Analyzing the Homeland Security of the U.S.-Mexico Border

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Abstract

We develop a mathematical optimization model at the intersection of homeland security and immigration, which chooses various immigration enforcement decision variables to minimize the probability that a terrorist can successfully enter the U.S. across the U.S.-Mexico border. Included are a discrete choice model for the probability that a potential alien crosser will attempt to cross the U.S.-Mexico border in terms of the likelihood of success and the U.S. wage for illegal workers, a spatial model that calculates the apprehension probability as a function of the number of crossers, the number of border patrol agents and the amount of surveillance technology on the border, a queueing model that determines the probability that an apprehended alien will be detained and removed as a function of the number of detention beds, and an equilibrium model for the illegal wage, which balances the supply and demand for work and incorporates the impact of worksite enforcement. Our main result is that detention beds are the current system bottleneck (even after the large reduction in detention residence times recently achieved by Expedited Removal), and increases in border patrol staffing or surveillance technology would not provide any improvements without a large increase in detention capacity. Our model also predicts that surveillance technology is more cost-effective than border patrol agents, which in turn are more cost-effective than worksite inspectors, but these results are not robust due to the difficulty of predicting human behavior from existing data. Overall, the probability that a terrorist can successfully enter the U.S. is very high, and it would be extremely costly and difficult to significantly reduce it. We also investigate the alternative objective function of minimizing the flow of illegal aliens across the U.S.-Mexico border, and obtain qualitatively similar results.

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1 Introduction

Immigration is one of the most complex and contentious public policy issues facing the U.S. Government [1], as evidenced by Congress's failure to pass an immigration law in the summers of 2006 and 2007. The September 11, 2001 attacks have added further complications by extending the concerns about the porous U.S.-Mexico border beyond immigration to homeland security [2]. The U.S. Visitor and Immigrant Status Indicator Technology (US-VISIT) Program [3], which uses biometric matching at the U.S. ports of entry to detect people on the terrorist watchlist, may cause some terrorists who seek to enter the U.S. to do so illegally at the U.S.-Mexico border. The directors of the CIA and FBI testified to the Senate Intelligence Committee that new intelligence strongly suggests that Al Qaeda has considered entering the U.S. illegally across the U.S.-Mexico border [4].

This study focuses on the narrow aspect of immigration that intersects with homeland security. We develop a mathematical optimization problem for how the U.S. Government should allocate its resources across border control (i.e., border patrol agents and technology), detention and removal (i.e., detention beds) and worksite enforcement (i.e., worksite inspectors) to maximize the probability that a terrorist who attempts to cross the U.S.-Mexico border will be apprehended and removed; we also consider the alternative goal of minimizing the amount of illegal crossing at the border. We also investigate the impact on homeland security of legalizing illegal workers that are currently in the U.S. or introducing a guest worker program, although we do not address the vital issue of whether or not these workers should be offered a path to U.S. citizenship. More generally, competing Congressional bills have placed varying emphasis on border security, and our model assesses the enhancement in homeland security from additional investments in immigration enforcement.

The model is described in §2 and the parameter estimation process is reviewed in §3. Our results appear in §4 and are discussed in §5.

2 The Model

The detailed formulation of the mathematical model and the estimation of its parameter values appear in the Appendix. The model's shortcomings are taken up in §5. The model consists of four submodels. An overview of the model is provided in §2.1 and the four submodels are described in §2.2-§2.5.

2.1 Model Overview

Most aliens who cross the U.S.-Mexico border illegally are Mexican [5] and all other aliens are referred to as OTMs (Other Than Mexicans). Nearly all (adult male) aliens who cross illegally are seeking (or already have) employment in the U.S., although a few may be terrorists. Conceptually, for Mexicans and for OTMs, our model (Fig. 1) consists of four key relations (probability is abbreviated by prob.):

$$\text{crossing rate} = f(\text{apprehension prob., detention policy, removal prob., illegal wage}), \quad (1)$$

$$\text{apprehension probability} = f(\text{crossing rate, border patrol agents, border technology}), \quad (2)$$

$$\text{removal probability} = f(\text{crossing rate, detention policy, apprehension prob., DRO beds}), \quad (3)$$

$$\text{illegal wage} = f(\text{worksite enforcement policy, legalization policy}), \quad (4)$$

where $f(\cdot)$ is shorthand for "is a function of," and on the right sides of relations (1)-(4) we have included only the key decision variables and the variables from the left sides of these relations. This set of relations, which can be viewed as fixed-point equations for the crossing rates of Mexicans and OTMs by substituting the right sides of (2)-(4) into the right side of (1), is embedded into an optimization framework: choose the decision variables (i.e., detention policy, border patrol agents, border technology, DRO beds, worksite enforcement policy, legalization policy, guest worker program) to maximize the probability that an OTM (who happens to be a terrorist) is successfully apprehended and removed (which can be computed from the values of the left sides of relations (2)-(3)), subject to a budget constraint on border patrol agents, border technology, DRO beds and worksite inspectors.

We are implicitly assuming that a terrorist would be treated no differently than an OTM, and in particular, would have the same likelihood of being detained until removal as a non-terrorist OTM; because these detention decisions are not supposed to be based solely on the alien's race, ethnicity, nationality or religion [6], we are essentially assuming that the terrorist is non-violent while crossing and does not arouse suspicion (e.g., during a background check). We are also assuming that a terrorist (unlike a non-terrorist OTM) will not be deterred (e.g., by a high apprehension probability) from crossing the border; i.e., we are minimizing the probability that he will successfully enter the country conditioned on his attempting to do so. In our alternative objective function, which is from the perspective of immigration enforcement rather than homeland security, we minimize the number of OTMs who successfully sneak into the U.S.

2.2 The Discrete Choice Submodel

Relations (1)-(4) are mathematical models that will be referred to as submodels. Relation (1) is the Discrete Choice Submodel, which specifies the fraction of potential illegal aliens who decide to illegally cross the U.S.-Mexico border. This submodel captures the fact that potential crossers are more apt to illegally enter the country if they believe they will get a job that pays significantly more than what they can make in their home country. We use two versions (one for Mexicans and one for OTMs) of the multinomial logit model [7], which is the most widely used random utility model and which captures the heterogeneity in preferences (e.g., aversion to being apprehended and detained), resources (e.g., money to buy fraudelent documents or hire a coyote, i.e., human smuggler) and perceptions (e.g., about job opportunities or the risk of dying while crossing the border) across people. In this submodel, each potential crosser can either stay in his home country or try to enter the U.S. illegally, and we compute the expected utility for each of the two possibilities, which depends on the wages they would receive in the U.S. and in their home country over a 2-year horizon, the costs for traveling to the border and for being detained (both the loss of income and the psychological toll), the apprehension probability at the border, and the probability of removing an apprehended alien. Although apprehended (nonviolent and noncriminal) Mexicans are typically returned to Mexico within several hours without entering a detention facility (in contrast, OTMs are supposed to be held until they can be removed to their home country, and so are not offered this so-called voluntary departure), we also allow the possibility of detaining Mexican aliens who have been apprehended a fixed number of times, which is referred to as "detention policy" in relation (1).

2.3 The Apprehension Submodel

The Apprehension Submodel represented by relation (2) takes a macro approach to the apprehension probability by incorporating the impact of the alien flow and enforcement effort (both labor and technology), and ignores the micro-structural variables [8] that provide insight into the personal and community characteristics of the types of people who are apt to be apprehended at the border. This submodel is a spatial model on a 1933-mile line segment representing the U.S.-Mexico border, and can be viewed as one step in a sequential Stackelberg game in which the U.S. Government is the leader, who chooses the spatial allocation of agents (the number of agents and where on the line they are located) and technology (the number of miles along the border that is monitored by the Integrated Surveillance Intelligence systems, or ISIS, which are remote video surveillance systems [2]), and the illegal crosser is the follower, who observes the spatial allocation of agents and technology and then decides where to cross. As initial conditions, we assume that the arrival rate of illegal aliens to each location on the line and the density of border patrol agents at each location on the line are sinusoidal functions with the same frequency and relative amplitude, which captures the observation that some parts of the border are busier than others (the frequency is chosen so that there are 10 peaks along the 1933-mile border), and that these sinusoidal functions are similar to the crossing locations in the previous time period (e.g., year). Moreover, we assume that for a given fraction of the border that is monitored by technology, the technology is employed at those portions of the border that have the highest values of these sinusoidal functions (i.e., at the busier parts of the border). That is, the Government will reallocate border patrol according to where aliens recently crossed, and aliens will arrive at the border at the locations where aliens recently crossed. The aliens do not cross at the same location where they arrive. Rather, their crossing location is chosen according to a multinomial logit model with a continuum of choices (each point on the line segment being a choice), where their utility function depends on the likelihood of apprehension (they – or more likely, the coyotes – can observe the locations of the technology and border patrol agents) and the cost to travel along the border.

To capture the congestion effects at the border, the detailed apprehension process at each point on the line is modeled as a single-server loss queueing system [9]. The server is a border patrol agent who drives back and forth along a small portion of the border (the reciprocal of the density of the border patrol agents at this location on the line segment) and the customers arrive uniformly along this small part of the line segment according to a temporal Poisson process with a rate equal to the crossing rate at that location. If a crosser arrives to the border and finds the agent busy apprehending someone else, then he crosses successfully. If the agent is idle, then the probability of apprehension depends on the random distance between the agent and the crosser and on whether technology is present at this location of the border. If the distance between the agent and crosser is larger than an exponential random variable whose mean depends on whether or not technology is present (the technology makes apprehension more likely), then the crosser is not apprehended, and if this distance is smaller than the exponential random variable then the crosser is apprehended. The Apprehension Submodel is a fixed point functional equation for the crossing rates at each location.

2.4 The Removal Submodel

The Removal Submodel in (3) is a queueing model that was developed in [10]. The customers to this queue are the aliens who the U.S. Government wants to detain and remove. Some of the customers come from the apprehensions along the border while others (mostly coming from U.S. jails and in the process of being removed) are exogenous to the model. The servers in our model are DRO beds and the service time corresponds to the residence time in the DRO facility until the alien is removed from the U.S. and returned to his home country. Customers are either mandatory (e.g., criminals) or nonmandatory; in our model, we assume that the apprehended OTMs are nonmandatory. The customers to this queue arrive according to a (temporal) sinusoidal Poisson arrival process that captures the seasonal nature of illegal crossings. If a nonmandatory alien arrives and finds all beds filled, then he is released into the U.S. If a mandatory alien arrives and finds all beds filled, then a detained nonmandatory alien is released into the U.S. to make room for the mandatory alien. Released nonmandatory aliens are given a notice to appear in immigration court, but only 13% of nondetained aliens with final removal orders are actually removed [11]. If all beds are filled with mandatory aliens, then a new bed is temporarily rented for an arriving mandatory alien until there is a free DRO bed. The output of this queueing model is the probability that an apprehended alien who is desired to be detained and removed (i.e., an apprehended OTM or a Mexican alien who is apprehended a specified number of times) will actually be removed from the U.S. and returned to his home country.

2.5 The Illegal Wage Submodel

The Illegal Wage Submodel in (4) is an equilibrium model that equates unskilled labor demand (arising from a Cobb-Douglas production function) and the unskilled labor supply, which includes legal and illegal workers. The model allows for the legalization of illegal workers who are currently in the U.S. and for a guest-worker program that brings in new legal workers. In addition, worksite inspectors monitor workplaces and penalize employers who hire illegal aliens. The U.S. Government has 5 decision variables in this submodel: the number of illegal workers who are legalized, the number of new legal workers from a guest-worker program, the number of worksite inspectors, the fraction of inspections that are targeted (as opposed to random - we assume that the number of illegal workers in a firm is an exponential random variable to capture the fact that many illegal workers are concentrated in a handful of industries [12]), and the size of the fine for employing an illegal alien. Employers in our model pass on the expected worksite enforcement sanctions to the illegal workers in the form of lower wages. There are four sources of labor supply. The labor supply from the legal U.S. workers is modeled using the neo-classical labor supply function [13]. The second source comprises the illegal aliens who have been working in the U.S. but may have their pay reduced by increased worksite enforcement. We consider a two-step process for these workers. First, we use a multinomial logit model to decide what fraction of these workers stay in their reduced-wage job. Those who quit their job from an untargeted firm return home, and those who quit their job from a targeted firm enter a matching process (of the Cobb-Douglas form with constant returns to scale [14], where the multinomial logit model generates a probability distribution for the wage that these workers are willing to accept rather than returning to their home country) between the workers who quit their job and the jobs that were vacated. Illegal workers who are not matched with a vacated job return home. Finally, the newly legal laborers (those that have been legalized) use a multinomial logit model to decide whether to return home or to stay and receive the equilibrium legal wage (nearly all choose the latter option), and the new guest workers all stay.

3 Parameter Estimation

All parameters are estimated using existing data, as described in §5 in the Appendix. The parameters for the Removal Submodel were estimated in [10] using government data. After the study in [10] was performed, nonmandatory OTM residence times in detention were reduced through the use of Expedited Removal, and so we first consider the base case without Expedited Removal and then assess this program's impact. The Wage Submodel parameters use a variety of data, including the number of illegal workers currently working in the U.S., the unemployment rate of U.S. high school dropouts, the manufacturing wage in Mexico, the aggregate labor supply elasticity, the elasticity with respect to employment, and the wage elasticity of demand. The most difficult parameters to estimate are the detention cost (which includes a psychological component), the multinomial logit parameter (which dictates population heterogeneity in preferences), and the two exponential parameters that specify the effectiveness of apprehension in the absence and presence of surveillance technology. They are jointly estimated using data on the sensitivity of the number of apprehensions to the U.S.-Mexico wage ratio, the fraction of apprehensions that are aided by surveillance technology, and the base-case apprehension probability (for both Mexicans and OTMs). The values of these 4 parameters are tightly coupled. More specifically, for a given value of the multinomial logit parameter, there is a somewhat narrow range of detention costs that give stable values for the two apprehension parameters. For example, if we increase the detention cost above this range, too many crossers travel to regions on the border where there is no surveillance technology, making it impossible for the surveillance technology to aid in a sufficient fraction of apprehensions. In addition, we found 2 solutions for the values of these 4 parameters, the main difference being that the multinomial logit parameter was 6-fold higher in one solution than in the other (i.e., the values of the other 3 parameters changed only slightly). The solution with the high value of the multinomial logit parameter generated an illegal unemployment rate of 41%, and we consequently discarded this solution and used the solution with the low value of the multinomial logit parameter.

4 Results

4.1 Base-Case Results Without Expedited Removal

Our main performance measure is the probability that an OTM terrorist successfully enters the U.S., which is denoted by P_T. If we let P_a be the probability that an OTM is apprehended at the border and P_r be the probability that an apprehended OTM is removed from the country, then $P_T = 1 - P_a + P_a(1 - P_r)$. In our base case (apprehended Mexicans are not detained, no illegal workers are legalized, no new guest workers are introduced, 65 worksite inspectors perform 60% of their inspections at targeted firms with a fine of $5 per illegal worker-hour, 15% of the U.S.-Mexico border is monitored by surveillance technology, 1636 border patrol agents are on the border at all times, Expedited Removal is not being used, and there are 22,580 DRO beds; see §5 in the Appendix for details), we have $P_a = 0.2$, $P_r = 0.137$, and hence $P_T = 0.973$. The annual cost of this strategy is $2.7B. Other notable features of the base-case results include: the multinomial logit parameter implies considerable population heterogeneity, many border crossers are willing to travel to avoid apprehension (Fig. 1 in the Appendix), the impact of worksite enforcement is minimal (the difference between the annual legal and illegal wage is $180), the illegal U.S. wage is 4.5-fold larger than the wage in the home country, the detention cost incurred by an OTM is 1.8 times the annual illegal wage, $\approx 90\%$ of potential crossers decide to cross the border, the exponential apprehension parameter is 31.3-fold larger without technology than with technology, and the illegal labor supply in the U.S. is 7.76M (implying a 7.2% unemployment rate among illegal aliens).

4.2 The Impact of Detaining Apprehended Mexican Crossers

If all apprehended nonmandatory Mexicans are detained, then P_T increases to 0.989 (Fig. 2 in the Appendix) because the apprehended Mexicans overwhelm the DRO facilities. Even a dramatic increase in DRO capacity (e.g., 10^5 beds) would not be able to accommodate the detained Mexicans. Not detaining nonmandatory Mexicans until their fourth apprehension is nearly equivalent to not detaining them at all (Fig. 2 in the Appendix) because the probability of being apprehended four consecutive times is less than $0.2^4 = 1.6 \times 10^{-3}$. Hereafter, we assume that nonmandatory Mexicans are never detained.

4.3 The Impact of Expedited Removal

In 2006, Immigration and Customs Enforcement expanded the use of Expedited Removal authority, in which nonmandatory OTMs could be removed without an immigration hearing, to the entire U.S.-Mexico border, which reduced the mean residence time for nonmandatory OTMs to 19 days [15]. In our model, this dramatic reduction in residence times increases the removal probability P_r from 0.137 to 0.430 and reduces P_T from 0.973 to 0.932. Hereafter, we assume that Expedited Removal is used in the base case.

4.4 Optimizing Non-Worksite Decision Variables

Increasing the number of border patrol agents 6-fold or deploying surveillance technology on the entire U.S.-Mexico border each has a negligible impact (P_T decreases by 0.01 to 0.922) if done in isolation (or in combination) because there is no DRO capacity to handle the increase in apprehensions (Fig. 3a,b in the Appendix). Increasing DRO capacity by 33% to 30k beds (leaving other decision variables at their base-case values) reduces P_T from 0.932

to 0.880; further increases have no effect because the bottleneck resource is no longer DRO beds (Fig. 3c in the Appendix).

