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OA3302 Simulation Modeling
Final Project

Naval Postgraduate School
Emergency Management for "Rage Virus" Biological Events

Background

The Naval Post Graduate School's (NPS) Emergency Management (EM) systems fail to address significant security threats like the Rage Virus. In 2003, Great Britain's outbreak nearly destroyed the country in only ~28 days, with less than 1 out of every 3800 persons surviving. In the 21 years since the outbreak, Rage Virus research has been insufficient to protect U.S. interests. The NPS is a critical institution for defense relevant technological advances and is vulnerable to similar biological events.

The word "Zombie" first came into the English lexicon in 1819 and comes from the Haitian root word zombi. Zombi generally referred to "an undead person who was created through the reanimation of a corpse, usually through magic or witchcraft" (Nugent et al., 2018). The concept of Zombies became popularized in American culture in 1968, when George Romero released the film *Night of the Living Dead* (Wikipedia, 2024). "Modern" zombies or those whose characteristics and lore are more consistent with viral pathology than magic, are much newer by comparison and their origin can be traced to the 2002 cult-classic film *28 Days Later*. This modern approach to zombies provides researchers with an opportunity to study zombies in a more scientific way.

Modern zombie research has been growing in popularity and funding, with the results of this research being utilized to help the public. The Federal Emergency Management Agency (FEMA) and the U.S. Department of Homeland Security (DHS) have detailed zombie mitigation strategies such as urban design to minimize zombie threats, how to recognize the signs of someone becoming a zombie and combat techniques to survive a zombie encounter (Heide et al., 2019). The Center for Disease Control and Prevention (CDC) illustrated the possible hardships of a zombie pandemic through a graphic novel and designed a packing list for apocalypse "go-bags" that would best prepare the average American (CDC, 2011).

Zombies are frequently modeled using either a mathematical model or a Susceptible-Exposed-Infected-Recovered (SEIR) model. Mathematical models typically attempt to understand the existing relationships between factors in a zombie event. Figure 1 shows the diffusion of infection across a group for different infection rates (Woolley et al., 2014). SEIR models are different in that they try to apply existing zombie frameworks to populations of interest to extract scenario specific insights. Reed Cartwright created an interactive SEIR model that allows users to specify initial population parameters and several rates such as infection rate, to dynamically provide results. A noticeable gap in research is the absence of agent-based simulation methods which could effectively model human and zombie behaviors. Insight into human and zombie interactions could better inform key stakeholders and ensure human survival.

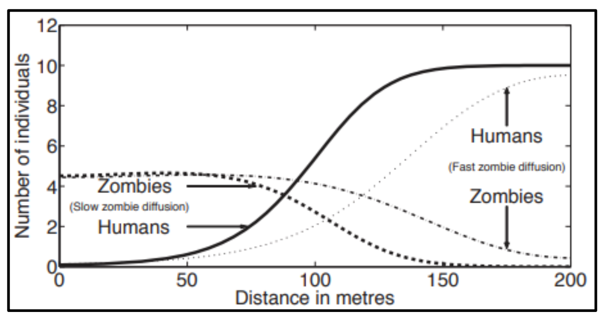

Figure 1: Infective Wave Solutions

Methodology

Our objective was to improve NPS's zombie related readiness and resilience, so it is best prepared to deal with zombie events and similar infectious diseases. We chose to utilize an agent-based simulation integrated with mixed-queuing techniques so that we could effectively model student and zombie behavior on the NPS campus. Below are the research questions and measures of performance we determined prior to collecting data.

Research Questions

1) How long could humans survive a Zombie event at NPS?
2) What factors influence infection rate?
3) Is Shelter-in-Place procedures an effective plan?
4) What are the safest and most dangerous buildings?
5) Is student hand-to-hand lethality a major factor?
6) Is there a critical threshold of infection for NPS?

Measures of Performance

1) Time of key milestones: 75%, 50%, 25%, 0% survival
2) Human / Zombie "win" rate
3) Rate of infection & its major factors
4) Foot traffic by building
5) Most defended vs. most human deaths by building
6) Number of zombies and humans alive at termination

Data Collection

Despite the popularity of zombies, we did not initially know what type of data could be readily found or its veracity. We chose to explore what data was available to answer our research questions prior to determining what constraints, limitations or assumptions were necessary. This was done because if data was not available then it would directly impact those decisions. We collected data in two phases; Zombie and NPS.

