would be practical .

4.4. Sheltering in Basements

The 15.7% reduction in deaths among survivors of the prompt effects (from 43.6k to 42.5k among pedestrians and from 56.7k to 42.1k among people in vehicles) by decreasing the self-evacuation rates from 90% to 10% is rather modest, but conservatively assumes that everyone shelters above ground. In contrast to the avoidance self-evacuation assumption, there is no compelling reason why people cannot shelter in basements: most buildings near Washington, DC, have a basement, and if people can be educated to shelter inside then they should be able to be convinced to shelter in a basement. If people shelter in basements, our results are somewhat more optimistic. Reducing self-evacuation rates from 90% to 10% reduces the number of deaths among prompt survivors by 44.7% (57.7% among people in vehicles, 28.0% among pedestrians), from 96.8k to 53.5k. With sheltering in basements, the shelter/evacuation decision becomes overwhelmingly straightforward: it is optimal for only 0.2% of pedestrians to evacuate when $\tau_e = 12$ hours (compared to 16% in Fig. 3 of Supporting Information), and—mimicking earlier calculations for vehicles—it is optimal for 9.6k (rather than 35.8k) people to self-evacuate in vehicles if $f_p = f_n = 0$, and the break-even false positive probability (where we are indifferent between sheltering everyone or attempting to evacuate this small group of people) for these people is 0.005 (rather than 0.3). In other words, after one accounts for compliance, informed evacuation is bound to backfire if many people are sheltering in basements. In addition, when sheltering is in basements rather than above ground, the benefits from medical care and improved

situational awareness increase, as does the optimal time for delayed evacuation.

4.5. Model Limitations

In our view, the biggest threat to the robustness of our “everyone should shelter” recommendation is that the topology of our highway network is an idealized version of the actual network; we used this idealized topology because it is tractable enough to allow for explicit optimization of traffic flow during delayed evacuation. However, calculations in the second paragraph of Section 3.3 in Supporting Information suggest that our idealized network is a reasonable representation of the actual network, and the number of casualties is very insensitive to the number of lanes on each road because the bottleneck shifts to the one-lane exit ramps (Fig. 2). In addition, several of our assumptions lead us to underestimate the amount of traffic congestion, making our recommendation to shelter more conservative. We use the nominal highway capacities in Reference 24, although some researchers assume that roads operate at only 80% of their nominal capacity to account for accidents (which could be exacerbated by flash blindness⁽²⁸⁾) and vehicles running out of gas, etc.⁽³⁵⁾ Moreover, we ignore the possibility that some roads may close to secure key officials⁽¹⁴⁾ and assume that the roads are empty at the time of the detonation.

A second aspect of the model that has the potential to impact the shelter versus evacuation strategy is our use of a Gaussian plume model. Differing wind speeds at different altitudes can lead to non-Gaussian plumes that are somewhat more diffuse.⁽²⁸⁾ Our use of a Gaussian plume model favors evacuation (and hence is a conservative assumption) in two ways: evacuees will have to travel a shorter distance on average to get out of the plume, and people who shelter in the middle of the plume will have a lower likelihood of survival (as noted earlier, a third possible way that favors evacuation—that situational awareness is easier—is not exploited in our model).

Although our recommendation to shelter is reasonably robust, our casualty estimates are not. Recent modeling suggests (details appear to be for official use only) that urban terrain mitigates thermal effects⁽³⁶⁾ and prompt radiation effects.⁽³⁷⁾ Although we currently account for this with our indoors and outdoors transmission factors, our approach is not very refined. In addition, we make the extreme assumption that being in a burned building is 100%

fatal. We also do not explicitly account for additional blast injuries due to broken glass. If we assume that the probability of glass injury is 0.01 (it would clearly be upper bounded by 0.1, which is the blast injury probability in a moderately damaged building,⁽⁵⁾ and someone would have to be close to a window and receive a serious injury from the glass) for people living between 1.5 and 4 km, then there would be an extra 5.3k blast injuries (few of these would be combined injuries), which does not qualitatively change any of our results. Indeed, all of these modeling refinements only affect the initial conditions in our model, and have no impact on the sheltering versus evacuation comparison.

Among the parameters in our model, the two that have a large impact on the number of deaths are the fraction of people who have access to a vehicle that evacuate (P_{ev}) and the angle ϕ between the wind direction and the closest highway ray. The effect of the latter is nonlinear, and if the wind direction coincides with a ray, then the number of deaths can increase >50% over our base case; a related factor (not fully investigated here) is the wind direction itself, which generates different results because the population density around Washington, DC, is not isotropic.

Predicting evacuation behavior is very difficult. At the Three Mile Island nuclear accident, which is perhaps the event in U.S. history that is most closely related to the fallout from an IND, 3,500 people were told to evacuate (pregnant women and preschool children within 5 miles) and people within 10 miles were told to shelter. However, 200k people within 25 miles evacuated,⁽³⁾ including 76k within 10 miles, 144k within 15 miles (which was 39% of the population in this range⁽³⁸⁾), and 195k within 20 miles.⁽³⁹⁾ Moreover, in a 2007 survey of 1,505 urban residents, 65% would evacuate after a dirty bomb in the absence of a government recommendation, and 39% would evacuate if the government advised against evacuation.⁽⁴⁾ These data suggest that our base-case value of $P_{ev} = 0.5$ is not impractical.

In summary, given the considerable uncertainty about the weather, citizen behavior, and the size of an IND that terrorists could obtain, it is very difficult to precisely estimate the number of casualties, even if the model refinements mentioned earlier were incorporated.

