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Homeland Security: From Mathematical Models to Policy Implementation: The 2008 Philip McCord Morse Lecture

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This paper is the archival record of the INFORMS Philip McCord Morse Lecture delivered in 2008. It describes the author's research on four topics in homeland security and public health: preparedness and response to a bioterror anthrax attack, preparedness and response to a bioterror attack on the food supply, routes of transmission and infection control for pandemic influenza, and biometrics (e.g., fingerprint matching) to prevent terrorists from entering the country. The paper focuses on the modeling, policy recommendations, and implementation of these recommendations. The author draws lessons about policy implementation from these examples and from examples from his other homeland security work with colleagues, including a bioterror smallpox attack, preventing nuclear weapons from entering the country on a shipping container, preventing nuclear weapons from entering a city, and preventing terrorists from crossing the border between the United States and Mexico.

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1. Introduction

I am aware of five ways that terrorists could cause a mass casualty event—say, 100,000 deaths—on U.S. soil. For much of the last seven years since the September 11, 2001 attacks, I have formulated and analyzed mathematical models of most of these scenarios, developed recommendations for how to prevent the attack or mitigate its impact, and gone to Washington, D.C., to try and convince policy makers to follow these recommendations.

These five scenarios include attacks with the three catastrophic biological agents—smallpox, anthrax, and botulinum toxin (Danzig 2003)—a nuclear attack and a chemical attack. For the chemical scenario, which is the easiest of these attacks for terrorists to undertake, I have written opinion pieces (Wein 2006a, 2007), but have not performed any mathematical analyses. At the 2008 INFORMS annual meeting, I gave a 90-minute tutorial that covered my work on eight topics under two broad headings: bioterrorism and borders. Under bioterrorism, I discussed the three catastrophic scenarios and a nonterrorist scenario, pandemic influenza, that dwarfs—both in terms of likelihood and impact—these terrorist scenarios. A bioterror attack is extremely difficult to prevent, and so these analyses focus on how to minimize the number of deaths from such an attack.

The goals of the four border analyses are to keep nuclear weapons and terrorists out of the country. For a nuclear attack, much of the damage is done as soon as the weapon is detonated, and we focus on how to prevent such an attack from occurring by trying to detect a weapon as it enters the country in a shipping container or as it enters a city in a vehicle. Most of these attacks require terrorists to be in the country, and they can enter either at a port of entry, such as an airport, or between the ports of entry, such as sneaking across the U.S.-Mexico border, and we perform analyses for both approaches.

In this talk, I will briefly cover four of these eight topics (see §§2–5): anthrax, botulinum toxin in the food supply, pandemic influenza, and a biometric analysis of the U.S. Visitor and Immigrant Status Indicator Technology (US-VISIT) Program used at ports of entry. In each of these four cases, I will provide the basics of the mathematical formulation, highlight the main results, and discuss the implementation issues. However, when I discuss the common themes of this type of work at the end of this talk (see §6), I will also draw on my experiences from the other four topics.

2. Anthrax

Unlike smallpox or influenza, anthrax is not a contagious agent. However, its deadliness and durability make it

perhaps the gravest of the bioterror threats. The inhalational form of anthrax is fatal >90% of the time if there is no medical intervention (Inglesby et al. 2002). After an outdoor release, the indoor concentration would be 5%–10% of the outdoor concentration (Wein and Craft 2005), and these spores would remain viable indoors for decades (Manchee et al. 1981). The former Soviet Union produced thousands of metric tons of anthrax annually and—along with several other countries—put it into missiles (Miller et al. 2001). Unlike smallpox and botulinum toxin, we have had a proof of principle: In the fall of 2001, five envelopes laden with anthrax spores were inserted into the U.S. postal system, killing five people (Jernigan et al. 2001).

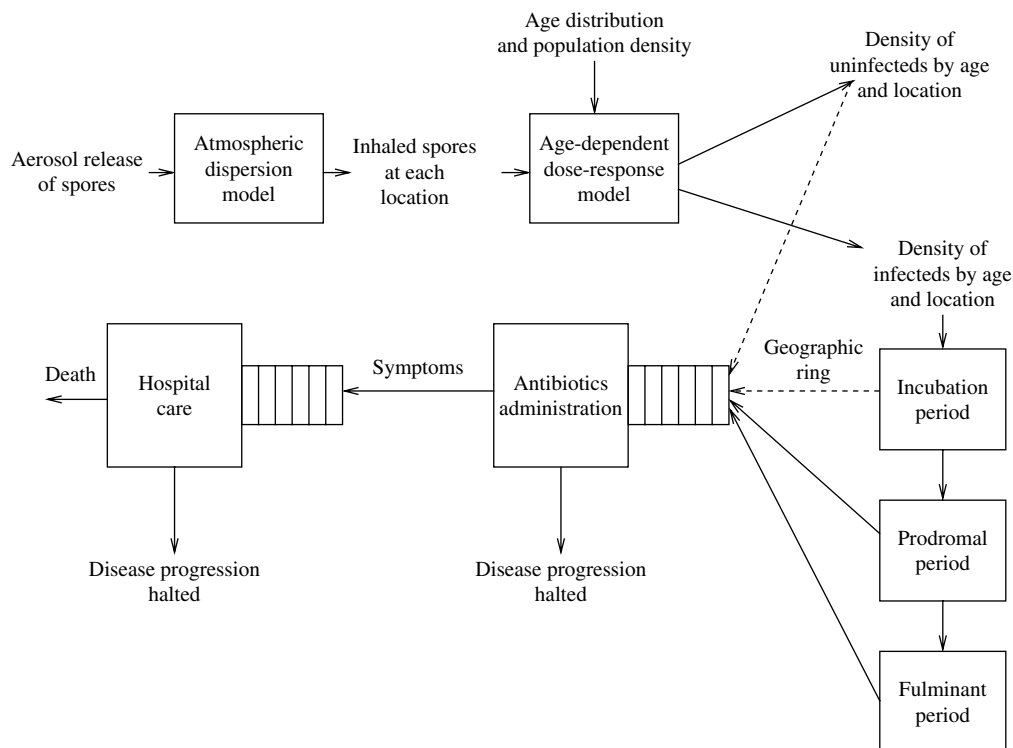
In all of this homeland security work, the first thing my coauthors and I do is to try to understand what the government's plans are to deal with the problem. At the time (Jernigan et al. 2001), the government had no detailed response plan in place for dealing with an anthrax attack. The goal of our initial study was to develop an outline for such a plan. Our spatiotemporal model (see Figure 1) is a set of partial differential equations that tracks the events after a hypothetical release of 1 kg of anthrax spores from a 30-story building in New York City (Wein et al. 2003). A Gaussian plume model determines how many anthrax spores are inhaled by someone who is a certain distance downwind and crosswind from the release (Hanna et al. 1982). An age-dependent dose-response curve (the elderly appear to be more vulnerable to infection), when combined