The Zombie phase consisted of reviewing relevant literature from government organizations such as the CDC, relevant zombie research and modeling, and a detailed examination of several zombie documentaries. We chose the cult classic film *28 Weeks Later* as the foundation for this project's zombie lore. This film was chosen because due to an ongoing legal battle, *28 Days Later* was not available and this film is both that film's successor and maintains its inspired archetypal zombie lore. Furthermore, choosing one film as the lore basis enabled consistency throughout the study. Table 1 contains the data collected in the zombie phase.

The NPS phase consisted of finding the appropriate population size, identifying key components of the NPS building network, determining what connections existed between those buildings and measuring distances for those connections. Google Maps and several pages on the NPS website like the *Faculty Directory* or *NPS at a Glance* provided useful information on distances and population sizes. Table 2 and Figure 2 contain the data collected in the NPS phase.

	Samples					Expected Value
Transmission Time (sec)	13	24	10	7	8	12.4

	Time	Human Wins	Zombie Wins	Probability Human Wins
1:1 Fights	Day	4	5	4/9 or 44.4%
	Night	1	6	1/7 or 14.3%

	Before Virus	After Virus	Survival Rate
England's Population	55.98 M	15,000	1/3733 persons

	Vision	Hearing	Smell	Navigation	Critical Thinking	Strength	Pain Tolerance
Zombie vs Human Traits	- -	=	++	=	-	+	++

	Zombie Decay Rate	Injury : Kill Ratio
Uncategorized	~1.5 days without prey	3:1

Table 1: Zombie Data

NPS Element	Value
Resident Students	1,616
Faculty	598
Total Population	2,214
Expected Survivors	0.6642 persons

Table 2: NPS Data

Key	Name
G	Glasgow
L	Library
I	Ingersoll
HWB	Watkins
R	Root
BLDG s	Del Monte
H	Herrman
SK	King

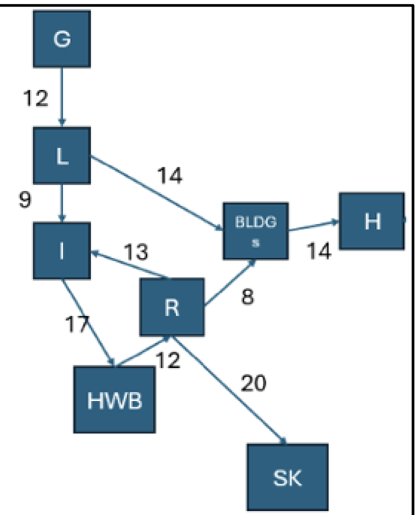

Figure 2: NPS Network & Key. Distances are in 0.01 km units.

Constraints

1) Movement rules & set paths were simplified. Entities will not run across campus when safer and closer options exist, despite it being a possibility.
2) Entity types were scoped down to two distinct groups; zombies and humans. Differences in sub-groups like faculty, students, or even students of different curriculum types were not modeled.
3) Interaction rules: move, defend, fight. Many possible actions exist in the setting of a zombie outbreak, but these are not tractable in a small-scale computer simulation.

Limitations

1) Simplified Behavior for sustainment. Humans have minimal needs other than survival.
2) Day/night cycle adds significant complexity and may not be relevant when considering class times. Cycle is not fully represented in the simulation.
3) Accurately modeling Class IV consumption requires use of Engineer Estimates for make-shift construction materials, which does not exist. Class IV may also be repurposed or consumed in a non-military manner. Class IV is unlimited in this simulation.
4) Buildings are treated as equally defendable, despite the varying construction materials and avenues of approach.

Assumptions

1) Closed system: no entities may enter the system, though some may leave by dying.
2) Zombies & Humans share physical properties. Zombie lore shows that they retain many of the capabilities of their human self.
3) Infection is through physical contact with blood or saliva.
4) Human attributes and responses can be generalized to the population.
5) No advanced warning of the infection for any students in the simulation.
6) Human to Zombie transition period is approximately instantaneous.

Experimental Design

After testing the baseline system from the collected data, we wanted to determine which factors of the infection and NPS were most critical. We developed the following experiments to test predicted critical factors:

1) “Regular Zombie”: Our control and baseline for the simulation.
2) “Smart Zombie”: The virus enables higher level brain function and is capable of adeptly pathfinding around defenses or dismantling them.

