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Validating Deterrence Models for Scanning Technologies

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Validating Deterrence Models for Scanning Technologies

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Abstract

The use of scanning systems (such as radiation portal monitors and X-ray imagers) at border checkpoints is said to act as a deterrent to the smuggling of radiological/nuclear materials, drugs, and other illicit items. Can such deterrent effects be measured? The author examines several mathematical formulations of the deterrence function—the probability that a contemplated act of smuggling will be carried out, given that scanning occurs at a given rate and level of effectiveness. These formulations are further developed as "extended" models that can incorporate the different motivations, perceptions, and decision-making behaviors of different smuggling populations. Extended model predictions regarding deterrence thresholds are compared to individual cases of radiological/nuclear smuggling and aggregated data on drug smuggling activity. These comparisons point to some tentative conclusions regarding the conditions under which scanning systems might or might not act as a deterrent. Such conclusions are necessarily limited by the study's reliance on open-source information, the relatively small number of cross-border radiological/nuclear smuggling cases on record, the high level of aggregation in the drug smuggling data used, the need to make very rough estimates of some intermediate variables, and the fact that cognitive and behavioral models (including models of decision-making under conditions of risk and uncertainty) have not been validated for the specific populations being studied here.

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I. Introduction

A. Background and Purpose

Large-scale scanning systems,[1] such as X-ray imagers and radiation portal monitors, are important tools in combating the smuggling of dangerous materials. Although their principal contribution has been to *detect* such materials, they are also said to help *deter* smuggling activity.[2] Measuring this contribution, however, is difficult, since direct measurement of deterrence requires the ability to observe an event that did not happen. Lacking such knowledge, policymakers are forced to make decisions about scanning technologies, utilization rates, and deployments with less than a full understanding of the operational impacts. As a result, scarce resources could potentially be used unproductively, and the benefits of improved technologies may not be fully realized.

The goal of this study was to help CBP and other stakeholders measure the deterrence value of large-scale scanning systems in preventing the smuggling of illegal goods or instruments of terror. Rather than attempt to measure deterrence directly, the author chose a different approach: namely, arriving at deterrence measures indirectly, through systematic face validation of extended screening, scanning, and deterrence models. Extended models are those that incorporate factors outside the framework of detection, such as the different motivations, perceptions, and behaviors exhibited by different types of smuggling enterprises or smuggling populations.

B. Screening, Scanning, and Deterrence

In the context of border security operations, scanning systems operate as part of a larger screening and detection architecture, such as the simple example shown in Figure 1.

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[1] U.S. Customs and Border Protection (CBP) refers to these systems as examples of Non-Intrusive Inspection (NII) technology (CBP 2013).

[2] In its first strategic plan, CBP stated that one goal of its NII technology program was to "improve [the] ability to detect *and deter* illicit radiological materials and nuclear devices" (CBP 2005, p. 20, Objective 1.3, emphasis added). The U.S. Government Accountability Office (GAO) notes that "according to the Department of Homeland Security, detecting and interdicting these materials as far away from the United States as possible increases the probability of successfully deterring nuclear and radiological smuggling into the United States" (GAO 2016). Some other examples of a claimed deterrent effect include the following: "Defenses [against nuclear proliferation extended to terrorist organizations and other non-state actors] include radiation detection systems *to deter* and disrupt nuclear and radioactive material smuggling" (NNSA 2019, p. iv, emphasis added); "The technical and nontechnical detection capabilities of the [global nuclear detection] architecture can contribute to the deterrence of nuclear terrorism by increasing the risks and costs of mounting an R/N attack" (Guthe 2014); and "Both fixed and mobile applications of radiation detection systems can provide a deterrent to potential nuclear material smuggling" (Arrieta and Ekman 2014). With respect to drug smuggling at the Mexico-U.S. border, former CBP Commissioner Kevin McAleenan testified that "the use of technology in the border environment … allows us to more quickly deter, and more safely detect illegal activity" (DHS 2018). Another CBP official testified that "[CBP's] investments and improvements in our drug detection technology and targeting capabilities … are critical components of CBP's ability to identify *and deter* the entry of dangerous illicit drugs in all operational environments (Perez 2017, emphasis added).

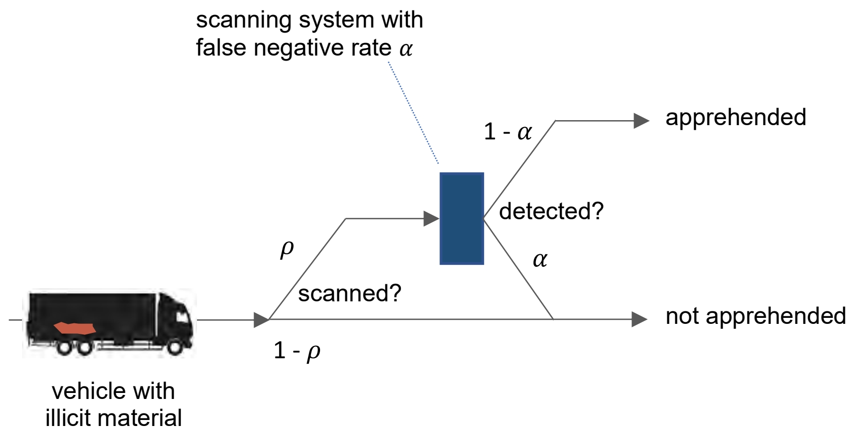

Figure 1. Simple Example of a Screening Architecture

Within this context, the deterrent effect of scanning systems can be represented as follows. Given some time unit of interest (such as a year, a day, or an eight-hour shift), let I be the number of intentionally illicit[3] entry attempts and C be the number of such attempts that are caught. Suppose illicit entries[4] are scanned at a rate ρ by a system with a false negative rate[5] of α. Then one can write

$$\textit{Number of illicit attempts}:\ I = I_0\delta(\alpha,\rho) \tag{1}$$

$$\textit{Number caught}:\quad C = \rho(1-\alpha)I = \rho(1-\alpha)I_0\delta(\alpha,\rho) \tag{2}$$

where I_0 is the number of intentionally illicit attempts at some baseline condition (for example, in the complete absence of scanning).

The expression $\delta(\alpha,\rho)$ is the "deterrence function": the probability that an illicit entry is attempted, assuming that scanning occurs with given effectiveness at a specified rate. An attempt to measure the deterrence value of scanning technologies must answer the question: how does the value of δ change with changes in α and/or ρ?

[3] Only *intentionally* illicit attempts are considered here: an individual who is carrying illicit material unknowingly cannot be deterred.

[4] Notice that ρ is the scanning rate for *illicit* entries, not all entries. Thus, it can be understood as a conditional probability: namely, the probability that the entry will be scanned given that it contains illicit materials. The distinction between conditional and unconditional probabilities will be important later in the analysis.

[5] The false negative rate is the probability that that the system fails to detect contraband, given that it is present. This too is a conditional probability. The effectiveness of the scanning system is $(1-\alpha)$, the probability that contraband is detected, given that it is present. Another conditional probability of interest is the false positive rate, defined as the probability that the system detects contraband, given that it is *not* present. A system with a high false positive rate requires more resources for alarm resolution and increases the average time required to process each entry, with resultant negative impacts on the free flow of legitimate commerce. Although false positives are important in their own right, they are not central to the problem of measuring deterrence. The supporting reasoning is that smugglers' willingness to make the attempt will depend on whether they believe that they themselves are likely to be screened and apprehended, not on whether they believe innocent crossers will be appropriately dealt with.

Different researchers have proposed different mathematical representations for the deterrence function $\delta(\alpha, \rho)$. Probably the most widely used form is based on the concept that an illicit act will not be attempted if the probability of being detected and apprehended is higher than a certain value.[6] In other words, for the screening architecture shown in Figure 1,

$$\begin{aligned} Deterrence\ function\colon\ \delta(\alpha,\rho) &= 1 \quad if\ \rho(1-\alpha) < \tau_0 \\ &= 0 \quad otherwise \end{aligned} \tag{3}$$

The value τ_0 can be termed a "deterrence threshold." This representation assumes that illicit crossers use accurate estimates for the probability of being detected/apprehended, and that they are rational decision-makers; that is, they attempt to maximize the expected value, or utility, that will result from their choices.[7]

Different individuals may have different deterrence thresholds: "there is not likely to be a specific 'tipping point' … that deters all offenders" (Che and Benson 2013, p. 14). Therefore, when analyzing the behavior of a smuggling population as a whole, it may be more appropriate to consider a range of thresholds over the interval $[\tau_1, \tau_2]$. When the probability of being detected by the scanning system is sufficiently small, no one is deterred; when it is sufficiently large, everyone is. In other words, for the screening architecture shown in Figure 1,

$$\begin{aligned} \delta(\alpha,\rho) &= 1 \quad if\ and\ only\ if\ \rho(1-\alpha) \le \tau_1 \\ &= 0 \quad if\ and\ only\ if\ \rho(1-\alpha) > \tau_2 \end{aligned} \tag{4}$$

For values of $\rho(1-\alpha)$ between τ_1, and τ_2, some fraction of the group is deterred. That fraction depends on the functional form of $\delta(\alpha, \rho)$. Since a higher probability of detection should deter more individuals, δ should be a strictly decreasing function.

Although these formulations are simple and elegant, they leave important questions unanswered: what is an appropriate functional form of $\delta(\alpha, \rho)$, and how should one go about determining appropriate values for the terms τ_0, τ_1, and τ_2? In other words, where exactly do deterrence thresholds lie?

C. Underlying Premises

This study was based on three premises.

First, quantitative predictions about deterrence and deterrence thresholds associated with scanning technologies should consider not only the effectiveness of those systems but also the

[6] For example, this form appears in studies of airline passenger screening (Martonosi and Barnett 2006), nuclear smuggling (Merrick and McLay 2010), highway safety enforcement (Eeckhout et al. 2004), and a wide range of criminal behavior in general (Chalfin and McCrary 2017, pp. 7–8).

[7] Both these assumptions are open to question, and section IV.B of this report considers other decision-making models. For additional background on rational choice, see Briggs 2019.

motivations, perceptions, and risk tolerance of those whose actions are to be deterred.[8] This premise follows from the notion that deterrence is an attempt to influence a choice made under conditions of uncertainty and risk. It motivates the exploration of "extended" screening models in section IV.B.

The second premise follows from the first: the deterrent effect of large-scale scanning systems will depend on who is being deterred (an individual crosser? a group of individuals? a smuggling ring?) and what type of smuggling activity they are contemplating (smuggling nuclear weapons? smuggling drugs through a border checkpoint? smuggling drugs between border checkpoints?). To learn whether there are aspects of deterrence that are generalizable, it will be necessary to consider at least two different smuggling populations and/or types of smuggling activity.

Third, empirical testing or validation of deterrence predictions is best accomplished indirectly. In other words, if a model predicts that smuggling will occur and it does not, no conclusion about deterrence can be drawn because we usually do not know *why* the event did not occur.[9] However, a model prediction of *no* smuggling under conditions in which we *do* observe smuggling (in the form of a detection and subsequent apprehension) tells us that deterrence *did not* occur and therefore that the postulated threshold τ that was used to make the prediction is too low. This premise dictates an approach that concentrates on identifying "mismatches"—model predictions of deterrence (i.e., no activity) that are belied by observation—and adjusting model parameters accordingly.

[8] Cf. Che and Benson (2013): "The fact that the effectiveness of deterrence also depends on (i.e., varies with) factors other than the probability of detection and severity of its consequences is an important point to consider in the context of observations of drug-smuggling behavior."

[9] Indeed, we usually do not even know *that* an event was contemplated but did not occur. In a few special cases, however, it may be possible to learn about such a non-event. For example, a captured smuggler may reveal to law enforcement personnel that he or she initially planned to make a crossing at a certain location, but changed their plans because they concluded that scanning systems in operation there would pose too great a risk. GAO (2016, p. 23) discusses an example in which the presence of radiation portal monitors at a land border crossing forced two individuals attempting to smuggle Cs137 to take a more difficult and circuitous route to avoid the official crossing. (They were later apprehended.) See section V.G.

II. Study Objectives and Approach

The study goal encompassed four specific objectives:

- Identify and categorize mathematical constructs for modeling the deterrent effect of scanning systems. Identify the parameters (including extended model parameters) whose values must be estimated.
- Characterize at least two types of smuggling activity and associated smuggling populations that might be expected to behave differently. Assign initial values to extended model parameters based on available information.
- Generate model predictions and identify mismatches based on documented smuggling activity.
- Diagnose mismatches and draw appropriate conclusions regarding values of deterrence parameters.

The following sections discuss each of these objectives.

Identify Mathematical Constructs

The author reviewed the literature on screening, scanning, and deterrence modeling to identify mathematical formulations of the deterrence function $\delta(\alpha, \rho)$ that have been studied in the past. The review also included more general mathematical models of decision-making and deterrence, including those incorporating motivations, perceptions, and risk behaviors. These two sets of results were combined in the form of an extended model.

The results of this portion of the analysis are reported in section IV. Analysis – Mathematical Constructs.

Characterize Smuggling and Smuggling Populations

This study focused on two types of illicit materials: radiological/nuclear materials and illegal drugs. The analysis of radiological/nuclear smuggling was geographically unconstrained (i.e., worldwide[10]) and included known activity spanning approximately 25 years (1993–2018). For drug smuggling, the study considered movement of drugs through land ports of entry (LPOEs) along the southwest border (SWB) of the United States over the 6-year period 2014–19.[11]

For each of these two types of activity, the author reviewed available open-source materials to compile information on known instances and/or levels of smuggling, categorize the smuggling populations of interest (for example, low-level mules versus high-level leaders of smuggling organizations), and find estimates for the values of extended model parameters, such as their criteria for “success” or degree of risk tolerance. In many cases, these values are not available

[10] In practice, most documented activity has occurred in the former Soviet Union, eastern Europe, and the Black Sea/Transcaucasus region. See section V.A.

[11] Most attempts to smuggle illicit drugs into the United States occur at the southwest border (Finklea 2019, p. 10).

directly; rather, it was necessary to draw inferences and make estimates on the basis of other information.

The author also reviewed available information on the screening and detection architectures used to combat radiological/nuclear smuggling and drug smuggling, as well as published information on radiation detection portals, mobile radiation detection vans, and X-ray and gamma imaging systems currently in use.[12] This information was used to estimate the probability that the illicit material in question would be scanned and, if scanned, detected.

The results are reported in section V. Analysis – Radiological/Nuclear Smuggling and section VI. Analysis – Drug Smuggling at Mexico-U.S. Land Ports of Entry) For purposes of continuity, each of those two sections also includes the associated results for the remaining study objectives.

Generate Model Predictions and Identify Mismatches

For some smuggling types and populations, it was not possible to estimate model parameters from available information. Where it was possible to do so, the author exercised the extended model to generate predictions of deterrence and smuggling activity, expressed as a function of scanning rate and level of effectiveness. These predictions were compared with documented instances and/or levels of smuggling, to determine whether they were consistent.

Diagnose Mismatches and Draw Conclusions

There are many possible reasons for a mismatch between model predictions and documented activity. For example, a case may have been improperly characterized because of an unwarranted assumption about smugglers' prior knowledge. The author reviewed anomalous results to determine whether there were explanations other than the need to adjust model parameters.

By following this process, it was possible to reach some tentative conclusions regarding the deterrent effects of scanning systems. The author identified several factors that limit the strength of these conclusions and identified conditions under which they could be tested further.

[12] CBP also uses a variety of smaller, handheld systems that provide complementary capabilities, as discussed in sections V.F and VI.C. Looking beyond current systems, section VI.F discusses the development of new large-scale imaging systems and their potential deterrent effects.

III. Sources, Data, Terminology, and Notation

A. Sources – Mathematical Constructs

The academic literature includes a wealth of information on mathematical constructs applicable to this study. The author reviewed publications related to operations analysis, security studies, risk analysis, law enforcement, behavioral economics, and the psychology of criminal behavior. These sources are cited in section IV. Analysis – Mathematical Constructs.

B. Sources and Data – Radiological/Nuclear Smuggling Activity

This study was constrained to publicly available information only—a significant limitation. In addition to the general academic and security studies literature, the following sources are noteworthy:

- IAEA ITDB. In 1995, the International Atomic Energy Administration (IAEA)[13] established an "Incident and Trafficking Database (ITDB)" (see IAEA n.d.) on incidents of unauthorized activities and events involving nuclear and other radioactive material outside of regulatory control—including the illegal movement of such material across national borders. The usefulness of this source is limited for two reasons. First, although the agency publishes periodic summary reports based on the data, the details regarding specific incidents are made available only to participating governments—not to the general public. Second, the database includes only incidents confirmed by the participants, and the degree to which these governments contribute information varies widely.[14]
- CNS Global Incidents and Tracking Database. The James G. Martin Center for Nonproliferation Studies (CNS)[15] maintains the "Global Incidents and Tracking Database" (NTI 2019-10), which includes details on incidents of nuclear and other radioactive material that has been lost, stolen, or is otherwise out of regulatory control. This effort is sponsored by the Nuclear Threat Initiative.[16] Entries are generated from publicly available data and news reports, and the database is freely available to the public. As of October 2019, it included details on over 1,150 incidents that have occurred since 2013. In addition, NTI's "NIS Nuclear Trafficking Collection" (NTI 2013) contains abstracts of many earlier incidents, taken from open sources and presented on an as-reported basis.

[13] The IAEA, established in 1957, serves as an intergovernmental forum for scientific and technical cooperation in the peaceful applications of nuclear technology. Although it is an autonomous international organization, it reports to the United Nations General Assembly and Security Council.

[14] "Data provided to the IAEA by national governments often is not provided in a timely manner and … is neither comprehensive nor totally reliable" (Potter and Sokova 2002).

[15] The James G. Martin Center for Nonproliferation Studies is affiliated with the Middlebury Institute of International Studies, Monterey, CA. For additional information, see Middlebury Institute (n.d.).

[16] The Nuclear Threat Initiative was founded in 2001 by former U.S. Senator Sam Nunn and philanthropist Ted Turner to prevent catastrophic attacks with weapons of mass destruction. See NTI (n.d.).

- Other published compendia. Over the years, various researchers have compiled summaries or chronologies that include information on radiological/nuclear smuggling incidents (see, for instance, Woessner and Williams 1996; Potter and Sokova 2002; GAO 2002, pp. 31–39; Mohtadi and Murshid 2006; Schmid and Spencer-Smith 2012). These summaries, often performed in the context of a specific study, cover different time periods. They differ in other respects as well—for example, some are selective while others aim to be more comprehensive. Such compendia were useful in augmenting the IAEA and CNS data.
- News reports. The author independently searched the internet for news media reports, press releases, and other such information on instances of radiological/nuclear smuggling. In some cases, these reports provided more in-depth understanding of specific incidents, which was useful in diagnosing and resolving anomalies in the analysis results.
- Case studies and in-depth reviews. Bronner (2008) and Sheets (2008) provide detailed descriptions of one particular 2006 incident. Although much of the information is specific to that incident, both reports include background material applicable to other incidents in the same geographic region.