To better understand the interaction of the decision variables, we leave the worksite enforcement decision variables at their base-case values, and choose the number of border patrol agents, number of miles of border monitored by surveillance technology and the number of DRO beds to maximize P_T subject to an annual budget constraint; solving this optimization problem for a variety of budgets generates an optimal P_T vs. cost curve (Fig. 2). For the base-case budget of \$2.7B, the optimal P_T is 0.686, compared to the base-case value of 0.932. This improvement is achieved by deploying more technology, more beds and less agents than in the base case. More generally, the optimal budget allocates much of its initial money to deploy surveillance technology on the entire U.S.-Mexico border, and then balances border patrol agents and DRO beds so as to maintain enough beds to remove $> 95\%$ of potential detainees. Increasing the budget 4-fold to \$10B reduces P_T to 0.514, but the P_T vs. cost curve is convex (i.e, generates diminishing returns).

4.5 The Impact of Positioning Border Patrol Agents

Recall that in our model, the crossers' arrival location and the border patrol agents' location both follow sinusoidal functions that have the same frequency and relative amplitude. The value of P_T can be reduced significantly (particularly for annual budgets >\$2B) by using a relative amplitude for the border patrol agents' location that is smaller than the relative amplitude of the crossers' arrival location; indeed, the optimal relative amplitude for the border patrol agents appears to be zero (Fig. 4 in the Appendix). That is, a uniform spacing of border patrol agents along the border prevents crossers from moving to remote locations where there are fewer agents, thereby improving the apprehension probability.

4.6 The Impact of Worksite Decision Variables

Leaving the non-worksite decision variables at their base-case values, we first investigate how the equilibrium illegal wage is influenced by the worksite decision variables. When the employer fine is \$5/worker-hr, the annual illegal wage drops from the base-case value of \$22.3k to \$12.3k as the number of worksite inspectors is increased from its negligible base-case value of 65 to 10,850 (which causes every firm to be inspected every year), and the illegal wage is smaller when the fraction of randomized inspections is higher (Fig. 5a in the Appendix). We also consider a 5-fold higher fine of \$25/worker-hr, which is closer to the value used in Germany [16]. This larger fine lowers the annual illegal wage to \$5k, which is the home-country wage, with 4k to 9k inspectors, depending upon the fraction of inspections that are targeted (Fig. 5b in the Appendix). In contrast to the scenarios with a \$5/worker-hr fine, when the fine is \$25/worker-hr the illegal wage increases as the fraction of randomized inspections increases. The annual illegal wage drops by $\approx$ \$200 (and by $\approx$ \$150 when the fine is \$25/worker-hr) for every 1M illegal workers that are legalized or every 1M new legal workers that are introduced via a guest worker program (Figs. 6a and 6b in the Appendix). Both of these policies increase the supply of legal labor, which reduces the equilibrium legal wage, which in turn reduces the illegal wage for any given level of worksite enforcement.

To understand the effect of wage reduction, we note that when the annual illegal wage drops from \$22.3k to \$5k, the probability that an illegal alien attempts to cross the border decreases from 90% to 43% (Fig. 7 in the Appendix); the large population heterogeneity embodied in the multinomial logit parameter prevents a larger drop. This 90-to-43% reduction in attempted border crossings in turn has two main effects: it increases the apprehension probability P_a from 0.158 (note that Expedited Removal reduces P_a from 0.2 to 0.158 in the base case) to 0.212 because of reduced congestion at the border and it causes the removal probability P_r to increase from 0.430 to 0.605 because of reduced congestion at DRO. In the calculation of $P_T = 1 - P_a + P_a(1 - P_r)$, it is the former effect that dominates because P_T

changes from 1-0.158+0.158(1-0.43)=0.932 to 1-0.212+0.212(1-0.605)=0.872.

In our model, the cost of one border patrol agent (on the border at all times) is equal to the cost of 4.8 worksite inspectors, and border patrol agents are more cost-effective than worksite inspectors at lowering P_T for all budget values. More specifically, with 100% deployed surveillance technology, evenly-spaced agents, and ample DRO beds (i.e., $P_r = 1$, so that $P_T = 1 - P_a$), putting additional money into border patrol agents decreases P_T 5-fold more than putting money into worksite inspectors (Fig. 8a in the Appendix). Hence, even if worksite inspectors are included as a decision variable in the optimization problem, the optimal budget allocation remains identical to that in Fig. 2.

4.7 Sensitivity Analyses

To assess the robustness of the desirability of surveillance technology, we fix the exponential apprehension parameter without technology and increase the apprehension parameter with technology (thereby degrading the effectiveness of technology) to the point where, with the base-case annual budget of \$2.7B, we are indifferent between using surveillance technology along the entire border and not using the technology at all. The breakeven ratio of the two parameters is 1.03, compared to the base-case ratio of 31.3. This small breakeven ratio (a ratio of 1.0 corresponds to useless technology) suggests that surveillance technology need only be marginally effective to merit inclusion in a P_T-minimizing strategy.

A central question in this study is whether border patrol or worksite enforcement is the more cost-effective approach to minimizing P_T. We investigate this question with respect to a decision variable (the workforce penalty) and 3 parameters that are difficult to estimate: the detention cost, the initial legal labor supply, and the multinomial logit parameter. First, cutting the detention cost for both OTMs and Mexicans by a factor of 10 (so that the OTM detention cost is 0.18 times the annual illegal wage) leads to very little change in the results relative to the base case. Next, we fix the worksite fine at \$25/worker-hr and change the initial (i.e., before legalization or a guest worker program) legal labor supply from its base-case value of 30M to either 20M or 40M. The initial legal labor supply dictates the reduction in the illegal wage as a result of an increase in the supply of legal labor via a legalization policy or a guest worker program. The annual illegal wage dropped by $150 for every 1M new legal workers with the base-case initial legal labor value of 30M, but the magnitude of the sensitivity is asymmetric: this value increases to $250 when the initial legal labor supply is 20M and decreases to $125 when the initial legal labor supply is 40M. This reduction to 20M is not nearly sufficient to tip the tradeoff from border patrol agents to worksite inspectors.

For the last two parameters, the worksite penalty and the multinomial logit parameter, we seek breakeven values that would lead to indifference between investments in border patrol agents and worksite inspectors. In each case, we assume there are ample DRO beds (which allows us to focus on apprehension rather than detention and removal) and consider two scenarios: the base-case scenario that has surveillance technology along 15% of the border and a spatially-heterogeneous allocation of border patrol agents, and an alternative scenario that has technology along the entire border and evenly-spaced agents. Using Fig. 8a in the Appendix, which assumes the latter of these two scenarios, we find a breakeven value for the enforcement fine of $41.20/worker-hr, which is 65% larger than the fine currently used in Germany [16]. In the base-case scenario, the breakeven value is only $17.00/worker-hr because it is easier in this scenario for crossers to find portions of the border that are not under surveillance and have few border patrol agents.

Finally, an increase in the multinomial logit parameter leads to a more responsive alien population, which has two major effects: wage reductions would cause a larger drop in the crossing probability than we see in the base case (Fig. 7 in the Appendix), and crossers would more aggressively seek out poorly patrolled areas of the border, leading to a reduction in the apprehension probability. In the base-case scenario, the breakeven value for the multinomial logit parameter is 2.6-fold higher than the base-case value. There is no breakeven value for the multinomial logit parameter in the alternative scenario, where savvy crossers are less able to exploit weaknesses in border security (in this case, crossers cross at high-traffic locations).

4.8 Maximizing Immigration Enforcement

We now consider the objective function of minimizing the number of OTMs that successfully sneak across the border, which is equivalent to minimizing P_T times the OTM crossing probability, which is the left side of equation (1). We refer to the product of these two probabilities as the OTM success probability, P_{OTM}. In the base case, $P_{\text{OTM}} = 0.863$ without Expedited Removal and $P_{\text{OTM}} = 0.816$ with Expedited Removal. The optimal P_{OTM} vs. budget curve and the optimal allocation of non-worksite decision variables (Fig. 3) are very similar to those under the homeland security objective of minimizing P_T (Fig. 2), except that the percentage reductions achieved for a given budget are somewhat larger for P_{OTM} than for P_T. While worksite enforcement plays only an indirect role (i.e., by reducing congestion at the border and at DRO) in minimizing P_T, it plays a direct role in minimizing P_{OTM}. If we assume 100% surveillance technology deployment, evenly-spaced agents and ample DRO beds, then border patrol is 35% more cost-effective than worksite enforcement (Fig. 8c in the Appendix) for this objective, rather than 5-fold more cost-effective, as when minimizing P_T.

5 Discussion

Immigration is a difficult issue to mathematically model: even restricting our attention to the small part of immigration that affects homeland security leads to an unwieldy system of equations and a formidable parameter estimation task. The level of detail in our submodels is dictated by the level of detail in the available data. The Removal Submodel is the only one of the four submodels that we are confident provides a reasonably accurate model of reality, due to our previous calibration of the model with the ample data on detention and removal operations [10]. While the Discrete Choice Submodel is a workhorse in a wide variety of fields and seems like a natural choice here, the multinomial logit parameter and the cost of detention are very difficult to estimate, even to within an order of magnitude. Although the Apprehension Submodel is spatially nonhomogeneous and captures the game-theoretic and congestion aspects of apprehension, it is still a mere caricature of the evolving struggle between border crossers (and coyotes) and border patrol agents, and the data on the efficacy of surveillance technology is very sparse. The Illegal Wage Submodel is also a very crude idealization of reality that – while capturing many important features of the problem – uses simple toy models such as the Cobb-Douglas production function and the neo-classical labor supply function, and does not attempt to employ detailed data from different industrial sectors (e.g., as in [17]). Furthermore, as broad as our model is, it omits entire aspects that have a direct bearing on the issues, including (i) other ways to sneak into the U.S., such as along the U.S.-Canada border (although Canada has a better infrastructure than Mexico for catching illegal aliens upon arrival), by private boat or airplane, or at legal points of entry; (ii) the interaction between illegal border crossing and drug trafficking; (iii) the policies (including the number of staff, which dictates visa waiting times) of the U.S. Consulate and the availability of visas; (iv) whether legalized workers are offered a path to U.S. citizenship; and (v) the efficacy of U.S. Government investments to strengthen the Mexican economy.

Consequently, the model's numerical output is not intended – and indeed is unable – to capture the quantitative impact of various decisions with any degree of accuracy, and so the model is incapable of directly guiding policy, except in a very crude manner. Rather, this study – by framing the immigration/homeland security problem in a way that captures most of its salient features – is meant primarily as a vehicle for rational dialog about a complex problem that often elicits strong emotional responses.

Our main policy question is how to allocate funds across border patrol agents, DRO beds, surveillance technology, and worksite enforcement (and the related question of the appropriate size of the budget), although we also look at the impact on homeland security of the detention policy (whether apprehended Mexicans should be detained), the legalization policy (whether illegal workers should be legalized), and a guest worker program. Our objective of minimizing $P_T = 1 - P_a + P_a(1 - P_r)$ makes clear that there are two sequential operations, apprehension followed by detention and removal, that need to be successfully completed to prevent a terrorist from entering the U.S. Investments in border patrol agents, surveillance technology and worksite enforcement increase the probability of apprehension, while DRO beds and worksite enforcement increase the probability of detention and removal. Our analysis reveals that detention and removal was a severe bottleneck under the existing resource allocation through 2005, and hence further investments in technology and border patrol agents without a significant concomitant increase in DRO beds did not reduce P_T during this period. The implementation of Expedited Removal in 2006, which significantly reduced residence times for nommandatory detainees but raised human rights concerns [18], caused a modest reduction in P_T. Nonetheless, Congressional plans still lead to significant underfunding of DRO: the security triggers (i.e., before initating guest worker and legalization programs) in the proposed May 2007 Senate immigration bill called for 18k border batrol agents (which corresponds to 2587 agents in our model) and 27.5k DRO beds [19], whereas our model's optimal bed allocation when there are 2587 agents is 40k beds. It seems doubtful that increased border patrol and surveillance would provide a deterrent effect in the absence of ample DRO capacity, given the fact that many aliens (and coyotes) had been well aware of the pre-2006 catch-and-release strategy [20]. We also show that detaining apprehended Mexicans would overwhelm DRO, leading to an increase in P_T. These two results – DRO is the bottleneck and detaining apprehend Mexicans would overwhelm DRO – are the only ones that we can state with confidence.

Surveillance technology appears to be cost-effective in our model, but there are two important caveats beyond the fact that the data on its efficacy are sparse. First, regardless of whether the technology is passive (e.g., video that requires a human to detect a suspicious event) or active (i.e., sets off its own alarm), its efficacy relies on having sufficient human resources to process and screen the output data of these systems and to quickly communicate information to the appropriate border patrol agents; such resources have been woefully inadequate in recent years [2]. Second, it is important to keep in mind that our model does not include the U.S.-Canada border or approaches by air or sea. If effective surveillance technology was actually deployed along the entire U.S.-Mexico border, it seems likely that potential crossers would choose an alternative route into the U.S. Hence, the U.S. Government would need to provide surveillance technology along the entire U.S.-Canada border and along the nation's shores and airspace, which seems daunting, both financially and logistically.

Our analysis also suggests that, at least over the longer run, spacing agents evenly along the border is more effective than concentrating them in the busiest areas. This result is driven by viewing the apprehension submodel as a Stackelberg game [21] in which the U.S. Government moves first (decides where to locate border patrol agents) and the aliens (perhaps with the help of coyotes) move second (i.e., decide where to cross). This Stackelberg assumption is not only conservative (relative to, e.g., seeking a Nash equilibrium in which both players move simultaneously) but realistic, in that many aliens cross at remote locations on the border in response to increased security [22], and the apprehension probability along the U.S.-Mexico border has actually dropped over the last several decades despite large increases in technology deployment and the number of border patrol agents [23]. On a related note, a nonobvious aspect of our results is that crossers become more savvy (i.e., are more willing to cross at remote locations on the border) when there are more severe consequences of being apprehended. In particular, a large increase in the number of DRO beds (or equivalently, a large reduction in DRO residence times, as was achieved with Expedited Removal) leads to a reduction in the apprehension probability because more crossers are willing to pay the cost of traveling to remote areas to avoid being removed (as opposed to being released) upon apprehension.

An important goal of our analysis is to understand the extent to which border patrol agents and worksite inspectors are substitutes for one another, and which resource is more cost-effective. Although our model predicts that border patrol agents are $\approx$ 5-fold more cost-effective than worksite inspectors at reducing P_T, ultimately our apprehension submodel and illegal wage submodel are too idealized – and the values of some of the key parameters (particularly the behavioral parameters) too difficult to estimate accurately – for us to make any policy recommendations based on these results. Nonetheless, our analysis does shed light on the detailed mechanics that are at play. Worksite enforcement (and, to a much lesser extent, a legalization policy or a guest worker program) acts to reduce the wage of illegal workers because employers pass the risk on to the illegal workers in the form of lower wages, which reduces the crossing probability of aliens because the illegal U.S. wage looks less attractive relative to the wage in their home country, which in turn increases the apprehension probability (and hence our objective, P_T) by reducing congestion along the border (i.e., reducing the likelihood that an agent cannot apprehend a crosser because he is busy apprehending someone else) and increase the removal probability by reducing congestion at DRO. In contrast, an increase in the number of border patrol agents has a two-pronged effect: as with increased worksite enforcement, it has a deterrent effect (the deterrent effect achieved by worksite enforcement is approximately two-fold more cost-effective than the deterrent effect achieved by border patrol agents, Fig. 8b in the Appendix) by reducing the crossing probability and hence congestion at the border, but it also directly increases the probability of apprehension at the border.

Our cost estimates do not include two important components that each represent $\approx$ \$1000 per removed alien [24]: the transportation costs associated with removal and the legal costs associated with prosecution. The transportation costs are not relevant to our optimization problem because they do not vary with how the alien was detected (i.e., at the border vs. at the workplace): in either case, the alien needs to be flown to his home country. However, legal costs may differ by how the alien was detected. In particular, the legal costs associated with border apprehension have been significantly reduced by the implementation of Expedited Removal. The majority of legal costs associated with worksite enforcement may be due to prosecuting employers as opposed to removing illegal workers. To the extent that legal costs are higher for worksite enforcement than for border apprehension, our omission of legal costs biases our results on the border patrol agents vs. worksite inspectors tradeoff in favor of the latter. That is, the omission of legal costs strengthens our argument that border patrol agents are more cost-effective than worksite inspectors.

Our results are qualitatively similar, regardless of whether we are maximizing homeland security (Fig. 2) or maximizing immigration enforcement (Fig. 3). The main difference is that while border patrol agents are clearly more cost-effective than worksite inspectors for maximizing homeland security, the tradeoff is much less one-sided when maximizing immigration enforcement because of the strong deterrent effect of worksite enforcement on the OTM crossing probability.

Several other issues pertaining to worksite enforcement deserve mention. In particular, a tamper-proof identification system is a prerequisite to implementing an effective worksite enforcement program. Judging by the cost of – and problems plaguing – the US-VISIT program [25] and the document fraud and third-party worker-verification firms that were encountered during IRCA [26] and still persist today [27], the cost of such a system would be huge and the risk (i.e., whether the system actually worked as intended) would be high. On the other hand, a worksite enforcement program – and more generally, bringing all the employment of aliens above ground – would have other impacts that may be at least as important as homeland security, such as improving worker conditions [1], and perhaps affecting the unemployment rate and wages of native unskilled workers [28, 29, 30].

In conclusion, because our model has focused on only the narrow set of issues at the intersection of homeland security and immigration, we are not in a position to make concrete recommendations about the size and composition of the U.S. Immigration and Customs Enforcement (ICE) budget, aside from the observation that DRO capacity is currently lacking relative to border patrol capacity. However, it seems clear that the current security system at the U.S.-Mexico border is very porous ($P_T > 0.93$ in the base case) and efforts to meaningfully reduce P_T (e.g., to 0.1 or 0.2) would be immensely costly and might not succeed.

Acknowledgment

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Figure Legends

Fig. 1. A conceptual overview of the model, in which the rectangles contain quantities computed in the submodels described in equations (1)-(4) and the ovals contain decision variables by the U.S. Government.