with the output of the Gaussian plume model and the age distribution and population density, yields the density of infected and uninfected people for each age and each location, which are essentially the initial conditions of our dynamic model. Each infected person progresses through three lognormal stages of transmission: an incubation period (i.e., asymptomatic), a prodromal period (i.e., early symptomatic), and a fulminant period (i.e., late symptomatic).

In the model, the city and its surrounding region are split into zones, and each zone has a two-stage tandem queueing system, with the first stage administering antibiotics (to citizens in a certain geographic ring, as explained in Wein et al. 2003) and the second stage providing hospital care. Antibiotics, if taken as directed, are thought to be 100% effective at preventing an asymptomatic infected from ever developing symptoms (Inglesby et al. 2002). The antibiotics are also partially effective at preventing someone who is in the prodromal stage from proceeding to the fulminant stage, as is aggressive hospital care (Jernigan et al. 2001). Anyone in the fulminant stage is assumed to die within several days, regardless of treatment.

Our four main recommendations, which are summarized in a concise form in Wein and Kaplan (2003), are: (i) it is important to start intervention after the first case is detected (although biosensors appear to have very limited value for an anthrax attack because—in contrast to smallpox—some people have short incubation periods of ≈ 24 hours; nonetheless, more rapid detection enables a more rapid

Figure 1. Graphical depiction of the anthrax model.



Note. Figure taken from Wein et al. (2003).

response); (ii) the most important management lever is rapid antibiotic distribution; (iii) drug compliance is very important and needs to be the focus of public health education after an attack; and (iv) surge medical care capacity could increase the number of lives saved.

More specifically, we propose that pulmonary specialists from untargeted cities fly into the attacked city to increase surge capacity and that the U.S. Postal Service be used to deliver antibiotics door-to-door in an eight-hour period (Wein and Kaplan 2003). We briefed various governmental agencies on our findings. The first of these two proposals was not implemented, and we believe that it was perceived as too cost ineffective. However, under the auspices of the Cities Readiness Initiative (Centers for Disease Control and Prevention 2007), which is a program to prepare 72 major U.S. cities to effectively respond to a large-scale bioterrorist event by dispensing antibiotics to their entire identified population within 48 hours of the decision to do so, three successful exercises have been carried out in Seattle, Philadelphia, and Boston that dispense antibiotics using mail carriers (Smith 2007). In addition, Washington, D.C. has agreed to adopt this approach in the event of a large-scale anthrax attack (U.S. Postal Service 2004), and this alternative to the traditional Points Of Dispensation (PODs) scheme (in which people pick up their pills at local sites such as high schools) appears to be gaining momentum. At the time of this writing, an amendment is pending to the fiscal year 2009 budget, which requests up to \$20 million for the U.S. Postal Service to aid in the delivery of medical countermeasures for bioterrorism (Bush 2008). See Wein (2008) for a more detailed comparison of the postal approach and PODs, and for recommendations pertaining to the management of the strategic national stockpile that would maximize the benefits of the postal approach.

3. Botulinum Toxin in Milk

The three catastrophic bioterror threats to humans identified by Danzig (2003) are catastrophic for different reasons: smallpox is highly contagious and somewhat deadly, anthrax allows for widespread aerosol dispersion, and is extremely durable and highly fatal; and botulinum toxin in milk (Danzig specifies botulinum toxin in a soft drink) combines the deadliest substance known to humans with the large-scale storage and production and rapid distribution and consumption of a substance that is consumed by Americans at the rate of seven billion gallons per year. Indeed, the dairy industry has experienced two natural salmonella outbreaks of approximately 200,000 people each during the past several decades (Sobel et al. 2002).