These sources were used in concert. For example, an incident identified in one database or compendium was routinely checked against others for consistency, and very often triggered a focused internet search for additional details and/or useful context. Information derived from a broad internet search was always cross-checked with corresponding entries in the above-referenced databases and compendia.

Most of the incidents catalogued in the above databases and chronologies are not relevant to this study. These include incidents dealing with:

- Failure to properly secure materials
- Unwitting transport of materials
- Transport of large quantities of low-grade materials (e.g., contaminated scrap metal)
- Activity that did not include smuggling
- Smuggling that did not cross one or more national boundaries

Only a few incidents involve deliberate attempts to smuggle radiological/nuclear materials across a national boundary without being detected. Almost all of these incidents involve attempted border crossings in the former Soviet Union, eastern Europe, or the Black Sea/Transcaucasus region.

The resulting data set for this study is limited in some important ways. First, there is no way to judge the degree to which our list of incidents is comprehensive. This limitation may affect the strength of our conclusions.[17] Second, the completeness of open-source reporting on incident

[17] Schmid and Spencer-Smith (2012) caution: “The principal problem with open source data on radiological and nuclear smuggling and trafficking incidents are inherent selection biases. Such data therefore should not be used for inferential statistics on all incidents of a radiological and nuclear nature.”

details varies widely across incidents. In some cases, important details such as the mass and/or level of radioactivity of the source, the presence or absence of shielding, and even the specific border where the attempted crossing occurred were simply not given. In such cases, the author either attempted to make a reasonable inference or else discarded the incident altogether. Again, this limitation significantly impacts the strength of our conclusions.

C. Sources and Data – Radiological/Nuclear Scanning Systems

From 1998 to the present, the Department of Energy's National Nuclear Security Administration (NNSA) has provided approximately 4,000 radiation portal monitors (including over 100 large-scale mobile systems) to more than 60 foreign governments as part of a program to strengthen their capabilities to deter, detect, and investigate nuclear smuggling. These monitors, together with handheld detection equipment, collectively cover over 500 international border crossings, including approximately 100 airports and 300 land border crossings (NNSA n.d.; GAO 2016, pp. 15, 33–36; Brock 2016, p. 6; ORNL 2019). The Department of Defense has provided radiation portal monitors to Ukraine, Azerbaijan, Uzbekistan, and Kazakhstan (GAO 2006, p. 53). Ad hoc assistance has also been provided by other members of the international community: for example, the European Union, the International Criminal Police Organization (INTERPOL), and the governments of Norway, Sweden, Finland, Canada, the United Kingdom, New Zealand, and South Korea (Fedchenko and Anthony 2018, p. 3; State Border Guard Service of Ukraine 2017; Office of Second Line of Defense 2012, p. 7).

For reasons of operational security, data on the exact numbers, locations, and operating status of radiation detection equipment deployed overseas is not publicly available. The author was therefore forced to make broad estimates regarding the prevalence of such systems, over time, at the different borders under study. These estimates were informed by the following sources:

- U.S. Government documents. NNSA periodically reports on the status of its Nuclear Smuggling Detection and Deterrence (NSDD) program (for example, Brock 2016). In addition, the U.S. Government Accountability Office (GAO) frequently assesses the status of U.S. nuclear nonproliferation initiatives, including the deployment of large-scale detection equipment (for example, GAO 2002; GAO 2006, pp. 42–44; GAO 2016, pp. 10, 15, and 33–36). These documents, along with other agency reports and public statements, represent a set of snapshots, with information that can be used to develop very rough estimates of prevalence by country over time. Such information includes the rank ordering of countries by number of systems deployed, the numbers of detectors collectively deployed in a specified subset of countries, the cumulative number of sites equipped with radiation detectors worldwide, approximate ranges of the number of covered sites per country, and, for certain countries, the percentage of border crossings equipped with radiation detection equipment.
- Reports prepared by international agencies. The IAEA, for instance, regularly sponsors conferences to address ongoing issues in nuclear security and nonproliferation. Conference proceedings occasionally include very specific information regarding the

extent to which participating countries have deployed radiation detection systems at their borders.[18]

- Publicly available information on border crossings and checkpoints. The numbers and locations of these checkpoints are readily available on the internet (e.g., Beltur n.d.). This information was used, together with the estimated number of detection systems in a particular country at a specified point in time, to provide rough estimates of the degree to which a border of interest might have been considered "covered."
- Other sources of information on border security, including academic literature, news reports, and foreign press releases. Often, although not always, the delivery of detection equipment is reported by news agencies and/or foreign governments (e.g., Kazinform 2009). Useful pieces of information can also be found from time to time in the literature on nonproliferation, international affairs, and regional security (e.g., Welt 2005).

The resulting estimates represent the author's attempt to provide a quantitative estimate based on a sparsely populated mosaic of available data points. It should not be considered authoritative or highly accurate.

Quantitative estimates of detection probabilities and effectiveness rates were derived from available published information as discussed in section V.F.

D. Sources and Data – Drug Smuggling at Mexico-U.S. Land Ports of Entry

Because the level of drug smuggling activity is so high compared to radiological/nuclear smuggling, the analysis was performed at a much broader level, using aggregated data rather than individual cases. Authoritative data usually reports on the weight of drugs seized, rather than the number of seizures. Therefore, the author estimated the number of seizures and smuggling attempts using related figures published by CBP, the Drug Enforcement Administration, and other sources, as detailed in section VI.A. Section VI.D explains how the author derived estimates for the effectiveness of imaging systems and CBP screening procedures.

E. Terminology and Notation

The following terms figure prominently in the analysis:

- Deterrence. "Deterrence" is understood as the decision, based on the threat of detection and its associated consequences, to refrain from one or more contemplated smuggling attempts. Estimates of deterrence should specify the decision-maker: for example, deterring an individual courier is very different from deterring the activities of the organization he or she is working for. Estimates of deterrence should also specify the scope of the smuggling activity in question. For example, suppose the activity is defined as multiple attempts to smuggle drugs overland across the SWB. If increased detection results in a shift of some of this traffic to air or sea routes, or a shift of some land-based

[18] To take just one example among many: "[In Belarus] only 8 out of 32 road checkpoints are now equipped with portal monitors. None of 19 railway checkpoints is equipped with portal monitors" (Piotukh 2001, p. 474).

activity from drug smuggling to a different type of criminal behavior, we would say that deterrence *has* occurred; if it results in a redistribution of loads across different overland routes, deterrence has *not* occurred.

- Smuggling and Trafficking. For purposes of this analysis, "smuggling" refers to the surreptitious movement of an item across a national border. "Trafficking" is understood as a broader term that includes illegally manufacturing, transporting, importing, and/or selling smuggled items. Although these definitions are broadly consistent with legal terminology, some sources use the terms interchangeably. In this report, a "smuggler" is an individual who surreptitiously carries one or more items across the border. Individuals who function as planners and organizers, or who direct smuggling conducted by others, are defined here as leaders of smuggling organizations—even though some sources may refer to them as "smugglers."
- Screening and Scanning. "Screening" is understood to be the general process of separating some crossers from others, for the purpose of detecting smuggled items. It can use a wide range of methods, including (but not limited to) visual inspection, document checks, and subjective judgments regarding a crosser's behavior. "Scanning" is here defined as the use of penetrating electromagnetic radiation (X-rays or gamma rays) to gain information on the contents of a vehicle or container without physically inspecting it. Scanning can be active (e.g., X-ray or gamma ray imaging systems) or passive (e.g., radiation detection systems that measure the gamma radiation emitted by an object). This study focuses on large-scale scanning systems, as opposed to smaller, handheld equipment. Nonetheless, all these systems are considered as part of the larger screening and detection architecture, and deterrence is analyzed in the context of that architecture.

Finally, different sources use a variety of different symbols, expressions, and mathematical conventions to refer to similar concepts and quantitative relationships. Original source expressions were translated as necessary to maintain consistency throughout this report.

IV. Analysis – Mathematical Constructs

A. Mathematical Formulations for the Deterrence Function

Section I.B introduced the concept of the deterrence function, $\delta(\alpha, \rho)$ and posed two possibilities: a step function with threshold τ_0 (Equation 3), and a function that decreases from 1 to 0 over a range of thresholds $[\tau_1, \tau_2]$. As previously noted, the step-function approach has been widely used in closed-form static models involving scanning and deterrence. It has also been embedded within dynamic representations such as game-theoretic models or agent-based simulations of smuggling networks.[19] This section explores some alternative forms for the function δ over the interval $[\tau_1, \tau_2]$. (For purposes of illustration, the screening architecture is assumed to be as shown in Figure 1; for the more general case, see section IV.B.)

Alternative Forms of $\boldsymbol{\delta}$

One of the simplest forms, used by Crane (1999) in an analysis of drug smuggling, is based on the assumption that deterrence is linear over the interval $[\tau_1, \tau_2]$. In other words,

$$\delta(\alpha, \rho) = 1 - \frac{min[max(\rho(1-\alpha)-\tau_1, 0), (\tau_2-\tau_1)]}{(\tau_2-\tau_1)} \tag{5}$$

A different form is given by Jacobson et al. (2005), whose study of checked-baggage scanning postulated the relationship

$$\delta(\Delta, \rho) = 1 - \Delta\rho^{\eta} \tag{6}$$

The authors refer to $\eta > 0$ as the "deterrence exponent," a quantity that measures how quickly an increased rate of scanning increases the deterrent effect. The parameter $(1 - \Delta)$ is the "deterrence multiplier," a quantity that "captures the maximum possible impact of [scanning upon] deterrence." This definition follows from the fact that $\delta(\Delta, 1) = 1 - \Delta$, where the value of Δ may be greater than zero. In other words, the model allows for the possibility that even 100 percent scanning might not provide absolute deterrence. Note that a relationship between Δ and α is not specified. If $\eta = 1$ and $\Delta = 1 - \alpha$, Equation 6 reduces to $\delta(\alpha, \rho) = 1 - \rho(1 - \alpha)$, a special case of the linear model (Equation 5) with $\tau_1 = 0$ and $\tau_2 = 1$.

Relationship to $\boldsymbol{f(\tau)}$

These and other possible representations of the deterrence function $\delta(\alpha, \rho)$ can understood by viewing the deterrence threshold τ as a random variable with a density function $f(\tau)$. With that understanding, the value of $\delta(\alpha, \rho)$ can be calculated using the relationship

$$\delta(\alpha, \rho) = 1 - \int_0^{\rho(1-\alpha)} f(\tau)d\tau \tag{7}$$

[19] Specific examples in the literature include simulations of nuclear smuggling (Haphuriwat et al. 2011), critical infrastructure protection (Tacquechel and Lewis 2016), and drug smuggling (Krebs et al. 2003; Magliocca et al. 2019).

For example, Equation 3 corresponds to the choice of

$$f(\tau) = 1 \quad if\ \tau = \tau_0, \\ = 0 \quad if\ \tau \neq \tau_0 \tag{8}$$

whereas Equation 5 results from choosing

$$f(\tau) = 0 \quad if\ \tau \leq \tau_1, \\ = 1/(\tau_2 - \tau_1) \quad if\ \tau_1 < \tau \leq \tau_2, \\ = 0 \quad if\ \tau > \tau_2 \tag{9}$$

and Equation 6 results from

$$f(\tau) = \Delta\eta\tau^{\eta-1} \tag{10}$$

In other words, the step-function model of deterrence (Equation 3) uses a discrete, single-valued probability distribution for the threshold τ; the linear model (Equation 5) corresponds to a uniform distribution of thresholds τ over the interval $[\tau_1, \tau_2]$; and the power-function model (Equation 6) assumes that τ follows a beta distribution with parameters η and 1 over the interval $[0, 1]$. The key point is that *any* postulated mathematical form for the deterrence function $\delta(\alpha, \rho)$ can be understood in terms of a corresponding distribution of deterrence thresholds over a specified interval.

Single-Valued vs Multiple-Valued Distributions

The choice of a single- versus many-valued distribution depends on the nature of the problem and, in particular, the number of decision-makers and decisions at play.

For a single decision-maker and a single decision (for example, a case study of an individual smuggling attempt), a single-valued distribution seems most appropriate. The deterrence threshold τ_0 will be unique to this individual and this attempt; for different individuals making an attempt under identical circumstances, different thresholds may apply. When analyzing the decision-making of an individual smuggler over time, it may be that a single threshold applies to all decisions. However, the circumstances of later attempts may be different, or the individual's risk tolerance may change, in which case $f(\tau)$ may take on multiple values. Another example of a single decision-maker making multiple decisions might be the leader of a smuggling organization who must decide how many and which attempts should be made. If all these attempts have similar payoffs and risks, a single threshold may apply; if not, there may be a range of thresholds. Even when all circumstances are similar, a leader might be willing to accept different levels of risk in different areas of the operation, and thus a range of thresholds might apply.

If multiple decision-makers are responsible for a single decision, they must ultimately reach a consensus, which can be represented by a single threshold. (The question of how groups reach consensus is beyond the scope of this study.) Finally, the analysis of multiple decision-makers and multiple decisions—for example, an analysis of the collective smuggling behavior of many individual smugglers—would require a many-valued distribution.

Figure 2 summarizes this discussion. An analysis based on a collection of individual cases (for example, section V. Analysis – Radiological/Nuclear Smuggling) will be concerned with individual thresholds for each case (the upper-left quadrant) as well as the resulting distribution of thresholds for the group as a whole (the lower-right quadrant). An analysis based solely on aggregated data (for example, section VI. Analysis – Drug Smuggling at Mexico-U.S. Land Ports of Entry) must try to determine the range of thresholds corresponding to the collective decisions of multiple individuals and organizations (lower-right quadrant), although it may also consider how the thresholds and decisions of individual smugglers and organization leaders (upper-left and upper-right quadrants) affect the total level of activity.

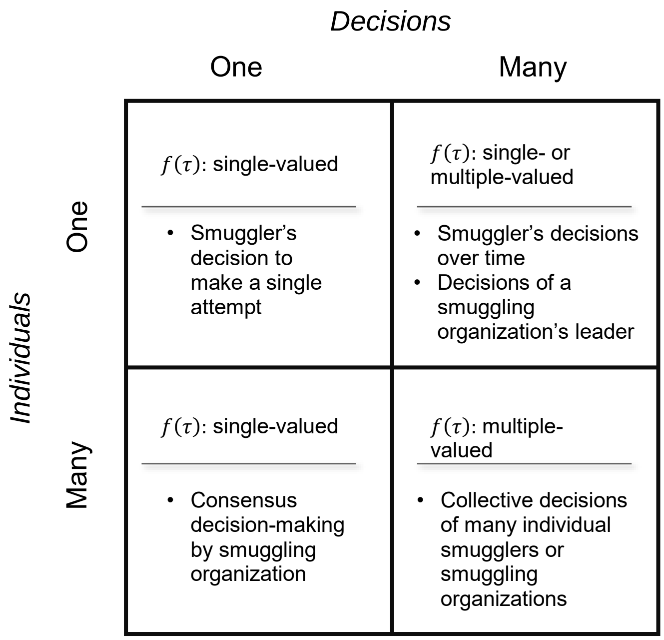

Figure 2. Single versus Multiple-Valued Threshold Distributions

B. The Extended Model

The extended model attempts to parameterize $\delta(\alpha, \rho)$ and τ based on variables that reflect the different motivations, perceptions, decision-making, and risk tolerance of different smuggling populations.

Motivations – Definitions of Success

What constitutes success in relation to smuggling? The answer depends on who is making the choice and what they hope to achieve.

For the individual contemplating a single illicit attempt, success means avoiding detection and apprehension. The individual may make subsequent attempts; however, each such attempt constitutes its own distinct undertaking, and each one must be undetected. By contrast, a terrorist organization may be willing to tolerate many failed smuggling attempts on the way to an undetected entry and subsequent attack.[20] Finally, an organization engaged in smuggling as part of an ongoing criminal enterprise (for example, a drug trafficking organization) may require that a certain percentage of attempted entries be undetected so that the resulting sales generate sufficient profits.[21]

To capture these distinctions in mathematical form, suppose that success requires at least E undetected entries out of A attempts. Let p^1 be the probability of being detected and apprehended on a single attempt.[22] Then the probability of failing to achieve success, denoted p^*, can be expressed as follows:

$$Probability\ of\ failure\colon\ p^* = 1 - \sum_{i=E}^{A} \binom{A}{i} [1-p^1]^i [p^1]^{A-i} \tag{11}$$

For the step-function model of deterrence with a single threshold τ_0,

$$\begin{aligned} Deterrence\ function\colon\ \delta(\alpha,\rho) &= 1 \quad if \quad p^* < \tau_0 \\ &= 0 \quad otherwise \end{aligned} \tag{12}$$

and for the linear deterrence model, with deterrence thresholds uniformly distributed over the interval $[\tau_1, \tau_2]$,

$$Deterrence\ function\colon\ \delta(\alpha,\rho) = 1 - \frac{min[max(p^*-\tau_1, 0), (\tau_2-\tau_1)]}{(\tau_2 - \tau_1)} \tag{13}$$

which satisfies the condition

$$\begin{aligned} \delta(\alpha,\rho) = 1 \quad if\ and\ only\ if \quad p^* \leq \tau_1 \\ \delta(\alpha,\rho) = 0 \quad if\ and\ only\ if \quad p^* > \tau_2 \end{aligned} \tag{14}$$

For the individual decision-maker contemplating a single attempt, $A = E = 1$ and Equation 11 yields $p^* = p^1$; that is, failure occurs if the attempt is detected.

The mathematical form of p^1 depends on the screening architecture. In general, it is the sum of probabilities over all paths that lead to detection and apprehension. The example architecture shown in Figure 1 features only one such path, and the probability of following that path is $\rho(1-\alpha)$. Thus, for a single attempt against this architecture, $p^* = p^1 = \rho(1-\alpha)$, and Equations 12, 13, and 14 reduce to Equations 3, 5, and 6, respectively.

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[20] It is an oft-quoted maxim that "The terrorist only needs to succeed once." Some commentators reply that an attack requires many steps and they must all succeed; therefore, the terrorist actually needs to succeed many times (MacKew 2013, p. 15). However, this reasoning applies only to the steps that occur within a single attempted attack, not to the fact that many attempts may be made.

[21] Keefe (2012) quotes a former chief of intelligence at DEA: "The goal of these folks is not to [smuggle] drugs … It's to earn a spendable profit and live to enjoy it."

[22] The value of p^1 is assumed to be the same for all A of these related attempts.