Fig. 2. The optimal budget allocation across border patrol agents, border technology, and DRO beds. The numbers appearing along the curves are the optimal number of agents (on the border at any given time), miles of technology, and DRO beds at various budgets. The * denotes the base-case allocation with Expedited Removal, which represents current practice.

Fig. 3. For the alternative objective of minimizing the OTM success probability (P_{OTM}), the optimal budget allocation across border patrol agents, border technology, and DRO beds. The numbers appearing along the curves are the optimal number of agents (on the border at any given time), miles of technology, and DRO beds at various budgets. The * denotes the base-case allocation with Expedited Removal, which represents current practice.

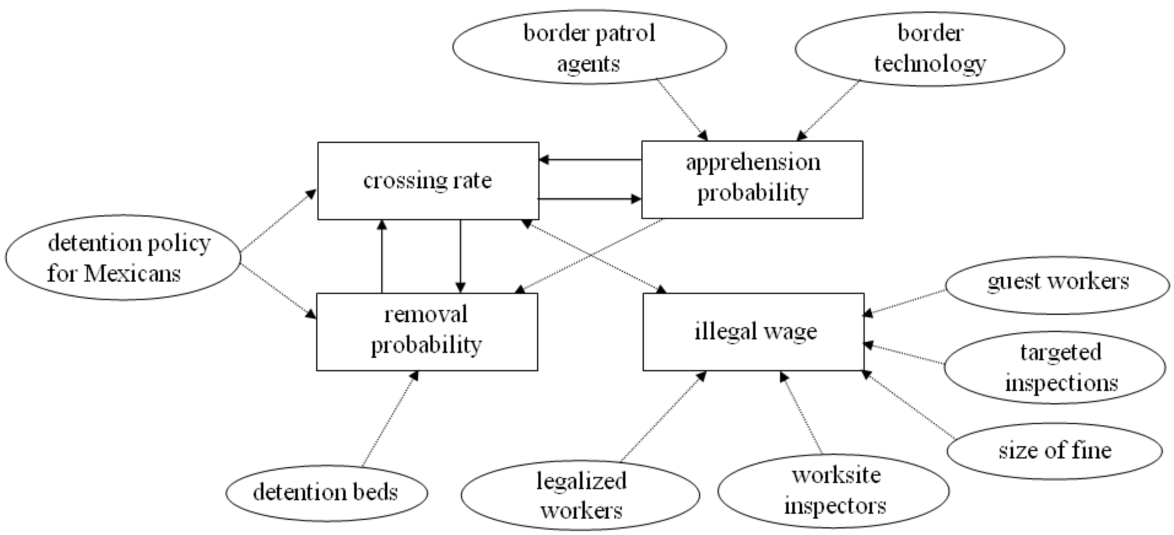
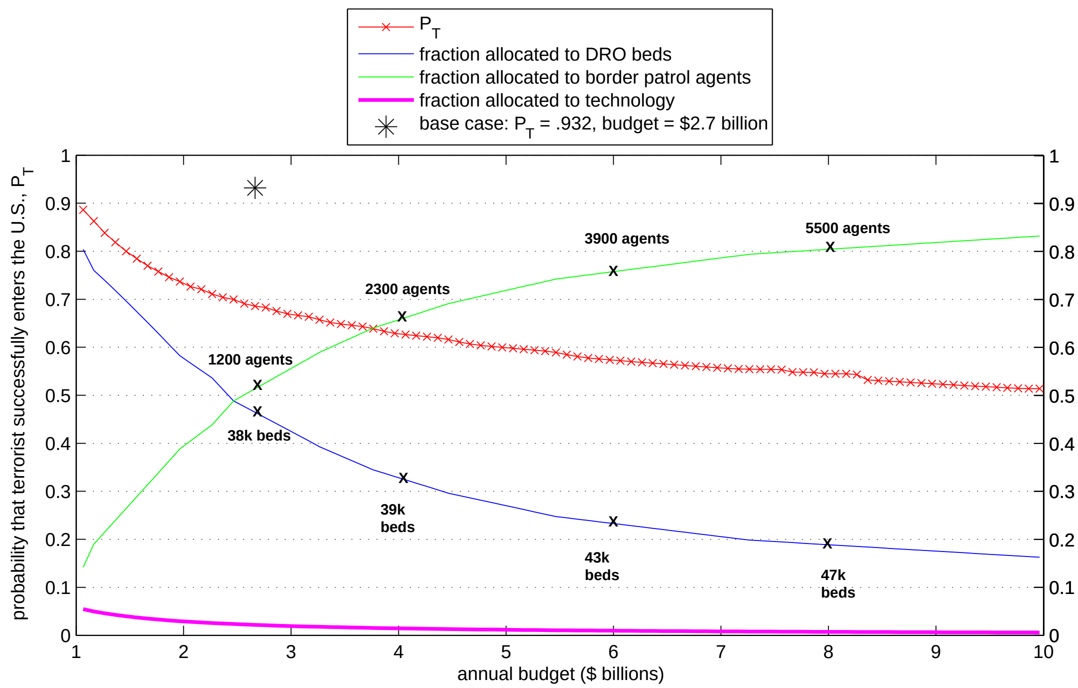

border patrol agents
border technology
crossing rate
apprehension probability
detention policy for Mexicans
removal probability
illegal wage
guest workers
targeted inspections
size of fine
detention beds
legalized workers
worksite inspectors

Figure 1



P_T
fraction allocated to DRO beds
fraction allocated to border patrol agents
fraction allocated to technology
base case: P_T = .932, budget = $2.7 billion
probability that terrorist successfully enters the U.S., P_T
annual budget ($ billions)
1200 agents
2300 agents
3900 agents
5500 agents
38k beds
39k beds
43k beds
47k beds

Figure 2

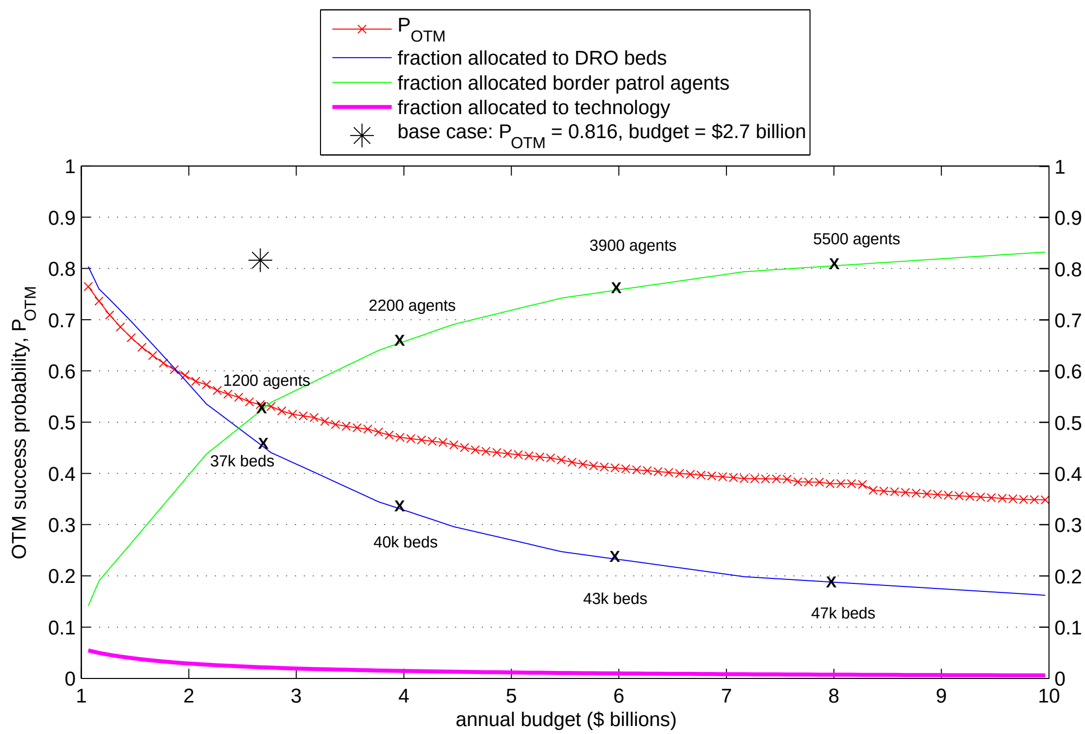

P_OTM
fraction allocated to DRO beds
fraction allocated border patrol agents
fraction allocated to technology
base case: P_OTM = 0.816, budget = $2.7 billion
OTM success probability, P_OTM
annual budget ($ billions)
1200 agents
2200 agents
3900 agents
5500 agents
37k beds
40k beds
43k beds
47k beds

Figure 3

APPENDIX

This appendix formulates the mathematical model described in the main text. The Discrete Choice Submodel for aliens is given in §1, the Apprehension Submodel appears in §2, the Removal Submodel is depicted in §3, and the Illegal Wage Submodel is derived in §4. The submodels in these four sections correspond to relations (1)-(4) in the main text, respectively. Parameter estimation is carried out in §5 (parameters are listed in Tables 1-5), and supporting computational results are in Figures 1-8.

1 Discrete Choice Submodel

For Mexicans ($i = 1$) and OTMs ($i = 2$), we assume there are n_i aliens that are considering entering the U.S. illegally. In this section, we introduce two discrete choice models, one for Mexicans and one for OTMs, that specify the fraction of these potential border crossers that choose to illegally enter the U.S. ($j = 1$) and the fraction that choose to stay at home ($j = 2$). We need two models because apprehended Mexicans are typically offered voluntary departure, i.e., they are allowed to withdraw to Mexico without penalty rather than being detained, whereas OTMs cannot be returned to Mexico. We begin with the simpler model, which is for OTMs.

1.1 OTM Decision Model

We use the multinomial-logit model, which is the most widely used random utility model, particularly in the area of consumer choice (e.g., [1]). This model implicitly captures the heterogeneity in preferences, resources (e.g., money to buy fraudulent documents or hire a coyote, i.e., a human smuggler) and perceptions (e.g., about job opportunities or risk of being apprehended while crossing the border) among the population of potential border crossers. The model assumes that the utility for an OTM from choosing option j has a deterministic component u_{2j} plus a random component that is an independent and identically distributed (iid) logistic random variable with mean zero. According to the model, the probability P_{2j} that an OTM will choose option j, in terms of the expected utility u_{2j} received from this option and the scale parameter θ, is

$$P_{2j} = \frac{e^{\theta u_{2j}}}{e^{\theta u_{21}} + e^{\theta u_{22}}} \quad \text{for} \quad j = 1, 2. \tag{1}$$

This model becomes deterministic as $\theta \to \infty$ and becomes a pure random choice model as $\theta \to 0$. Equation (1) is closely related to the logistic regression models used for analyzing the apprehension probability at the border, which replace u_{ij} by a linear function of independent variables.

Because the great majority of illegal immigrants are looking for a job in the U.S., the expected utilities are taken to be the expected undiscounted earnings over τ years minus the cost of migration. Let w_u be the mean annual wage of an illegal immigrant in the U.S., which is computed in §4, and let w_o be the mean annual wage in the home country; in our model, these two quantities do not depend on whether the alien is Mexican or an OTM. If the potential crosser decides to stay at home, his utility is

$$u_{22} = w_o \tau. \tag{2}$$

Let c_2 denote the one-way cost of migration for an OTM. In the case where a crosser is apprehended, detained and removed, he does not pay his way home but incurs a cost d_2 due to lost wages in the home country and the physical and psychological toll of detention. We let P_{ai} be the probability that an alien of type i is apprehended while crossing the border; this quantity is computed in §2. Because OTMs are not offered voluntary departure to Mexico, apprehended OTMs are supposed to be detained and then removed to their home country. However, due to lack of beds in the detention and removal operations (DRO), an apprehended OTM will only be detained and removed with probability P_r, which is computed in §3. Otherwise, the apprehended OTM is released into the interior of the U.S., where he is free to (illegally) seek work; however, before being released, he incurs a cost of fd_2, where f is the fraction of the total detention cost d_2 incurred before removal. Because f varies with the the number of DRO beds, which is a decision variable in our model, in a complex way, in §5.1 we approximate f by means of a quadratic function of the removal probability P_r. Hence, the expected utility for an OTM if he decides to attempt an illegal crossing is

$$u_{21} = (1 - P_{a2})(w_u \tau - c_2) + P_{a2}(1 - P_r)(w_u \tau - c_2 - fd_2) + P_{a2} P_r (w_o \tau - c_2 - d_2). \tag{3}$$

1.2 Mexican Decision Model

We assume that an unauthorized Mexican is offered voluntary departure to Mexico the first $a - 1$ times that he is apprehended, where a is a decision variable for the U.S. Government. Upon being apprehended for the a^{th} time, a Mexican alien is detained if there are DRO beds available and is offered voluntary departure to Mexico if there are no DRO beds available. Moreover, after the Mexican alien is detained, there is still the possibility for him to be forced out of DRO before his removal due to lack of bedspace, and in this case we assume that he is offered voluntary departure when he is forced out of DRO. We allow Mexicans who accept voluntary departure after apprehension (and perhaps some detention) to make the choice of whether to cross again or to stay in Mexico.

As explained in §5.1, we set $a = \infty$ in the base case, so that border patrol agents turn apprehended migrants back into Mexico. In this case, we assume that migrants keep crossing until they succeed, as in [2]. Because this case is much simpler than when a is finite, we treat it separately. When $a = \infty$, the probability that a Mexican will choose option j is

$$P_{1j} = \frac{e^{\theta u_{1j}}}{e^{\theta u_{11}} + e^{\theta u_{12}}} \quad \text{for} \quad j = 1, 2, \tag{4}$$

where the utility from choosing option 2 is

$$u_{12} = w_o \tau. \tag{5}$$

If we let $\tilde{d}_1$ be the cost incurred each time an alien is apprehended at the border and returned to Mexico, then the expected utility from choosing option 1 is

$$u_{11} = w_u \tau - c_1 - \frac{P_{a1}}{1 - P_{a1}} \tilde{d}_1. \tag{6}$$

Now we turn to the case where a is finite. For stage $k = 1, 2, \ldots$, let $u_{1j}^{(k)}$ denote the expected utility from stage k onward for a Mexican immigrant if he chooses option j at stage k, i.e., after being apprehended $k-1$ times, and let $P_{1j}^{(k)}$ be the probability of making this choice. As in equation (3), we use the multinomial-logit model and get

$$P_{1j}^{(k)} = \frac{e^{\theta u_{1j}^{(k)}}}{e^{\theta u_{11}^{(k)}} + e^{\theta u_{12}^{(k)}}} \quad \text{for} \quad j = 1, 2 \quad \text{and} \quad k = 1, \ldots, a. \tag{7}$$

If we view c_1 as the one-way cost between a Mexican's hometown and the U.S.-Mexico border, then $u_{12}^{(1)} = w_o\tau$ because the alien never travels to the border in this case, and $u_{12}^{(k)} = w_o\tau - c_1$ for $k \geq 2$ because the cost to get to the border is already sunk by the time he has been apprehended $k-1$ times, but the cost to get home from the border still needs to be incurred for choice $j = 2$.

In the remainder of this subsection, we formulate and solve a recurrent relation between the $P_{11}^{(k)}$'s and the $u_{11}^{(k)}$'s. For stage $k = 1, \ldots, a$, if the alien is apprehended then he is returned to Mexico and incurs the cost $\tilde{d}_1$, and his expected utility at stage $k+1$ will be $P_{11}^{(k+1)}u_{11}^{(k+1)} + P_{12}^{(k+1)}u_{12}^{(k+1)}$. Because the one-way travel cost is sunk after the alien arrives at the border, if we define $I_{\{x\}}$ to be the indicator function of the event x, then we have the relation

$$u_{11}^{(k)} = (1-P_{a1})w_u\tau + P_{a1}(P_{11}^{(k+1)}u_{11}^{(k+1)} + P_{12}^{(k+1)}u_{12}^{(k+1)} - \tilde{d}_1) - c_1 I_{\{k=1\}} \quad \text{for} \quad k = 1, \ldots, a-1. \tag{8}$$

Beginning at stage a, if the alien still chooses to cross, he risks being detained and removed. With probability $P_{a1}P_r$, he will be detained and removed and have utility $w_0\tau - c_1 I_{\{k=1\}} - d_1$, where d_1 is the detection cost for Mexicans. With probability $P_{a1}(1-P_r)$, he will not be detained in DRO until removal and will be offered voluntary departure after incurring a loss of fd_1; he can then make a decision at stage $a+1$. Hence, at stage a the relation is

$$u_{11}^{(a)} = (1-P_{a1})w_u\tau + P_{a1}(1-P_r)(P_{11}^{(a+1)}u_{11}^{(a+1)} + P_{12}^{(a+1)}u_{12}^{(a+1)} - fd_1) + P_{a1}P_r(w_0\tau - d_1) - c_1 I_{\{k=1\}}. \tag{9}$$

Moreover, because aliens face the same situation at each stage $k \geq a$, we have $u_{11}^{(k)} = u_{11}^{(a)}$ and $P_{11}^{(k)} = P_{11}^{(a)}$ for all $k \geq a$, where

$$u_{11}^{(a)} = (1-P_{a1})w_u\tau + P_{a1}(1-P_r)(P_{11}^{(a)}u_{11}^{(a)} + P_{12}^{(a)}u_{12}^{(a)} - fd_1) + P_{a1}P_r(w_0\tau - d_1) - c_1 I_{\{k=1\}}. \tag{10}$$

Because $P_{12}^{(k)} = 1 - P_{11}^{(k)}$, equations (7), (8) and (10) are a system of $2a$ equations in terms of the $2a$ unknowns, $u_{11}^{(k)}, P_{11}^{(k)}$ for $k = 1, \ldots, a$. We solve these equations using backwards recursion in a fashion reminiscent of optimal stopping problems [3]; indeed, the decision problem faced by an individual Mexican is an optimal stopping problem, but we are solving this problem over the aggregate Mexican alien population using the multinomial-logit model. First, we jointly solve equation (7) with $k = a$ and equation (10) for $P_{11}^{(a)}$ and $u_{11}^{(a)}$; the existence of a unique solution to these two equations, and an approach to numerically solve them, is shown in [4]. With $P_{11}^{(a)}$ and $u_{11}^{(a)}$ in hand, we use equation (8) for $k = a-1$ to get $u_{11}^{(a-1)}$, and then use equation (7) to get $P_{11}^{(a-1)}$, and then recursively solve for $u_{11}^{(a-2)}$, $P_{11}^{(a-2)}, \ldots$ in a similar manner until we obtain $u_{11}^{(1)}$ and $P_{11}^{(1)}$.