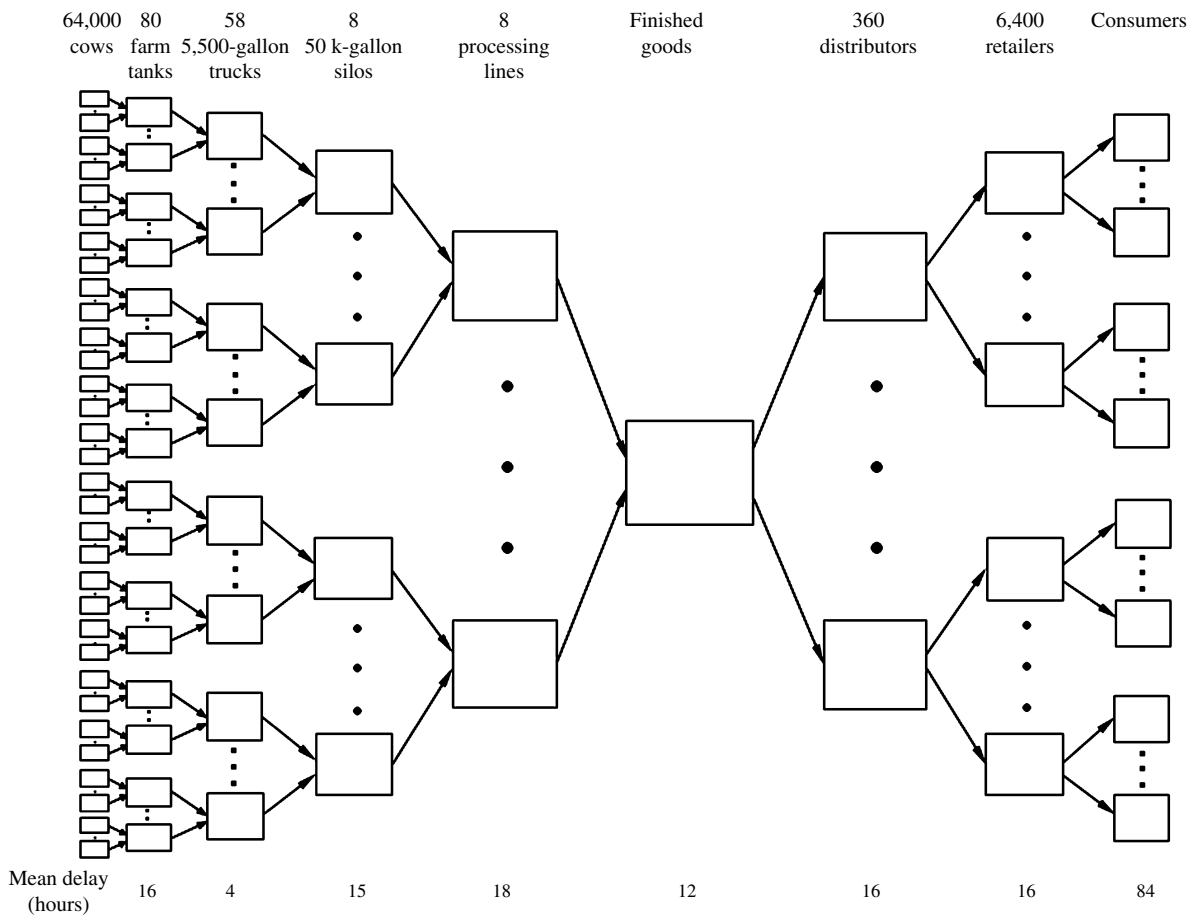
In Wein and Liu (2005), we develop a mathematical model of the cows-to-consumers supply chain that centers around a single dairy processing facility; however, the model and methods are applicable to other hourglass-shaped food supply chains. We walk through the scenario illustrated in Figure 2, which is based loosely on a dairy

processing facility in California (over 19% of the nation's milk is processed in California; California Dairy Quality Assurance Program 2007). Cows are milked twice a day, and the milk is placed in a storage tank on the farm. Once or twice a day, a 5,500-gallon milk truck makes a traveling salesman tour around neighboring farms, collects the milk from the storage tanks, and then travels to the dairy processing facility, where the milk is transferred into a 50,000-gallon silo.

A terrorist has a 2.5-gallon jug of an acid-mud mixture containing 10 grams of botulinum toxin. Whether the contents of this jug are inserted into a tank on a farm, a tank truck while the driver is parked at a truck stop (there are no laws that require the tank or the truck to be locked), or a silo, the 10 grams of toxin end up well mixed inside the silo.

By law, the silo needs to be emptied and cleaned every 72 hours. An application of Little's Law implies that approximately 125,000 gallons of milk are contaminated with the toxin. Some of this toxin is inactivated while the milk is heat pasteurized; in our analysis, we assume that 31.6% of the toxin is inactivated, based on data from creamed corn, which has a similar pH (pH is thought to be a strong factor in the inactivation rate of botulinum toxin in food). If the attack goes undetected (as was the case with the two large salmonella outbreaks), then these 125,000 gallons are consumed by approximately 500,000 people. The majority (roughly 400,000) of these people would be poisoned. Although a person who comes down with an isolated case of botulism has a 90% chance of survival if given antitoxins and hospital care, there is very little antitoxin available and the death rate in this scenario is likely to be near 50%. Of the 200,000 dead, a disproportionate number would be children because they drink more milk per capita than adults, they have smaller bodies and hence a lower infectious dose, and—at least during the school year—would be the early sentinels because most dairy processing facilities ship half-pint cartons directly to schools without going through the downstream portion of the supply chain in Figure 2.