The significance of Equations 12 and 14 is that they allow us to draw conclusions about deterrence thresholds, provided that the probability of failure p^* can be independently measured. For example, if a single attempt is made under the condition $p^* = 0.3$, the obvious conclusion is that $\tau_0 > 0.3$ (otherwise, the attempt would not have been made). For a data set that encompasses many decisions (e.g., a collection of smuggling incidents), the observation that *some* smuggling occurs at $p^* = 0.3$ signals that $\tau_2 > 0.3$ (otherwise, there would be no activity at all). However, the same observation provides no information about τ_1, because the fact that some smuggling occurs tells us only that $\delta(\alpha, \rho) > 0$, not that $\delta(\alpha, \rho) = 1$.

Perceptions

Equations 12 through 14 assume that the individual or organization to be deterred has perfect knowledge of the scanning rate ρ. That assumption might not be valid. In other words, the deterrence function δ should be evaluated using the *perceived* value of the scanning rate, denoted $\bar{\rho}$.[23] (In contrast, when calculating the number of detections and apprehensions (Equation 2), the *actual* scanning rate ρ is used.)

Smugglers are known to underestimate, rather than overestimate, the likelihood of detection and apprehension; therefore, we should expect $\bar{\rho} < \rho$.[24] This is due in part to their risk-seeking behavior (see the following subsection, "Decision-Making and Risk Tolerance"). Nevertheless, there are practical limits to the extent of this underestimation.

A lone smuggler may approach a checkpoint with no more knowledge of the true scanning rate ρ than what is available to the general public. However, if many direct observations over time can be combined (for example, by a smuggling organization that repeatedly challenges the system), the scanning rate can be estimated much more accurately. Kohout et al. (2015) considered the case in which there are n observations. If n is sufficiently large, an approximate 95 percent confidence interval for the scanning rate will be

$$\text{Lower bound for scanning rate: } 1 - \mathrm{B}_{inv}\left(1 - \frac{0.05}{2}, n - n\rho + 1, n\rho\right)$$
$$\text{Upper bound for scanning rate: } 1 - \mathrm{B}_{inv}\left(\frac{0.05}{2}, n - n\rho, n\rho + 1\right) \quad (15)$$

[23] In this paper, the distinction between perceived and actual values is applied only to the scanning rate. A similar treatment might also be warranted with respect to scanning system effectiveness $(1 - \alpha)$.

[24] Cece (2012) characterizes drug smugglers as having "a sense of invulnerability." Layne et al. (2001, pp. 13, 16) provides several examples, based on interviews with Colombian drug smugglers operating in the Caribbean. Decker and Chapman (2008) found that these individuals underestimated the odds of detection and arrest. More generally, Savona (2009, p. 58) remarks: "While there is some evidence that criminals are more informed than the general public about enforcement and penalties, there may also be a tendency for individuals to … underestimate the likelihood of being caught."

where B_{inv} is the inverse of the so-called beta cumulative distribution function.[25] Figure 3 shows a representative set of results generated from Equation 15, indicating that the true scanning rate can be estimated to within ± 0.15 on the basis of roughly 40 such observations (Kohout et al. 2015, pp. A12–13). This equation can also be used to show that roughly 200 observations suffice to sharpen the estimates to within ± 0.05.

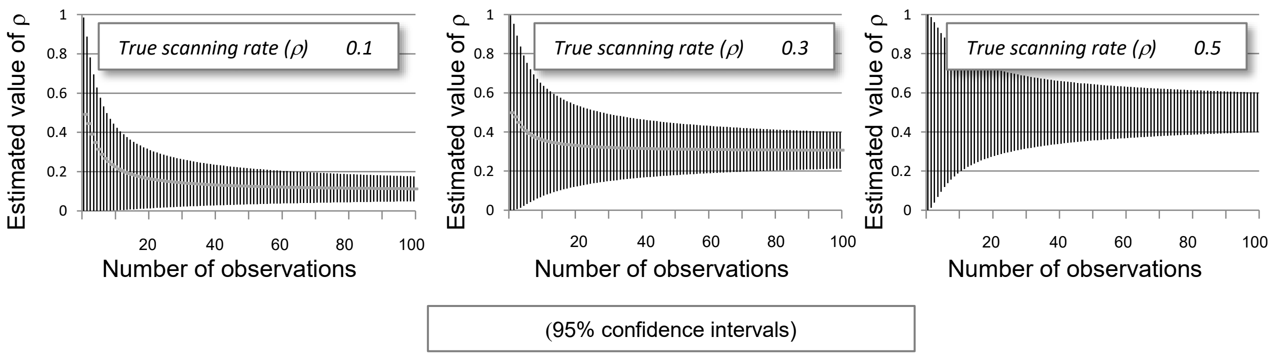

Figure 3. Estimating the Scanning Rate Through Repeated Observation

Equation 15 is useful in incorporating the elements of perception and learning into a closed-form, static model. In a dynamic simulation, learning can be modeled explicitly. For example, Magliocca et al. (2019) developed an adaptive simulation of cocaine smuggling networks, using an embedded Bayesian learning model to represent changes in smugglers' knowledge and perceptions over time.[26]

Decision-Making and Risk Tolerance

Earlier, "success" was defined as achieving E undetected entries out of A attempts. The question remains, however: what exactly do smugglers hope to gain by making these entries, and what do they stand to lose if they fail? Moreover, how do they weigh these potential gains and losses when making decisions under conditions of uncertainty?

One of the earliest representations of decision-making is the so-called rational choice model. Although the roots of this model date back to the work of the English philosopher Jeremy Bentham, its modern applications to criminal behavior began with the seminal work of the economist Gary Becker (1968). (For a concise exposition and discussion, see Chalfin and

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[25] In mathematical terms, B_{inv} (p, a, b) is the value x for which $\frac{\int_0^x t^{a-1}(1-t)^{b-1}dt}{\int_0^1 t^{a-1}(1-t)^{b-1}dt} = \text{p}$. For smaller values of n, the use of $n\rho$ (rather than k, the number of observations for which scanning is seen to occur) in the formulas for lower and upper bound renders the estimates "conservative" in the sense that they center somewhat more accurately around ρ than may actually occur in practice. As n increases, k will approach $n\rho$ for any given sample (Scholz 2019; Mayfield n.d.).

[26] In each step of this complex adaptive systems model, smugglers positioned at various network nodes compare the updated probability of interdiction (cf. $\bar{\rho}(1-\alpha)$) to a "risk threshold" (cf. τ_0): the ratio of these two quantities, along with a "loss tolerance" percentage, is incorporated into an objective function that also includes such quantities as profit margin and transportation cost.

McCrary 2017, pp. 7–8.) Two versions of the rational choice model are considered here: expected value theory (EVT) and expected utility theory (EUT).

In EVT, decisions are based on the monetary value of the potential economic benefits and penalties that might occur as a result of smuggling. Representing these terms as $B \geq 0$ and $P < 0$,[27] the expected outcome of a decision to smuggle is[28]

$$Outcome\ of\ decision\ to\ smuggle\ (EVT){:}\ [1 - p^*]B + p^*P \tag{16}$$

If this value is greater than 0, smuggling becomes attractive. The necessary condition is that the perceived probability of failure p^* is below some threshold value: specifically, $p^* < \tau_0$, where[29]

$$\tau_0 = B/(B - P) \tag{17}$$

Thus, for example, if the magnitude of the punishment $|P|$ were four times as large as the potential benefit from smuggling (that is, $P = -4B$), a scanning system that caused smugglers to estimate their chance of failure as 0.20 or more would act as a deterrent. If $B \gg |P|$ (that is, the benefit is much greater than the magnitude of the potential punishment), then Equation 17 yields $\tau_0 \approx 1$, indicating that smugglers are deterred only if they are virtually certain of failure.

By contrast, EUT assumes that B and P are not necessarily accurate indicators of value; rather, value is assumed to be subjective.[30] A benefit that measures $2B$, for instance, may not be considered twice as desirable as a benefit of B. Instead, decisions are made on the basis of $u(B)$ and $u(B - P)$, where $u(x)$ is a “utility function” that represents the subjectively determined value of x. The expected outcome is now

$$Outcome\ of\ decision\ to\ smuggle\ (EUT){:}\ [1 - p^*]u(B) + p^*u(P) - u(0) \tag{18}$$

and the deterrence threshold τ_0 is

[27] Punishment is often meted out in non-monetary form: for example, a certain number of years’ imprisonment. In such cases, P is the monetized value of the punishment. Different individuals may monetize punishment in different ways, a phenomenon that makes the value of P difficult to determine in practice.

[28] This formulation assumes that benefits accrue if and only if the smuggling attempt is successful, and that punishments occur if and only if it is unsuccessful. For some situations, that may not be the case (see section V.G.).

[29] Or, equivalently, $\tau_0 = B/(B + |P|)$. This relationship appears in different forms in the literature. For example, some authors define B as the expected benefit (i.e., the probability of success times the magnitude of the benefit), rather than the potential benefit (i.e., the magnitude only). Under that definition of B, one would instead write $\tau_0 = B/|P|$. Moreover, some authors define P not as the potential punishment resulting from detection/apprehension, but the potential punishment resulting from detection/apprehension *and conviction*. In this report, the emphasis is on detection, and P is taken as the product of two variables: the probability that punishment will occur if an individual is detected and apprehended (how likely is it that the smuggler, once detected and apprehended, will be convicted of a crime?) and the magnitude of such punishment (what will be the resulting sentence; how much of it will actually be served?). These two variables are commonly termed the “certainty” and “severity” of punishment.

[30] Che and Benson (2013), assessing the body of interview material generated by Decker and Chapman (2008), conclude: “Success allows smugglers to buy what they see as ‘the good life’ for themselves and/or their families … What [is] generally important … are the things that money can obtain, not the money itself.”

$$\tau_0 = [u(B) - u(0)]/[u(B - P)] \tag{19}$$

where $u(0)$ is the utility associated with the decision to do nothing (i.e., to engage in legitimate activity). If $u(x) = x$ (the expected-value assumption), these equations reduce to Equations 16 and 17, respectively.

EVT and EUT differ in their representation of individuals' risk tolerance. In EUT models, the utility function u can be convex, linear, or concave. If u is convex (that is, $u''(x) > 0$), then not only do increased gains represent greater utility, the rate of increase grows as the benefits become larger. Under such conditions, individuals may be willing to engage in an activity for an expected utility that is actually less than the expected value of the benefit: they will pay a risk premium rather than requiring a higher expected benefit. Such behavior is termed "risk-seeking."[31] The net effect is to raise the threshold τ_0, making deterrence more difficult than it otherwise would be. In EVT models, $u''(x) = 0$ and behavior is always risk-neutral.

Rational choice models have been tested and applied to study many different types of criminal behavior over the last 50-odd years. Researchers such as Pillavin et al. (1986) and Matsueda et al. (2006) found that these models produced close agreement with observed outcomes and behaviors. Others, such as Paternoster (1987), found "very little relationship … between [criminals'] estimates of the certainty and severity of punishment, and their behaviors," owing to other factors, such as the desire for social conformity, that defy measurement. Taken as a whole, the findings have been quite mixed, with different conclusions on the extent to which deterrence is most strongly related to the probability of detection and apprehension, the certainty of punishment, or the severity of punishment—or whether deterrent effects occur at all. A recent assessment of the literature on rational choice models concludes: "In sum, the state of deterrence theory is still confusing. … It seems as though deterrence works for some people, but not for others. Some individuals are 'deterrable,' while others are not" (Tomlinson 2016, p. 37).

An alternative approach, cumulative prospect theory (CPT), is based on the notion that human decision-makers do not always make optimal decisions, but instead use heuristics and other cognitive shortcuts. The economist Daniel Kahneman and the cognitive scientist Amos Tversky observed that these departures from classical rationality appeared to be systematic, and sought to capture the resulting patterns of behavior in model form (Tversky and Kahneman 1992).

Under CPT, a decision to smuggle is an example of a "mixed prospect" (a choice between or among alternatives that feature a mix of potential gains and losses). The expected outcome of the choice to engage in smuggling is[32]

$$Outcome\ of\ decision\ to\ smuggle\ (CPT){:}\ \pi^{+}(1 - p^{*})u(G|R) + \pi^{-}(p^{*})u(L|R) \tag{20}$$

[31] Similarly, a convex form of u would correspond to risk-averse behavior. For a more complete (and graphical) explanation, see Che and Benson (2013), pp. 5–8.

[32] Equation 20 represents a very simple case involving one potential gain and one potential loss, with respective probabilities $1 - p^{*}$ and p^{*}; CPT is applicable to choices involving many possible outcomes

where G and L are the respective gains and losses, and π^+ and π^- are weighting functions for the probabilities of gain and loss. The utility function u is conditioned on the value of a reference point R, generally taken to be the current state. In other words, the value of a given level of benefit or punishment depends on the individual's frame of reference.[33]

The functions u, π^+, and π^- have the following important properties:[34]

$u''(x) > 0 \; if \;\; x < 0$	Behavior is risk-seeking with respect to losses
$u''(x) < 0 \; if \;\; x > 0$	Behavior is risk-averse with respect to gains
$u(x) \;\; < -u(-x)$	Losses are weighed more heavily than gains
$\pi''(p) \; < 0 \;\; if \;\; p \; \approx 0$	Small probabilities are overweighted
$\pi''(p) \; > 0 \;\; if \;\; p \; \approx 1$	Large probabilities are underweighted (21)

Based on empirical data, Tversky and Kahneman (1992) proposed the following expressions:[35]

$$u(x) = x^{0.88} \;\; for \;\; x \geq 0$$
$$= -2.25(-x)^{0.88} \;\; for \;\; x < 0$$

$$\pi^+(p) \; = \frac{p^{0.61}}{[p^{0.61} + (1-p)^{0.61}]^{(1/0.61)}} \;\; for \;\; x \geq 0$$

$$\pi^-(p) \; = \frac{p^{0.69}}{[p^{0.69} + (1-p)^{0.69}]^{(1/0.69)}} \;\; for \;\; x < 0 \qquad (22)$$

33 Some sources simply write $u(B)$, with the understanding that B is measured relative to a reference point; for clarity and emphasis, the text keeps the conditional term.

34 Some researchers caution that these patterns of behavior may not be as universal as initially believed. For example, Harbaugh (2002) argues that attitudes toward risk change with age. In particular, he found that children tend to underweight small probabilities and overweight large probabilities—directly opposite the predictions of the "standard" CPT model. In a study measuring the utility of life duration, Attema et al. (2013) found concave rather than convex utility with respect to losses. The authors speculate that "life years are arguably very different from monetary outcomes" when it comes to judgments regarding utility. However, Berns et al. (2007) found that "standard" probability weighting did apply when non-monetary losses were delivered in the form of electric shocks.

35 Harrison and Swarthout (2016) point out that the parameter values shown in Equation 22 capture only measures of central tendency (e.g., the median over many test subjects) and thus do not reflect the potential range of differences among individual decision-makers. Moreover, even if the properties of u and π specified in Equation 21 are accepted as universal, one must ask whether the specific forms and parameter values proposed in Equation 22 are valid in contexts outside Tversky and Kahneman's 1992 experiment (in which graduate students were presented a set of two-outcome prospects with given monetary outcomes and numerical probabilities). Harrison and Swarthout (2016, pp. 33–42) review the findings of other researchers who have arrived at different representations. One notable example is Pachur et al. (2010), who found that convicted criminals displayed risk behavior different from that of non-criminals. Although Pachur et al. used the same functional forms shown in Equation 22, they arrived at different values for the numerical parameters. Phillips and Pohl (2014, pp. 146–47), in an analysis of terrorist decision-making, applied Equation 22 but cautioned that "if [CPT] and its dominant models are to be used to analyse terrorist behaviour, it is an important task for future research to determine the values of these parameters within each terrorism context." The same can be said for smuggling.

If the gains, losses, and probabilities associated with the decision to smuggle are known, Equations 20 and 22 can be used to evaluate the expected outcome of that decision. Smuggling would be expected when the value of that outcome is greater than zero. These equations do not provide a closed-form solution for the deterrence threshold τ_0; however, τ_0 can be computed numerically as the value of p^* for which the expected outcome of the decision to smuggle is equal to zero.

Figure 4 shows the deterrence threshold τ predicted by both the EVT and the CPT models (Equations 17, 20, and 22), as a function of the relative magnitude of benefit and punishment, $B/|P|$.[36] The figure suggests that for a fixed punishment P, an increase in the smuggler's perceived probability of failure p^* can be overcome (in terms of its deterrent effect) by raising the level of benefit B. For example, if benefit and punishment are equal in magnitude ($B = 1$, $P = -1$), the CPT model predicts that $\tau_0 = 0.20$; that is, smuggling will be initiated when the perceived probability of failure is less than 0.20. If increased scanning were to raise this probability to 0.30, an increased benefit $B \cong 1.5$ will raise the threshold to $\tau_0 = 0.30$, sufficient to warrant the initiation of smuggling as before.

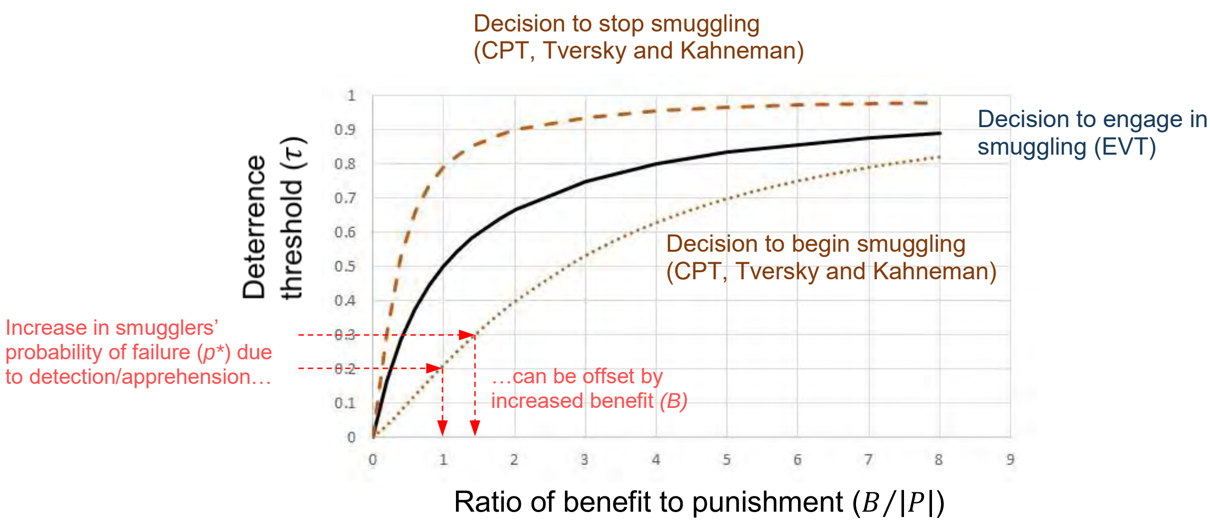

Figure 4. Deterrence Threshold as a Function of Benefit and Punishment

Note that while EVT does not distinguish between the decision to start smuggling and the decision to stop, CPT predicts that for a given value of $B/|P|$, the latter decision carries a higher deterrence threshold. This reflects the asymmetry of behavior with respect to gains and losses that is one of the hallmarks of CPT. Specifically, for the decision to begin smuggling, the prospective gains and losses are simply $G|R = B$ and $L|R = P$. However, for the decision to stop smuggling, the prospective gain is the avoidance of punishment and the prospective loss is the foregone benefit of smuggling; that is, $G|R = -P$ and $L|R = -B$. Since gains and losses are not treated symmetrically under CPT (that is, $u(x) \neq -u(-x)$), the outcome of the decision to stop

[36] The threshold τ_0 depends only on the ratio $B/|P|$, rather than the individual values B and P, because a) the prospect in question has only two outcomes, and b) the same exponent (0.88) is used in Equation 22 for both positive and negative values of x.

smuggling is not simply the negative of the outcome for initiating it.[37] In other words: decreasing the profits of a smuggling organization by increasing the probability of detection/apprehension alters its reference point and its risk tolerance. It will likely try to recapture its losses by engaging in more risky behavior (Che and Benson 2013, p. 19).