2 The Apprehension Submodel

The goal of this section is to compute the apprehension probability P_{ai} at the border for type i aliens. Our macro approach to the apprehension probability captures the impact of the alien flow and enforcement effort (both labor and technology), and ignores the micro-structural variables that provide insight into the personal and community characteristics of the types of people who are apt to be apprehended at the border; see [5] for an example of the latter approach. Espenshade and Acevedo [6] obtain a R^2 of 0.768 in a regression model that includes alien flow and enforcement effort. Our model also incorporates the fact that aliens adapt to the presence of enforcement effort by (often with the help of coyotes) choosing more remote routes [7].

Although the U.S. Government deploys a variety of technologies, including several helicoptors and drones, for detecting border crossers, we focus on the Integrated Surveillance Intelligence Systems (ISIS), which are remote video surveillance systems consisting of a central command center and two infrared and two daytime cameras spanning a 3-5 mile radius [8]. As of 2005, these surveillance systems monitored approximately 15% of the U.S.-Mexico border [9], and hence are more prevalent than helicoptors and drones. Although the Government has over 10,000 seismic, magnetic and thermal sensors on the U.S.-Mexico border [8], in areas without surveillance technology, border patrol agents need to travel – sometimes considerable distances – to investigate all sensor alarms, which are often nuisance alarms (e.g., animals); consequently, these sensor alarms are frequently ignored in these areas [8]. In areas with surveillance technology, the operator can use the video cameras to investigate the sensor alarms, which greatly enhances the effectiveness of these sensors [8].

We model the border as a straight line segment of length L. For $x \in [0, L]$, let the indicator function $I_{\{x\}}$ equal 1 if location x is monitored by surveillance technology, and equal 0 otherwise. Let $n_b(x)$ be the density of border patrol agents at location $x \in [0, L]$ in units of miles^{-1}, where $n_b = \int_0^L n_b(x)\, dx$ is a decision variable that represents the total number of border patrol agents (working at one time). Similarly, for $x \in [0, L]$, let $\lambda_{bi}(x)$ be the arrival rate of type i aliens ($i = 1$ is Mexican, $i = 2$ is OTM) at location x, which has units of miles$^{-1}\times$ time^{-1}, where $\lambda_{bi} = \int_0^L \lambda_{bi}(x)\, dx$ is the total number of type i crossings per year. Due to the complexity of the model in this section, we do not capture the fact that arrivals to the border are seasonal; §3 incorporates seasonality of arrivals to DRO because it plays a bigger factor there than at the border (at least in the base case) due to the extreme lack of bedspace.

We can determine λ_{bi} from our analysis in §1. Recalling that n_i is the total number of potential border crossers of type i, we have that

$$\lambda_{b2} = n_2 P_{21}. \tag{11}$$

If $a = \infty$, then

$$\lambda_{b1} = \frac{n_1 P_{11}}{1 - P_{a1}}. \tag{12}$$

If a is finite, the expected number of k^{th} crossings by Mexicans is $n_1 P_a^{k-1} \Pi_{i=1}^k P_{11}^{(i)}$ for $k = 1, \dots, a$. For $k > a$, there is the possibility of detention and removal, and the expected number of k^{th} crossings is $n_1 P_{a1}^{a-1} \Pi_{i=1}^{a} P_{11}^{(i)} (P_{a1}(1-P_d)P_{11}^{(a)})^{k-a}$. Therefore, the arrival rate of illegal Mexican aliens to the border is

$$\lambda_{b1} = n_1[\sum_{k=1}^{a} P_{a1}^{k-1} \Pi_{i=1}^{k} P_{11}^{(i)} + \sum_{k=a+1}^{\infty} (P_{a1}^{a-1} \Pi_{i=1}^{a} P_{11}^{(i)})(P_{a1}(1-P_d)P_{11}^{(a)})^{k-a}], \quad (13)$$

$$= n_1[\sum_{k=1}^{a-1} P_{a1}^{k-1} \Pi_{i=1}^{k} P_{11}^{(i)} + \sum_{k=a}^{\infty} (P_{a1}^{a-1} \Pi_{i=1}^{a} P_{11}^{(i)})(P_{a1}(1-P_d)P_{11}^{(a)})^{k-a}], \quad (14)$$

$$= n_1\left[\sum_{k=1}^{a-1} P_{a1}^{k-1} \Pi_{i=1}^{k} P_{11}^{(i)} + \frac{P_{a1}^{a-1} \Pi_{i=1}^{a} P_{11}^{(i)}}{1 - P_{a1}(1-P_d)P_{11}^{(a)}}\right]. \quad (15)$$

An alien arriving at location x will not necessarily cross there. We let $\lambda_{ci}(x)$ be the total crossing rate at location x (in units of miles$^{-1}\times$ time^{-1}), where $\int_0^L \lambda_{ci}(x)\, dx = \lambda_{bi}$. We are essentially modeling this process as a Stackelberg game with the U.S. Government as leader (choosing $n_b(x)$) and the aliens as followers (choosing where to cross, i.e., $\lambda_{ci}(x)$). However, we can think of this game as being part of an ongoing sequence of Stackelberg games. If we think in terms of discrete time periods, in each time period there are three decisions: first, the government chooses the spatial allocation of agents ($n_b(x)$), then the aliens choose where to arrive ($\lambda_{bi}(x)$), and finally the aliens choose where to cross ($\lambda_{ci}(x)$). It is natural to assume that the government adapts in period t by choosing $n_b(x)$ to be proportional to the $\lambda_{c1}(x) + \lambda_{c2}(x)$ from period $t-1$ (i.e., $\frac{n_b(x)}{\lambda_{c1}(x)+\lambda_{c2}(x)}$ is a constant for all x). Similarly, it is not unreasonable to assume that the aliens choose $\lambda_{bi}(x)$ in period t to be proportional to the $\lambda_{ci}(x)$ from period $t-1$.

There are very busy areas and very quiet areas along the border. To capture the spatial heterogeneity in the simplest possible way, we assume that both $\lambda_{bi}(x)$ and $n_b(x)$ are sinusoidal functions with the same frequency ω_b (where $\omega_b L$ is an integer) and relative amplitudes $\alpha_b \in [0,1]$ and $\tilde{\alpha}_b \in [0,1]$:

$$\lambda_{bi}(x) = \frac{\lambda_{bi}}{L} + \frac{\lambda_{bi}}{L}\alpha_b \sin(2\pi\omega_b x) \quad \text{for} \quad x \in [0, L], \quad (16)$$

$$n_b(x) = \frac{n_b}{L} + \frac{n_b}{L}\tilde{\alpha}_b \sin(2\pi\omega_b x) \quad \text{for} \quad x \in [0, L]. \quad (17)$$

For simplicity, we assume that $\lambda_{bi}(x)$ and $n_b(x)$ are proportional to each other, which would be the case if $\lambda_{c1}(x)$ and $\lambda_{c2}(x)$ were proportional to each other (although they are not).

We introduce the decision variable s_b, which is the number of miles along the border that are monitored by surveillance technology. We assume that surveillance technology is implemented at the busiest parts of the border, so that

$$I_{\{x\}} = \begin{cases} 1 & \text{if} \quad x \in [\left(\frac{i}{\omega_b} + \frac{1}{4\omega_b}\right) - \frac{1}{2\omega_b}\left(\frac{s_b}{L}\right), \left(\frac{i}{\omega_b} + \frac{1}{4\omega_b}\right) + \frac{1}{2\omega_b}\left(\frac{s_b}{L}\right)] \quad \text{for} \quad i = 0, \ldots, \omega_b L - 1; \\ 0 & \text{otherwise.} \end{cases} \quad (18)$$

The main modeling challenge is to determine $\lambda_{ci}(x)$ given both $\lambda_{bi}(x)$ and $n_b(x)$. Let $u_i(x, y)$ be the utility of a type i alien who arrives at location x (we assume the cost to get to location x on the border is sunk) and crosses at location y. Let $P_a(y)$ be the apprehension probability at location $y \in [0, L]$ and let k be the cost of traveling (in units of miles^{-1}) for aliens of type $i = 1, 2$. Then the utility for OTMs is given by

$$u_2(x, y) = (1 - P_a(y))w_u\tau + P_a(y)((1 - P_r)(w_u\tau - fd_2) + P_r(w_o\tau - d_2)) - k|x - y|. \quad (19)$$

For simplicity, we assume that Mexicans are not detained and will keep attempting to cross (at their chosen location) until they succeed, and that each time they are apprehended they are immediately returned to Mexico and suffer a cost $\tilde{d}_1$. In essence, in this submodel we assume that if the U.S. Government became more aggressive about detaining Mexicans (e.g., reduced a to 1 or 2), then this would deter Mexicans at the initial decision stage of whether or not to travel to the border, and those who traveled to the border would be undeterred. Hence, we have

$$u_1(x, y) = w_u\tau - \frac{P_a(y)}{1 - P_a(y)}\tilde{d}_1 - k|x - y|. \quad (20)$$

At location y, there is a border patrol agent every $\frac{1}{n_b(y)}$ miles. Each agent can be viewed as the server in a single-server loss queueing system with (at this point unknown) arrival rate $\frac{P_a(y)[\lambda_{c1}(y)+\lambda_{c2}(y)]}{n_b(y)}$ and mean apprehension time m_b, which is only incurred when aliens are actually apprehended (i.e., aliens that go undetected, or are detected but not apprehended, experience no service time, because most of the apprehension time is devoted to transporting – or waiting for transportation for – the apprehended alien). It follows that the probability that the agent is busy with an apprehension is $\frac{\rho_b}{1+\rho_b}$, where

$$\rho_b(y) = \frac{P_a(y)[\lambda_{c1}(y) + \lambda_{c2}(y)]m_b}{n_b(y)}. \quad (21)$$

We now derive an expression for the apprehension probability at location y, $P_a(y)$. If a crossing occurs while the agent at this location is busy with another apprehension, then the agent will not apprehend the crosser. We assume that the arrivals near location y follow a spatially homogeneous Poisson process and the location of the agent is random (i.e., he spends his time driving back and forth along the $\frac{1}{n_b(y)}$ miles), so that the distance between the agent and the alien at the time of crossing is the random distance between any two points that are uniformly distributed on $[0, \frac{1}{n_b(y)}]$, which has pdf

$$f(x) = \frac{2(\frac{1}{n_b(y)} - x)}{(\frac{1}{n_b(y)})^2}. \quad (22)$$

If there is no technology deployed at location y (i.e., $I_{\{y\}} = 0$), then we assume that an idle agent will detect and apprehend the crosser with probability $e^{-\alpha_1 x}$ if the agent and alien are at a distance x apart at the time of crossing (i.e., apprehension occurs if the distance between them is less than an exponential random variable with parameter α_1). Similarly, if there is technology deployed at location y (i.e., $I_{\{y\}} = 1$), then we assume that an idle agent will detect and apprehend the crosser with probability $e^{-\alpha_2 x}$ if the agent and alien are at a distance x apart at the time of crossing, where it is natural to expect that $\alpha_2 < \alpha_1$

(i.e., technology aids in detection and apprehension). Taken together, the probability of apprehension at location y is

$$P_a(y) = \frac{1}{1+\rho_b(y)}\left[I_{\{y\}}\int_0^{\frac{1}{n_b(y)}} f(x)e^{-\alpha_2 x}\ dx + (1-I_{\{y\}})\int_0^{\frac{1}{n_b(y)}} f(x)e^{-\alpha_1 x}\ dx\right]. \tag{23}$$

We now use a multinomial logit model with a continuum of choices to compute $P_{ci}(x,y)$, which is the probability that an alien arriving at location x will cross at location y. This model is given by

$$P_{ci}(x,y) = \frac{e^{\theta u_i(x,y)}}{\int_0^L e^{\theta u_i(x,y)}\ dy} \quad \text{for} \quad i=1,2. \tag{24}$$

Hence, the crossing rate of a type i alien at location y is given by

$$\lambda_{ci}(y) = \int_0^L \lambda_{bi}(x)P_{ci}(x,y)\ dx. \tag{25}$$

Equation (25) is a fixed-point equation for $\lambda_{ci}(y)$ because $P_{ci}(x,y)$ on the right side of (25) is a function of $u_i(x,y)$ in equation (24), which is a function of $P_a(y)$ in equations (19)-(20), which is a function of $\rho_b(y)$ in (23), which is a function of $\lambda_{ci}(y)$ in (21).

Finally, we obtain the apprehension probability P_{ai} for type i aliens, which is

$$P_{ai} = \frac{\int_0^L \lambda_{ci}(y)P_a(y)\ dy}{\lambda_{bi}}. \tag{26}$$

Equation (26) corresponds to equation (2) in the main text.

3 The Removal Submodel

The goal of this section is to compute P_r, the probability that an illegal alien apprehended at the border is detained and removed, given that the U.S. Government would like to detain and remove him (i.e., given that he is either Mexican on at least his a^{th} apprehension or an OTM). The DRO facilities, which consist of eight large facilities in the U.S. plus contracted beds at a variety of other facilities, house aliens while they are waiting for removal proceedings to be completed. Most detained OTMs are ready to be voluntarily removed, but need to be detained until the home country verifies their identification (most come with no identification). There are mandatory detainees and non-mandatory detainees. Nearly all criminals are mandatory detainees, and some noncriminals are mandatory [10]. We model this facility as the following 2-class, infinite-server, partial-loss queueing system that has been analyzed elsewhere [11]. Because nearby DRO facilities are used if the closest facility is full, we model this system by a single pooled queue, which should be an accurate approximation [12, 13]. We let aliens of class i ($i=m$ is mandatory, $i=n$ is nonmandatory) arrive according to a sinusoidal Poisson arrival process with average rate $\bar{\lambda}_i$, frequency ω_d and relative amplitude α_d; i.e., the arrival rate for class i aliens at time t is $\bar{\lambda}_i + \bar{\lambda}_i\alpha_d \sin(2\pi\omega_d t)$.

Let λ_{d1} be the rate at which Mexicans are apprehended at the border on at least their a^{th} apprehension and let λ_{d2} be the rate at which OTMs are apprehended at the border. We know from §1.1 that

$$\lambda_{d2} = n_2 P_{21} P_{a2}. \tag{27}$$

Similarly, λ_2 equals the expected number of a^{th} and later crossings multiplied by apprehension probability, which by (15) is

$$\lambda_{d1} = n_1 \frac{P_{a1}^{a-1} \Pi_{i=1}^{a} P_{11}^{(i)}}{1 - P_{a1}(1-P_d)P_{11}^{(a)}} P_{a1} \tag{28}$$

if a is finite, and $\lambda_{d1} = 0$ if $a = \infty$.

Aliens arriving to DRO are apprehended not only at the U.S.-Mexico border, but also at the other borders, at the ports-of-entry, in the interior, and from jails (i.e., they have finished serving jail time but are yet to be removed). Hence, we need to determine a relationship between the mean arrival rates of mandatory and nonmandatory aliens to DRO, $\bar{\lambda}_m$ and $\bar{\lambda}_n$, and the U.S.-Mexico border rates in equations (27) and (28). Because most of the criminals entering DRO come directly from jails, not from the border, we assume that λ_m is an exogenous parameter that is independent of λ_{di}. We assume that

$$\bar{\lambda}_n = a_n + b_n[\lambda_{d1} + \lambda_{d2}], \tag{29}$$

where the constants a_n and b_n are computed in §5.3 using DRO data. Equation (29) implicitly assumes that the nonmandatory apprehensions away from the U.S.-Mexico border are roughly proportional to the nonmandatory apprehensions at the U.S.-Mexico border, as they were before and after the Hold The Line operation [6]. The rationale is that as the number of aliens apprehended at the border increases, the number that successfully cross the border also increases, which should increase the number of apprehensions that occur in the interior.

The residence time for class i aliens is an exponential random variable with mean m_i for $i = \{m, n\}$. When a mandatory detainee arrives to the system he is detained. If there is not sufficient bed space, then one is rented and he is moved into a DRO bed later if room becomes available [8]. When a nonmandatory detainee arrives to the system, he is blocked from entering the system if no beds are available. As explained in §1, a blocked Mexican is returned to Mexico and a blocked OTM is released into the interior of the U.S. If all DRO beds are filled but at least one nonmandatory detainee is being detained, then a nonmandatory detainee is released into the interior of the U.S. and the bed is given to the arriving mandatory detainee. In this case, we say that the mandatory detainee is preempted.