Our analysis suggests that we have a reasonable estimate of how many people could get infected, but are highly uncertain about whether terrorists could pull this off. This uncertainty does not revolve around whether the acid-mud mixture could be made—this is rather straightforward, using decades-old technology. The largest source of uncertainty is the infectiousness of botulinum toxin (the ID_{50} , which is the dose that would poison half the population, is thought to be approximately 1 μg , but could be off by two orders of magnitude in either direction; see Wein and Liu 2005 for an extensive discussion). Moreover, the inactivation rate of the heat pasteurization process is not in the public domain, and so our estimate using creamed corn may be inaccurate. Finally, the capabilities (beyond the use of standard technology) of terrorists in concentrating the toxin in the acid-mud mixture is unknown (we conservatively assume that they use standard technologies).

Figure 2. The milk supply chain.

Note. Figure taken from Wein and Liu (2005).

However, a huge attack, with 10^5 – 10^6 people poisoned, seems plausible.

We make three recommendations in Wein and Liu (2005). First, invest in prevention. The Food and Drug Administration suggests that tanks and trucks be locked, and one person from each layer of the supply chain be present when milk is transferred across layers. However, these are voluntary guidelines. In our view, if a dairy processing facility in the hands of a terrorist is just as dangerous as a nuclear or chemical facility, then voluntary guidelines should be made mandatory by law. Second, investigate the heat pasteurization process: Identify whether the time and/or temperature can be increased so as to inactivate more of the toxin without sacrificing nutrition or taste. Finally, develop a rapid, highly specific in-process test for botulinum toxin in milk. A tank truck arriving to a dairy processing facility has to wait 45 minutes before releasing its contents into a silo; during this time, an antibiotic residue test is performed to make sure the cows have not been injected with too many antibiotics. Therefore, if a test existed for botulinum toxin in milk that could produce results within 45 minutes (so that it would not slow down the supply chain) with few false positives (these trucks

would need to be set aside until a lengthy confirmatory test could be performed), then it could go a long way toward taking this nightmare scenario off the table.

The remainder of this section discusses what transpired after the research was completed. When I first presented these results to government officials in the autumn of 2004, the only in-line test for botulinum toxin in milk that anyone was aware of was an enzyme-linked immunosorbent assay (ELISA) test, which has a three- to four-hour time delay. However, in the spring of 2005, shortly before Wein and Liu (2005) was to be published, I learned about a commercially available immunomagnetic-electrochemiluminescent assay that took only 15 minutes (this test was made by BioVeris, which was sold to Roche in 2007). Moreover, because of the large size of the tank trucks, the testing cost would be only three cents per gallon of milk, which is less than 1% of the price. This new knowledge led me to write an op-ed piece (Wein 2005).

Wein and Liu (2005) was originally set to be published at 5 P.M. EST on Monday, May 30, 2005, the same day as the op-ed appeared. However, on the previous Wednesday, a CNN reporter downloaded the paper from the journal website (the media can gain access to the journal's

papers up to five days before publication) and promptly forwarded it to government officials, asking them for comments. On Thursday morning, a letter written jointly by the Assistant Secretary of Public Health Emergency Preparedness, Department of Health and Human Services, and the acting Commissioner of the Food and Drug Administration, was received by the President of the National Academy of Sciences and the editor-in-chief of the journal, asking them not to publish the paper because it was a roadmap for terrorists. Publication of the paper was temporarily delayed until the journal could go back through the paper in detail and assess the validity of this claim.

Approximately one month later, Wein and Liu (2005) was published, accompanied by an editorial by the President of the National Academy of Sciences (Alberts 2005) that refuted the above claim. This editorial revealed that after the September 11, 2001 attacks, the government was extremely concerned about the botulinum-in-milk scenario, funded experimental investigations of intensified heat pasteurization processes, and—working with the U.S. dairy industry—intensified the heat pasteurization formula in a large number of facilities.

Beyond the intensified heat pasteurization formula for milk, the U.S. Government has done very little in the past seven years to move beyond food safety (i.e., preventing the accidental contamination of food) to food security (i.e., preventing the deliberate contamination of food). No one knows whether botulinum in milk is the unique catastrophic scenario among biological food attacks, or whether it is merely the tip of an iceberg. Toward this end, we derived a mathematical expression that approximates the mean number of casualties from a generic food attack based on the characteristics of the biological or chemical agent (e.g., ID_{50} , incubation period) and the type of food (e.g., size of storage containers, speed of distribution, consumption rate). This equation (Liu and Wein 2008b) was also embedded into an interactive Web-based system that was given to the U.S. government. Although government researchers told us that they found it to be correct and interesting, we are not aware of it being used.

