Agent-Based Modeling of a Crowd Attacked with Sarin

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Abstract. The aim of this project was to create an agent-based model of human behavior and health outcomes following a silent attack with the chemical weapon sarin on the National Mall in Washington, DC. The impacts of how quickly pedestrians become alerted to the attack, how crowding reduces the speed of pedestrians, and how evacuation routes can direct pedestrians away from contaminated areas were modeled. The simulation was run 50 times each with 1000, 1500, and 2,000 pedestrians, for a total of 150 runs. During each run, each pedestrian's sarin exposure was calculated based on how long the pedestrian spent within one of the three level zones of sarin contamination. At the end of each run, the numbers of pedestrians with no, mild to moderate, severe, and critical/lethal symptoms were counted. Regardless of the total numbers of pedestrians, the majority (more than 75%) were able to escape without exposure or symptoms. Nonetheless, more than 1 in 5 pedestrians received doses that caused at least mild symptoms, and 5% or more experienced critical/lethal symptoms. Key findings include the low number of severe cases because most of these pedestrians were unable to escape and eventually accumulated a lethal dose; the low impact of crowding on outcomes in open areas; and the value of evacuation routes which allowed pedestrians to flee with minimal exposure to the sarin. This project also highlights the value of an alert system to detect a chemical attack and warn people to flee the area immediately.

Keywords: Agent-based modeling, chemical weapon, terrorist attack.

1 Background

Chemical weapons have been used rarely but with devastating effect by terrorist groups. A chemical weapon is any toxic chemical intentionally used to cause death or harm. Nerve agents are the most dangerous types of chemical weapons since they are extremely toxic, have rapid onset of symptoms, do not generate any distinctive smells or visual signatures when released, and can cause harm through either cutaneous or inhalation routes [1]. The nerve agent sarin has been infamously used as a chemical weapon by terrorists due to its ability to rapidly cause breathing paralysis and death in small doses. For example, in 1994, the Japanese cult Aum Shinrikyo sprayed 20-30 kilograms of the nerve agent sarin outdoors in a residential area of Matsumoto, killing 7 and injuring more than 100. In 1995, the cult released 6-7 liters of sarin inside the Tokyo subway system, killing 12 and injuring more than 1,000 [2]. Since chemical weapons such as sarin can be produced using easily available chemicals, it is important to understand the size of the threat posed by these weapons in various settings.

Sarin can be dispersed into the air silently, with people being unaware they are under attack until they witness the chemical's effects on themselves or others. As a result, they may not run to safety until they encounter someone who is injured or dead, thus increasing their own exposure time. In addition, because the source of sarin may not be obvious during a silent attack, people may not run in the correct direction to reduce their exposure. The aim of this project is to create an agent-based model (ABM) of human behavior and outcomes following a silent sarin attack on a crowd at the National Mall in Washington, DC. In doing so, the general goal is to provide insights into the preparedness and response measures that can be taken to mitigate the consequences of such an attack.

2 Methods

2.1 ABM Overview

The model was created using the NetLogo program [3] for agent-based modeling. Each patch represented a 5x5m² square of the National Mall in Washington, DC, including lawn, nearby buildings, and roads. The total area was 204 x 102 patches (1020m x 510m). Each simulation run began with 1000, 1500, or 2000 pedestrians and a sarin dispersal at the Washington Monument on the National Mall. The starting location of pedestrians was randomly assigned over the entire area. At the start of each run, all pedestrians walked in a random pattern. One tick/step in the simulation was equal to 10 seconds. The model ran for 60 steps (10 minutes). Those who happened to enter the sarin plume accumulated exposure over time and then attempted to flee the contaminated area when their accumulated dose reached the threshold for experiencing mild symptoms. If unalerted pedestrians encountered symptomatic individuals, they, too, began to flee, triggering additional pedestrians whom they encountered along the way to become alerted and flee as well.

2.2 Sarin Dispersal

The release of 100 grams of sarin as an aerosol on the National Mall was modeled using the Environmental Protection Agency's (EPA's) Area Locations of Hazardous Atmospheres (ALOHA) tool [4]. ALOHA models toxic chemical dispersal after a release for emergency response planning purposes. The release plume was then plotted onto the National Mall using the EPA's Mapping Application for Response, Planning, and Local Operational Tasks (MARPLOT) program [5]. These software tools were used to model the size and shape of the overall sarin plume on the map, including three zones within the plume that corresponded to low, medium, and high levels of sarin concentrations. The low concentration zone was modeled to have an area equivalent to 53780m², medium concentration zone of 6359m², and high concentration zone of 1466m².

The plume was generated assuming a wind speed of ~2.2 mph, cloud coverage of 50%, air temperature of 65°F, relative humidity of 50%, and no inversion layer (an atmospheric condition common around dawn and dusk that traps air near the ground).

For each model run, the release occurred near the center of the second-from-the-left large grass-covered area corresponding to the location of the Washington Monument. Each run lasted 10 minutes (60 steps), consistent with the fact that aerosolized sarin is nonpersistent, fully dissipating in approximately 10 minutes [6]. Over the course of each run, the sarin concentration in the plume gradually increased, reached its maximum level by three minutes (18 steps), and then gradually dissipated until it was essentially nonexistent in all plume zones after seven more minutes (42 more steps).