3) “More Lethal Zombie”: Zombies do not preference infection over killing their victims.
4) “Less Infectious”: Zombies are less able to infect students due to protective gear, vaccinations or reduced viral efficacy.
5) “Better Infrastructure”: NPS has upgraded facilities that can better repel a zombie invasion. Infrastructure is closer to an operational base than an academic institution.
6) “Larger Class Size”: NPS is at max capacity for class size due to increased need for educated leaders.

Model Development

System Components

1) System – The students of NPS and a subset of major buildings: Glasgow, Dudley Library, Ingersoll, Del Monte, Root, Watkins, Herrman, King
2) Entity – Humans and Zombies
3) Attribute – Starting location, probability of fighting & winning
4) Activity – Movement times, breaching, searching
5) Event – Fighting outside, defense breached, fighting inside, death of entity, human infection
6) State Variable – # of humans / zombies: alive, at or enroute to “To_”

Input Analysis

Several aspects of the simulation and data required generalizations to deterministic values or fitted distributions. The human win rate was calculated by using a weighted average of the day and night win rate by the expected number of limited visibility hours in Monterey. This results in a human win rate of approximately 25% or a zombie win rate of 75%. Travel times between buildings constructed as a uniform distribution that reflects running or sneaking between buildings. The running time was calculated using a lower bound of the average high school 40yd dash time (~5-6 seconds). The upper bound was calculated as 10x the lower bound. Table 3 highlights the necessary transformations from data to simulation input for the inter-building travel times.

Location	Connection 1	Connection 2	Connection 3
Library	Glasgow U(18,180)	Del Monte U(22,220)	Ingersoll U(12,120)
Del Monte	Root U(12,120)	Herrmann U(21,210)	
Watkins	Ingersoll U(25,250)	Root U(18,180)	
Root	Ingersoll U(18,180)	King U(30,300)	

Table 3: Building Travel Time Distributions. Times are in seconds and paths are undirected.

Model Mechanics

The model consists of one template subsystem used across all 8 buildings. The only distinct differences between the subsystem are the connections and travel times between buildings. Each subsystem enables human and zombie entities to interact through four mechanics: movement, fight, defend, inside. Figure 4 gives an overview of the Herrmann Hall Subsystem.

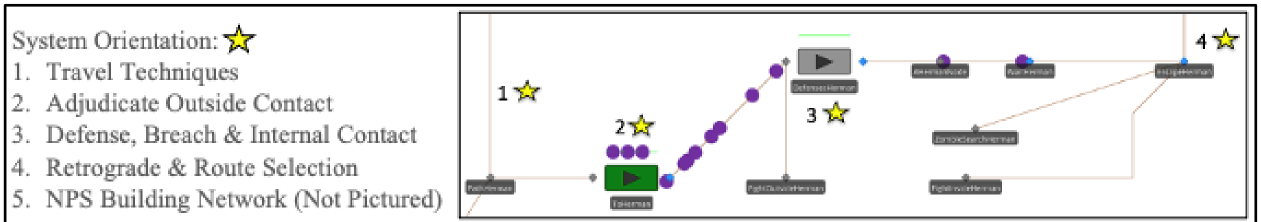

Figure 3. Herrmann Hall Subsystem, NPS Outbreak Model.

Movement: Humans and zombies make decisions on which building to move to next after reaching an "Escape_" node. This decision is probabilistically based on the number of humans at the other buildings. Humans wish to find safety in numbers while zombies are looking for targets.

Fight: Entities are potentially thrust into combat at two points in the system, one at the "To_" node and once after a defense has been broken. At the end of movement, if zombies and humans occupy a "To_" node they will enter the fight process where they can die, turn into a zombie or flee unharmed. The same options are available after a defense has been broken but the fight probability is based on the relative number of zombies and humans.

Defend: Humans build a hasty defense inside a building that zombies try to breach. Zombies have a deterministic probability of breaking down the defense every 30 seconds. If a zombie destroys the defense all zombies can freely enter the building where humans are hiding. This triggers the inside mechanic.