4. Infection Control for Pandemic Influenza

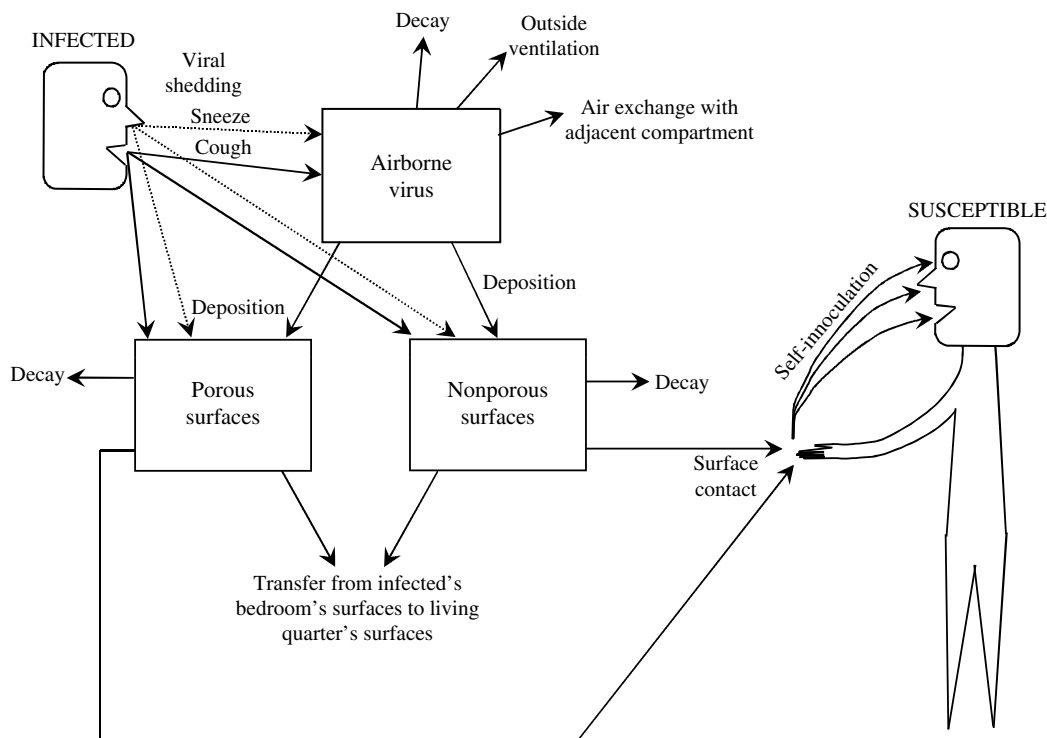
Although an influenza pandemic (influenza A subtype H5N1) would be a natural outbreak not instigated by terrorists, an event on the scale of the 1918 pandemic would cause many more deaths than any terrorist attack (even a nuclear one). If this were to happen in the next several years, we would not have a vaccine during the first wave of the pandemic (Health and Human Services Department 2004), and prophylactic antivirals would be in insufficient supply, and quite possibly ineffective (Homeland Security Council 2006). Moreover, hospitals would be totally overwhelmed and the public health community would be urging home care.

In the absence of pharmaceutical measures, we will need to rely on infection control measures such as school closures and enhanced hygiene practices (e.g., frequent hand-washing, face protection). Although our research goal is to assess various forms of infection control in the home, we quickly realized that a prerequisite for this assessment is to have a solid understanding of how influenza is transmitted from an infected person to a susceptible person. There are three routes of transmission (Health and Human Services Department 2004): aerosol transmission (droplet nuclei from an infected's sneeze or cough linger in the air and are inhaled by a susceptible), contact transmission (virus from an infected's hand is transferred—either directly, e.g., via a handshake, or indirectly via fomites—to a susceptible's hand, who then inserts the virus into his eyes, nose, or mouth), and droplet transmission (an infected sneezes or coughs directly into a susceptible's eyes, nose, or mouth).

Remarkably, the relative importance of these three transmission routes is unknown (Health and Human Services Department 2004). In Atkinson and Wein (2008), we use mathematical modeling and empirical data in an attempt to gain some insight into this issue. More specifically, we develop a detailed mathematical model (Figure 3) that tracks the expelled virus from an infected's sneezes and coughs. This model is an infinite set of ordinary differential equations that measures the concentration of virus particles in the air that are of each size, as well as the concentration of virus that is on porous and nonporous surfaces. Depending on the size of the expelled particles, some virus deposits directly on the surfaces, whereas other virus becomes airborne and deposits on the surfaces at a size-dependent rate. The virus also decays naturally in the air and on surfaces, decaying more quickly on porous surfaces (e.g., clothes) than nonporous surfaces (e.g., countertops), and ventilation causes the indoor air to be slowly exchanged with virus-free outdoor air.

The key to this study is its use of data for rhinovirus, which is the virus that causes the common cold. Because it is not ethical to perform controlled human experiments with influenza, relevant data are more sparse for influenza than for rhinovirus. Moreover, many of the model parameters would be identical, whether we are considering influenza or rhinovirus; examples include the physiological parameters such as the breathing rate, the aerosol parameters such as the deposition rate of particles, and the behavior of infecteds and susceptibles during the presymptomatic period.

In the first step of this analysis, we use the classical Poisson dose-response model to calculate the likelihood of infection for a given dose (Wells 1955). That is, we derive the probability of infection to be $1 - e^{-(c_a+c_s+c_d)}$, where we have explicit mathematical expressions (by solving the differential equations) for the constants c_a (for aerosol), c_s (for contact transmission), and c_d (for droplet transmission). We add the subscript i for influenza and r for rhinovirus, and initially ignore droplet transmission, and

Figure 3. A graphical depiction of the influenza model.

Note. Figure taken from Atkinson and Wein (2009).

consider the infection probabilities for the two diseases to be $1 - e^{-(c_{ai}+c_{si})}$ and $1 - e^{-(c_{ar}+c_{sr})}$. To assess the relative importance of aerosol transmission and contact transmission for influenza, it suffices to compare the relative values of c_{ai} and c_{si} . However, this comparison would require us to estimate some model parameters that are exceedingly difficult to estimate, such as the fraction of surface virus that is picked up by a susceptible, and the fraction of this virus that is transferred to the eyes, nose, or mouth. However, all of these difficult-to-estimate parameters cancel out when we look at the interdisease ratios c_{ai}/c_{ar} and c_{si}/c_{sr} . These two ratios depend on only seven parameter values for each disease, each of which is well quantified in the literature: the total shed virus, the ID_{50} of the respiratory epithelium, the ID_{50} for the nose (the nasal ID_{50} is the same as the ID_{50} for the eyes), and the death rate of virus in the air, on porous surfaces, on nonporous surfaces, and on hands. When we substitute these 14 values (seven for influenza and seven for rhinovirus) into these ratios, we find that $c_{ai}/c_{ar} = 0.77$ and $c_{si}/c_{sr} = 4.2 \times 10^{-10}$. Although this nine orders of magnitude difference between the two ratios seems to suggest the dominance of aerosol transmission over contact transmission for influenza, this argument is not conclusive because contact transmission may be highly dominant for rhinovirus (i.e., c_{sr} could be very large).