2.3 Sarin Exposure Levels and Health Effects

While aerosolized sarin poses both cutaneous and inhalation health hazards, only inhalation hazards were modeled since the effects of cutaneous exposure to sarin vapor are small enough that they can be ignored [6]. Because the dose of sarin someone receives depends on its concentration and the duration of exposure [7], a pedestrian's cumulative sarin exposure over a 10-minute model run was determined by the total amount of time the pedestrian spent in any of the three sarin plume concentration zones. Assignments of health effects to exposed pedestrians were based on sarin dose according to U.S. military designations [8]. (see Table 1.)

Table 1. Symptoms of inhaled sarin at varying dosages

Cumulative dosage	**Symptoms**
$\leq$0.4 mg*min/m³	None
0.5-25 mg*min/m³	Mild to moderate
26-35 mg*min/m³	Severe
$\geq$36 mg*min/m³	Critical/lethal

2.4 Pedestrian Behavior

Before each run, pedestrians spawned at random locations on lawns and roads (not buildings which were treated as impenetrable). Each pedestrian had a 4-in-5 chance of spawning within one of the two lawn areas on the left side of the map near the sarin release location at the Washington Monument. When each run started, all pedestrians behaved unalert, walking in random headings at a speed of 60m/min (2 patches/step). During the course of a run, three parameters (alertness, fleeing, and crowding) could affect pedestrian behavior. In terms of alertness, initially unalert pedestrians who wandered into the contamination plume became alert and attempted to flee upon passing the minimum sarin dosage threshold for experiencing mild to moderate symptoms. Unalerted pedestrians could become alert not only by experiencing symptoms themselves, but also by encountering a fleeing pedestrian with or without symptoms within a 25m (5-patch) radius. Upon becoming alert, pedestrians set their heading 180° away from the closest fleeing person and also fled. To flee, pedestrians moved at the increased speed of 120m/min (4 patches/step) until encountering a road, if not already on one, and stayed on roads to reach the nearest map edge. Pedestrians who accumulated sufficient sarin dosage to experience severe symptoms had to reduce their fleeing speed to 15m/min (0.5 patches/step). The subset of pedestrians who went on to accumulate a sufficient sarin dose to experience critical/lethal symptoms stopped moving entirely. Pedestrians' fleeing speeds were also impacted by crowding. Depending on the number of other individuals located in the immediately surrounding patches, pedestrians reduced their fleeing speed to 75m/min (2.5 patch/step) if 2 neighbors, 60m/min (2 patches/step) if 3 neighbors, and 45m/min (1.5 patches/step) if 4 or more neighbors were nearby.

2.5 Pedestrian Outcomes

The simulation was run a total of 150 times: 50 runs were completed for each population count of 1000, 1500, and 2000 pedestrians. For each run, the numbers of pedestrians within each of the four different symptom severity categories were recorded and a mean ± standard deviation for each category calculated over the 50 runs. This was done for each population count.

3 Results

In this model, simulated sarin release was associated with sizable numbers of symptomatic pedestrians, even when the population was as low as 1000 (Figure 1 and Table 2). The numbers of symptomatic pedestrians increased with increasing population size. Regardless of whether the total number of pedestrians was 1000, 1500 or 2000, the majority of pedestrians were able to escape without symptoms (76.6% vs. 77.5% vs. 78.3%, respectively). Still, more than 1 in 5 pedestrians received doses that were associated with at least mild symptoms, and 5% or more experienced critical/lethal symptoms regardless of population size.

Regardless of population size, virtually no pedestrians ended runs with severe symptoms since the majority of exposed pedestrians were either able to escape as soon as they became alert due to their mild to moderate symptoms, or continued to be exposed due to their reduced travel speed such that they eventually developed critical/lethal symptoms.

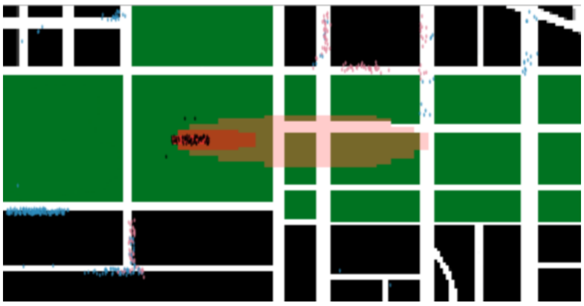

Figure 1. Model run with 1000 pedestrians, simulating 10 minutes after sarin release on the National Mall in Washington, DC. (Blue pedestrians: no symptoms; pink

pedestrians: mild to moderate symptoms; yellow pedestrians: severe symptoms; black pedestrians: critical/lethal symptoms. Dark-red plume area: high dosage zone; medium-red plume area: medium dosage zone; pink plume area: low dosage zone.)