An equation for the mean total number of nonmandatory aliens released (i.e, blocked plus preempted) per year is derived in [11], which allows us to compute the detection probability P_r in terms of the seven DRO parameters: the number of DRO beds (s), the mean arrival rate of mandatory ($\bar{\lambda}_m$) and nonmandatory ($\bar{\lambda}_n$) detainees, the mean residence time of mandatory (m_m) and nonmandatory (m_n) detainees, and the frequency (ω_d) and relative amplitude (α_d) of the sinusoidal arrival rates. To this end, for $i = \{m, n\}$, let f_{it} and F_{it} be the probability density function (pdf) and cumulative distribution function (cdf) of a normal random variable with mean and variance

$$\bar{\lambda}_i m_i \Big(1 + \frac{\alpha_d}{1 + (2\pi m_i \omega_d)^2}[\sin(2\pi\omega_d t) - 2\pi m_i \omega_d \cos(2\pi\omega_d t)]\Big). \tag{30}$$

Then the mean number of detainees released per year (the frequency is $\omega_d = 1/\text{yr}$) is

$$R = \int_0^{\omega_d^{-1}} R(t)\; dt, \tag{31}$$

where

$$R(t) = \lambda_n(t)\Big(\int_0^s \frac{f_{mt}(x)f_{nt}(s-x)}{F_{nt}(s-x)}\ dx + 1 - F_{mt}(s+1)\Big), \tag{32}$$

and the probability of removal is

$$P_r = 1 - \frac{R}{\bar{\lambda}_n}, \tag{33}$$

which is the mathematical version of relation (3) in the main text.

Our main performance measure, denoted by P_T, is the probability that an OTM terrorist successfully enters the country, which is given by

$$P_T = 1 - P_{a2} + P_{a2}(1 - P_r). \tag{34}$$

Preempted nonmandatory aliens are released (on bond) from the DRO facilities but are still processed, and approximately 1% of these overflow cases are released on order of supervision. However, more than 90% of nondetained aliens do not appear in court, and only 13% of nondetained aliens (and only 6% from countries believed to support terrorist activites) with final removal orders are actually removed [14]. Electronic home-monitoring of low-risk nondetained aliens has been tested and appears to be moderately successful [15]. From a homeland security viewpoint, we assume in equation (34) that a terrorist who is released on bond will not appear in court.

4 The Illegal Wage Submodel

The goal here is to construct a model that quantifies how changes in worksite enforcement, including fines for hiring illegal aliens and the number of worksite inspectors, as well a guest-worker program that brings new aliens into the country as legal workers and an amnesty program that would legalize illegal workers currently in the U.S., would impact the wages of illegal aliens that sneak across the border.

It appears that the 1986 Immigration Reform and Control ACT (IRCA) sanctions did not work because of the widespread use of illegal documents and contracting firms, the easy way out for employers (they were protected as long as they filled out I-9 forms and looked at workers' identification cards), and the low level of sanctions enforcement [16]. We assume an idealized system that works according to plan (e.g., perfect document security for employment verification, employers cannot pass the risk along to subcontractors), with five controllable variables: the number of currently illegal workers that are legalized, the number of newly legal workers who participate in a guest-worker program, the number of worksite inspectors, the extent to which the inspections are targeted (characterized by the parameter r_w in equation (35)), and the size of the fine (we focus on a hiring fine, even though the IRCA enforcements relied mostly on paperwork fines).

Our model is described in three subsections: how the Government deploys its worksite enforcement resources and what the employers do in the face of this enforcement, the labor demand, and the labor supply.

4.1 Work Site Enforcement

Suppose m_w worksite enforcement agents are hired, each of which performs inspections at μ_w firms per year. Let $n_w = m_w\mu_w$ be the number of firms inspected per year, N_w be the total number of firms in the U.S. that hire illegal aliens, and N_i be the total number of illegal workers in the U.S. For mathematical simplicity, we assume that the number of illegal workers in a firm is an exponential random variable with mean $\frac{N_i}{N_w}$, which succinctly captures the phenomenon that many illegal workers are concentrated in a handful of industries [17].

The only study to explicitly address how the Government should allocate enforcement resources across firms is [18], which solves a constrained optimization problem and finds that only firms in industries with the largest number of illegal employees should be inspected, and that among inspected industries, the fraction of firms in an industry that should be inspected is linearly increasing with the number of illegal workers per firm in that industry. However, in contrast to this policy, approximately 60% of the IRCA investigations were aimed at suspected companies/industries, and the remaining investigations were essentially random [19].

We follow what was used during IRCA and assume a hybrid targeted-random strategy, where a fraction r_w of inspections are targeted and the remaining inspections are random. We assume that the Government knows which firms have the most illegal workers, and the targeted inspections are aimed at these firms. That is, the firms in the highest $\frac{r_w n_w}{N_w}$ fractile of illegal workers are targeted, which corresponds to the firms with more than $\frac{N_i}{N_w}\ln\left(\frac{N_w}{r_w n_w}\right)$ illegal workers. The remaining fraction $1-r_w$ of inspections are randomly sampled from the untargeted industries, so that the annual probability of inspecting a firm that hires x illegal aliens is

$$p_w(x) = \begin{cases} \frac{(1-r_w)n_w}{N_w - r_w n_w} & \text{if} \quad x < \frac{N_i}{N_w}\ln\left(\frac{N_w}{r_w n_w}\right); \\ 1 & \text{if} \quad x \geq \frac{N_i}{N_w}\ln\left(\frac{N_w}{r_w n_w}\right). \end{cases} \tag{35}$$

In the face of sanctions, we assume that employers pass the expected penalties on to the illegal workers in the form of lower wages [18, 20]. Due to our assumption about perfect document security, employers can fully discern the legal status of workers. Therefore, illegal laborers at a firm with x illegal laborers are paid, assuming that employment decisions are made on an annual basis so that the expected fine is allocated over one year,

$$w_i(x) = \max\{w - p_w(x)f_w, 0\}, \tag{36}$$

where w is the legal wage that is determined in §4.3 and f_w is the fine per illegal worker per hour of work.

4.2 Labor Demand

We take the view that immigrants tend to fill jobs that native workers do not want, and that in the absence of these workers, many of these jobs would be replaced by capital or move offshore [21]. Hence, we ignore high-skilled labor in our model, and assume that each of the N_w firms has a Cobb-Douglas production function with two factors, unskilled workers and capital [20], i.e., the output equals $Y = L^{\alpha_w}K^{1-\alpha_w}$, where r is the cost of capital and w

is the cost of labor, which includes wages and expected sanctions; because employers pass the expected penalties on to the workers, this w is the same as in equation (36). The cost-minimizing demand for labor is $\left(\frac{\alpha_w r}{(1-\alpha_w)w}\right)^{1-\alpha_w} Y$ [22]. If we assume that the parameters α_w, r and w and the output Y are common across all N_w firms (the assumption on Y is only for notational simplicity), then the annual labor hours demanded is $\left(\frac{\alpha_w r}{(1-\alpha_w)w}\right)^{1-\alpha_w} N_w Y$. To ease the parameter estimation task, we express this as

$$L_d = A_w \left(\frac{1}{w}\right)^{1-\alpha_w}, \tag{37}$$

where $A_w = \left(\frac{\alpha_w r}{1-\alpha_w}\right)^{1-\alpha_w} N_w Y$.

4.3 Labor Supply

The unskilled labor is supplied by both legal and illegal workers currently in the U.S., which are assumed to have equal skill levels. Let the total legal labor supply be initially fixed at N_l and recall that N_i be the total number of illegal workers currently in the U.S. We model legalization by the decision variable $\Delta_l \in [0, N_i]$, which is the number of illegal workers that are legalized, and we model a guest-worker program by the decision variable N_g, which is the number of new aliens that are legally brought into the U.S. to work. We assume that the guest-worker slots are allocated to Mexicans and OTMs in proportion to n_i, so that the number of potential border crossers that are Mexican and OTM is reduced to

$$n_1 - \frac{n_1}{n_1 + n_2} N_g, \tag{38}$$

$$n_2 - \frac{n_2}{n_1 + n_2} N_g. \tag{39}$$

Hence, we have four pools of labor supply: N_l originally legal, $N_i - \Delta_l$ illegal, Δ_l newly legal and N_g new guest workers. The legal laborers (i.e., all but the $N_i - \Delta_l$ illegal workers) are paid the equilibrium legal wage w, while an illegal laborer at a firm with x illegal laborers is paid $w_i(x)$ in equation (36).

As in [20], we use the neo-classical labor supply function to compute the number of legal labor hours the N_l originally legal people are willing to work at wage w. This model (§4.1 of [23]) assumes each person has the utility $\alpha_0 \log(q_0 - \gamma_0) + (1 - \alpha_0)\log(q - \gamma)$, where q_0 is the number of waking hours minus the number of labor hours, q is the quantity of goods bought at price p, α_0 is a weighting factor, and γ_0 and γ are committed leisure and consumption, respectively. The utility-maximizing amount of legal labor supplied per person, subject to the budget constraint $wq_0 + pq = wT + \mu$, where T is 24 hr, μ is nonlabor income, and p is an index of consumption good prices, is (§4.1 of [23])

$$(1 - \alpha_0)(T - \gamma_0) + \frac{\alpha_0 \gamma p}{w} - \frac{\alpha_0 \mu}{w}. \tag{40}$$

To reduce the number of parameters to estimate, we multiply (40) by $365N_l$ and express the annual legal labor hours supplied by

$$N_l\Big(\kappa_1 - \frac{\kappa_2}{w}\Big), \tag{41}$$

where $\kappa_1 = 365(1-\alpha_0)(T-\gamma_0)$ and $\kappa_2 = 365\alpha_0(\mu - \gamma p)$.

Because the base-case amount of worksite enforcement is negligible, and because we are interested in the impact of greater levels of enforcement, we implicitly assume that most illegal workers are already employed before enforcement. In our model, illegal aliens who have their wages lowered due to worksite enforcement have the option of staying in their present job, quitting and looking for a job with a U.S. firm that has a lower probability of being inspected, or returning home. Because there are only two different illegal wages offered (see (35)-(36)), we assume that illegal workers who quit a job at an untargeted firm will return to their home country because the other untargeted firms pay the same wage and the targeted firms pay a lower wage. In contrast, we consider the possibility that illegal workers who quit a job at a targeted firm may prefer to fill a vacated job at an untargeted firm rather than go home. Hence, we consider a matching process between the illegal workers who quit a job at a targeted firm, and the jobs at untargeted firms that were vacated by illegal aliens; illegal workers who are not matched return to their home country. This matching process takes place before the firms decide to raise the legal wage and/or increase the amount of capital in response to the vacated jobs.

We again use a multinomial logit model similar to equation (1) to compute how many people stay in their reduced-wage job. The expected utility if an illegal alien returns home is $w_0\tau - c_1$ where w_0 is the annual home wage and c_1 is the cost to return home (we use c_1 because most illegal workers are Mexican). The expected utility if he stays in the U.S. is $hx\tau$ if he is offered the hourly wage x, where h is the number of hours worked per worker per year.

By equation (35), the probability that an illegal worker works in a targeted firm is

$$P_t = \frac{N_w \int_{\frac{N_i}{N_w}\ln(\frac{N_w}{r_w n_w})}^{\infty} x \frac{N_w}{N_i} e^{-N_w x/N_i}\, dx}{N_i}, \tag{42}$$

$$= \frac{r_w n_w}{N_w}(1+\ln(\frac{N_w}{r_w n_w})). \tag{43}$$

Equation (36) implies that an illegal worker will be offered the hourly wage

$$w_t = \max(w - f_w, 0) \tag{44}$$

with probability P_t (i.e., if he works at a targeted firm), and the hourly wage

$$w_r = \max(w - \frac{f_w(1-r_w)n_w}{N_w - r_w n_w}, 0) \tag{45}$$

otherwise. Then the probability that an illegal worker will stay at his reduced-wage job is the weighted average of the multinomial logit models,

$$P_t \frac{e^{\theta h w_t \tau}}{e^{\theta h w_t \tau} + e^{\theta(w_0\tau - c_1)}} + (1-P_t)\frac{e^{\theta h w_r \tau}}{e^{\theta h w_r \tau} + e^{\theta(w_0\tau - c_1)}}. \tag{46}$$

We now describe the matching process for those who leave their job. Our matching process uses a Cobb-Douglas form with constant returns to scale, which is consistent with the empirical literature [24]. If U is the number of unemployed workers looking for a job, V is the number of vacated jobs, and M is the number of matches, then

$$M = \min\{U, V, A_m U^{\alpha_m} V^{1-\alpha_m}\}, \tag{47}$$

where A_m and α_m are constants. In analyzing this matching process, note that we can interpret $\frac{e^{\theta hx\tau}}{e^{\theta hx\tau}+e^{\theta(w_o\tau-c_1)}}$ as a cdf that represents the fraction of illegal workers that prefer to work at hourly wage x rather than return to their home country. Hence, U is given by the number of illegal workers times the probability that a worker is originally in a targeted firm, quits his job because he is unwilling to work at wage w_t, but is willing to work at wage w_r,

$$U = N_i P_t \left(\frac{e^{\theta h w_r \tau}}{e^{\theta h w_r \tau} + e^{\theta(w_o\tau - c_1)}} - \frac{e^{\theta h w_t \tau}}{e^{\theta h w_t \tau} + e^{\theta(w_o\tau - c_1)}} \right). \tag{48}$$

Similarly, V is given by the number of illegal workers times the probability that a worker is originally in an untargeted firm and quits his job because he is unwilling to work at wage w_r,

$$V = N_i(1-P_t) \left(\frac{e^{\theta(w_o\tau - c_1)}}{e^{\theta h w_r \tau} + e^{\theta(w_o\tau - c_1)}} \right). \tag{49}$$

By equations (46)-(49), the annual illegal labor supply (for ease of presentation, in the remainder of this section we assume that the Cobb-Douglas term achieves the minimum in (47)) is

$$\begin{aligned} & N_i h \Big[\frac{P_t e^{\theta h w_t \tau}}{e^{\theta h w_t \tau} + e^{\theta(w_0\tau - c_1)}} + \frac{(1-P_t) e^{\theta h w_r \tau}}{e^{\theta h w_r \tau} + e^{\theta(w_0\tau - c_1)}} \\ & + A_m \Big(\frac{P_t e^{\theta h w_r \tau}}{e^{\theta h w_r \tau} + e^{\theta(w_o\tau - c_1)}} - \frac{P_t e^{\theta h w_t \tau}}{e^{\theta h w_t \tau} + e^{\theta(w_o\tau - c_1)}} \Big)^{\alpha_m} \Big(\frac{(1-P_t) e^{\theta(w_o\tau - c_1)}}{e^{\theta h w_r \tau} + e^{\theta(w_o\tau - c_1)}} \Big)^{1-\alpha_m} \Big]. \end{aligned} \tag{50}$$

The newly legal workers Δ_l also have the option to go home, but are getting paid exactly w, and hence the amount of newly legal labor supplied annually is

$$\Delta_i h \frac{e^{\theta h w \tau}}{e^{\theta h w \tau} + e^{\theta(w_0\tau - c_1)}}. \tag{51}$$

We assume that the new guest workers all stay, providing

$$N_g h \tag{52}$$

hours of work annually.

The equilibrium condition is found by equating the labor demanded, which is the right side of (37), to the labor supplied, which is the sum of (41), (50), (51) and (52):

$$\begin{aligned} A_w \left(\frac{1}{w}\right)^{1-\alpha_w} = \; & N_l(\kappa_1 - \tfrac{\kappa_2}{w}) + \Delta_i h \frac{e^{\theta h w \tau}}{e^{\theta h w \tau} + e^{\theta(w_o\tau - c_1)}} + N_g h \\ & + N_i h \Big[P_t \frac{e^{\theta h w_t \tau}}{e^{\theta h w_t \tau} + e^{\theta(w_0\tau - c_1)}} + (1-P_t) \frac{e^{\theta h w_r \tau}}{e^{\theta h w_r \tau} + e^{\theta(w_0\tau - c_1)}} \\ & + A_m \Big(\frac{P_t e^{\theta h w_r \tau}}{e^{\theta h w_r \tau} + e^{\theta(w_o\tau - c_1)}} - \frac{P_t e^{\theta h w_t \tau}}{e^{\theta h w_t \tau} + e^{\theta(w_o\tau - c_1)}} \Big)^{\alpha_m} \Big(\frac{(1-P_t) e^{\theta(w_o\tau - c_1)}}{e^{\theta h w_r \tau} + e^{\theta(w_o\tau - c_1)}} \Big)^{1-\alpha_m} \Big]. \end{aligned} \tag{53}$$

We solve (53) for the equilibrium legal wage w. By equation (50), we set the annual illegal wage w_u in §1 equal to

$$w_u = \frac{\frac{P_t e^{\theta h w_t \tau} w_t}{e^{\theta h w_t \tau}+e^{\theta(w_0\tau - c_1)}} + \frac{(1-P_t)e^{\theta h w_r \tau} w_r}{e^{\theta h w_r \tau}+e^{\theta(w_0\tau - c_1)}} + A_m w_r \left(\frac{P_t e^{\theta h w_r \tau}}{e^{\theta h w_r \tau}+e^{\theta(w_o\tau - c_1)}} - \frac{P_t e^{\theta h w_t \tau}}{e^{\theta h w_t \tau}+e^{\theta(w_o\tau - c_1)}}\right)^{\alpha_m} \left(\frac{(1-P_t)e^{\theta(w_o\tau - c_1)}}{e^{\theta h w_r \tau}+e^{\theta(w_o\tau - c_1)}}\right)^{1-\alpha_m}}{\frac{P_t e^{\theta h w_t \tau}}{e^{\theta h w_t \tau}+e^{\theta(w_0\tau - c_1)}} + \frac{(1-P_t)e^{\theta h w_r \tau}}{e^{\theta h w_r \tau}+e^{\theta(w_0\tau - c_1)}} + A_m \left(\frac{P_t e^{\theta h w_r \tau}}{e^{\theta h w_r \tau}+e^{\theta(w_o\tau - c_1)}} - \frac{P_t e^{\theta h w_t \tau}}{e^{\theta h w_t \tau}+e^{\theta(w_o\tau - c_1)}}\right)^{\alpha_m} \left(\frac{(1-P_t)e^{\theta(w_o\tau - c_1)}}{e^{\theta h w_r \tau}+e^{\theta(w_o\tau - c_1)}}\right)^{1-\alpha_m}}. \tag{54}$$

Equation (54) corresponds to relation (4) in the main text.