Many other decision-making theories have been proposed; however, modeling them all would not, in the author's judgement, substantially change the conclusions presented in this paper. Among the theories not considered further here are rank-dependent utility (RDU) theory (a special case of CPT in which $\pi^+ = \pi^-$), dual theory (a special case of RDU theory in which $u(x)$ is constrained to be a linear function), disappointment aversion theory (a different method of parameterizing π^+ and π^-), and salience theory (a generalization of CPT in which π^+ and π^- may have an explicit dependence on x as well as p).[38]

C. Applying the Extended Model

For a single smuggling decision, modeling the deterrence function $\delta(\alpha, \rho)$ requires the ability to determine the threshold τ_0. For an analysis of many decisions that result in a given level of smuggling activity, it requires knowledge of how threshold values are distributed—or, at the very least, the interval $[\tau_1, \tau_2]$ over which deterrent effects may occur. The extended model provides three ways to measure these thresholds:

- If smuggling is attempted and the smuggler's a priori perception of the probability of failure, p^*, can be measured, this value represents a lower bound for τ_0 and/or τ_2.
- If it is known that a smuggler contemplated a border crossing but was deterred by the presence of scanning systems, and the smuggler's a priori perception of the probability of failure, p^*, can be measured, this value represents an upper bound for τ_0 and/or τ_1.
- If smugglers' estimates of the benefits B and punishments P associated with success and failure can be independently measured, the tenets of decision-making theories such as EVT and CPT can be used to develop estimates of τ_0, τ_1, and/or τ_2.

In sections V and VI, this approach is tested with respect to two very different types of smuggling activity. Each section addresses several key questions: How is this particular type of smuggling conducted? Who is involved, and whom exactly are we trying to deter? What do we know about their definition of success? How do they view gains and losses? How are scanning

[37] By contrast, the symmetry of outcomes under EVT can be demonstrated as follows. For the decision to stop smuggling, the probability of realizing a gain is the difference between the certainty of not being punished (if the smuggler refrains) and the probability $1 - p^*$ of not being punished (if he/she continues). Similarly, the probability of realizing a loss is the difference between the certainty of foregoing the benefit and the probability p^* of foregoing it. Thus, the outcome of the decision to stop smuggling under EVT is $p^*(-P) + [1 - p^*](-B)$. Comparing this expression with Equation 16, it is clear that the two outcomes are simply the negatives of each other; thus, when one expression takes the value zero, the other one does as well. In other words, the threshold is the same for both decisions. The asymmetry of outcomes under CPT results not only from the properties of the utility function u, but also from the differences in the relative probability weightings.

[38] Magliocca et al. (2019) incorporated salience theory into their simulation of drug smuggling networks as complex adaptive systems, and reported good agreement with observed behaviors.

systems used, how effective are they, and how to they impact smugglers' perceptions of potential success and failure? Answers to these questions allow comparison of model predictions to observed smuggling levels and patterns.

V. Analysis – Radiological/Nuclear Smuggling

A. Radiological/Nuclear Smuggling: An Overview

Illicit trafficking in radiological and/or nuclear weapons represents a potentially serious threat to the security of the United States. It also poses public health, safety, and environmental risks. Although radiological/nuclear smuggling has been a concern since the early days of the Cold War (Downs et al. 2019, Bunn et al. 2016, pp. 133ff.), the level of concern increased significantly following the dissolution of the Soviet Union in 1991. The states of the former Soviet Union (FSU) inherited vast quantities of highly enriched uranium (HEU) and plutonium—some 650 tons scattered among 300 buildings at more than 50 facilities (Lee 2003, p. 95)—in conditions that made them potentially attractive for theft. A number of smuggling incidents were reported during 1991–93, and international concerns heightened in 1994, when small quantities of smuggled Pu239 were discovered for the first time (Woessner and Williams 1996, p. 43). After 1994, the number of confirmed cases of illicit radiological/nuclear smuggling declined somewhat; however, such incidents continued to persist through the remainder of the 1990s, along with reports of diverted radiation sources (Zarimpas 2000, pp. 505–6).

In response to this continuing threat, the international community initiated efforts to improve the protection, control, and accountability of radiological and nuclear materials, share information, and combat illicit trafficking. In 1998, the United States established a program to provide radiation detection equipment[39] and other support to the government of Russia, deploying large-scale systems at road and rail crossings, airports, and selected seaports. In 2001, the program was expanded to include other FSU states and selected countries in eastern Europe; it has further widened over subsequent years, and now includes over 60 partner countries. These efforts are currently managed under the Department of Energy's NSDD program (NNSA n.d.). The radiation detection equipment installed under this program includes fixed, large-scale scanning systems (radiation portal monitors), large-scale (truck-mounted) mobile systems, and smaller-scale equipment, such as backpack systems and handheld detectors. The United States provides maintenance and technical support for an initial period (ideally, 3 to 5 years); after this time, the recipient government assumes the responsibility.

As these detection systems were deployed during the early 2000s, the number of nuclear trafficking cases detected at national borders rose dramatically. During the 1990s, there were 64 cases in which radiological/nuclear materials were found by border control agencies; the

[39] It is important to note that "Radiation detection is only one of many tools for reducing the risk of nuclear terrorism, and not the most effective one" (Bunn et al. 2016, p. 131). Keeping radiological/nuclear materials away from smugglers in the first place (i.e., protection, control and accountability) is generally seen as a more tractable problem than dealing with "the myriad pathways by which nuclear items might be smuggled, the huge size of countries and enormous length of their borders, the weak radiation and small size of weapons-usable nuclear material (which would fit in a briefcase), the huge and varied legitimate traffic across national borders, and the many areas of the world with little control over border crossings" (Bunn et al. 2016, p. 131; see also Cochran and McKinzie 2008). In this light, a realistic goal for the deployment of scanning systems is to "[motivate] smugglers to either transport only smaller amounts of material, which means more trips and more opportunities for detection, or to use shielding, which is itself detectable by weight, size, and X-ray image. It provides an impetus for smugglers to use alternate routes, which are hopefully more risky to them" (Erickson and Martin 2001).

corresponding figure for the 2000s was 454 (Zaitseva 2010).[40] Most of those cases involved the inadvertent transport of material. Nonetheless, incidents of deliberate radiological/nuclear smuggling for illicit purposes have continued to occur.

There have been two important changes in smuggling patterns since the late 1990s.

First, radiological/nuclear smuggling routes shifted southward. The earliest smuggling incidents involved materials moving from Russia to central Europe (Zarimpas 2000, p. 506; Zaitseva 2007). Sometime during the late 1990s, however, "more persistent nuclear smugglers … identified direct and less dangerous routes from Russia to the Middle East and Southwest Asia through the Caucasus, Central Asia, Turkey, and the Balkans" (Zaitseva 2007).[41] This new pattern has largely persisted: since 2010, there have been notable seizures of radiological/nuclear materials at border crossings in Uzbekistan, Armenia, Georgia, Romania, Moldova, and Ukraine, as well as Belarus (NTI 2019-7; also see section V.D of this report).

Second, some post-2001 smuggling attempts began to exhibit a "high degree of sophistication in trafficking modes and methods" (Williams 2007). A likely reason is that would-be radiological/nuclear smugglers began to seek assistance from established drug and commodity smugglers, criminal organizations, and other groups with greater experience, wider networks, and more substantial infrastructure.

These two developments are related, and point to the need to understand exactly who is involved in radiological/nuclear smuggling.

B. Radiological/Nuclear Smugglers and End-Users

Zaitseva and Hand (2003, p. 827) characterize the universe of radiological/nuclear smuggling in terms of suppliers, middlemen (including smugglers), and end-users (see also Williams and Woessner 2002, p. 322; and Kershner 2014, p. 17).

- Suppliers are those who have, or can facilitate, access to the materials. They may include employees of the legitimate radiological/nuclear enterprise, corrupt government officials, and, less often, criminals who divert material while it is in transit.
- Middlemen are responsible for finding buyers and transporting the material to them, smuggling it across national borders if necessary. Radiological/nuclear smugglers may be amateurs, opportunist businessmen, members of small-scale criminal organizations,

[40] These figures are roughly consistent with other estimates; for example, in 1995 Russian customs service officials claimed to have intercepted four shipments of radioactive material, whereas the corresponding figure for 2004 was approximately 200 (Russian Customs Officials 2005, p. 3).

[41] Many others also commented on this shift. For example, Williams and Woessner (2002, p. 313) reported that "stolen nuclear and radioactive material is no longer traveling through Germany and West Europe, it is going south—through the Caucasus, Central Asia, and the Balkans." As of 2010, the reported consensus of experts in nuclear smuggling was that "since 2001, [radiological/nuclear] trafficking has been routing south from Russia to Iran, or through Iran to Jordan or Turkey and beyond, whereas before 2001, such smuggling was seen going directly westward" (GMU TraCCC 2010, p. 5).

crime-controlled businesses, transnational criminal organizations (TCOs), or ethnically based smuggling organizations.

- End-users are those who wish to acquire and/or use the material to accomplish some objective (e.g., through blackmail, intimidation, or attack). In theory, this could include nation states, terrorist organizations, religious sects, separatist movements, or criminal organizations.

Since this analysis is concerned with detection and deterrence, rather than accountability and control, suppliers are not considered further.

Smugglers

Most of the earliest incidents resulted directly from the breakdown of materials control regimes across the FSU. Low-level workers were able to steal radiological/nuclear materials and attempt to sell them for a quick profit. These cases displayed the hallmarks of what has been termed "low-end smuggling": amateur smugglers carrying sub-weapons-grade material, often with little or no attempt at concealment (e.g., in a suitcase) (Lee 2003, p. 103). Some of these individuals caused great harm to themselves through improper handling of radioactive materials.[42] This period also saw the emergence of scam artists, who tried to cash in on the confusion by misrepresenting the nature of materials in their possession (Butler and Devali 2004).[43]

Potter (1995) concluded that radiological/nuclear smuggling was the province of individuals operating on their own: "To date, most evidence linking organized criminal groups to nuclear material smuggling is anecdotal and not well documented. U.S. officials thus continue to maintain there is no solid evidence that organized criminal groups—as distinct from individuals with possible ties to organized crime—have been directly engaged in the theft or trafficking of sensitive nuclear materials."

Through the first two decades of the 21st century, observers have maintained that *most* nuclear smuggling attempts are still the work of amateurs and opportunists.[44] However, there is clear evidence that from the late 1990s onward, at least some attempts to transport radiological/nuclear materials illicitly have been the work of small groups engaged in criminal activities. This phenomenon is likely related to the change in radiological/nuclear smuggling pathways that occurred about that time.

[42] Woessner and Williams (1996) cite the example of one amateur smuggler who died after carrying an unspecified quantity of Cs137 in his shirt pocket.

[43] Radiological/nuclear scams have not gone away. According to a recent report, "One nuclear security stakeholder estimated that about 95 percent of all illicit trafficking cases involve scams or a grave overestimation on the part of the smuggler of the value of the substance being transferred" (Fedchenko and Anthony 2018).

[44] For example: "The market as a whole is populated by amateur criminals, scam artists, and (on the demand side) undercover police and police decoys" (Lee 2003, p. 101). "Most seizures … involve amateur smugglers with relatively small amounts of material" (Goodby et al. 2007, p. 6). "According to one UN official with good knowledge of the matter, most of the relatively few trafficking attempts in the [Black Sea] region have been of an opportunistic nature by persons trying to sell low radioactive material and fake nuclear materials (scams)" (Fedchenko and Anthony 2018, p. 24).

As the southward shift began, Zarimpas (2000, p. 507) warned that "Existing drug smuggling routes, such as those in the volatile region of Central Asia, that are not as well policed or equipped with modern detection systems as the ones leading to Europe may offer alternatives to nuclear smugglers." Under these circumstances, it was perhaps inevitable that radiological/nuclear smugglers would begin to develop ties to established smuggling organizations of various kinds. Bronner (2008, p. 6) quotes Dr. Louise Shelley of George Mason University's Transnational Crime and Corruption Center: "Whatever is a viable smuggling route remains a viable smuggling route, whether you're selling drugs, arms, people, or other contraband. Nuclear materials move right along with everything else—that's the genius of it." In contrast to earlier incidents, radiological/nuclear smuggling activity reported in Georgia, Armenia, and elsewhere in the region began to feature the involvement of individuals with "extensive smuggling experience" (Heighton 2010). These developments indicate the potential for at least some radiological/nuclear smuggling activity to take on the characteristics of what Lee (2003, p. 103) termed "high-end" smuggling: the illicit transport of weapons grade material, with the assistance of crime organizations and/or front companies, using established smuggling routes and sophisticated methods of concealment.

By 2007, "the involvement of organized criminal groups—albeit relatively small and unsophisticated—in nuclear smuggling activities" was well established (Zaitseva 2007).[45] This involvement continues today: Cotton et al. (2018, p. 5) note that "Despite their overall rarity, these incidents demonstrate a continued interest by criminals in trafficking radioactive materials for profit."

By contrast, evidence for the involvement of TCOs is unclear. Zaitseva (2007) speculated that such organizations might engage in radiological/nuclear smuggling "as a sideline activity, if the criminals believe it can be profitable," but pointed out that "given the enormous profits organized crime makes from their traditional criminal activities, such as narcotics or people smuggling, nuclear trafficking may not be its first choice." The consensus of a group of experts convened in 2010 was that:

> "Cases in Georgia and elsewhere also suggest that members of [large-scale] organized crime groups tend not to be involved in the smuggling of items directly related to weapons of mass destruction. They view this 'market' as uncertain and unstable as a source of regular income, and fear that involvement in such activities would harm their more traditional and lucrative criminal enterprises, e.g., by damaging relations with corrupt government bureaucrats and others who operate in the legitimate worlds of government and commerce, or by inviting sharper law enforcement scrutiny" (GMU TraCCC 2010).

[45] Zaitseva (2007) analyzed some 400 nuclear trafficking incidents drawn from the Database on Nuclear Smuggling, Theft, and Orphan Radiation Sources (DSTO) operated by the University of Salzburg in Austria. The incidents occurred between January 2001 and December 2005. She found 40 incidents that involved a) actual (versus claimed) theft of materials, b) involvement of more than one individual, and c) evidence of "continuing criminal activity" by these individuals, with the intention of realizing a profit from them. The mean size of the criminal group was five individuals, with two-thirds of the cases involving 17 or fewer persons. Six cases involved seizures of both narcotics and radioactive materials; four included parallel seizures of small arms caches.

Kershner (2014) analyzed open-source data specifically to determine whether there is evidence of a connection between TCOs and the smuggling of nuclear and radiological material (either on behalf of a terrorist organization, or independently, for profit). Although he found a very small number of cases that seemed to implicate a TCO, his conclusion was that "there [are] no indicators that pointed to [TCOs] migrating into this market" (Kershner 2014, p. vii).

End Users

The universe of end-users is best described as "shadowy" (Zaitseva and Hand 2003). Zaitseva (2007), in analyzing some 400 instances of illicit trafficking, pointed out that "In over 80 percent of the cases, neither the final destination nor the end-user of the radioactive material could be determined. It is likely that in many cases they did not exist, since the material was either resold from one group to the next … or sold to undercover security agents in a sting operation."[46] Murauskaitė (2015, p. 185) noted that seizures generally result in identification of the origin of the material along with the smugglers, "but the clients who sought it tend to remain unknown." Zarimpas (2000) concluded that "circumstantial evidence does not support claims of the existence of a well-organized nuclear black market"; Lee (2003, p. 109) observed that "The actual design and extent of the illicit market for nuclear goods are largely a mystery."

Efforts by nation-states to acquire nuclear materials through cross-border smuggling have been hinted at in the open literature; however, little is publicly known, other than the fact that such incidents could "conceivably" have occurred (Lee 2003, p. 98).

Neither have actual smuggling incidents been publicly linked to terrorists or rogue state networks (Brown and Schapiro n.d., quoting Potter). Early post-2001 reports of terrorist involvement in nuclear smuggling rest on "accounts of varying credibility" (Lee 2003, p. 109). In 2003, a Syrian arms dealer with ties to the IRA reportedly promised to deliver Ir192 from Istanbul to London; in 2005, an Armenian arms dealer offered to sell HEU to an undercover FBI agent in support of a purported terrorist attack targeting the New York subway system (Zaitseva 2007). Both incidents are "highly speculative"; neither involved any actual seizure of material. More recently, FBI sting operations in Moldova led to the arrest of smugglers who offered to sell both Cs137 and "bomb grade" U235 to what they thought were representatives of the Islamic State of Iraq and Syria (ISIS). There was, however, no actual ISIS connection (Williams 2015). Zaitseva's (2007) conclusion on this point is most likely still accurate: "If terrorists [have] attempted to gain access to nuclear materials in order use them for the construction of [weapons of mass destruction], such attempts have not been revealed to the public."

In any event, what is publicly known about the market for illicitly trafficked radiological/nuclear materials is that it consists primarily of "smugglers in desperate search of potential buyers" (Zarimpas 2000). The IAEA's 2007 Technical Reference Guide on the subject states that trafficking activities "appear to have been mainly supply-driven. In other words, the trafficking process was initiated by sellers with no pre-identified buyer" (IAEA 2008, p. 127). Murauskaitė (2015, p. 185) likewise concluded that "this activity is supply-driven: persons with access to radioactive materials attempt to put together schemes for selling them."

[46] With regard to prospective buyers of HEU or plutonium specifically, NTI (2011-12) states that there are only two instances on record where prospective buyers were identified: these buyers had no relation to terrorist groups.