We note that our results for this scenario are conservative with respect to a 10-kt attack in New York City (NYC): sheltering would save many more lives in NYC than in Washington for three rea-

sons: NYC's population density is much greater and so the population affected by the fallout would increase by nearly an order-of-magnitude,⁽²⁶⁾ NYC has many more tall buildings, which would allow for greater protection for those who shelter, and NYC has fewer roadways that exit the city, which would greatly exacerbate both pedestrian and vehicle evacuation.

4.6. Mitigation Options

In our model, 76.8k are killed by prompt effects, and afterward 23k–44k pedestrians die and 19k–57k people with vehicles die, depending upon the shelter/evacuation decisions, whether sheltering is above ground or in basements, and basic medical care (fluids and antibiotics); see Table I for a summary of the casualty count for various scenarios. Other mitigation factors that are not explicitly included in our model are decontamination, search and rescue operations, and specialized medical care. Decontamination is not considered a life-saving issue: showering and changing clothes or simply brushing it off garments should suffice.⁽²²⁾ Search and rescue, 90% of which is typically carried out by civilians,⁽⁴⁰⁾ is most practical in the moderate blast zone but outside of the burn zone and outside of the fallout plume. Because of the interaction of the prompt effects (Fig. 1 in Supporting Information), there are only 10k serious injuries due to prompt effects (concentrated in the 0.9–1.5 km region), 7k of whom are outside of the fallout zone. Only 15% of these people have blast injuries, and the others (with radiation and/or burn injuries) can probably evacuate by themselves. Hence, the mitigation potential of search and rescue operations is limited. Regarding medical care, drugs to reduce internal radiation will be in extremely short supply and are not effective against most radioactive isotopes.⁽¹⁾ We estimate that antibiotics and transfusion support has the potential to save ≈ 10 k lives. However, this would be a daunting logistical task that appears to be well beyond current response capabilities.^(9,41)

In contrast, reducing the fraction of people—particularly among those with access to a vehicle—who self-evacuate and convincing them to shelter in place in a basement for 12–24 hours has the potential to reduce the death toll by tens of thousands of people (and perhaps by several hundred thousand if this happened in NYC). Although the government recommendation is to shelter until given advice to evacuate, it does not

preclude the possibility of recommending immediate evacuation in certain areas.⁽²²⁾ Evacuation would be prioritized by radiation fallout intensity, adequacy of shelter, impending hazard (e.g., fire, building collapse), food and water availability, and special needs.⁽²²⁾ However, this recommendation does not appear to account for the fact that—in contrast to a bioterror or chemical attack—it may not be possible for the government to provide timely advice to the populace after the event. Moreover, as noted on page x of Reference 9, “efforts to prepare the public to take the appropriate steps to protect themselves from fallout are almost nonexistent.” The results of this article suggest that the government needs an aggressive outreach program that educates the public about this issue, encouraging them to shelter in place in their basement, and to store several days of food and water at home. The government should also encourage the private sector to develop a basement shelter strategy and to store food and water and perhaps antibiotics and blankets at their facilities that are located near large cities. This educational outreach would appear to be much more cost effective than other approaches (e.g., the \$877M contract for an anthrax vaccine⁽⁴²⁾) for mitigating the impact of catastrophic terrorist threats.

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SUPPORTING INFORMATION

The following supporting information is among that available for this article, but is not a complete list.

Table 1: Values of μ and $F(0)$ for the three categories of radiation, as a function of the distance r from the blast.

Table 2: Values of the plume width parameters in Equation (42) as a function of the distance along the wind direction (x) from the detonation. Data obtained from Ross & Marrs in a personal communication on June 29, 2009.

Fig. 1: Spatial probability of fatalities (—) or injuries (- - -) due to (a) blast effects, (b) thermal effects, (c) prompt radiation, and (d) combined effects.

Fig. 2: The fallout death and injury rate vs. the time at which delayed evacuation of pedestrians is initiated (τ_e), when personal situational awareness is (a) low ($r_p = 4$ km) and (b) high ($r_p = 17$ km).

Fig. 3: Spatial comparison of self-evacuation vs. delayed evacuation when $\tau_e = 12$ hr and $r_p = 4$ km. Each location (x, y) is categorized in one of three ways: the death probability is the same for self-evacuation and delayed evacuation ($\Delta(x, y) = 0$), the death probability is higher for self-evacuation ($\Delta(x, y) > 0$), or the death probability is higher for delayed evacuation ($\Delta(x, y) < 0$). The dose contours dictating the location of the evacuation stations for four values of τ_e are displayed, with the exception that evacuation stations cannot be within 1.5 km of the blast.

Fig. 4: Under the assumption that delayed evacuation offers neither improved situational awareness (via a narrower range of walking angles) nor less fallout exposure (via evacuation stations), we compute the optimal value of $\tau_e(x, y)$, which is the time to initiate delayed pedestrian evacuation from location (x, y).

Fig. 5: Delayed vehicle evacuation when everyone initially shelters. The number of deaths vs. the time that delayed vehicle evacuation is initiated (τ_e) under the assumption that $n(D_e) = f_n = f_p = 0$; i.e., all prompt survivors with access to a vehicle initially shelter in place.

Fig. 6: Delayed vehicle evacuation for varying false positive probabilities. With the false negative probability $f_n = 0.05$ and the delayed evacuation time $\tau_e = 24$ hr, for each value of the false positive probability f_p we choose the death-minimizing value of \bar{D}_e and plot the number of deaths vs f_p . The optimal value of $n(\bar{D}_e^*)$ is 39.1k for $f_p = 0.95$.

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