The second step of our analysis reconsiders controlled rhinovirus experiments performed at the University of Wisconsin in the 1980s. In the first set of experiments (Meschievitz et al. 1984), many susceptibles and infecteds

were placed together in a room, where they played video games and socialized, allowing for all routes of transmission. In the second set of experiments (Dick et al. 1987), susceptibles and infecteds sat around tables playing poker, but the susceptibles had constraining equipment on their arms that made it impossible for them to touch their eyes, nose, or mouth, thereby disallowing contact transmission. Fitting the data from these two experiments to our mathematical model implies that a significant portion (and perhaps most) of the rhinovirus transmission was via aerosol transmission, which—when combined with the ratios $c_{ai}/c_{ar} = 0.77$ and $c_{si}/c_{sr} = 4.2 \times 10^{-10}$ —strongly suggests that aerosol transmission dominates contact transmission for influenza.

For lack of space, we refer readers to Atkinson and Wein (2008) for our other supporting empirical and mathematical analysis, which suggests the dominance of aerosol transmission over contact transmission and droplet transmission. Although the rarity of close, unprotected, and horizontally directed sneezes leads us to suspect that droplet transmission does not play a large role, it is prudent to leave open the possibility of droplet transmission because there are insufficient data to estimate the frequency of close expiratory events.

From a policy viewpoint, Atkinson and Wein (2008) suggests that frequent handwashing—which would reduce the amount of contact transmission—would be of little use in an influenza pandemic, and that hygiene measures should focus on face protection, which would mitigate

both aerosol transmission and droplet transmission. In a companion paper (Atkinson and Wein 2009), we embed a three-room (susceptible's bedroom, infected's bedroom, and common living quarters) version of the model from Atkinson and Wein (2008) into an epidemic household model (Ball and Neal 2002) in which between-household contacts (and hence infections) occur in addition to within-household contacts. We use this hierarchical model to investigate the efficacy of face protection, ventilation (including open versus shut bedroom doors), and humidifiers (the death rate of airborne virus increases with humidity).

We find that face protection has the potential to significantly mitigate the size of the pandemic. There are two kinds of face protection: N95 respirators (e.g., worn by construction workers) and surgical masks (e.g., worn by dental hygienists). The performance of these items depends on three factors: the efficacy of the face filter, the face leakage (due to a loose fit), and the compliance (the fraction of time they are worn). Face leakage is approximately 10% for respirators (Coffey et al. 2004) and 37% for masks (Derrick and Gomersall 2005). Respirators are more uncomfortable than masks due to their tighter fit, and would likely lead to lower compliance. Filter efficacy is extremely high for respirators. The most surprising finding in Atkinson and Wein (2009) is that even though mask filters are ineffective for submicron particles, most expelled virus is in particles greater than $3 \mu\text{m}$, and consequently (certain brands of) face filters prevent at least 98% of the virus from being inhaled. Moreover, putting a nylon hosiery over a surgical mask eliminates nearly all of the face leakage (Cooper et al. 1983), suggesting that a surgical mask/nylon hosiery combination would be highly effective.

Finally, a respirator costs approximately 10 times more than a mask (roughly a dollar versus a dime). However, there is currently no excess manufacturing capacity in this industry, and 18 months would be required for the health-care supply companies to stockpile enough respirators and masks, which would be way too late to be of any help during a pandemic. Consequently, in a related op-ed. (Wein 2006b), we call for the government to sign contracts with manufacturers of masks and respirators and build a large stockpile for citizens prior to a pandemic, in the same way as it has entered into large contracts for stockpiling pharmaceuticals (e.g., vaccines, antibiotics) against influenza and bioterror agents.

At this point, despite briefing government officials in June, July, and October 2006, we have been unable to convince the U.S. government to stockpile masks and respirators for its citizens. However, the government has become more open to the possibility of aerosol transmission and its implications for face protection. In particular, Health and Human Services (2004, p. S-43) says, "There is little evidence of airborne transmission over long distances or prolonged periods of time" and "The relative clinical importance of each of these modes of transmission is

unknown," and Homeland Security Council (May 2006) makes no mention of face protection. However, Health and Human Services (October 2006) cites "...the possibility of short-range aerosol transmission" and states that health care providers should wear N95 respirators subject to availability, and should wear surgical masks otherwise. Seven months later, Health and Human Services (2007) states that surgical masks "should be considered" by anyone entering a crowd. Finally, on May 8, 2007, the Food and Drug Administration cleared for marketing the first N95 respirators for use during an influenza pandemic (U.S. Food and Drug Administration 2007).

5. Biometric Analysis of the US-VISIT Program

After the September 11, 2001 attacks, the U.S. Government implemented the U.S. Visitor and Immigrant Status Indicator Technology (US-VISIT) Program, which uses biometrics (primarily fingerprints) to screen noncitizens that enter the country. At visa application, two fingerprint images (from the left and right index fingers) are taken from each applicant and compared against the prints of several hundred million visa holders to detect identity fraud. At a U.S. port of entry (typically an airport), visitors have two new fingerprint images taken, which are compared against their original set of prints from the visa application (to ensure that they are who they say they are) and against the prints of approximately six million known criminals and suspected terrorists (U.S. General Accounting Office 2002). Although Wein and Baveja (2005) analyze both components of the US-VISIT Program, here we restrict ourselves to describing the results of the screening at the port of entry.