C. Implications for Deterrence

Motivations, Decision-Making and Risk Tolerance

Since almost nothing is known about potential end-users, this analysis concentrates on the value of scanning technology in deterring radiological/nuclear smugglers, whether operating as individuals or in small groups. The previous section suggests that documented cases should be treated as isolated instances; each attempt is a separate undertaking, in which success or failure rests on whether that particular attempt was detected.[47] In other words, using the terminology of the extended model (section IV.B), $A = E = 1$ and $p^* = p^1$.

The motivation for these attempts appears to be purely financial.[48] In terms of the extended model, the benefits B are the proceeds the smuggler expects to realize from the sale of the material (or, for a courier whose role is limited strictly to carrying the material across the border, the payment he or she receives). The penalties P are measured by the monetized value of the punishment consequent to detection and arrest.[49]

Figure 5 shows a few examples of prices and payments cited in published accounts over the last two decades. Prices sought by smugglers are not usually realized because the sales never occur. Nevertheless, these figures provide some sense of what smugglers expect or hope to gain. In rough terms, the figure suggests that anticipated gains may be on the order of $10,000 if the individual's role is limited (e.g., a courier) or the attempt involves relatively small amounts of material; otherwise, they may be on the order of $100,000. Assuming smugglers have high expectations of realizing these gains once safely across the border, these figures may be taken as a range of estimates for the benefit B of engaging in radiological/nuclear smuggling.[50]

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[47] Strictly speaking, this might not be true if a smuggler's plans involved multiple border crossings in rapid succession. NTI (2019), for example, includes a report on a 2014 case in which a freight railcar carrying Cs137 crossed from Kazakhstan to Russia at Tretyakovo, back into Kazakhstan at Veseloyarsk, and again from Kazakhstan to Russia at Kartaly. Radiation detection equipment, however, was only present at the last of these three crossings, and the smuggler may have been aware of that fact.

[48] "There is a general tendency to describe [radiological/nuclear] smugglers as [opportunists or scammers] motivated by money … As far as it is possible to judge from the available open sources, this description … is probably correct, at least in the vast majority of cases" (Fedchenko and Anthony 2018, p. 24). "[B]ased on multiple interviews with one-time offenders, as well as brokers … , financial motives seem to dominate" Murauskaitė (2015, p. 187).

[49] "The largest negative incentive to smuggling nuclear material is the risk associated with getting caught" (Kershner 2014, p. 39). It is important to note, however, that this statement applies only to the smuggler, not to the end-user. For example, if deterrence is being considered from the perspective of a terrorist organization planning an attack, the potential gain is the value of the damage that could be inflicted ($B > 0$), while potential losses include the cost of the undertaking (call it $P_C < 0$) and the retaliation that might follow from a successful attack (call it $\Delta_R P_R < 0$-, where P_R indicates the magnitude of the retaliation and Δ_R is equal to 0 or 1, depending on whether retaliation occurs). Notice that both B and P_R occur only if the smuggling attempt is successful, while P_C occurs regardless of whether the smuggling attempt succeeds. Under a policy of assured retaliation, the expected outcome, Equation 16, would be rewritten as $[1 - p^*](B + P_R) + P_C$, and in place of Equation 17 we would have $\tau_0 = 1 + P_C/(B + P_R)$ or, equivalently, $\tau_0 = 1 - |P_C|/(B - |P_R|)$. This form appears in studies that consider the threat of terrorist-sponsored smuggling (whether of radiological/nuclear materials or conventional weapons): for example, see Bier and Haphuriwat (2011) and Haphuriwat et al. (2011).

[50] This assumption may not be entirely correct. For example, a smuggler might have specific reasons to fear apprehension between the border crossing and the point of sale, or may not be confident of locating the buyer.

	Material	Amount	Number of Individuals	Approximate Gain per Individual ($K)[51]	Reference(s)
Sales Price ($K)					
$1,000	HEU	100g	>4	$60–$250	Bronner (2008)
$1,500	HEU	120g	>3	$90–$500	Badalova (2016)
$35 per kg	LEU	Up to 20kg	>3	$40–$230	Badalova (2016), Schmid (2012)
$3,000	U235	"a few pounds"	>5	$175–$600	Shuster (2017)
$100	Cs137	[unspecified]	>3	$6–$30	Georgia (2016), CDRF (2017)
$30	LEU	1kg	6	$5	Williams (2007)
$2,000	U238	200g	>7	$120–290	Rusnac (2014)
Courier Payment ($K)					
$15	HEU	170g	1	$15	Sheets (2008)
$16	Pu	[unspecified]	1	$15	Schmid (2012)

Figure 5. Financial Compensation for Radiological/Nuclear Smuggling

Such amounts loom large in the Black Sea and Transcaucasus regions, which are marked by "traditions of profound poverty" (Nanagoulian 2000; Bezemer 2006). For many countries in the region, gross domestic product per capita is on the order of $5,000 per year or less (World Bank 2020) and in the poorest areas, average income is closer to $1,000 per year (Shuster 2017). For both suppliers and smugglers, the sums shown in Figure 5 represent huge inducements (Lee 2003; Fedchenko and Anthony 2018).[52] A news report on recent radiological/nuclear smuggling incidents in Georgia noted that:

> Poverty appears to be a factor in [these] smuggling cases. Official unemployment is in the double digits, and the typical monthly income is pegged at just over $122 (284 laris). Thus, acting as a courier can be an economically attractive proposition for many Georgians. [The defense attorney for one of the men detained] told EurasiaNet.org that her client comes from a socially vulnerable family, and "would have accepted whatever he had been paid" to help sell the uranium (Edilashvili 2016).

In a similar vein, a report on smuggling incidents in Armenia stated that "The majority of [suspects in these incidents] were 'pensioners in their mid-70s' who 'needed more money to live on'" (CDRF 2017).

Not much is known about the magnitude of punishment P for radiological/nuclear smuggling, due to the general "lack of follow-up reporting" (Zaitseva 2007) on such incidents. For the 60-odd cases considered in this analysis (see section V.D), published information regarding conviction and sentencing appears in only five of them. The longest sentences (11, 13, and 14 years' imprisonment, for attempting to smuggle 18g of HEU) were overturned on appeal. One of the individuals in that case had been caught smuggling HEU four years earlier and sentenced to

[51] Upper limits for the approximate gain per individual assume that gains were to be shared only among the number of individuals arrested or otherwise cited in published reports. Lower limits assume a total group size of 17, based on the finding of Zaitseva (2007) that two-thirds of all such groups comprise 17 or fewer persons.

[52] With respect to suppliers, Lee (2003, p. 95) points to "the depressed economic situation of employees in parts of the nuclear complex, reflected in relatively low pay, a shrinking social safety net, and uncertain professional prospects."

2.5 years' imprisonment, but had been released after serving only a few months of his term (Heighton 2010). Other cases involved sentences of 4 to 8 years, 7 to 10 years, and 5 years; what portions of these sentences were actually served is not known. From this limited sample, it appears that expected punishments might range from 2 to 4 years imprisonment for an individual indicted on fewer counts (e.g., a courier) and perhaps 7 to 10 years otherwise.

It is impossible to say for certain how a prospective smuggler would monetize and/or assign utility to the threat of punishment arising from detection. The simplest assumption is that they might weigh only the lost income resulting from a term of imprisonment. A lower level of activity might then correspond to a potential loss of \$2,000–\$4,000, while an individual complicit at a higher level might incur a loss of \$21,000–\$30,000.[53]

Under these assumptions, the ratio of benefit to punishment $B/|P|$ might lie somewhere in the neighborhood of 2 to 5. The figure might be lower if prospective smugglers are less than certain that a successful border crossing will result in a sale, or if they weigh the threat of imprisonment as greater than the value of lost income. It might be higher if they believe they can avoid punishment even if caught—for example, by taking advantage of the "pervasive corruption" (Bezemer 2006) that exists in portions of the FSU, Transcaucasus, and Black Sea regions.

Perceptions

Would-be radiological/nuclear smugglers may vary greatly in their knowledge of the challenges they face when crossing a national border. For purposes of analysis, consider two possibilities.

The unsophisticated amateur or opportunist may have only a general knowledge regarding radiation detection systems at the border(s) they hope to cross. (For example, they may know that portal monitors are present at all, or most, or some, or none of those crossings; that the destination country operates many or only a few mobile systems; that deployed detectors are operating properly most of the time, or only seldom; and so on.) Moreover, they may have neither the flexibility nor the wherewithal to choose from among many alternate smuggling routes. In this case, the smuggler's perceptions of the scanning rate ρ might be very similar to the estimates developed in section V.E of this report, which is based largely on contemporaneous, publicly available reports.

On the other hand, criminal organizations may have detailed tactical-level knowledge they can exploit. In commenting on the involvement of established smuggling rings and small-scale criminal organizations, Williams (2007) observes:

[53] The assumption here is that lower-level individuals are among the most impoverished residents of the area, with an income of approximately \$1,000 per year, while the other group members' incomes are closer to \$3,000 per year. (For purposes of comparison, the latter figure is approximately equal to the average annual GDP per capita in the regions of Georgia outside the national capital, Tblisi (World Bank 2013, p. 12, Figure 1.10).) As an example of smugglers who are likely to have had "average" incomes, see the case detailed by Bronner (2008). The three individuals lived in the town of Kazbegi (located in the Mtskheta-Mtianeti region): one was a security guard, the second a taxi driver, and the third a failed small businessman.

> "[These smugglers] are believed to collect and share information on which Russian customs posts are equipped with radiation monitors and to route their shipments accordingly. … [They have] tested radiation detection devices by sending decoys across borders. … These professional smugglers know the terrain and the authorities who are either corrupt or even complicit in the smuggling activities."

A specific example of a suspected probe occurred in 2005 at Moscow's Sheremetyevo airport, where all the sensors at one terminal were set off in sequence. An official there stated, "We think they were just testing how well it worked, looking for a gap in the defensive line" (Chivers 2005). One of the smuggling incidents described in this report (see section V.G) featured a package that had the appearance of an illicit radiological/nuclear shipment, but no radiation sources were found; this, too, may have been a decoy or test.

For smugglers with sufficient tactical knowledge to pick a crossing without a detector, or to bypass a detector if one is present, the perceived probability of being scanned $\bar{\rho}$ would be equal to zero regardless of how prevalent detectors were generally.

D. Documented Incidents

Using the sources and incident criteria described in section III.B (a deliberate attempt to smuggle a known type of radiological/nuclear material across a specified national boundary), the author identified 56 incidents of interest over the period January 1993 through December 2018. For convenience, these cases are listed in two tables (Figure 6 and **Error! Reference source not found.**), covering the periods 1993–2003 and 2004–18, respectively.

A blank cell indicates that the information was not provided in any published reports. In some cases, it was possible to draw inferences from the available information. This will be discussed further below and also in section V.G.

The columns labeled "#" list the reference number assigned for purposes of this study. Initially, 64 cases were identified; however, eight cases were removed because it was not possible to infer or estimate one or more critical details missing from published reports. The included cases retain their original reference numbers.

The columns labeled "Date" show the date of the actual smuggling attempt (not, for example, the date the incident was reported). In a few cases, only the month and year were specified in published reports; those cases were arbitrarily assigned to the 15th of the month.

The columns labeled "From" and "To" indicate the border that was crossed. In some cases, the available information includes the specific airport, seaport, land border crossing, or border region where the incident occurred. That information is not shown here.

The columns labeled "Material" show the principal type of radiological/nuclear material that was smuggled. (In some cases, not all radioisotopes known to have been present are listed.) The notation HEU(x) or LEU(x) indicates the level of enrichment—that is, the percentage of U235, by mass—where that information is known.

The columns labeled "(g)" show the amount of material, in grams, where that information was given. In many cases, what was specified instead was a level or rate of exposure (in roentgens), activity (in curies or becquerels), or equivalent dose (in sieverts)—or some other description, such as "10 times above permissible levels" or "100 times above background levels." Such information allowed us to characterize the incidents for purpose of analysis.

The columns labeled "Shld?" indicate whether there is any information regarding evidence of an attempt to shield or otherwise disguise the material—for example, by placing it inside a specially designed container, or within a shipment of other materials with similar characteristics. The most commonly used measures include placing the material inside one or more containers lined with lead (designated "Y(Pb)") or, less commonly, gold (designated "Y(Au)"); intermingling the material with scrap metal (designated "Y(scp)"); and concealing it within a legitimate industrial source of radiation, such as a deicing sensor, anti-static device, or other measurement gauge (designated "Y(ind)"). Other methods, where specified, are described in the accompanying footnotes.

#	Date	From	To	Mode	Material	(g)	Shld?	Det?	Principal Reference(s)
1	20-Jan-93	Russia	Lithuania	Air	HEU(50)	150	Y[54]		Mohtadi (2006); Zaitseva (2004)
2	15-Mar-93	Azerbaijan	Turkey	Land	LEU	6000			Woessner and Williams (1996)
3	15-Oct-93	Germany	Turkey	Air	U238	2490			Woessner and Williams (1996)
4	15-Nov-93	Ukraine	Poland	Land	Sr90				Schmid (2012)
8	10-Aug-94	Russia	Germany	Air	Pu239[55]	363		N	GAO (2002); Potter (2002)
9	15-Oct-94	Bulgaria	Turkey	Land	[multiple]		Y(Pb)		Schmid (2012)
10	19-Oct-94	Azerbaijan	Turkey		LEU	650			Schmid (2012)
11	10-Dec-94	Hungary	Austria		DU	1750			Oehler (1996)
12	14-Dec-94		Czech	Rail	HEU(88)	2700	Y(Pb)	N	GAO (2002); Schmid (2012)
13	25-Jan-95	Belarus	Lithuania	Land	W180	[2 tons]		Y	Oehler (1996)
16	7-Nov-95	Poland	Czech	Land	Sr90	275			Oehler (1996)
17	15-Jun-98	Turkey	Bulgaria	Land	--[56]				Schmid (2012)
18	1-Jul-98	Iran	Turkey		[multiple]				Schmid (2012)
19	14-May-99	Kyrgyzstan	UAE	Air	Pu				Schmid (2012)
20	29-May-99	Romania	Bulgaria	Land	HEU(73)	10	Y(Pb)		GAO (2002); Schmid (2012)
21	22-Jul-99	Kazakhstan	Uzbekistan						Schmid (2012)
22	24-Aug-99	Vietnam	Cambodia		U238				Mohtadi (2006)
24	20-Sep-99	Russia	Ukraine	Land	Sr90		Y(Pb)		Mohtadi (2006); Schmid (2012)
25	20-Sep-99	Russia (?)	Georgia		LEU(16)	1000	Y[57]		Chabashvili et al. (2013); Gordon (1999)
26	3-Dec-99	Russia	S Korea	Sea	Cs137		Y(scp)		Mohtadi (2006)
27	30-Mar-00	Kazakhstan	Uzbekistan	Land	Sr90		Y(Pb)		Mohtadi (2006); Schmid (2012)
28	15-Apr-00	Russia	Georgia	Land	HEU(30)	920		Y	GAO (2002); Potter (2002)
30	16-Jul-01	Romania	France	Air	HEU(73)	5	Y(ind)		IAEA (2007); Potter (2002)
31	15-Oct-02	Russia	Azerbaijan	Land					Schmid (2012)
32	26-Jun-03	Armenia	Georgia	Land	HEU(89)	170	N	Y	Bronner (2008); Sheets (2008)

Figure 6. Documented Radiological/Nuclear Smuggling Cases: 1993–2003

[54] Embedded in 4.4 tons of beryllium and "mixed with … radioactive cesium."

[55] Plus approximately 200g of Li6.

[56] "Equipment of the kind commonly used in nuclear reactors."

[57] Carried in 219 "capsules"; no other description given.

#	Date	From	To	Mode	Material	(g)	Shld?	Det?	Principal Reference(s)
33	29-Dec-04	Russia	Kazakhstan	Land	DU	37000			Schmid (2012)
34	19-Sep-05	Bulgaria	Romania	Land	Hf	3400			Schmid (2012)
35	31-Jan-06	Russia	Georgia	Land	HEU(89)	100		Y	Bronner (2008); Sheets (2008)
36	1-Feb-06	Russia	Ukraine	Land	Sr90		Y(ind)		Schmid (2012)
37	20-Apr-06	Ukraine	Poland	Land	[multiple]			Y	Schmid (2012)
38	11-May-06	Uzbekistan	Turkmenistan		Cs127				Schmid (2012)
39	30-Jun-06	Russia	Kazakhstan		[multiple]				Schmid (2012)
40	13-Nov-06	China	Kazakhstan		Cs137	500			Schmid (2012)
41	22-Apr-07	Belarus	Lithuania	Land	U238	0			Schmid (2012)
42	15-Jun-07	Azerbaijan	Georgia	Land	Pu		Y(scp)	Y	Schmid (2012)
43	24-Oct-07	Georgia	Turkey		Lr103	2	Y(Au)		Schmid (2012)
44	11-Sep-08	Kazakhstan	Russia	Rail	Bi207		Y		Schmid (2012)
45	13-Apr-09	Czech	Russia	Air	Ra226	138		Y	Schmid (2012)
46	20-Jul-09	Kazakhstan	Russia	Rail	Cs137				Schmid (2012)
47	30-Jul-09	Kazakhstan	Russia	Rail	Co60	1000	N	Y	Blake (2011)
48	26-Aug-09	Armenia	Georgia	Land	Cs137			Y	Blake (2011); Badalova (2016)
49	21-Oct-09	Russia	China	Air	U238				Schmid (2012)
50	11-Mar-10	Armenia	Georgia	Rail	HEU(87)	18	Y(Pb)		Blake (2011)
51	18-Jul-11	Armenia	Georgia	Land	LEU(05)	1581			Chabashvili et al. (2013)
52	27-Jul-11	Russia	Moldova		HEU	7	Y(Pb)		NTI (2019, 2011–12)
54	30-Apr-14	Moldova	Ukraine	Land	U235	1500			NTI (2019)
55	4-Aug-14	Armenia	Georgia	Land	Cs137				NTI (2019)
56	25-Aug-14	Kazakhstan	Uzbekistan	Rail	Cs137			Y	NTI (2019)
57	12-Oct-14	Vietnam	Poland	Air	I125, Sr90		Y[58]		NTI (2019)
58	12-Mar-15	Ukraine	Belarus	Land			Y(ind)		NTI (2019)
59	9-Jun-15	Austria	Slovakia	Land				Y	NTI (2019)
60	19-Jun-15	Syria	Turkey	Land	Cs137	1240			NTI (2019)
61	22-Jun-15	China	Russia	Air	Th232			Y	NTI (2019)
62	5-Aug-15	Ukraine	Romania	Land	U238				NTI (2019)
63	11-Jan-16	Armenia	Georgia	Land	Cs137				NTI (2019)
64	29-Dec-18	Kazakhstan	Russia	Land				Y	NTI (2019)

Figure 7. Documented Radiological/Nuclear Smuggling Cases: 2004–18

The columns labeled “Det?” show whether the incident description mentioned the presence or absence of large-scale radiation detection systems, such as portal monitors. Note that a “Y” in this column indicates only that such a system was known to be present, not that it succeeded in detecting the material. In case 35, for example, it is believed that the HEU passed through an instrumented border crossing; however, the smugglers were apprehended only much later, in a “sting” operation conducted in the interior of the country.