5 Parameter Estimation

In the next four subsections, we estimate the parameters from the four submodels in §1-4. The parameter values for these four submodels are listed in Tables 1-4 and the base-case values of the decision variables appear in Table 5; although some of these parameters appear in several submodels, they appear in the table for the submodel in which they play the most central role.

5.1 Discrete Choice Parameters

We consider a time horizon of $\tau = 2$ yr. For lack of resources, the U.S. Attorneys Office does not prosecute an illegal immigrant until he has been apprehended 13 times [8]. Because $P_a^{13} \approx 10^{-9}$, it appears unlikely that many of those detained were held because they were previously apprehended a specific number of times. Consequently, as noted in §1.2, we set the decision variable $a = \infty$ in the base case.

We need values for the parameters w_o, w_u, c_i, d_i, $\tilde{d}_i$, f, P_{ai}, P_r, λ_{di}, n_i, and λ_{bi}. We begin with the wages and costs, and then estimate some of the apprehension and detention parameters. The more difficult parameters to estimate are discussed last.

The hourly wage in 2004 for production workers in manufacturing in Mexico was \$2.50 (Table 2 in [25]). Most OTM aliens are from Caribbean countries (e.g., Guatemala, Honduras, El Salvador) that have similar economic conditions. At 2000 hr/yr, we get $w_o = \$5000$/yr as the annual wage in the home country. The average wage of Mexican immigrants in the U.S. is \$22,300/yr [26]. Because there is currently a trivial amount of worksite enforcement, we set the annual illegal wage in the U.S. to be $w_u = \$22,300$/yr. Including the travel cost, the cost of a coyote (77% of aliens use coyotes [27]), the lost time, and the danger, we roughly estimate the one-way cost of migration to be $c_1 = \$1500$ and $c_2 = \$2500$.

We assume the detention cost d_i includes the cost of lost wages in the home country and an additional cost due to the physical and psychological toll of being detained. We assume d_i is proportional to the square root of the number of days in detention. The concavity of the square root function attempts to crudely capture the phenomenon that the very act of being detained carries a significant psychological toll, regardless of the length of detention. Although a fixed plus variable cost of detention may be more appropriate, this would require an additional parameter to estimate. More specifically, we let $d_i = \psi\sqrt{\tilde{m}_i}$, where ψ is the toll factor of apprehension (which is estimated later) and $\tilde{m}_i$ is the number of days that a type i

alien is detained until removal. Similarly, we let $\tilde{d}_1 = \psi\sqrt{2}$, where it is assumed that two days of U.S. salary are lost during the apprehension process (and the toll includes the possibility that the U.S. Government takes their fingerprints upon apprehension). In [11], we calculated that the mean uncensored residence time for nonmandatory aliens is 48.0 days, whereas the observed, right-censored residence times for Mexican noncriminals, OTM noncriminals, and all noncriminals is 10.5, 42.4, and 28.7 days, respectively, where the weighted average for all noncriminals uses the unblocked arrival rates (45,925 Mexican noncriminals and 61,312 OTM noncriminals) to determine the weights. If we assume that apprehended aliens in our model are noncriminal, and apply the censoring factor $\frac{48.0}{28.7}$ to the censored residence times for Mexican noncriminals and OTM noncriminals, we get $\tilde{m}_1 = \frac{48.0}{28.7}(10.5) = 17.6$ days and $\tilde{m}_2 = \frac{48.0}{28.7}(42.4) = 70.9$ days.

The parameter f is the fraction of the total detention cost incurred before release from DRO. The parameter g is the expected number of days detained before release from DRO (and voluntary departure to Mexico) conditioned on not being detained until removal, divided by the expected number of days detained until removal. Since the cost d_i is proportional to the square root of the detention duration, we approximate f by $\sqrt{g}$ (although the expected value of the ratio does not equal the ratio of the expected values in the computation of g, the two should be similar because the denominator is bigger than the numerator). In 2003, there were 28,000 blocked arrivals (i.e., people who were not detained at all) and 43,000 preempted arrivals (i.e., aliens who were detained but were released before removal) out of 93,976 total arrivals, so that probability of removal in 2003 was $P_r = 1 - \frac{71{,}000}{93{,}976} = 0.245$. Recalling that the mean censored residence time is 28.7 days and the mean uncensored residence time is 48.0 days, we get that in 2003 $g = \frac{43{,}000}{28{,}000+43{,}000}\frac{28.7}{48.0} = 0.36$. As mentioned in §1.1, the parameter g varies in a complicated way with the number of DRO beds. To enable the optimization of the entire system, we assume that g can be expressed as a quadratic function of the removal probability P_r. Fitting the three parameters of the quadratic function to the two (g, P_r) extreme points, (0,0) and (1,1), and the 2003 point (0.36,0.245) yields the relationship

$$f = \sqrt{g} = \sqrt{1.637P_r - 0.637P_r^2}. \tag{55}$$

The current removal probability is estimated to be $P_r = 0.137$ in §5.3, and so $f = 0.46$ in the base case. We assume that the base-case apprehension probability is $P_{a1} = P_{a2} = 0.2$ [7], which is lower than it was in the 1970s and 1980s [6].

This leaves six unestimated parameters: θ, ψ (embedded within d_i), n_1, n_2, λ_{b1}, and λ_{b2}. The parameters θ and ψ will be jointly estimated with two other parameters in §5.2. Here we provide one of the four equations that will be needed for their derivation. This equation is based on an analysis in [28], which estimates that the natural logarithm of the monthly apprehension rate at the U.S.-Mexico border increases by 0.049 times the ratio, for Mexican aliens, of the U.S. wage and the Mexican wage. Let $\tilde{\lambda}_{b1}$ be the value of λ_{b1} in (12) but with w_u replaced by $w_u + w_0$, which represents an increase of the wage ratio by 1.0. Noting that the monthly apprehension rate in [28] corresponds to $\frac{P_{a1}\lambda_{b1}}{12}$ in our model, our equation is given by

$$\ln\left(\frac{P_{a1}\lambda_{b1}}{12}\right) = \ln\left(\frac{P_{a1}\tilde{\lambda}_{b1}}{12}\right) - 0.049. \tag{56}$$

We complete this subsection by deriving values for n_1, n_2, λ_{b1}, and λ_{b2}. After obtaining values of $\theta = 6.83 \times 10^{-5}/\$$ and $\psi = \$1067/\sqrt{\text{day}}$ in §5.2, we can compute P_{1j} and P_{2j} in the base case, which yields $P_{11} = 0.903$ and $P_{21} = 0.887$. In 2005, 155k OTMs were apprehended at the U.S.-Mexico border [29], and so $\lambda_{d2} = 155\text{k/yr}$. By equation (27), $\lambda_{b2} = n_2 P_{21} = \frac{\lambda_{d2}}{P_{a2}}$ =775k/yr and $n_2 = 874\text{k}$. In the base case, we know $\lambda_{d1} = 0$. In 2004, 1.16M Mexican aliens were apprehended by Border Patrol agents [30]. Assuming these apprehensions all took place at the U.S.-Mexico border, in the base case ($a = \infty$) we have $\frac{n_1 P_{11} P_{a1}}{1-P_{a1}} = 1.16\text{M}$, which gives $n_1 = 5.14\text{M}$ and, by equation (12), $\lambda_{b1} = 5.80\text{M/yr}$.

5.2 Apprehension Parameters

We need to estimate values for the parameters L, ω_b, α_b, k, α_1, α_2, m_b, and θ, along with base-case values of the decision variables n_b and s_b, and the costs c_b and c_s for agents and surveillance technology. We start with the straightforward parameters, then turn to the decision variables and costs, and then finally to the more difficult parameters.

We let $L = 1933$ miles [8] and assume $m_b = 1$ hr based on conversations with government employees. The cost of a coyote increased \$800 when they needed to take more rural routes [7], and we assume $k = \$4/\text{mile}$ because each sector averages approximately 200 miles in length and it is clear from data that people cross in adjacent sectors in the presence of increased enforcement [7, 31]. We assume there are 10 peak crossing points that are evenly distributed across the U.S.-Mexico border (currently seven fences are in place with several more proposed [32], so that $\omega_b = \frac{10}{L} = 5.17 \times 10^{-3}/\text{mile}$. In the base case we assume the arrival rate $\lambda_{bi}(x)$ and border agent density $n_b(x)$ have the same amplitude, so that $\alpha_b = \tilde{\alpha}_b$. The largest apprehension rate per mile among the nine sectors divided by the smallest apprehension rate per mile among the nine sectors is approximately 40 [32], and so we set $\frac{\alpha_b+1}{\alpha_b-1} = 40$, which gives $\alpha_b = \frac{39}{41} = 0.951$.

Now we turn to the decision variables and costs. Assuming around-the-clock surveillance and 11,380 border patrol agents [17] who work 2000 hr/yr but spend only 63% of their time on the border [27], we have $n_b = \frac{0.63(11{,}380)(2000\text{ hr/yr})}{8766\text{ hr/yr}} = 1636$ agents at a given time on the border. We assume that a border patrol agent costs \$176k per year to work 40 hr/week [33], and that 63% of agent hours are on the border. Hence, the annual cost per n_b is $c_b = \frac{(\$176\text{k/yr})(168\text{ hr/wk})}{0.63(40\text{ hr/wk})} = \$1.173\text{M/yr}$. There are several different kinds of technologies, and we focus on surveillance cameras, which are far more prevalent than helicoptors and drones, and much more effective than thermal sensors [8]. Page 53 of [8] claims that 25% of the Laredo, El Paso and McAllen sectors are covered by surveillance technology, and the GAO reports that approximately 300 miles of the Northern and Southern borders are covered [9]. We set $s_b = 0.15L = 290$ miles in the base case. These surveillance systems cost \$90k/mile ([32], which is consistent with the estimate that each camera system costs \$650k [8]. However, we need to convert this to an annual cost. Each operator is in charge of several dozen cameras [8], and there are four cameras to cover five miles, and so this extra cost is approximately \$3000/yr. As a ballpark figure, we use c_s =\$30k/mile·yr, assuming a lifetime of approximately five years and some maintenance.

We conclude this subsection by computing the four remaining parameters, θ, ψ (embedded in d_i and $\tilde{d}_1$), α_1 and α_2, from four equations. One of these equations is (56). Two more equations are constructed by setting the right side of equation (26) equal to 0.2 for $i = 1, 2$ (i.e., $P_{a1} = P_{a2} = 0.2$), which is the base-case apprehension probability [7]. Page 41 of [8] states that technology (which covers approximately 15% of the U.S.-Mexico border) is responsible for up to 60% of apprehensions in some sectors on the U.S.-Mexico border. This 60% figure would appear to be an upper bound and we estimate the efficacy of surveillance technology by assuming that it plays a role in 45% of all apprehensions. Hence, by equations (23) and (26), the fourth equation is

$$\frac{\int_0^L \frac{\lambda_{ci}(y) I_{\{y\}} \int_0^{\frac{1}{n_b(y)}} f(x) e^{-\alpha_2 x}\, dx}{1+\rho_b(y)}\, dy}{\lambda_{bi}} = 0.09, \tag{57}$$

where we set $s_b = 0.15L$ in the definition of the indicator function in equation (18). The solution to these four equations is $\theta = 6.83 \times 10^{-5}/\$$, $\psi = \$1067/\sqrt{\text{day}}$ (and hence $\tilde{d}_1 = \$1509$, $d_1 = \$4476$, and $d_2 = \$8983$), $\alpha_1 = 9.08$/mile, and $\alpha_2 = 0.29$/mile.

5.3 DRO Parameters

We begin by estimating the constants a_n and b_n in equation (29). Because $a = \infty$ in the base case, no Mexicans are sent to DRO because they have been apprehended a specified number of times. Hence, we take a_n to be the annual number of nonmandatory Mexicans that are currently sent to DRO. In 2003, 45,925 Mexican noncriminals arrived to DRO [11]. The estimated fraction of noncriminal detainees that are nonmandatory is 0.6949, and so we set $a_n = 0.6949(45,925) = 31,913$/yr.

We estimate the multiplier factor b_n by the total potential (i.e., blocked and unblocked) nonmandatory OTM arrival rate to DRO divided by the total potential nonmandatory OTM apprehension rate at the U.S.-Mexico border; for lack of data, we assume that all detentions at the border are nonmandatory. The number of unblocked nonmandatory arrivals to DRO in 2003 was estimated to be 65,976 [11], and hence the number of unblocked OTM nonmandatory arrivals at DRO was 65,976-31,913=34,063. In addition, 28,000 nonmandatory OTMs were apprehended at the border but were blocked from entering DRO [11]. We also need to estimate the number of nonmandatory OTMs apprehended away from the border but blocked from entering DRO. To obtain this estimate, first note that in 2003, there were 905,065 apprehensions by border patrol agents on the U.S.-Mexico border (Table 37 in [34]), and 882,012 Mexican aliens apprehended by border patrol agents (Table 38 in [34]). If we assume all of these Mexican aliens were apprehended on the U.S.-Mexico border, then the number of OTMs detained at the border was $905,065 - 882,012 = 23,053$. There were 854,976 voluntary departures of Mexicans on the U.S.-Mexico border in 2003 (Table 41 in [34]), and hence the number of Mexicans detained at the border was $882,012 - 854,976 = 27,036$ and the total number of aliens detained at the border was 23,053+27,036=50,093. Recalling that there were 65,976 nonmandatory arrivals to DRO in 2003, the remaining 65,976-50,093=15,883 nonmandatory aliens were apprehended elsewhere (e.g., in the interior). If we assume that the likelihood of a potential nonmandatory detainee being blocked from entering DRO is independent of where he was apprehended, then the number of blocked nonmandatory apprehensions occuring away from the border was $\frac{28,000}{50,093} 15,883 = 8878$. Taken together, the total potential nonmandatory arrival rate to DRO, which is the numerator for calculating b_n, is 34,063 (actual arrivals) plus 28,000 (blocked at the border) plus 8878 (blocked away from the border), or 70,941. The denominator for b_n is the actual number of OTMs detained at the border (23,053) plus the number blocked (28,000), or 51,053. Hence, we obtain the estimate $b_n = \frac{70{,}941}{51{,}053} = 1.39$.

We assume there are $s = 22,580$ DRO beds, which was allotted in the 2006 budget. The values of the mean mandatory arrival rate $\bar{\lambda}_m$, the mean residence times m_m and m_n, and the relative amplitude α_d were estimated in [11] using 2003 data and appear in Table 1. The only major change at the border since 2003 is a large increase in OTM arrivals, i.e., $\lambda_{d2} = 155$k/yr. Hence, we set $\lambda_{d1} = 0$ in the base case and set $\bar{\lambda}_n$ =31,913+1.39(155k)=247,363/yr, and use equation (33) to solve for the removal probability, which is $P_r = 0.137$.

Finally, U.S. Immigration and Customs Enforcement requested \$31M for 950 additional detention beds (and additional support personnel) for fiscal year 2008 [35], and so we set $c_d = \frac{\$31\text{M}}{950} = \$32.6\text{k/yr}$.

5.4 Wage Parameters

We assume there are N_w =217k firms in the U.S. that hire illegal aliens [36]. Estimates of the service rate of a worksite inspector vary from approximately 7 firms per year [37] to nearly 50 per yr [38], and we assume $\mu_w = 20$/yr. The fraction of inspected firms that are inspected in a random manner is taken to be the same as during IRCA, $r_w = 0.4$ [37]. The current penalty is \$10,000 per illegal employee, and so in the base case, $f_w = \frac{\$10{,}000}{h}$ =\$5/worker-hr, where $h = 2000$ hours worked per worker per year. Also, in the base case, we assume that $m_w = 65$ (its value in 2004 [39]), which leads to $n_w = 1300$ firms investigated per year. The fiscal year 2007 budget requested \$41.7M for 171 additional worksite inspectors [40], and so we set $c_w = \frac{\$41.7\text{M}}{171} = \$243.9\text{k/yr}$.

We set the annual illegal wage w_u to be the wage of U.S. immigrants, which is \$22,300/yr [26]. In the Cobb-Douglas matching function in equation (47), we set the elasticity with respect to unemployment $\alpha_m = 0.7$ [41]. The labor demand function in equation (37) can be rewritten as $\ln L_d = \ln A_w + (\alpha_w - 1)\ln w$, and we set $\alpha_w - 1$ equal to the wage elasticity of demand, -0.63 [42], to get $\alpha_w = 0.37$.

Although there are 140.8M legal laborers in the U.S. [17], the subset of these workers that are in direct competition for jobs with illegal immigrants is geographically diverse [43] and difficult to estimate directly. In 2005, 29.5% of (i.e., 41.5M) workers aged 18 and older had income < \$20k and 39.0% (i.e., 54.9M) had income < \$25k [44]. Only a fraction of these workers are in direct job competition with illegal immigrants, and we use the rough estimate $N_l = 30$M. Hence, we still have six unknowns: the Cobb-Douglas matching parameter A_m, the illegal labor supply N_i, the equilibrium legal wage w, the Cobb-Douglas labor demand parameter A_w, and the labor supply parameters κ_1 and κ_2. We now state the six equations that can be solved simultaneously for these six unknowns.