Inside: Humans determine if they will fight the zombies based on the ratio of the opposing forces. Zombies will search the building for survivors if they cannot find any humans at the defense. Humans will inevitably die during the inside process, and if they become zombies they will spawn right where they died. This process also checks if any humans or zombies are still alive and will end the simulation if either side is eliminated.

Results

As mentioned before, our experimental design changed the initial parameters of the zombies to highlight the critical factors necessary for human survival. The initial parameters for the 'Regular Zombie' experiments are as follows.

1) Number of susceptible humans – 1,616
2) Number of starting zombies – 5
3) Infection Rate – 75% (25% instant death)
4) Break defenses – 1%
5) Zombie wins fight – 55%
6) Human wins fight – 45%

Each experiment changed one initial parameter to understand that factor's role in survival. Unfortunately, we were not able to get the 'Experiment' feature in SIMIO to function so individual ran the experiments 25 times with and manually captured the data. Table 4 outlines the parameter changed by experiment and the results to follow. As outlined by the table below, the only scenarios that led to a possible human survival (survival greater than 96 hours) was the better infrastructure and less infectious scenario. Figure 4 shows the decay and creation rate of humans and zombies over the course of the 'Regular Zombie' experiment. Each experiment showed a similar graph structure with differing rates of change and final populations for humans and zombies.

Experiment Name	Initial parameter changed	Survival Time (Hours)	Safest Building	Most Dangerous Building	Human Deaths (% - hour)			Avg individual survival time (hours)
					25%	50%	75%	
Regular Zombie	No changes	15.77	Glasgow	Del Monte	6.1	6.8	8.26	6.18
Smart Zombie	Break-In (10%)	3.2	King	Root	0.7	0.9	1.15	0.86
Better Infrastructure	Break-In (0.05%)	96 (max time)	Glasgow	Root	6.9	11.3	15.3	9.8
Lethal Zombie	Zombie Kill Rate (75%)	6.8	Glasgow	Ingersoll	1.2	2.5	3.02	2.56
Less Infectious	Infection Rate (50%)	96	King	Root	2.1	15.0	N/A	4.28
Larger Classes	Starting Zombies (40)	12.77	Glasgow	Ingersoll	0.85	3.2	4.15	3.1

Table 4: Experiment results

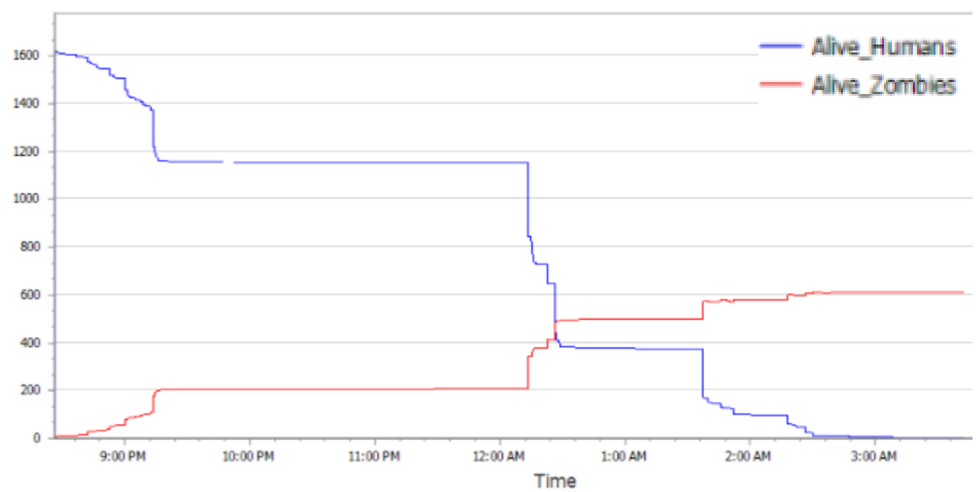

Figure 4: Decay and creation graph of zombies and human

Discussion

Overwhelmingly the outcome for humans in these scenarios is not favorable. Under 4 out of 6 scenarios, all humans are dead or infected. However, the humans did survive in some of the simulations with two of the scenarios, which will be discussed later. To answer our most important research question, ‘how long could humans survive a zombie event at NPS?’, our model shows that if no action is taken then at best, we will survive 15 hours. With action, a portion of the population may survive. The main factors that influenced this survival were the intelligence of the zombie and the infection rate per interaction.