For most cases, many published sources were consulted; for the sake of brevity, only a few are shown. The “Principal Reference(s)” include the majority of the available information on a given case.

[58] Concealed by “metal plates in cigarette packs” and placed inside a shipment of frozen crab.

E. Radiological/Nuclear Scanning at Border Checkpoints: Prevalence

Any attempt to analyze the deterrent effect of scanning systems with respect to the 56 cases identified in Figure 6 and **Error! Reference source not found.** must include some estimate of how likely it was that each smuggler would encounter such a system. For example, an analysis of case 28 must ask the question "How prevalent were large-scale radiation detection systems along the Russia-Georgia land border in the year 2000?" Thus, what is required is a rough picture of how the deployment of these systems evolved over both space (i.e., for each destination country) and time.

As noted earlier, a comprehensive set of data on radiation detection equipment quantities, locations, and deployment dates is not publicly available. Instead, the author developed a rough composite picture of detector prevalence over time by country, using the types of sources described in section III.C. For each destination country, the author considered:

- The number of border crossings and other entry points (such as international airports). Specifically excluded were land crossings that lack border controls, such as those within an open-border group of states.[59] Thus, for example, information regarding land border crossings into Poland is understood to refer to crossings from Belarus and Ukraine, but not from Slovakia, the Czech Republic, Germany, and Lithuania.
- The approximate number of large-scale radiation detection systems (both fixed and mobile) known to be available to that country for deployment at border crossings or other entry points. In almost all cases, total equipment quantities have increased over time.[60]
- Known limitations in operational availability rates. The availability of deployed systems depends on maintenance, staffing levels, training, and other factors. The maximum availability rate was assumed to be 90 percent.[61] Where there were documented instances of unusual limitations due to shortages of spare parts, unreliability of electrical power, and so forth (e.g., GAO 2002 and Welt 2005, p. 509), the author applied a multiplier based on the qualitative description of the problem ("few," "very often," "almost none," "some," etc.). Evasion of detectors (e.g., via bribery) was not treated as an availability issue; rather, it was considered in the analysis of individual cases (section V.G).

Figure 8 shows the resulting estimates for 15 countries that represent the vast majority of cases under study. These results should not be regarded as authoritative or accurate; they are the author's "best guesstimate" based on available information. For the purposes of this analysis,

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[59] A notable example is the Schengen Area, which comprises 26 European states where internal border checks have largely been abolished (Schengen Area 2020).

[60] Notable exceptions include Ukraine, where 29 systems were destroyed in 2014 during fighting between the Ukraine government and separatist groups backed by Russia (GAO 2016, p. 25; Tabirian 2016); Georgia, where eight monitors at three locations were damaged during conflicts in the Abkhazia and South Ossetia region circa 2008 (Tabirian 2016); and Kazakhstan, whose checkpoints on the Russian border were deactivated following its 2015 entry into the Eurasian Economic Union (Yeliseyeu 2019).

[61] In fiscal year 2018, the United States received data on radiation portal monitor availability for 837 of 3757 systems deployed. The average operational availability rate for these systems was 97 percent (ORNL 2019).

they serve as rough estimates of the perceived probability of being scanned $\bar{\rho}$, for those smugglers that fall into the "unsophisticated amateur or opportunist" category.

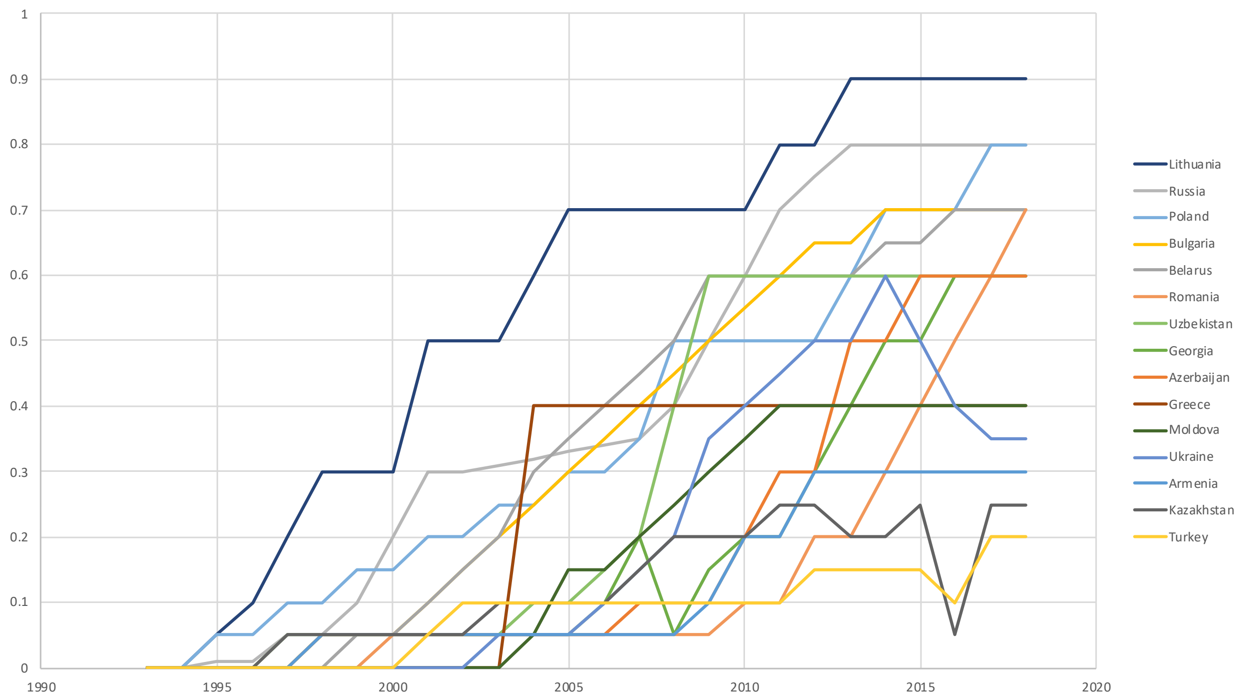

Figure 8. Prevalence of Large-Scale Radiological/Nuclear Detection Systems at Selected Borders[62]

F. Radiological/Nuclear Scanning at Border Checkpoints: Effectiveness

Radiological/Nuclear Screening Architecture

The screening architecture for a typical border checkpoint is shown in Figure 9. If a portal monitor is present (assumed to occur with probability ρ), all vehicles pass through it—typically, as they approach the manned checkpoint. In the figure, this step is labeled "pre-primary"

[62] Author's interpretation of data from multiple sources, including Arrieta and Ekman (2014), Barnes (2013), Belarus National Science Portal (n.d.), Beltur (n.d.), Brock (2016), Bronner (2008), Bunn and Weir (2005), Cablegate (2006), Cann et al. (2013), Chivers (2005), Contraband (2013), Djalilov et al. (2005), Dolchinkov (2016), Dowell (2019), Dunlop (2000), EGTRE (n.d.), EOP (2016), ESCAP (2018), Estonia Plans (2015), EU (2015), Fedchenko and Anthony (2018), GAO (2002), GAO (2006), GAO (2016), Greenberg (2007), Grigoras (2015), Hays (2016), INTERPOL (2016), IOM (2019), Jamestown Foundation (1995), Kazinform (2009), Kubiak (2014), Kuršelis and Stadalnikas (2001), Kvelashvili (2010), Maltezos et al. (2017), Marat (2006), Martin (2017), Mastauskas (2016), Menabde (2013), NNSA (2016), NRPA (2015), NTI (2007-6), NTI (2007-9), NTI (2011-02), NTI (2011-12), Nuclear Security Summit (2016), Nuclear Smuggling Outreach (2011), Office of Second Line (2012), PAA (2012), PAA (2014), PAA (2017), Petrenko et al. (2009), Piotukh (2001), Preiherman (2017), Radiation Detection (2007), Rickleton (2018), Russia Eases (1996), Russian Border Guards (1995), Russian Customs Officials (2005), SASC (2008), State Border Guard Service of Ukraine (2017), Stihel (2015), Stimson Center (2007), Suspected Kazakh (2018), Tabirian (2016), The EU Helping (2009), Tsolova (2015), Ukraine Installs (2019), Usmanov (2011), Wagoner (2009), Wahlstrom (2015), and Welt (2005).

screening. The portal monitor measures the gamma radiation emitted by the vehicle and its contents. Portal monitors deployed after 1998 are also assumed to include the ability to detect neutrons that would be emitted by materials such as U235 or Pu239.[63]

If the radiation exceeds the alarm threshold (assumed to occur with probability $1 - \alpha$), the vehicle is removed from the flow of traffic for further investigation. The purpose of this step, denoted "secondary inspection," is to localize the source of the radiation, if present, and identify the materials.[64] Typically, both driver and passengers are removed from the vehicle; they are then scanned using handheld radiation detectors and, if appropriate, searched. The vehicle is separately inspected. This process normally involves a combination of handheld detection equipment and physical inspection (to identify anomalies such as suspicious-looking containers).[65] Note that a vehicle might be referred to secondary inspection even in the absence of a portal monitor alarm. This could happen during the step labeled "primary screening," if, for example, the border control official observed suspicious behavior on the part of the driver. Vehicles can also be referred to secondary inspection on a random basis.

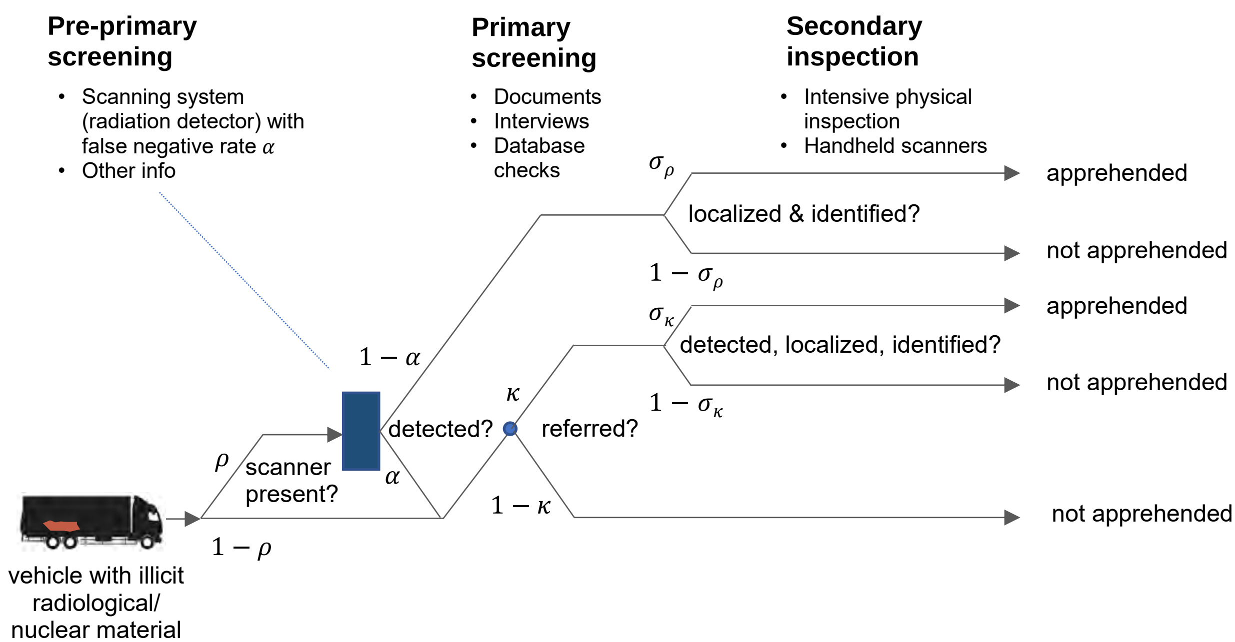

Figure 9. Screening Architecture: Radiological/Nuclear Smuggling

[63] Some systems deployed before 1998 included neutron detection. However, a combination lab/field test conducted by IAEA in 1998 found that most systems available at that time failed to meet the minimum detection requirement, defined as 99.9 percent probability (with false alarm rate less than 1 in 10,000) of detecting a neutron flux density of 20,000 n/s emitted from weapons-grade plutonium for a duration of 10 seconds at 2m distance from the reference point of the detector, with gamma radiation shielded to less than 1 percent (Beck et al. 2001; Schmitzer and Beck 2001).

[64] Gonzalez (2008, p. 31) quotes figures given by a Russian customs official: out of 14,000 detector alarms in 2004, approximately 200 were classified as illicit trafficking.

[65] Secondary inspection can also include the use of imaging systems to detect dense objects that may indicate the presence of shielding. For additional details on the secondary inspection process, see IAEA (2002, pp. 17–25), IAEA (2013, pp. 28–33 and 37–40), and Russian Customs Officials (2005, pp. 4–5).

It is clear from Figure 9 that the impact of the scanning system on the smuggler's chances of being apprehended depend not only on scanning rate ρ and scanning effectiveness $(1 - \alpha)$, but also on the general rate of referral to secondary inspection κ and the effectiveness of the secondary inspection process itself—which in turn may depend on whether an alarm was present (σ_ρ) or absent (σ_κ). The problem of determining values for the scanning rate ρ (and, equally important, the perceived scanning rate $\bar{\rho}$) was addressed in the previous section (section V.E) of this report. The following paragraphs address the remaining variables.

Scanning System Probability of Detection

In theory, the operational false negative rate of the scanner, α, can be modeled as a function of several variables. These include the specific radionuclide(s) present; the mass and activity of the source; its physical configuration (spherical, cylindrical, etc.); the source-detector geometry (source to detector distance and incident angle relative to the detector plane); the presence of benign gamma emitters (e.g., fertilizer, ceramic tiles, road salt); the nature of attenuating materials that lie between the source and the detector (truck or container walls, other cargo); the nature of deliberately engineered shielding (e.g., a lead container), if present; and the speed at which the vehicle passes through the portal. The author did not attempt to model α in this way for the simple reason that much of this information is unknown for the 56 incidents listed in Figure 6 and **Error! Reference source not found.**.

Instead, the analysis defines a set of categories, based on the type of radiation source and the way it is packaged (specifically, the presence or absence of engineered shielding). Figure 10 shows the corresponding estimates for the value of $(1 - \alpha)$, the probability that the detector will alarm given that an illicit source is present.

Packaging / Source	**Shielded**	**Unshielded**	**Unspecified**
Nuclear (Pu)	0.95	0.95	0.95
Nuclear (U)	0.20	0.90	0.90
Large radiological	0.50	1.00	1.00
Small radiological	0.20	0.95	0.95

"U" includes: HEU (typically ~1g to 1kg); LEU (typically ~1g to 10 kg), and U238, DU or UOx (typically ~10kg or above)
"Large radiological" designates a source with activity measured in the kCi to MCi range
"Small radiological" designates a source with activity measured in the μCi to mCi range

Figure 10. Radiological/Nuclear Scanning Systems: Estimated Probability of Detection

These figures are broadly consistent with statements in the open literature, along the following lines: "Most of the detectors that have been installed around the world would have a good chance of detecting plutonium or gamma-emitting radiological sources, but would not be likely to detect well-shielded HEU" (Bunn et al. 2016, p. 131).[66]

[66] Regarding nuclear materials, see also Lee (2003), Glaser (2007), and Bronner (2008). Several sources, including Ferguson and Potter (2004, p. 141), Ervin (2004), and Cochran and McKinzie (2008), describe a 2002 incident in which an ABC News correspondent traveled throughout Europe with a suitcase containing 6.8kg of DU shielded by a steel pipe with a lead lining. The suitcase traveled by passenger rail from Austria to Turkey; there were no signs of radiation detection equipment throughout the 47-hour trip. It was subsequently shipped from Istanbul to the United States. The shipment was targeted as high-risk and inspected by CBP, who did not detect the DU. A year later, a similar package was shipped from Jakarta to the United States—it was again targeted and inspected, but the DU was not detected. Regarding both large and small radiological sources, see Rubenstein (2006).

Other Screening Parameters

It is much more difficult to estimate the effectiveness of the secondary inspection process, which depends on such factors as the exact placement of handheld detectors, the thoroughness of the search, and the alertness of the inspector.[67] A generous estimate might be that inspectors have a 50 percent chance of locating and correctly identifying illicit radiological/nuclear material if they are responding to an alarm from the primary scanning system (i.e., $\sigma_\rho = 0.50$), but are only half as likely to discover it in other scenarios, such as a random inspection (i.e., $\sigma_\kappa = 0.25$).

The referral rate in the absence of an alarm is known to be quite low, due to the time-consuming nature of the secondary inspection process and the need to facilitate the flow of legitimate trade and travel.[68] A 2015 spot-check by an investigative journalist found that only about 1.5 percent of all vehicles at a busy border crossing from Ukraine to Poland were subjected to secondary inspection (Dooley n.d.). This analysis uses a value $\kappa = 0.01$ as representative.

G. Estimates of Deterrence Thresholds

Initial Estimates by Case

The key question for this analysis is: "How might smugglers have estimated their chances of failure prior to each of the 56 attempts listed in Figure 6 and **Error! Reference source not found.**?" The estimates developed in sections V.E and V.F can help shed light on this question.

Section V.C showed that each radiological/nuclear smuggling attempt is a singular event, and the probability of failure is the chance of being detected and apprehended during that attempt (in other words, $p^* = p^1$). This value is the sum of probabilities over all paths in Figure 9 that lead to apprehension. In other words:

$$Probability\ of\ failure:\ p^* = p^1 = \bar{\rho}(1-\alpha)\sigma_\rho + \bar{\rho}\alpha\kappa\sigma_\kappa + (1-\bar{\rho})\kappa\sigma_\kappa \tag{23}$$

To show how this expression is evaluated, consider the example of an unsophisticated smuggler attempting to transport unshielded HEU across a border with approximately half its crossings instrumented. Since the smuggler lacks detailed prior knowledge of detector deployment, the perceived scanning rate $\bar{\rho}$ is estimated at 0.50. (More generally, it is taken from the estimates of detector prevalence in Figure 8.) The scanning effectiveness $(1-\alpha)$ is estimated at 0.90, based on Figure 10 and using the value for unshielded HEU. The remaining terms are constant for all cases: per section V.F, the values are $\sigma_\rho = 0.50, \sigma_{\rho\kappa} = 0.25,$ and $\kappa = 0.01$. Using these values,

[67] CBP's Operational Field Testing Division conducts covert tests to assess its ability to detect and interdict the smuggling of radiological and nuclear materials into the United States. Although the program may occasionally conduct tests at international locations, the overwhelming majority are conducted at U.S. ports of entry. Results of these tests are treated as Sensitive Security Information (SSI) and are not available to the public (GAO 2014).