By equation (47), the parameter A_m represents the employment rate among illegals when there are an equal number of unhired workers and vacant jobs. There are 7.20M illegal immigrants working in the U.S. [17] and the first equation sets $N_i = \frac{7.2\text{M}}{A_m}$. The second and third equations are (53)-(54) using the base-case decisions in Table 5. The next two equations compute the labor supply parameters in terms of the legal wage rate. The annual wages of U.S. high school dropouts ($24,800) and Mexican immigrants ($22,300) are comparable [26], and the former have an unemployment rate of 14.3% [17]. If we assume that high school dropouts are competing with illegal immigrants for jobs, then our fourth equation states that the current legal wage generates a 14.3% unemployment rate among the legal labor population:

$$\kappa_1 - \frac{\kappa_2}{w} = \Big(2000\frac{\text{hr}}{\text{yr}}\Big)(1-0.143) = 1714\frac{\text{hr}}{\text{yr}}. \tag{58}$$

The aggregate labor supply elasticity is believed to be approximately three [45], and our fifth equation states that a 1% increase in the equilibrium wage leads to a 3% increase in the amount of legal labor supplied:

$$\kappa_1 - \frac{\kappa_2}{1.01w} = 1.03\Big(2000\frac{\text{hr}}{\text{yr}}\Big)(1-0.143) = 1765.4\frac{\text{hr}}{\text{yr}}. \tag{59}$$

Both sides of equation (53) are equal to 2000 hr/yr times the total number of workers, which is 7.2M illegal workers plus (1-0.143)N_l legal workers. Hence, our final equation is

$$A_w\left(\frac{1}{w}\right)^{1-\alpha_w} = 2000\frac{\text{hr}}{\text{yr}}[7.2\text{M} + (1-0.143)N_l]. \tag{60}$$

Solving these six equations jointly for the six unknown parameters yields an employment rate of $A_m = 0.927$, an illegal labor supply of $N_i = 7.76$M (and hence, by equation (**??**), an annual cost per worksite inspector of $c_w =$ \$180.9k/yr), an equilibrium legal wage of $w = 11.24$/hr (and hence, by equation (54), an equilibrium illegal wage in the base case of $w_u =$ \$22.3k/yr, or 11.15\$/hr), the Cobb-Douglas labor demand parameter $A_w = \$3.9 \times 10^{12}$/yr, and the labor supply parameters $\kappa_1 = 6905$ hr/yr and $\kappa_2 =$\$58.3k/yr.

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Notation	Description	Value
τ	Time horizon	2 yr
θ	Discrete choice parameter	6.83×10^{-5}/\$
w_o	Wage in home country	\$5000/yr
w_u	Illegal wage in U.S. in base case	\$22.3k/yr
c_1	One-way cost of Mexican migration	\$1500
c_2	One-way cost of OTM	\$2500
d_1	Cost of Mexican detention and removal	\$4476
$\tilde{d}_1$	Cost of Mexican detention	\$1509
d_2	Cost of OTM detention and removal	\$8983
f	Fraction of detention cost incurred	0.46
n_1	Potential Mexican border crossers per year	5.14M/yr
n_2	Potential OTM border crossers per year	874k/yr
λ_{b1}	Attempted annual border crossings by Mexicans	5.80M/yr
λ_{b2}	Attempted annual border crossings by OTMs	775k/yr

Table 1: Values for parameters in the Discrete Choice Submodel.

Notation	Description	Value
P_{a1}, P_{a2}	Apprehension probability in base case	0.2
λ_{d1}	Mexican apprehension rate ($\geq a^{\text{th}}$ time)	0/yr
λ_{d2}	OTM apprehension rate	155k/yr
L	Length of border	1933 miles
m_b	Mean time to apprehend an alien	1 hr
k	Cost to travel along the border	\$4/mile
ω_b	Frequency of sinusoidal arrival rates	5.17×10^{-3}/mile
α_b	Relative amplitude of sinusoidal arrival rates	0.951
$\tilde{\alpha}_b$	Relative amplitude of sinusoidal border patrol agent density	0.951
c_b	Cost per border patrol agent	\$1.173M/yr
c_s	Cost for surveillance technology	\$30k/mile·yr
α_1	Exponential apprehension parameter without technology	9.08/mile
α_2	Exponential apprehension parameter with technology	0.29/mile

Table 2: Values for parameters in the Apprehension Submodel.

Notation	Description	Value
a_n	Constant factor for nonmandatory detainees	31,913/yr
b_n	Multiplicative factor for nonmandatory detainees	1.39
$\bar{\lambda}_m$	Mean arrival rate of mandatory detainees	144,323/yr
$\bar{\lambda}_n$	Mean arrival rate of nonmandatory detainees	247,363/yr
m_m	Mean residence time of mandatory detainees	45.8 days
m_n	Mean residence time of nonmandatory detainees	48.0 days
ω_d	Frequency of sinusoidal arrival rates	1/yr
α_d	Relative amplitude of sinusoidal arrival rates	0.1474
P_r	Removal probability in base case	0.137
c_d	Cost per DRO bed	\$32.6k/yr

Table 3: Values for parameters in the Removal Submodel. Under Expedited Removal, m_n is reduced to 19.0 days [46].

Notation	Description	Value
μ_w	Service rate of worksite inspectors	20/yr
N_w	Total number of firms hiring illegals	217k
n_w	Total number of firms inspected per year	1300/yr
h	Hours worked per worker per year	2000 hr/yr
A_w	Linear parameter for Cobb-Douglas demand model	$\$3.9 \times 10^{12}$/yr
α_w	Exponential parameter for Cobb-Douglas demand model	0.37
κ_1	Labor supply parameter	6905 hr/yr
κ_2	Labor supply parameter	\$58.3k/yr
A_m	Linear parameter for Cobb-Douglas matching model	0.927
α_m	Exponential parameter for Cobb-Douglas matching model	0.7
w	Legal wage rate in base case	\$11.24/hr
N_l	Legal labor supply	30M
N_i	Illegal labor supply	7.76M
c_w	Cost per worksite inspector	\$243.9k/yr

Table 4: Values for parameters in the Illegal Wage Submodel.

Notation	Description	Value
a	Number of apprehensions until detention of Mexican	∞
n_b	Number of border patrol agents at border	1636
s_b	Length of border monitored by surveillance technology	290 miles
s	Number of DRO beds	22,580
r_w	Fraction of worksite inspectors that are random	0.4
m_w	Number of worksite inspectors	65
f_w	Fine per illegal worker-hour	\$5/worker-hr
Δ_l	Number of illegal workers legalized	0
N_g	Number of new guest workers	0

Table 5: Decision variables and their base-case values.

Figure Legends

Fig. 1. Border-crossing behavior in the base case. The OTMs' arrival rate to each location on the border ($\lambda_{b2}(x)$ in equation (16)), which is proportional to the density of border patrol agents at each location on the border ($n_b(x)$ in equation (17)), and the OTMs' crossing rate at each location on the border ($\lambda_{c2}(x)$ in equation (25)). Also depicted at the top of the plot is the spatial location of surveillance technology ($I_{\{x\}}$ in equation (18)).

Fig. 2. Impact of the Mexican detention policy. The probability that a terrorist successfully enters the U.S. vs. the number of apprehensions until a Mexican border crosser is detained (i.e., is placed in a DRO facility if there is available space). Other decision variables are set at their base-case values.

Fig. 3. Impact of isolated changes in non-worksite decision variables. The probability that a terrorist successfully enters the U.S. vs. **(a)** the number of border patrol agents on the border, **(b)** the number of miles of border monitored by surveillance technology, and **(c)** the number of DRO beds. Other decision variables are set at their base-case values.

Fig. 4. The optimal P_T vs. cost curve in the base case (i.e., as in Fig. 1 in the main text, where $\tilde{\alpha}_b = 0.951$) and when border patrol agents are distributed evenly across the border (i.e., when the relative amplitude $\tilde{\alpha}_b = 0$).

Fig. 5. Annual illegal wage vs. number of worksite inspectors for various fractions of inspections that are not targeted (r_w). The fine f_w is **(a)** \$5/worker-hr and **(b)** \$25/worker-hr.

Fig. 6. Annual illegal wage vs. number of worksite inspectors for various numbers of legalized workers (Δ_l, which is expressed as a fraction of the illegal labor supply N_i) and new guest workers (N_g). The fine f_w is **(a)** \$5/worker-hr and **(b)** \$25/worker-hr.

Fig. 7. The OTM crossing probability vs. the annual illegal wage for various values of the multinomial logit parameter, θ.

Fig. 8. These curves compare the impact of marginal investments in border patrol agents vs. worksite inspectors on **(a)** the apprehension probability P_{a2}, **(b)** the OTM crossing probability P_{21}, and **(c)** the alternative objective function $P_{21}[1 - P_{a2} + P_{a2}(1 - P_r)]$, which is proportional to the number of OTMs who successfully sneak into the U.S. In each case, the initial annual budget of \$7.2B uses technology along the entire border, has evenly spaced agents (i.e., $\tilde{\alpha}_b = 0$, and has sufficient DRO beds so that $P_r = 1$ (and the alternate objective function equals $P_{21}(1 - P_{a2})$), but has base-case values of 1636 border patrol agents and 65 worksite inspectors. Each curve is generated by adding either border patrol agents or worksite inspectors.

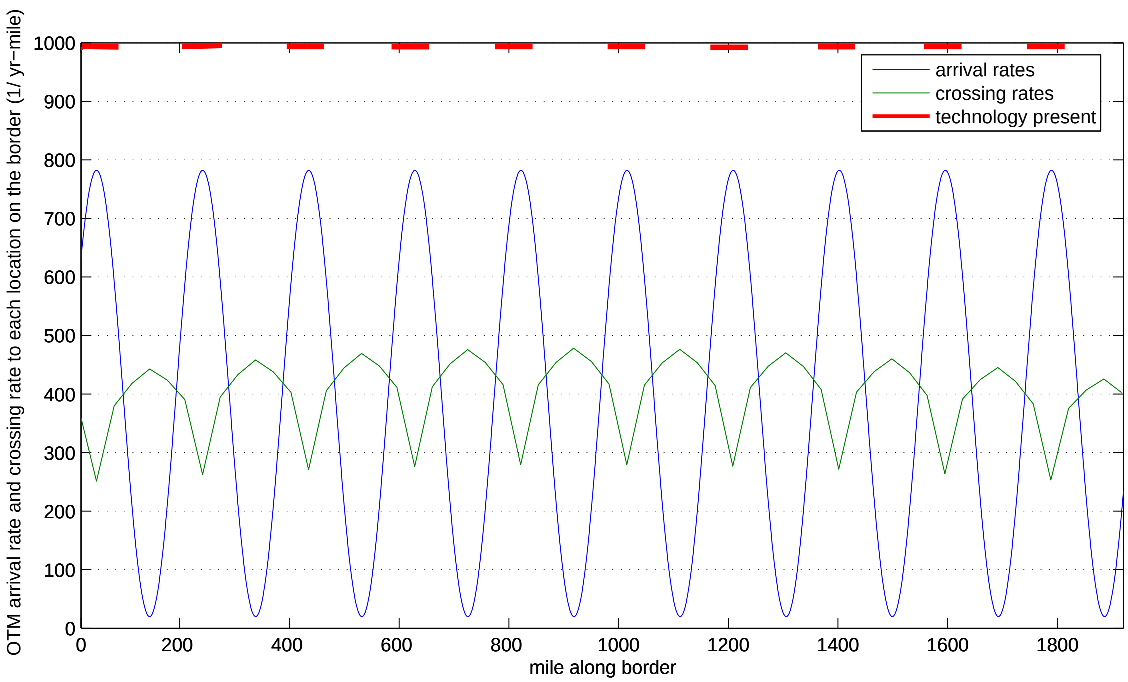

OTM arrival rate and crossing rate to each location on the border (1/ yr−mile)
1000
900
800
700
600
500
400
300
200
100
0
0
200
400
600
800
1000
1200
1400
1600
1800
mile along border
arrival rates
crossing rates
technology present

FIGURE 1

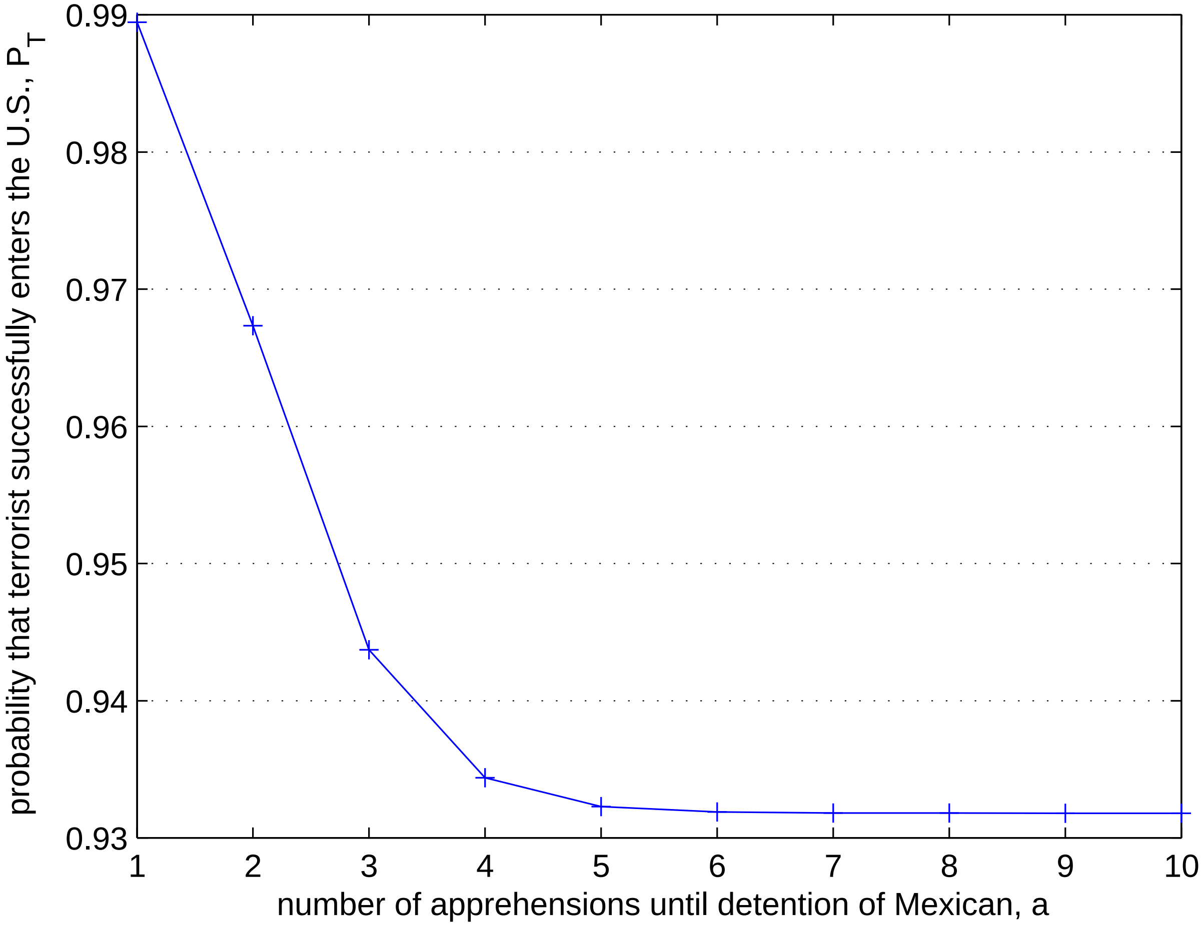
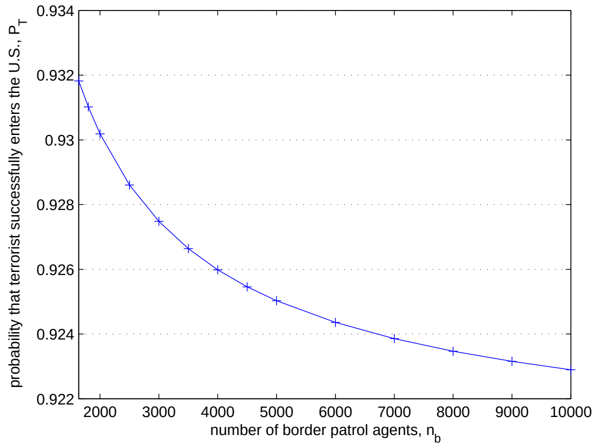
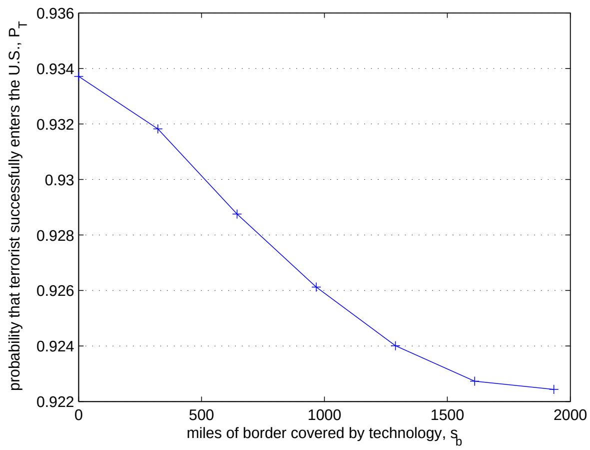

probability that terrorist successfully enters the U.S., P_T
0.99
0.98
0.97
0.96
0.95
0.94
0.93
1
2
3
4
5
6
7
8
9
10
number of apprehensions until detention of Mexican, a

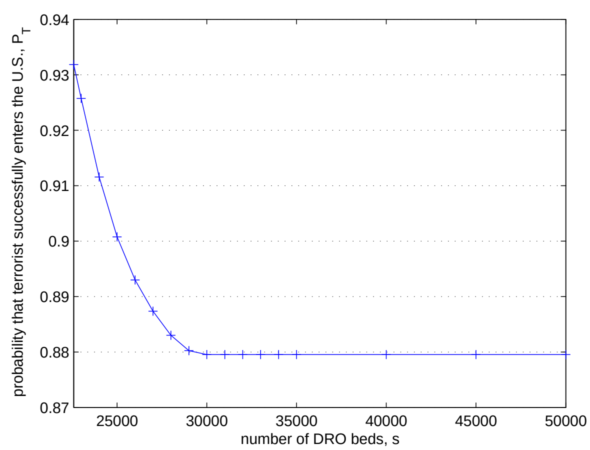
FIGURE 2


probability that terrorist successfully enters the U.S., P_T
number of border patrol agents, n_b

(a)


probability that terrorist successfully enters the U.S., P_T
miles of border covered by technology, s_b

(b)


probability that terrorist successfully enters the U.S., P_T
number of DRO beds, s

(c)