Interestingly, there is a tipping point when the zombies hit a critical mass and overwhelm the humans. As seen in Figure 4, the ‘tipping’ point appears at about 12:15 AM. In every scenario, this ‘tipping’ point is followed by a ‘long tail’ where the last survivors hold out for as long as possible.

In contrast, zombies have a less steep rise due to the mathematical difference in interactions between humans and zombies. When a zombie and human interact, there are six outcomes. The outcomes are as follows.

1) Nothing happens
$P(Zombie\ miss) \cdot P(Human\, miss) = 0.45 \cdot 0.55 = 0.2475$

2) The zombie dies, and the human survives.
$P(Zombie\ miss) \cdot P(Human\, kills) = 0.45 \cdot 0.45 = 0.203$

3) The zombie survives, and the human dies (permanently).
$P(Zombie\ kills) \cdot P(Human\, miss) \cdot P(Human\ not\ Infected) = 0.55 \cdot 0.55 \cdot 0.25 = 0.076$

4) The zombie survives and creates a new zombie.
$P(Zombie\ kills) \cdot P(Human\, miss) \cdot P(Human\ Infected) = 0.55 \cdot 0.55 \cdot 0.75 = 0.227$

5) The zombie dies and creates a new zombie.
$P(Zombie\ kills) \cdot P(Human\ \ kills) \cdot P(Human\ Infected) = 0.55 \cdot 0.45 \cdot 0.75 = 0.185$

6) Both the zombie and the human die.
$P(Zombie\ kills) \cdot P(Human\ \ kills) \cdot P(Human\ not\ Infected) = 0.55 \cdot 0.45 \cdot 0.25 = 0.061$

What these probabilities tell us is that humans die 0.55 times for every interaction, but a zombie is only created 0.412 times for every interaction. So, we expect that the zombie creation rate will be less than the human death rate, and this bears out in the data. This point is very pronounced in the 'tipping' point where human death averages about 2/3 to 4/5 of the population dying but only 1/3 to 2/5 is infected.

In fact, a stochastic analysis shows that a zombie is expected to only create 0.92 other zombies but kill 1.22 humans in its life cycle. In other words, the zombie does not effectively replace itself but merely outkills humans. This was unexpected and unfortunately leads to the erroneous conclusion that humans could outkill zombies, especially early on when there are so few. Unfortunately, the number of interactions that an 'early' zombie gets overwhelmingly changes this dynamic. When a zombie is surrounded by hundreds of humans, they can scratch, bite, or maim any that is close to within fighting distance. The more humans that decide to fight, the more zombies are created. Even a small chance of infection will eventually lead to a 'tipping' point. So, humans do not survive by preventing the 'tipping point' but by outlasting the zombies in the 'tail'.

In our results, the most dangerous situations were the 'smart' zombie, 'lethal zombie', and the 'large' starting population zombie. These results support the probability and stochastic analysis in the above paragraph. The more dangerous scenarios involved zombies that caused more interactions by being smarter or starting with more zombies or they increased their expected number of humans killed by being more lethal. These more dangerous scenarios led to a 50% decrease in the expected human lifetime. The overall scenario length was reduced by 25% to 80% depending on the scenario. The most drastic reductions were when the zombies were 'smart' because they more effectively removed the safety of infrastructure from humans. The lethality and increased number of zombies were not as effective as the 'smart' zombie in winning the scenario.

The safer scenarios are the 'better infrastructure' scenario and the 'less infectious' zombie. These scenarios effectively counter the scenario's above. The 'better infrastructure' scenario reduces the number of times that a human needs to interact with a zombie outside of infrastructure. This tips the odds of survival in the human's favor. The 'less infectious' scenario greatly reduces the number of zombies created from each interaction. This means that while a significant number of humans still die, there are less zombies to contend with compared to the other scenarios. This reduces the human-zombie interactions so that the zombies are killed off faster and do not have the necessary numbers at the end to kill the remaining humans.

These six scenarios and their results lead to very important recommendations to ensure the survival of humans in a zombie apocalypse. The following recommendations focused on reducing the number of zombie-human interactions and the probability of infection. We did not focus on the lethality of the human because the data did not support this as a viable solution.

Recommendations

After completing the six scenarios, we produced general recommendations as well as recommendations from each experiment. These recommendations are key to stimming the rate infection and ensuring human survival.