[68] In the European Union, customs administrations are required to keep 90 percent of vehicles waiting no more than 20 minutes, or about 40 minutes to cross both sides of a border point (World Bank 2000).

Equation 23 indicates that the a priori probability of failure p^* is 0.24. Following the logic outlined in section IV.C, the initial estimate of the deterrence threshold would be $\tau_0 > 0.24$.

If the smuggler knew that a detector would be present at the planned crossing location —but still decided to challenge the system — then $\bar{\rho} = 1$ and the result is $\tau_0 > 0.45$.[69]

Applying this method to the 56 cases in Figure 6 and **Error! Reference source not found.** yields the results shown in Figure 11 and Figure 12. For cases where the open-source information does not indicate whether a detector was present, it is not possible to calculate a value for the rightmost column. Cells highlighted in yellow indicate an a priori probability of failure estimated at 0.10 or greater.

#	Date	From	To	Material Type	Shielded?	Detector Present?	A Priori Prob Failure Prior Knowledge of Detector? No	 Yes
1	20-Jan-93	Russia	Lithuania	U	Y		0.01	
2	15-Mar-93	Azerbaijan	Turkey	U			0.01	
3	15-Oct-93	Germany	Turkey	U			0.01	
4	15-Nov-93	Ukraine	Poland	Rsm			0.01	
8	10-Aug-94	Russia	Germany	Pu		N	0.01	
9	15-Oct-94	Bulgaria	Turkey	Rsm*	Y(Pb)		0.01	
10	19-Oct-94	Azerbaijan	Turkey	U			0.01	
11	10-Dec-94	Hungary	Austria	U			0.01	
12	14-Dec-94		Czech	U	Y(Pb)	N	0.01	
13	25-Jan-95	Belarus	Lithuania	Rlg		Y	0.03	0.50
16	7-Nov-95	Poland	Czech	Rlg			0.01	
17	15-Jun-98	Turkey	Bulgaria	Rlg*			0.01	
18	1-Jul-98	Iran	Turkey	Rlg			0.01	
19	14-May-99	Kyrgyzstan	UAE	Pu			0.01	
20	29-May-99	Romania	Bulgaria	U	Y(Pb)		0.01	
21	22-Jul-99	Kazakhstan	Uzbekistan	Rsm*			0.01	
22	24-Aug-99	Vietnam	Cambodia	U			0.02	
24	20-Sep-99	Russia	Ukraine	Rsm	Y(pb)		0.01	
25	20-Sep-99	Russia (?)	Georgia	U	Y		0.01	
26	3-Dec-99	Russia	S Korea	Rlg	Y(scp)		0.03	
27	30-Mar-00	Kazakhstan	Uzbekistan	Rlg	Y(Pb)		0.01	
28	15-Apr-00	Russia	Georgia	U		Y	0.02	0.45
30	16-Jul-01	Romania	France	U	Y(ind)		0.01	
31	15-Oct-02	Russia	Azerbaijan	Rsm*			0.01	
32	26-Jun-03	Armenia	Georgia	U	N	Y	0.02	0.45

* = inferred

Figure 11. Initial Estimates of A Priori Detection Probabilities for Radiological/Nuclear Smuggling Cases: 1993–2003

[69] Still another possibility—that the smuggler knew the detector would be present but planned to evade the system altogether—would result in $\bar{\rho} = 0$. This possibility is discussed under "Anomalous Cases," below.

#	Date	From	To	Material Type	Shielded?	Detector Present?	A Priori Prob Failure Prior Knowledge of Detector? No	Yes
33	29-Dec-04	Russia	Kazakhstan	U			0.05	
34	19-Sep-05	Bulgaria	Romania	R			0.02	
35	31-Jan-06	Russia	Georgia	U		Y	0.05	0.55
36	1-Feb-06	Russia	Ukraine	Rsm	Y(ind)		0.01	
37	20-Apr-06	Ukraine	Poland	Rsm		Y	0.15	0.50
38	11-May-06	Uzbekistan	Turkmenistan	Rsm			0.05	
39	30-Jun-06	Russia	Kazakhstan	Rsm			0.05	
40	13-Nov-06	China	Kazakhstan	Rlg			0.05	
41	22-Apr-07	Belarus	Lithuania	U			0.30	
42	15-Jun-07	Azerbaijan	Georgia	P	Y(scp)	Y	0.10	0.50
43	24-Oct-07	Georgia	Turkey	Rsm	Y(Au)		0.01	
44	11-Sep-08	Kazakhstan	Russia	Rsm		Y	0.20	0.50
45	13-Apr-09	Czech	Russia	Rlg		Y	0.25	0.50
46	20-Jul-09	Kazakhstan	Russia	Rsm			0.25	
47	30-Jul-09	Kazakhstan	Russia	Rlg	N	Y	0.25	0.50
48	26-Aug-09	Armenia	Georgia	Rsm		Y	0.05	0.50
49	21-Oct-09	Russia	China	U			0.25	
50	11-Mar-10	Armenia	Georgia	U	Y(Pb)		0.02	
51	18-Jul-11	Armenia	Georgia	U			0.10	
52	27-Jul-11	Russia	Moldova	U	Y(Pb)		0.04	
54	30-Apr-14	Moldova	Ukraine	U			0.25	
55	4-Aug-14	Armenia	Georgia	Rsm			0.25	
56	25-Aug-14	Kazakhstan	Uzbekistan	Rsm		Y	0.30	0.50
57	12-Oct-14	Vietnam	Poland	Rsm	Y		0.35	
58	12-Mar-15	Ukraine	Belarus	Rsm*	Y(ind)		0.05	
59	9-Jun-15	Austria	Slovakia	Rsm*		Y	0.40	0.50
60	19-Jun-15	Syria	Turkey	Rlg			0.04	
61	22-Jun-15	China	Russia	Rsm		Y	0.40	0.50
62	5-Aug-15	Ukraine	Romania	U			0.20	
63	11-Jan-16	Armenia	Georgia	Rsm			0.30	
64	29-Dec-18	Kazakhstan	Russia	Rsm*		Y	0.40	0.50

* inferred

Figure 12. Initial Estimates of A Priori Detection Probabilities for Radiological/Nuclear Smuggling Cases: 2004–18

Discussion

During the 1990s and early 2000s, radiation detection systems were not widely deployed. Smugglers most likely believed that their odds of being detected at a border crossing checkpoint were quite low, as Figure 11 suggests.[70] Possible exceptions are case 13 (involving the attempted shipment of 2 tons of W180 into Lithuania) and cases 28 and 32 (920g and 170g, respectively, of unshielded HEU being carried into Georgia); in all three cases, the attempt was made despite the

[70] Most apprehensions during this period resulted from intelligence/law enforcement sting operations (Duftschmid et al. 2001, p. 384). By the mid-2000s, this picture had changed dramatically as a result of the widespread deployment of radiation detection equipment. Russian customs officials stated publicly that "95 percent of [radiological/nuclear smuggling] incidents are discovered by monitoring, not by documentation or intelligence" (Russian Customs Officials 2005, p. 4; Gonzalez 2008, p. 32).

presence of a detection system, which should have signaled roughly a 50 percent chance of being caught. The publicly reported information on these cases does not indicate whether the smugglers knew beforehand that such equipment was present. Since portal monitor deployments to those borders were just getting underway in all three cases, it is possible that they did not. Allowing for a generous margin of error, it seems reasonable to conclude that most, if not all, of attempts shown in Figure 11 were made under the assumption that there would be no worse than a 10 percent chance of being caught (i.e., $\tau_2 > 0.10$). As a point of comparison, GAO (2002, p. 24) paraphrased a border security official from an unnamed country to the effect that "a dedicated nuclear smuggler has a 90 percent chance of successfully defeating his country's border controls."

Figure 12 shows a very different pattern, with 20 cases featuring estimates of a priori detection probabilities at 25, 30, or 40 percent or even higher. Do these cases truly represent attempts to challenge the screening and detection architecture at those odds … or did smugglers have good reason to expect more favorable chances? The author reviewed the publicly available details of these cases to determine whether:

- The assumptions behind the computations in Figure 12 are valid
- Smugglers had prior knowledge that a detection system was present
- Smugglers believed that they could evade detection through some other means (e.g., by bribing border officials)

Anomalous Cases

Eight of the 20 highlighted cases shown in Figure 12 can be discounted for the purposes of this analysis.

- Case 35. This well-documented 2006 incident included the successful crossing of the Russia-Georgia border at a site equipped with a detector. Although the smugglers knew that the detector was present, one member of the group had a cousin who was a former customs officer. This smuggler, according to the Russian Federal Security Service, "used his connections with the customs officers to provide unchecked travel … through the Russian-Georgian border" (Bronner 2008, p. 10); hence, their estimate of being detected during the border crossing would be zero. (The smugglers were later arrested attempting to sell 100g of HEU in a "sting" incident organized by intelligence and law enforcement officials.) In short, this case provides no information on deterrence.
- Case 37 involved the attempted smuggling of military equipment (11 TZK-11 zenith tubes, 700 artillery compasses, 51 periscopes, 43 azimuth compasses, and 14 binocular telescopes) from Ukraine to Poland via minivan. Although the Ukraine-Poland border was fairly well equipped with radiation detectors at the time (2006), the smugglers may have been unaware that their cargo would set off radiation alarms. If so, this incident sheds more light on arms smuggling than on radiological/nuclear smuggling.
- Case 41. In this 2007 incident, two Belarus nationals were detained at the Lithuania-Belarus border on suspicion that they attempted to smuggle radioactive cargo from

Lithuania. During the inspection of the suspects' car, law enforcement officials discovered a metal container labeled in Russian "Uranium-238, 1991." On subsequent examination, the container was found to be empty. One possibility is that this attempt was designed as a probe, or test, in which case it does not provide information about deterrence thresholds.

- Cases 49 and 61 involve the Russia-China border. In the first instance, a Chinese man was arrested at the Irkutsk international airport for attempting to transport six pieces of rock containing natural uranium from Russia. In the second, a Russian man was arrested at Moscow's Sheremetyevo airport for attempting to smuggle radioactive jewelry (750 "black pendants") from China. The man was released pending an investigation to determine whether he knew the jewelry was radioactive. Although no further information is available, it is quite possible that both cases 49 and 61, although they involved deliberate smuggling, did not involve deliberate radiological/nuclear smuggling.
- Case 57. This 2014 incident involves a Vietnamese national who attempted to smuggle counterfeit Marlboro cigarettes into Poland. The individual's luggage included a container of frozen crabs; the cigarette packs were inside this container. The packs carried "extra metal plates, each laced with I125," and the covers were contaminated with Sr90. It seems quite possible that the individual did not know the counterfeit cigarettes were made with tobacco grown on contaminated soil; if so, this case provides no information about deterrence thresholds for radiological/nuclear smuggling.
- Case 59. Because this 2015 incident involved an attempted crossing into Slovakia, the initial estimate were based on the assumption that the movement was from east to west (i.e., from Ukraine). However, the vehicle was actually coming from Austria and entered Slovakia at the Jarovce border crossing, just south of Bratislava. Routine border checks at this crossing were discontinued in 2007, when Slovakia was admitted to the Schengen Area. The radiological materials in the vehicle may have been detected as the result of an unexpected spot-check (perhaps using a mobile detection system); if so, the smugglers' a priori estimate of being scanned would have been far lower than shown in Figure 12.
- Case 64. This 2018 case involved the movement of 292 "medical medallions" from Kazakhstan to Russia. A large number of radiation detectors were deployed to this border during the 2000s; however, the situation changed with the establishment of the Eurasian Economic Union (EAEU) in 2015.[71] Although border checks were largely eliminated at that time, the member states have since failed to agree on enforcement procedures regarding embargoes of agricultural products from the West. In recent years, "mobile groups consisting of Russian customs officers, border guards, police" and other officials have begun patrolling both the Russia-Belarus and the Russia-Kazakhstan borders (Yeliseyeu 2019). Under these circumstances, smugglers might well have estimated their chances of being stopped by one of these groups as being much lower than the value used to generate Figure 12.

Other cases, however, are less clear in their implications.

[71] The EAEU consists of five states (Russia, Kazakhstan, Belarus, Kyrgyzstan, and Armenia) that have agreed to form an integrated market to promote the free movement of goods and services. One of the original goals was to eliminate passport, customs, and other types of checks at the member states' mutual borders.

- Cases 44–47. All four of these cases occurred within a span of 10 months and involved attempts to transport radiological materials into Russia. Three of the cases (44, 46, and 47) involved rail crossings from Kazakhstan; the fourth (case 45) occurred at Saint Petersburg's Pulkovo airport. These attempts, in 2008–9, coincided with a sharp increase in the pace at which detection systems were being deployed to both Kazakhstan and Russia. If the smugglers lacked sophistication and experience, they may not have been aware of those deployments. On the other hand, these cases may be evidence of knowledgeable smugglers' willingness to challenge the detection architecture even with a 25 to 50 percent chance of being caught.
- Cases 51, 54–55, and 62–63. These five cases involve smuggling attempts that occurred in the Black Sea and Transcaucasus regions during the period 2011–16. Detection systems were much more prevalent than they had been just a few years previously; however, this same period was also marked by ongoing concerns over corruption among border control officers—presumably motivated by known cases of bribery. For example, in Georgia, "monthly salaries for border-control officers … increased from 350 laris ($165) in 2010 to an average of 1,000 laris ($472) [in 2016] … to counter the risk of corruption within the border service" (Georgia 2016).[72] Hence, it is possible, although by no means certain, that some or all of these incidents involved smugglers who knew that they could bypass a working detector. Such cases would tell us nothing about deterrence thresholds.

Finally, there are three cases that do not seem to fit any pattern.

- Case 42 is a disputed incident in which a truck entering Georgia from Azerbaijan in 2007 was turned back at the border after setting off an alarm. Officials from Georgia claimed it did not want to take custody of what they described as a plutonium-beryllium source; officials from Azerbaijan claimed the alarm was caused by contaminated scrap metal and that there was no plutonium source.
- Case 48 is a 2009 incident with no clear evidence of a radioactive source. Three Armenians crossed into Georgia and returned two days later, each time triggering an alarm. Border officials determined that the car was contaminated with Cs137; however, a search of the vehicle failed to turn up a source.
- Case 56, in 2014, involves a freight train traveling from Kyrgyzstan to Uzbekistan, via Kazakhstan. An alarm triggered a search of one of the freight cars, where inspectors found a metal object with a diameter of 20mm and a height of 10–12cm. It was determined to be a Cs137 source.

[72] Previously, the situation had been even worse. Welt (2005, pp. 508, 512) reported their monthly salary as 119 laris ($65) and concluded that "The border guards are in a very bad situation. They lack funds and are extremely poor."

Analysis

Considering the population of potential radiological/nuclear smugglers as a whole, the magnitude of potential gains and losses from smuggling provides one possible insight into deterrence thresholds. Earlier, the ratio of benefit to punishment $B/|P|$ was estimated to range from 2 to 5. If this estimate is accurate, then the CPT decision-making model described in section IV.B would predict that deterrence thresholds may range from approximately 0.40 to 0.70 (cf. Figure 4).[73]

Analysis of the individual cases in Figure 12 provides no information on the lower limit of the deterrence threshold (τ_1), since these are all cases for which deterrence did not occur. GAO (2016, p. 23) alludes to one or more incidents in which it was subsequently learned that scanning systems *did* deter a border crossing. If the associated a priori failure probabilities p^* were known, they would collectively establish an upper bound for the value of the threshold τ_1; however, the details of those incidents are not publicly available. Nevertheless, we know that $p^* \leq \sigma_\rho$ (in other words, even if the scanning system is present and works perfectly, the probability of failure—i.e., detection—is limited by the effectiveness of the secondary inspection). Combining this result with the estimates from the previous paragraph, a reasonable conclusion might be that $\tau_1 \cong min(0.40, \sigma_\rho)$.

The view that the absolute deterrence threshold τ_2 might be as large as 0.70 is not contradicted by the individual cases, since no case involves an estimated p^* of that magnitude. If at least some of the highlighted cases (notably, 44–47, 51, 54–55, or 62–63) represent deliberate challenges at the odds shown, we could conclude that $\tau_2 > 0.50$. (If not, we would be left with the rather unhelpful estimate $\tau_2 > 0.10$.) Once again, however, note that the specific value 0.50 emerges in Figure 12 only because of our assumption that $\sigma_\rho = 0.50$. A better statement would be that the analysis of individual cases raises the possibility that $\tau_2 > \sigma_\rho$. Using this logic, a reasonable conclusion would be that $\tau_2 \cong max(0.70, \sigma_\rho)$.

Summary (Radiological/Nuclear Smugglers)

It appears probable that at least some would-be radiological/nuclear smugglers may not be deterred unless they perceive a 50 percent or higher probability of detection and apprehension, which would entail an extremely high probability of being detected by a scanning system. This conclusion comes with several caveats:

- Estimates of smugglers' prospective gains and losses are based on a very small sample of cases for which information is publicly available. The information in those cases is

[73] These figures correspond to the CPT model, with parameter values per Tversky and Kahneman (1992); for the EVT model, the figures would be higher. Keep in mind that both values of $B/|P|$ and deterrence thresholds may be lower than the figures given here if the smuggler feels less than certain to accrue the gain B following a successful crossing, or weighs the threat of punishment as being greater than the value of lost income. Thresholds may be higher if smugglers believe they can avoid punishment even if caught. Details of this nature are not available in the open-source descriptions of specific smuggling incidents.

incomplete. Moreover, there are no available data that show how smugglers monetize potential losses, or whether an estimate based solely on lost income is a reliable guide to their decision-making process. There is also uncertainty regarding smugglers' beliefs that they will realize the intended gains from a sale (if the crossing is successful), or that they will actually be sentenced and serve a full term (if it is not).

- The applicability of decision-making theories such as EVT and CPT is fraught with questions. Regarding the former, the assumption that smugglers are perfectly rational is open to challenge. Regarding the latter, the use of Equations 20 and 22 assumes that the specific value and probability weighting functions proposed by Kahneman and Tversky can be generalized to multiple contexts, including smuggling—again, open to challenge.
- Open sources provide very limited information on the basic facts of each radiological/nuclear smuggling case. Key information that is missing from a great many incident descriptions includes the specific border crossing or point of entry where the attempt was made, whether that location was equipped with large-scale radiation detection equipment, whether smugglers knew beforehand that such equipment was present, whether the equipment was functioning normally at the time of the attempt, whether it alarmed, and whether smugglers were able to bypass the system by bribing one or more officials. Knowledge of these details could lead to a different conclusion.
- Values of some intermediate variables used to compute the probability of apprehension and detection are based on very rough estimates. These include the prevalence of detection systems over time along various national borders, the false negative rates of these systems with respect to different types and quantities of radioactive material, and the effectiveness of the secondary inspection process.