Fingerprint-matching systems create a similarity score when matching any two fingerprint images. A visitor to a port of entry is assigned two similarity scores (for the left and right index finger) against each of the six million people in the criminal/terrorist watchlist. If either the left score or the right score exceeds a given threshold, or the sum of the left and right scores exceeds a second threshold, then the corresponding person on the watchlist is placed on the visitor's candidate list. If the candidate list is nonempty, then the visitor undergoes secondary inspection by a U.S. Customs officer.

A visitor is referred to as illegal if he is on the watchlist, and as legal otherwise. An illegal visitor has a set of prints on the watchlist, which is referred to as the visitor's mate. On the surface, the biometric performance of the US-VISIT Program is quite impressive: tests by the National Institute of Standards and Technology (NIST) determine that for a watchlist of size six million, the detection probability (i.e., the probability that an illegal visitor's mate is on the visitor's candidate list) is 0.959, whereas the false positive probability (i.e., the probability that a legal visitor's candidate list is nonempty) is only 0.0031 (Wilson et al. 2004).

So, what's the problem? The fingerprint-matching software also produces an image quality for each fingerprint

(the US-VISIT Program uses an eight-point scale, where quality 1 is the highest quality and quality 8 is the lowest quality), and the performance is highly quality dependent, with quite poor performance if one of the two images in a match is of quality 8 (Wilson et al. 2004). Our analysis is based on the premise that terrorist organizations can exploit this quality-dependent performance by choosing from their pool of potential U.S.-bound terrorists those that have inherently poor (5%–10% of people have image quality 8) or deliberately degraded (e.g., surgery, sandpaper, chemicals) image quality.

Consequently, we model the problem as a Stackelberg game (Gibbons 1992): The U.S. government is the leader and specifies the biometric identification strategy to maximize the detection probability subject to a constraint on the mean total (i.e., the time it takes to take the fingerprint images during primary inspection—the matching itself is done while the visitor is being interviewed at primary inspection—plus the mean secondary inspection time) biometric processing time per legal visitor, and then the terrorist is the follower and chooses the image quality to minimize his detection probability.

Using NIST data (Wilson et al. 2003, Tabassi et al. 2004, Wilson et al. 2004), we estimate the probability mass function of the image quality, assuming that the image quality of a match is the worse of the image qualities in the match, and estimate the parameters for eight intraperson gamma distributions and eight interperson lognormal distributions.

We compare three strategies in Wein and Baveja (2005): the government strategy and two optimized strategies. Due to the Stackelberg setup, all visitors achieve the same detection probability under an optimized strategy, regardless of image quality. The strategy used by the US-VISIT Program achieves a detection probability of 0.526, which is much less than the aggregate performance of 0.959 because the terrorist optimally chooses image quality 8. The second strategy allows the two thresholds (one for the right or left finger, and one for the sum of the left and right) to depend upon image quality, which increases the detection probability from 0.526 to 0.733. Note that this strategy is worse in aggregate than the current US-VISIT strategy (0.733 versus 0.959), but better in the worst case as reflected by the Stackelberg assumption (0.733 versus 0.526). Finally, we consider a multifinger strategy, where the number of fingers tested (between 1 and 10) and the threshold both depend on the image quality, and a person is placed on the candidate list if at least one finger's score exceeds its threshold. This strategy generates a detection probability of 0.949, thereby achieving excellent aggregate performance and robustness against gaming. The essence of this entire analysis is that there is not enough information on two quality-8 fingerprint images to make good matches, but there is enough information on 10 quality-8 images.

On September 30, 2004, I testified at a joint hearing before the Subcommittee on Infrastructure and Border Security and the Subcommittee on Intelligence and

Counterterrorism of the Select Committee on Homeland Security, House of Representatives (U.S. House of Representatives 2004), recommending a shift from a 2-finger system to a 10-finger system. Several weeks later, the ranking member of this committee wrote an open letter to Tom Ridge, the Secretary of Homeland Security, citing our testimony, and asking for the enhancement from 2 fingers to 10 fingers (O'Harrow and Higham 2004). On July 13, 2005, the new Homeland Security Secretary, Michael Chertoff, announced that the US-VISIT Program would shift from a 2-finger system to a 10-finger system (Department of Homeland Security 2005).

6. Concluding Remarks

We conclude by discussing seven factors that have affected the success or failure of this research to impact policy. The first three factors pertain to performing the research, and the last four factors are related to disseminating the research. Because I have not been privy to what happens behind the scenes, some of these thoughts are simply my impressions, which could be mistaken.

Problem Choice. It goes without saying that a prerequisite for having policy impact is to work on real problems. All of these problems involve operational issues, although most of them consider strategic decisions (e.g., smallpox vaccination strategies, resource allocation among a variety of options for anthrax and botulinum attacks, and port and border security). Among the problems that are operational in nature (e.g., Wein et al. 2007, §5; Wein and Atkinson 2007), the optimal design and control of the system could have a large impact on performance. My rule of thumb for working on a problem was whether the answers to the following four questions were yes, no, no, and yes: Is the problem very important (i.e., could it directly or indirectly lead to catastrophic consequences)? Has the problem been sufficiently addressed in the academic literature? Has the problem been satisfactorily addressed by policy makers? Would the problem be fun (i.e., sufficiently challenging) to work on?