Table 2. Number of pedestrians at a given symptom level varying population size

Total number of pedestrians	Number of pedestrians at a given symptom level*, mean±sd			
	None	**Mild to moderate**	**Severe**	**Critical/ lethal**
1000	776 ± 340	177 ± 80	0.02 ± 0.04	58 ± 24
1500	1163 ± 526	255 ± 114	0 ± 0.04	84 ± 36
2000	1566 ± 5690	337 ± 152	0.08 ± 0.04	98 ± 47

As expected, pedestrians who received sarin doses sufficient to cause critical/lethal symptoms were unable to leave the contamination zone, resulting in a steady increase in their accumulated dosage over time. By contrast, pedestrians with sarin doses associated with mild to moderate symptoms could leave the contamination area, and if they did escape, their cumulative dosage plateaued (Figure 2).

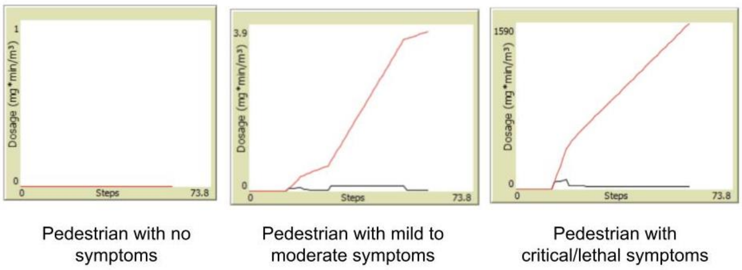

Fig. 2. Three randomly selected pedestrians' dosage accumulation rates over 10 minutes (60 steps). (Black lines indicate dose per step, and red lines indicate cumulative dosage over time.)

The total number of pedestrians who had sarin dosage levels associated with mild to moderate symptoms (0.4-25 mg*min/m) and the number who had critical/lethal dosage levels (>35 mg*min/m³) steadily increased over the course of a run (Figure 3). However, the number of pedestrians who had dosages associated with severe symptoms (25-35 mg*min/m³) over time was very irregular, suggesting that this represented a sporadic, temporary phase for these pedestrians.

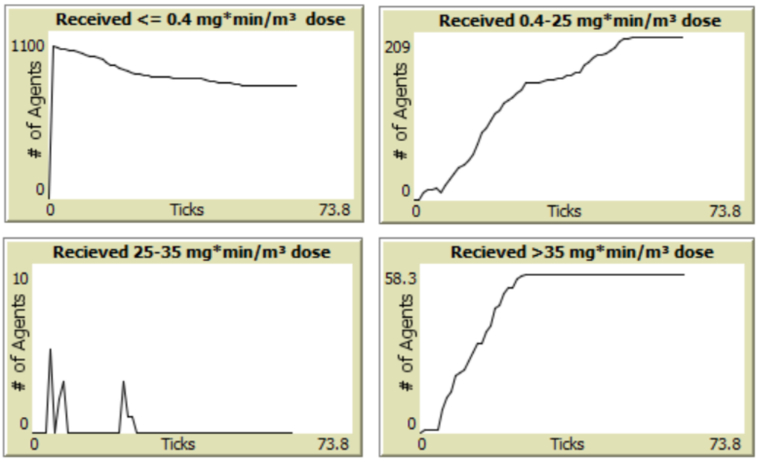

Fig. 3. Total number of pedestrians receiving various sarin dosages over 10 minutes (60 steps) in a population of 1000.

4 Discussion

This project generated several key findings. First, there were almost no pedestrians who ended runs having severe symptoms after the sarin release. This is because pedestrians who suffered severe symptoms were less able to escape the contaminated area due to their reduced speed and therefore were more likely to accumulate additional sarin dosage which moved them into the critical/lethal category. Second, the crowding feature of the program did not have a major effect. The expectation at the beginning of the project was that as the number of pedestrians in the simulation was increased, crowding would become more common and would reduce the speed of enough pedestrians to increase the proportion of injured and dead pedestrians since they would be exposed to the sarin for longer periods of time. This did not occur since large groups formed only after pedestrians reached the roads which were generally farther away from the high-concentration areas of sarin. Therefore, the reduced speeds of the pedestrians in these crowds did not usually increase their exposure to sarin. It is likely that the results would have been different if the model runs included a larger population size, or if the simulated sarin release occurred in a more congested location such as a subway station or sports stadium. Third, most pedestrians were able to escape since the aerosolized sarin dissipated quickly in the open area of the National Mall. Results could have been different if the model involved a persistent chemical weapon, such as VX or sulfur mustard, that would have lingered even in an open area. Fourth, this simulation supports the idea of having designated evacuation routes in case of an attack, as the pedestrians in this model were able to flee more quickly when they followed a road that led them away from the sarin. Finally, the results uncovered by this project highlight the potential value of a chemical agent detection and warning system that could instruct people to flee from an area immediately when a toxic chemical is detected. The model shows that there would have been fewer pedestrians with critical/lethal symptoms if everyone fled from the area the moment the sarin was released.

5 Conclusion

This project demonstrates that ABM is an effective tool for estimating the potential impacts of a chemical weapon release in a crowded public area. The overall harms to a population caused by an aerosolized chemical weapon such as sarin are significant but may be limited by optimizing human behaviors.

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