FIGURE 3

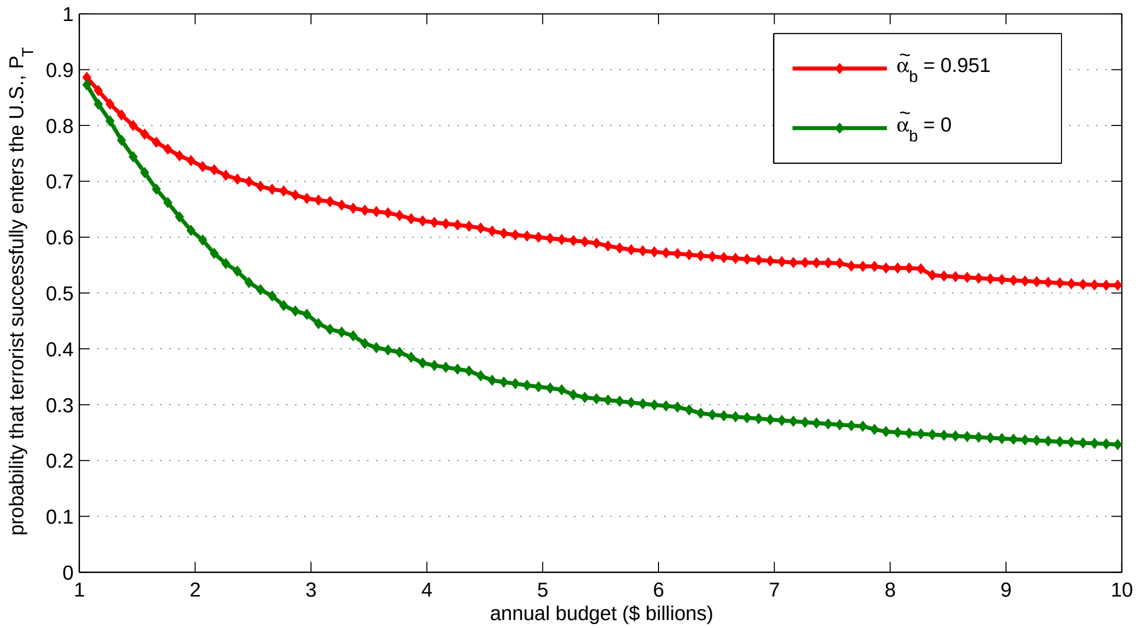
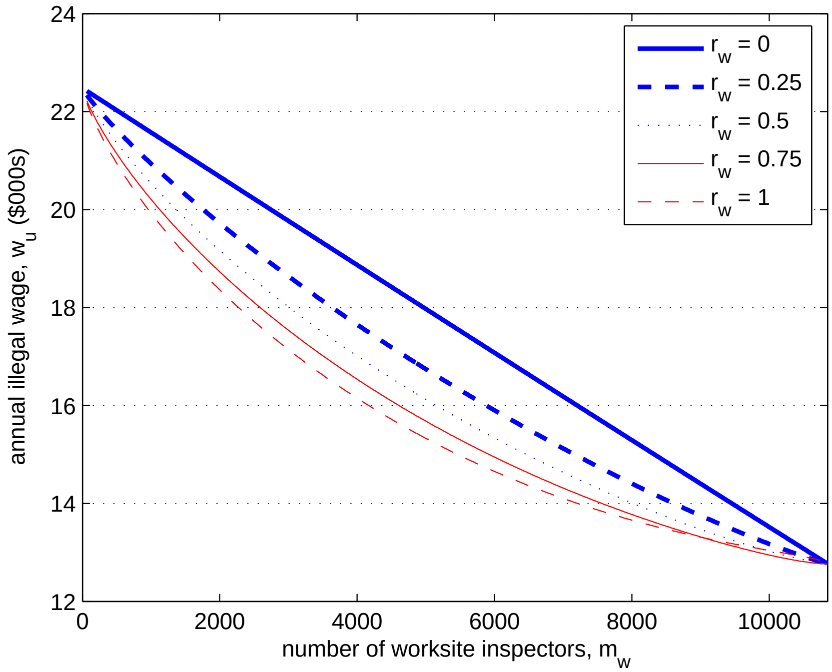
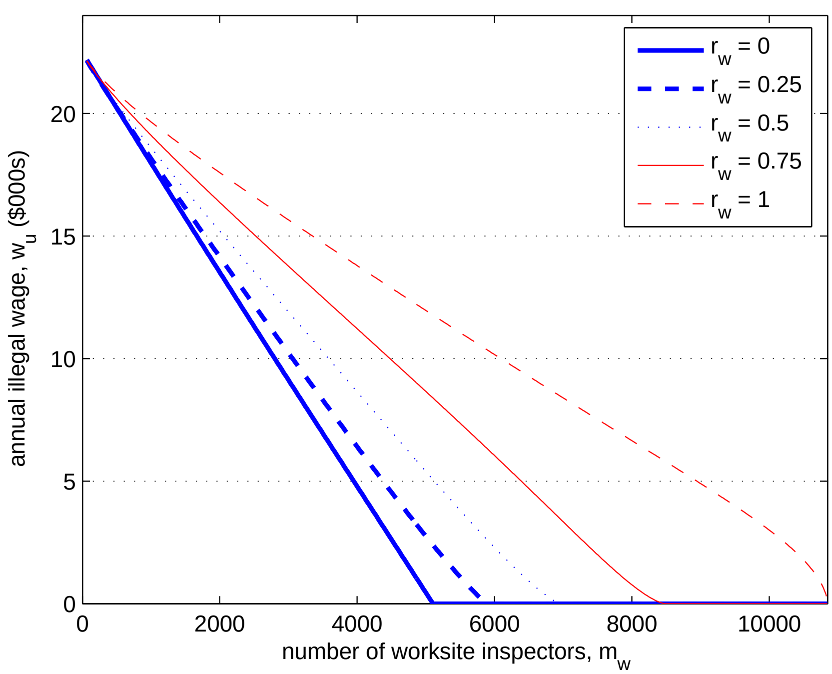

$\tilde{\alpha}_b$ = 0.951
$\tilde{\alpha}_b$ = 0
probability that terrorist successfully enters the U.S., P_T
annual budget ($ billions)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1
2
3
4
5
6
7
8
9
10

FIGURE 4

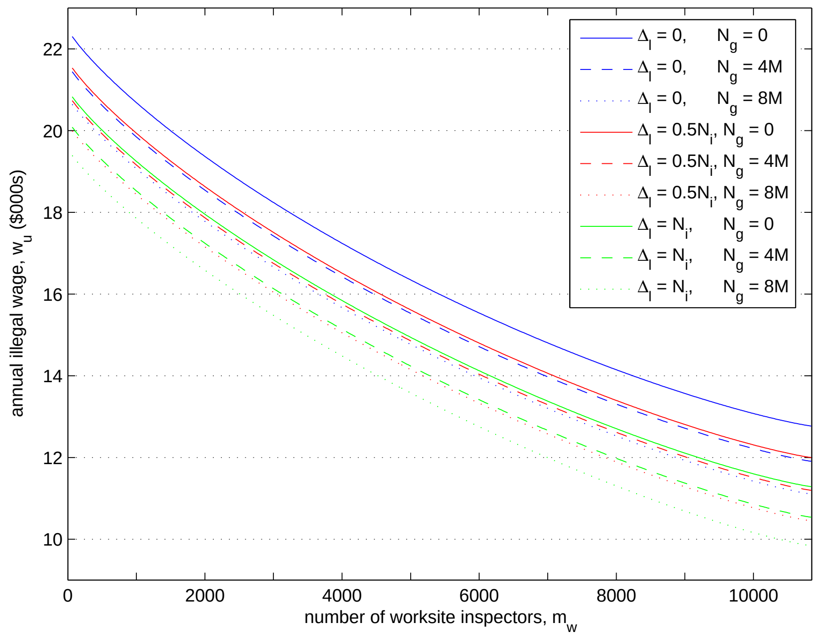

24
22
20
18
16
14
12
0
2000
4000
6000
8000
10000
annual illegal wage, w_u ($000s)
number of worksite inspectors, m_w
r_w = 0
r_w = 0.25
r_w = 0.5
r_w = 0.75
r_w = 1

(a)


20
15
10
5
0
0
2000
4000
6000
8000
10000
annual illegal wage, w_u ($000s)
number of worksite inspectors, m_w
r_w = 0
r_w = 0.25
r_w = 0.5
r_w = 0.75
r_w = 1

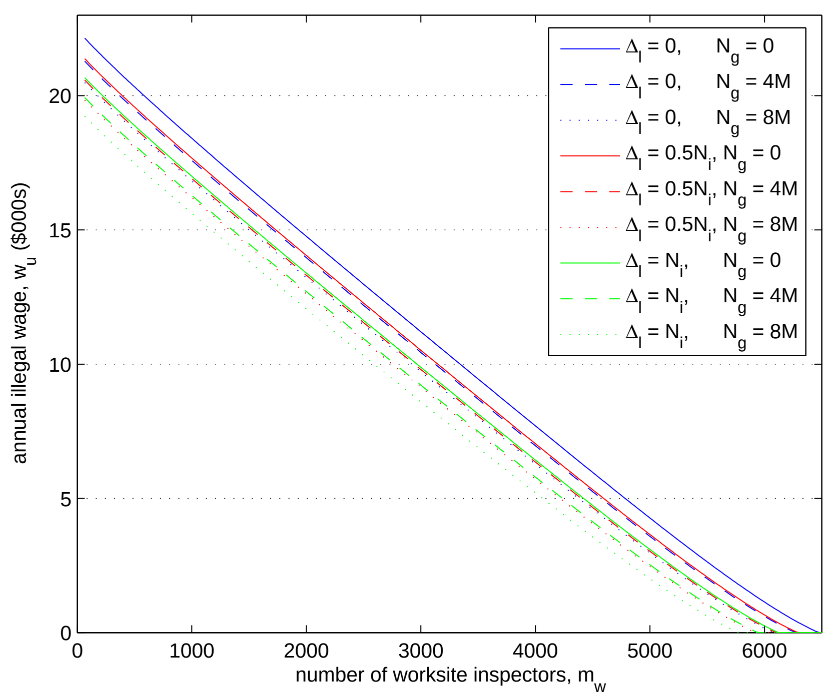
(b)

FIGURE 5



22
20
18
16
14
12
10
0
2000
4000
6000
8000
10000
annual illegal wage, w_u ($000s)
number of worksite inspectors, m_w
Δ_I = 0, N_g = 0
Δ_I = 0, N_g = 4M
Δ_I = 0, N_g = 8M
Δ_I = 0.5N_i, N_g = 0
Δ_I = 0.5N_i, N_g = 4M
Δ_I = 0.5N_i, N_g = 8M
Δ_I = N_i, N_g = 0
Δ_I = N_i, N_g = 4M
Δ_I = N_i, N_g = 8M

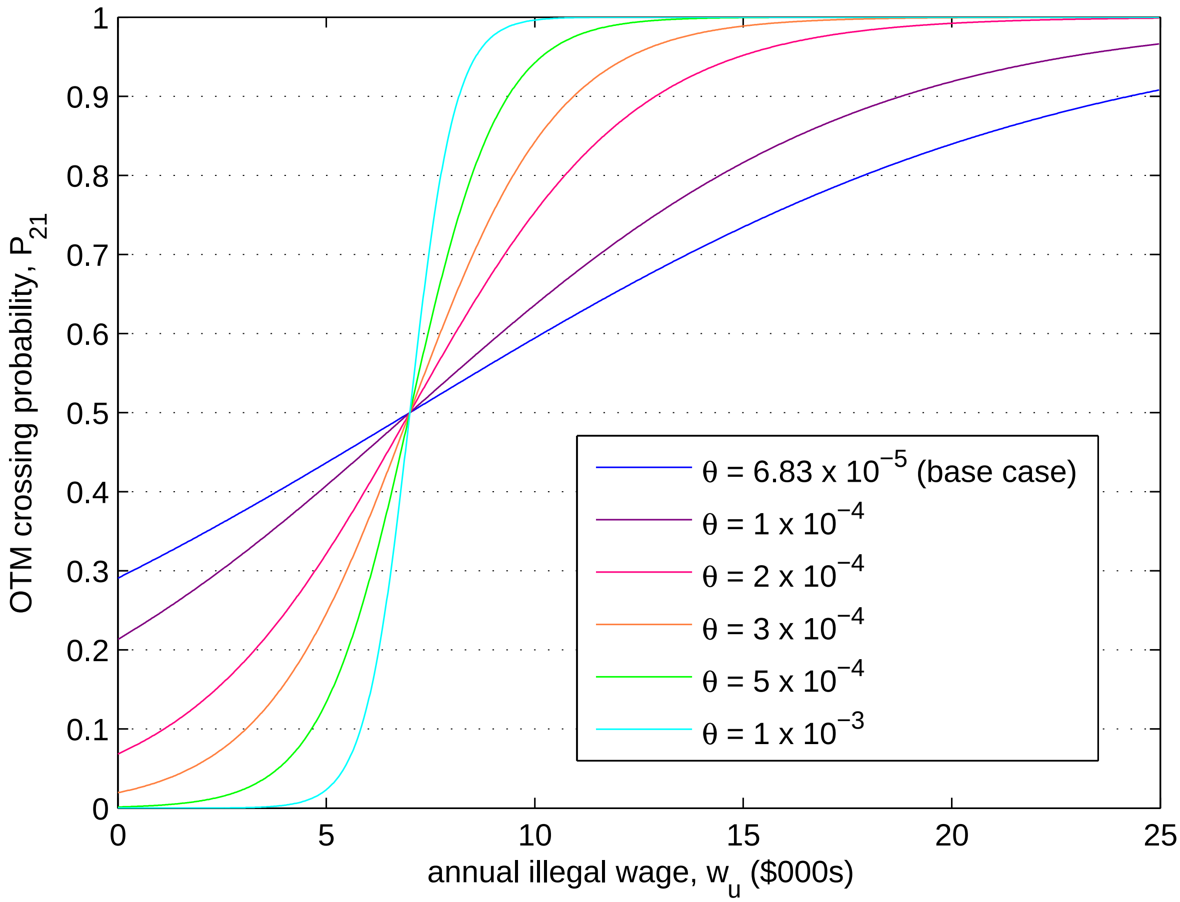
(a)



20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
annual illegal wage, w_u ($000s)
number of worksite inspectors, m_w
Δ_I = 0, N_g = 0
Δ_I = 0, N_g = 4M
Δ_I = 0, N_g = 8M
Δ_I = 0.5N_i, N_g = 0
Δ_I = 0.5N_i, N_g = 4M
Δ_I = 0.5N_i, N_g = 8M
Δ_I = N_i, N_g = 0
Δ_I = N_i, N_g = 4M
Δ_I = N_i, N_g = 8M

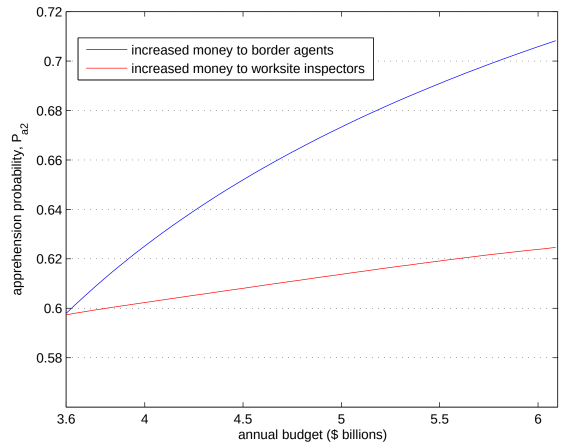
(b)

FIGURE 6



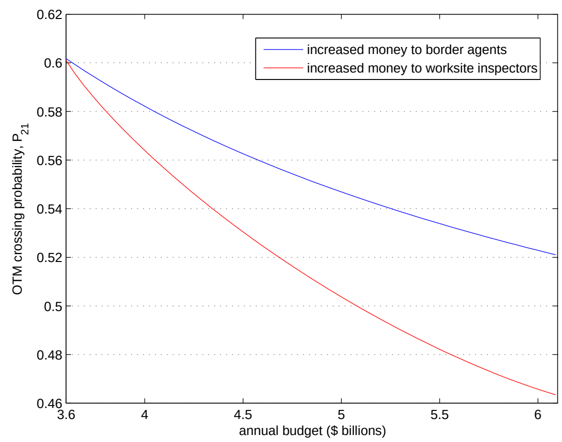
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
OTM crossing probability, P21
0
5
10
15
20
25
annual illegal wage, wu ($000s)
θ = 6.83 x 10−5 (base case)
θ = 1 x 10−4
θ = 2 x 10−4
θ = 3 x 10−4
θ = 5 x 10−4
θ = 1 x 10−3

FIGURE 7



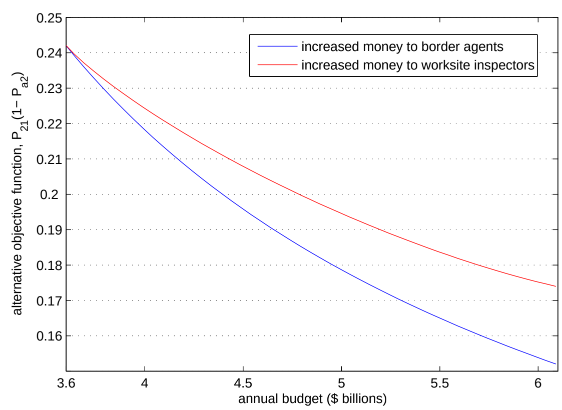
increased money to border agents
increased money to worksite inspectors
apprehension probability, P_{a2}
annual budget ($ billions)

(a)



increased money to border agents
increased money to worksite inspectors
OTM crossing probability, P_{21}
annual budget ($ billions)

(b)



increased money to border agents
increased money to worksite inspectors
alternative objective function, $P_{21}(1-P_{a2})$
annual budget ($ billions)

(c)

FIGURE 8