General

The safest buildings in our model are Glasgow Hall and Herrman Hall. This is due to their lack of pathways to other buildings. The most dangerous buildings are Root Hall and Del Monte Café. This is due to their geographic centeredness on NPS. The obvious recommendation is to avoid the center of NPS and find defensible infrastructure on the edges of the base. Key to success of any infrastructure is that it also maintains an exit. Herrmann Hall does have an advantage in this sense given its size.

'Regular Zombie'

The base model zombie is simulated from the data pulled from the movie '28 Weeks Later'. The most important recommendation from this experiment is that having less people on campus at one time results in a safer campus. This means increasing the number of virtual lectures and recorded labs where feasible. With the historical precedence of COVID-19, this solution has the digital infrastructure to make this transition much easier.

'Smart Zombie'

The 'Smart Zombie', or a zombie that can intelligently breakdown defenses, is by far the most difficult zombie to deal with. This scenario is catastrophic for the NPS students, so we recommend an immediate recommendation to bring in less intelligent students to reduce the chance of a 'Smart Zombie' being produced. While not advantageous to the overall mission of NPS, it is a critical step to ensure a physically fit and 'Smart Zombie' is produced.

'Better Infrastructure'

This scenario produced one of the two results where humans could survive. Critical to this is reducing the chance that a zombie breaks through by half. In this scenario humans attempt to outlast the zombies. If a decay rate was modelled this strategy would be a very effective strategy. To support this strategy, we recommend GSA Class 5 vault doors, Terror Screen SR4 rolling security shutters, and 3 x DOS per student at max capacity for each room.

'More Lethal Zombies'

Due to the increased lethality of this zombie, it is imperative to avoid situations with this zombie. A zombie is considered more lethal at night due to the likelihood of ending up perilously close to a zombie and the higher difficulty of defending against one. We recommend ending all classes by 1400 to ensure that students have enough time to be in defensible positions before sunset.

'Less Infectious'

This scenario is the second scenario where the humans have a chance of survival. This is because more humans outright die instead of turn into a zombie. With a modest reduction in infection rate, the humans' chances of survival were greatly increased. We have two recommendations in this scenario. First, to take preventative measures to research and produce Zombie-Immunization that is based on the zombie-ant virus. Second, train individuals to not help others in the zombie apocalypse or they could add to the zombie population.

'Larger Class Size'

With a higher starting zombie population there is a much higher number of interactions early in the experiment. The most dangerous part of the scenario is the initial outbreak because of the number of people intermixed with the zombies. This scenario makes that initial outbreak even more dangerous. Our recommendation is to limit class sizes to no more than 20. A starting zombie population from 30-40 results in a very rapid spread of the virus and is in the top three of the most dangerous scenarios.

Conclusion

Our model's unique mixture of agent-based modelling and queueing techniques produced a successful 'Zombie Survival' model that conforms with other forms of modelling such as mathematical modelling, SEIR modelling, and Agent Based Modelling. While it may seem facetious to use a fictional zombie outbreak as the basis for the model, it is actually a very useful, dynamic, and unique provisional method for modelling a future unknown disease. As mentioned in the background, our model successfully fills the gap between SEIR modelling and Agent Based Modelling through simplified behaviors in complex environments, thereby reducing computation complexity.

Real-World Applicability

The main recommendations of improving infrastructure and reducing the intelligence of zombies lend themselves to real-world applications despite having a humorous tone. Improving our infrastructure in the context of infectious diseases means keeping 'healthy' people away from 'sick' people, which can be done through improving ventilation systems, for example. The recommendation of reducing the intelligence of zombies is analogous to altering infected humans' behaviors to not break down defenses. This would involve increasing self-monitoring and taking more precautionary actions based on the results of said monitoring.

Expandability

Our model can be rapidly expanded to other locations where a by-building analysis is important, and it stays within the gap of agent-based modelling and a SEIR Model. The model's parameters can be adjusted to mirror other infectious diseases as needed. This flexibility makes the model an important addition to current infectious disease research and showcases a unique use of modelling techniques. We hope others will increase the complexity of the model to provide more accurate and further insights. In the meantime, the authors will be 'grabbing Cody, going to the Trident Room, having a nice cold pint, and waiting for this quarter to blow over' (Edgar Wright, 2004).

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