The problems we worked on arose from a variety of sources. Ed Kaplan and I were aware that smallpox (Kaplan et al. 2002) and anthrax were considered the most dangerous bioterror threats, both from reading (e.g., Henderson 1999) and from conversations. Similarly, the botulinum toxin work was started after reading Danzig (2003). Our work on port security (Wein et al. 2006) and border security (Wein et al. 2008) were stimulated by detailed nonmathematical descriptions of these very complicated problems by the Center for International Security and Cooperation (CISAC) Stanford Study Group (2004) and Turner (2004), respectively. Finally, the influenza research in §4 and work on indoor remediation after an anthrax attack (Wein et al. 2005) were posed to me by former Navy Secretary Richard Danzig, and the biometric work in §5 was undertaken after Lawrence Livermore National

Laboratories researchers engaged me in the queueing problems at ports of entry caused by the US-VISIT Program.

Contextual Learning. I did not know very much about any of these problems when I embarked on these topics. The government has groups of scientists (e.g., epidemiologists, biologists, nuclear physicists, computer scientists) who are specialists in each of these problem domains, as well as policy makers who are very knowledgeable about these topics. I do not think this body of work would have had any impact if we had not invested the time to master the appropriate literatures on these problems. This includes not just the mathematical models, but more importantly, all of the relevant data that provide estimates for model parameters. In some instances, this involves calibrating a mathematical model from scratch using government data (e.g., Liu and Wein 2008a and §5). In other cases, insufficient data are available (e.g., the ID_{50} for botulinum toxin and anthrax, people's behavior during a contagious outbreak) and interpretation of experiments and sensitivity analysis become a key aspect of the investigation. In several cases, some of the data are not in the public domain (e.g., the heat pasteurization formula for milk, the capability of detection equipment at ports), and the limitations of the study must be made clear. Finally, in two other cases (Baveja and Wein 2009, Liu and Wein 2008a), the research was enabled by people (the CEO and CTO of Cogent Systems, which is the vendor for the fingerprint-matching software in the US-VISIT Program, and the statistician of the Detention and Removal Office within Immigration and Customs Enforcement, respectively) giving us data.

Expert Coauthors. One way of ensuring a sufficient degree of contextual learning is to find coauthors who are experts on these topics. I have been fortunate to have two coauthors (Steven Flynn on Wein et al. 2006 and Terry Leighton on Wein et al. 2005) who were able to contribute contextual details (on port security and anthrax decontamination, respectively) to the research that would have been impossible to find in the open literature.

Self-Funding. Moving from doing the research itself to disseminating the research, I have been extremely fortunate to have my research funded by the Graduate School of Business at Stanford University. This funding enhances the impact of the work in several ways. First, because I can do the work without waiting for research proposals to be funded, the work was produced in a more timely fashion than it otherwise would have been. Second, depending upon the exact source of the funding, it may be more difficult to directly disseminate the research to the appropriate policy makers, either because the funding agency prefers to disseminate it themselves or due to turf issues within the government (many of these problems are multidisciplinary and partially owned by several groups). Third, when I present research that is self-funded, policy makers are perhaps more apt to view me as being politically impartial.

High-Profile Outlets. I have been fortunate to publish some of this work in high-profile outlets, such as the *Proceedings of the National Academy of Sciences* and several

major newspapers. The op-eds (and the media coverage of research) play the dual role of educating the public about homeland security issues and putting some pressure on policy makers to make the nation safer.

Educate Policy Makers. Ultimately, the main goal of this line of work is to educate policy makers so that they can make informed decisions. The U.S. government is very large and complex, with multiple groups having influence on each homeland security problem. When I present research in Washington D.C., I cast as wide a net as possible because it is difficult to know who might resonate with my recommendations and attempt to run with them, and who might be in a position to influence policy. Besides going to the appropriate parts of the Department of Homeland Security (e.g., the Science and Technology Directorate, the Inspector General, the US-VISIT Program, Customs and Border Protection, Immigration and Customs Enforcement), I typically try to brief policy makers at the White House (Homeland Security Council and staff in the Office of the Vice President), staff (and occasionally members) of Congress, and—depending upon the problem at hand—several agencies among Health and Human Services, Centers for Disease Control and Prevention, Environmental Protection Agency, Department of Defense, and Government Accountability Office. Presidential candidates are another potential conduit for getting research ideas out to the public. Although this face-to-face dissemination is extremely time-consuming and at times very contentious, I think it is quite likely that none of this work would have had any impact if I (or Ed Kaplan, in the case of our smallpox work) had stayed in my office.

Politics. This type of research has the potential to be co-opted for political purposes, or at least to become a tool for a broader political agenda. One example is that my Congressional testimony on the US-VISIT Program occurred five weeks before the 2004 Presidential election, and it is conceivable that Democratic congressmen were looking for ways to make the Bush administration look weak on homeland security (see O'Harrow and Higham 2004). Another possible example is our smallpox work, which recommends mass vaccination as the appropriate postattack response to a smallpox attack (Kaplan et al. 2002). It is conceivable that our smallpox work resonated with certain policy makers who sincerely believed (at the time)—and perhaps wanted to highlight the possibility—that Iraq had weapons of mass destruction. Although these examples (if they are true—I do not know) may make some people uncomfortable, my own view is that as long as the research is sound (note that a postattack vaccination policy has little to do with the prior likelihood of attack) and the recommendations help make the nation safer, I will take all the help I can get.

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