VI. Analysis – Drug Smuggling at Mexico-U.S. Land Ports of Entry

A. Estimates of Smuggling Activity

This portion of the analysis focused on the smuggling of illegal drugs across the southwest border (SWB) of the United States via land ports of entry (LPOEs). Drug smuggling differs from radiological/nuclear smuggling in many ways. One of the most important differences is the level of activity.

Deterrence is defined and measured in terms of smuggling *attempts* (the probability that a single contemplated attempt will or will not be carried out, or the percentage of multiple contemplated attempts that are or are not carried out). Unfortunately, most data on drug smuggling activity are reported in terms of the total weight of illegal narcotics seized. Therefore, one of the first steps in the analysis was to estimate the total number of smuggling attempts based on reported drug seizures.

Approach

For this analysis, total weights (in pounds) are converted to estimated numbers of seizures based on the estimated average number of pounds per seizure.[74] Note that the resulting estimates may be slightly high, because some seizures involve multiple drugs (for example, the same load—and thus the same seizure—may contain fentanyl, methamphetamines, and heroin) (DEA 2018, pp. 33–34).

For cocaine, heroin, marijuana, and methamphetamines, total seizures by weight at SWB LPOEs specifically were estimated using two methods.

Method 1 started with published statistics on the total weight of drugs seized annually by CBP's Office of Field Operations (OFO) (CBP n.d.). These amounts exclude Border Patrol seizures[75]; however, they do not distinguish between drugs seized at the SWB and those seized at other POEs (for example, those on the northern border). Therefore, the author multiplied these quantities by the estimated ratio of OFO's SWB seizures to its nationwide seizures. The latter estimate was based on the average of SWB to nationwide seizures between 2011 and 2018 as reported by U.S. Border Patrol interior checkpoints, using CBP data compiled by Kaplan

[74] Estimated average pounds per seizure: 12.3 (cocaine), 3.7 (heroin), 127.8 (marijuana), and 8.0 (methamphetamine) (derived from data in Kaplan 2019). These averages are based on seizures at Border Patrol interior checkpoints, which are generally located within 25 to 100 miles of the border (GAO 2009). Some of the loads on which these figures are based might have been partially broken down for interior distribution prior to the seizure, in which case they would be somewhat low for purposes of this analysis. Note that this analysis makes no attempt to measure the potency or purity of the drugs seized: for purposes of measuring deterrence, only the numbers of seizures (and attempts) are relevant.

[75] CBP's Office of Field Operations is responsible for enforcement at POEs, where the majority of large screening systems are deployed. The Border Patrol is responsible for seizures between POEs. Border Patrol seizure data are not included in this analysis, which focuses on screening and detection at POEs.

(2019).[76] The resulting estimates[77] are broadly consistent with other published data that appear to include both OFO and Border Patrol statistics (e.g., Woody 2016).

Method 2 started with statistics on the total weight of drugs seized annually at the SWB, as published by the U.S. Drug Enforcement Administration (DEA 2016, 2017, and 2018). Although these figures are specific to the SWB, they include both OFO and Border Patrol data. Therefore, they were multiplied by the estimated ratio of OFO to total seizures at the SWB.[78] Because the DEA data extended only through FY 2017, estimates for FYs 2018 and 2019 were generated by applying the corresponding annual rates of change resulting from Method 1.

For fentanyl, Method 1 was modified somewhat because CBP has published data that include not only total OFO seizures by weight, but also the number of seizures (CBP 2019).[79] These data cover only the period 2016 through 2018; the estimates shown below for FY 2015 and 2019 are based on the corresponding rate of change in the total weight of fentanyl seized by OFO, compared to the adjacent years (i.e., FY 2016 and 2018, respectively). For Method 2, the only data available was for FY 2016 and 2017. The number of seizures was not estimated because estimates of the average number of pounds per seizure were not considered sufficiently accurate.

Estimated Number of Seizures

Figure 13 through**Figure 17** show the resulting estimates, by type of drug, for the number of incidents that resulted in detection and seizure by OFO at SWB LPOEs over the six-year period FY 2014 through 2019.

[76] In other words, the assumption here is that the ratio of SWB to nationwide activity at interior checkpoints is similar to the ratio of SWB to nationwide activity at the nearby LPOEs themselves.

[77] Estimated fraction of total nationwide OFO seizures that occur at SWB LPOEs: 0.67 (cocaine), 0.98 (heroin), 0.99 (marijuana), 0.98 (methamphetamines).

[78] Estimated fraction of OFO to total SWB seizures: 0.85 (cocaine, methamphetamine); 0.99 (heroin); 0.20 (marijuana) (Finklea 2019, pp. 7–8).

[79] These data are broken down by entry mode. For this analysis, only the figures for entry modes designated “land” were used; thus, seizures associated with express consignment, international mail, and other air shipments were excluded. Although the data in CBP (2019) do not specifically indicate where the seizures occurred, most if not all overland fentanyl smuggling is generally known to occur at the SWB (DEA 2018, p. 33).

Cocaine	Method 1			Method 2		
FY	Total OFO Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**	Total SWB Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**
2014	45,323	30,200	**2,500**	17,018	14,500	**1,200**
2015	38,346	25,500	**2,100**	19,651	16,700	**1,400**
2016	52,838	35,200	**2,900**	23,551	20,000	**1,600**
2017	62,415	41,600	**3,400**	29,116	24,700	**2,000**
2018	51,592	34,400	**2,800**	24,067	20,500	**1,700**
2019	89,207	59,400	**4,800**	41,614	35,400	**2,900**

Figure 13. Estimated Number of Seizures, SWB LPOEs (Cocaine)

Heroin	Method 1			Method 2		
FY	Total OFO Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**	Total SWB Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**
2014	4,356	4,300	**1,140**	4,030	4,000	**1,070**
2015	6,023	5,900	**1,580**	4,674	4,700	**1,230**
2016	4,224	4,100	**1,110**	3,719	3,700	**990**
2017	3,398	3,300	**890**	5,042	5,000	**1,340**
2018	5,205	5,100	**1,370**	7,723	7,700	**2,040**
2019	5,427	5,300	**1,420**	8,053	8,100	**2,150**

Figure 14. Estimated Number of Seizures, SWB LPOEs (Heroin)

Marijuana	Method 1			Method 2		
FY	Total OFO Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**	Total SWB Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**
2014	438,146	437,300	**3,400**	1,878,233	375,600	**2,900**
2015	602,821	601,600	**4,700**	1,802,690	360,500	**2,800**
2016	516,122	515,100	**4,000**	1,591,988	318,400	**2,500**
2017	366,627	365,900	**2,900**	1,041,241	208,200	**1,600**
2018	299,419	298,800	**2,300**	850,367	170,100	**1,300**
2019	289,529	288,900	**2,300**	822,279	164,500	**1,300**

Figure 15. Estimated Number of Seizures, SWB LPOEs (Marijuana)

Metham-phetamines	Method 1			Method 2		
FY	Total OFO Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**	Total SWB Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**
2014	19,613	19,300	**2,400**	32,960	28,000	**3,500**
2015	25,495	25,100	**3,100**	41,362	35,200	**4,400**
2016	33,086	32,600	**4,100**	53,265	45,300	**5,600**
2017	46,247	45,600	**5,700**	64,453	54,800	**6,800**
2018	57,440	56,600	**7,000**	80,053	68,000	**8,500**
2019	68,585	67,600	**8,400**	95,586	81,200	**10,100**

Figure 16. Estimated Number of Seizures, SWB LPOEs (Methamphetamines)

Fentanyl	Method 1			Method 2		
FY	Total OFO Seizures (lbs)	OFO Seizures at LPOEs (all assumed at SWB) (lbs)	**OFO Seizures at LPOEs (all assumed at SWB) (#)**	Total SWB Seizures (lbs)	Estimated OFO Seizures at SWB (lbs)	**Estimated OFO Seizures at SWB (#)**
2014	N/A	N/A	N/A	--	--	--
2015	70	44	**2**	--	--	--
2016	596	378	**20**	496	420	--
2017	1875	1,039	**87**	1144	970	--
2018	1895	1,442	**182**	--	--	--
2019	2545	1,937	**244**	--	--	--

Figure 17. Estimated Number of Seizures, SWB LPOEs (Fentanyl)

Figure 18 combines the preceding information and presents a summary estimate for the total number of seizures at SWB LPOEs. Ranges correspond to the different estimates generated under Methods 1 and 2, ignoring any estimates that were inconsistent with one of the two starting figures used. (In other words, OFO seizures at the SWB cannot be greater than the total of OFO seizures nationwide, nor can they exceed total seizures at the SWB.)

	Estimated Number of Seizures at SWB LPOEs (#)					
FY	Cocaine	Heroin	Marijuana	Metham-phetamines	Fentanyl	**Total (# in thousands)**
2014	1,200	1,100–1,140	2,900–3,400	2,400	N/A	**7.6–8.1**
2015	1,400	1,300–1,580	2,800–4,700	3,100	2	**8.6–10.8**
2016	1,600	1,000–1,110	2,500–4,000	4,100	20	**9.2–10.8**
2017	2,000	890	1,600–2,900	5,700	87	**10.3–11.6**
2018	1,700	1,370	1,300–2,300	7,000	182	**11.6–12.6**
2019	2,900	1,420	1,300–2,300	8,400	244	**14.3–15.3**

Figure 18. Total Estimated Number of Seizures, SWB LPOEs

Figure 18 suggests that drug smuggling through SWB LPOEs represents a level of activity many orders of magnitude greater than the worldwide cross-border smuggling of radiological/nuclear materials (64 reported incidents over 25 years). The figure shows a year-to-year increase of roughly 10 to 20 percent in the total number of seizures, a rate that appears to reflect longer-term trends.[80] A steady rate of growth suggests a system that is more or less in a state of managed equilibrium.

There are, however, different trends at work with respect to different types of drugs. Figure 15, for instance, indicates that the quantity of marijuana seized by OFO in FY 2019 was less than half the FY 2015 figure.[81] The decrease in marijuana smuggling may reflect recent legalization initiatives by several U.S. states[82] along with increases in domestic production (DEA 2017, pp. 106–7; DEA 2018, pp. 82, 88). At the same time, trafficking in less bulky drugs such as cocaine, methamphetamines, and fentanyl has increased dramatically.[83] The shift from large, relatively bulky loads (hundreds of pounds) to smaller loads (ranging from a few pounds to tens of pounds)[84] may make screening, scanning, and detection more challenging in the future.

Estimated Number of Attempts

The number of seizures at SWB LPOEs is a measure of "unsuccessful" attempts (from the point of view of the smuggler). Successful attempts are by definition unobserved and therefore difficult to estimate. DHS is currently working to establish a rigorous method for estimating the total number of attempts; however, this method does not yet exist (GAO 2019, p. 28).

Previous researchers have constructed models based on the presumed relationship between smuggling, domestic supply, and the demand for these drugs. Such models include information not only on border seizures, but also on estimates of foreign and domestic production, interior law enforcement data (undercover purchases, sales, local seizures, eradication, arrests, levels of drug-related crime, etc.), evidence of domestic drug usage, and available data on the price and

[80] For comparison, the number of narcotics seizures at the SWB totaled 6,956 and 5,392 in FY 1996 and 1995, respectively (HJC 1997). How many of these seizures were made at (rather than between) LPOEs is not specified.

[81] Border Patrol seizures, which account for most of the marijuana seized at the SWB, have dropped even more dramatically, from over 2 million pounds in FY 2012 to roughly 500,000 pounds in FY 2019 (Finklea, p. 8).

[82] In 2012, Colorado and Washington became the first states to legalize marijuana for recreational purposes. Eight more states have since done so. (In addition, Vermont and the District of Columbia allow use, but continue to bar sales for recreational purposes.) (Lopez 2019)

[83] Fentanyl traffic currently consists of a smaller volume of high-purity shipments arriving via express consignment and international mail from China, plus a larger volume of relatively low-purity shipments smuggled overland from Mexico (DEA 2018, p. 33). Only the latter amounts are reflected in Figure 17.

[84] DEA (2018, p. 33) states that fentanyl crossing the border from Mexico is typically smuggled in "multi-kilogram quantities" (roughly 5 to 20 pounds) in personally owned vehicles. Recent years, however, have seen much larger seizures. A noteworthy event in January 2019 was the seizure of 254 pounds of fentanyl, along with 395 pounds of methamphetamines, in an 18-wheel truck at the Mariposa POE in Nogales, Arizona (Carranza 2019). This was the largest single fentanyl seizure in U.S. history; the previous record of 145 pounds involved fentanyl seized at an apartment building in New York (DEA 2018, p. 27). Similarly, a February 2020 seizure found 895 pounds of methamphetamines (along with some 200 pounds of marijuana) concealed in a tractor-trailer carrying fresh broccoli (Liu 2020). Whether these incidents signal a dramatic and lasting change in smuggling patterns is not yet clear.

purity of drugs offered for sale.[85] One such model, the Sequential Transition and Reduction (STAR) model, was used to measure the flow of cocaine from producer nations, through transit zones, across the nation's borders, and throughout the United States during the period 1996–2000. Model results suggested that seizures at the U.S. border represented between 11 and 15 percent of total U.S.-bound flow (Abt Associates 2002, p. 13). The results of a similar analysis conducted by the Office of National Drug Control Policy (ONDCP) for the period 2000–2006 suggest seizure rates (as a percentage of total inbound flow) ranging between 10 and 18 percent for cocaine, roughly 15 percent for heroin, and 10 to 20 percent for marijuana (ONDCP 2012, pp. 48–50, 69–70, 89, and 105–6).

The above figures are generally consistent with responsible officials' public statements and open-source reporting over a long period. (For example, see GAO (1983, pp. ii, 14–19), GAO (1987), Hudson (2003, p. 23), Trevino (2013), Kilmer et al. (2014, pp. 98–102), and Kiernan (2018).) Presumably, these statements are informed by the results of available models as well as the intelligence reporting that feeds them. Accordingly, this analysis assumes that seizures represent roughly 10 percent of total inbound shipments. If these seizures are distributed more or less evenly across various types of incidents, the total number of attempts to smuggle drugs through SWB LPOEs in FY 2019 may have been in the neighborhood of 150,000, an average of over 400 attempts per day.

B. The Drug Smuggling Enterprise

Illegal drug smuggling from Mexico to the United States is not a collection of separate smuggling incidents. It reflects the activity of an ongoing enterprise with a polity, culture, and organization of its own. Understanding the nature of this enterprise is essential to an analysis of deterrence.

Organizational Model

Mexican drug trafficking organizations (DTOs) rose to prominence in the early 2000s following the decline of the "integrated, hierarchical" Colombian drug cartels (Stewart 2016; Llorente and McDermott 2014, p. 2; Kurrle 2013, p. 3, Beittel 2019, p. 11). Initially, activity was dominated by an organization dubbed the "Guadalajara" cartel. Later, the founder decided to split the organization and formed four new spinoffs: cartels designated Tijuana, Juarez, Golfo, and Sinaloa. The original intent was for the new organizations to collaborate in the distribution of smuggling routes and other infrastructure (Nieto-Gomez 2013, p. 151). Instead, these organizations began competing with one another, fueling a wave of violence that has continued to the present day (Beittel 2019, pp. i, 8, 11; Nieto-Gomez 2013, p. 152). These groups have continued to reorganize and fragment over time. Depending on the criteria used to judged size and impact, the number of "major" Mexican DTOs is currently assessed at somewhere between six and nine (DEA 2018, pp. 97–98; Beittel 2019, pp. 14–27).[86]

[85] See, for example, ONDCP (2012), Kilmer and Hoorens eds. (2010), and Becker et al. (2006, pp. 45ff.).

[86] Some sources place the number even higher (e.g., Bagley 2012, p. 9), depending on their definition of what constitutes a "major" organization.

In contrast to the hierarchical cartels of the 1980s and 1990s, the large Mexican DTOs have adopted a relatively flat, networked approach (Kurrle 2013, pp. 41–43; Layne et al. 2001, pp. 67ff.).[87] This "multi-nodal" model consists of a small core that engages the services of many peripheral cells or groups. These cells provide specialized services (growing, processing, packaging, storage, transportation, armed protection, cross-border smuggling, money laundering, secondary distribution, and so on) on an outsourced basis, and may in turn engage others (such as individual drug smugglers, or couriers). As independent contractors, peripheral cells often have little to do with each other, and each is privy only to the information it needs to perform its particular service. A given task or function may be contracted out to one cell only, or to multiple cells. Estimates of the size of the large Mexican DTOs vary: Kurrle (2013) indicates that the core may be as small as 15 to 50 individuals, with a total payroll at any given time of as many as 2,000 or more individuals. Based on accounting books confiscated by the Mexican government, a peripheral smuggling cell may have from 60 to 600 employees. The payroll also includes some 100 to 1,000 individuals who receive bribes (OAS 2013, p. 24). The number of those "working … indirectly" for the DTO can be "upwards of 150,000" (Kurrle 2013). On average, smuggling cells remit approximately 20 percent of their operating funds to the DTO (OAS 2013, p. 25).

The above picture aligns with the developmental smuggling model developed earlier by Lichtenwald (2003, 2004). That model includes three levels: Group 1 (low-level couriers), Group 2 (small groups consisting of a "constellation of friends" or a "looser social network of associates" who typically remain engaged in smuggling (and possibly dealing) for some three to five years), and Group 3 (organizations with "extensive experience" who typically "formulate a business plan specifically to engage in the transportation of contraband").

Accordingly, this analysis considers deterrence at three organizational levels: large DTOs, smaller drug-smuggling cells, and individual smugglers/couriers.[88]

Organizational Attributes

For the drug smuggling enterprise, the multi-nodal model provides:

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[87] Interestingly, the drug trafficking organizations that have survived in Colombia appear to have adopted this type of model themselves—possibly because they now work directly with Mexican DTOs (Llorente and McDermott 2014, pp. 2, 12; DEA 2018, p. 100). Nor is this transformation unique to the Americas. Wilson and Stevens (2016, p. 4), in their description of DTOs in western Europe, state that "[our understanding] has moved from the model of large-scale criminal syndicates such as the mafia or drug cartels to include fluid organisations that connect small groups of independent entrepreneurs able to trust one another through kinship or friendship ties."

[88] The organization of the Mexican drug smuggling enterprise continues to evolve. In recent years, the rate of fragmentation among the large Mexican DTOs appears to have increased. Beittel (2019, pp. 14–15, 28), while noting that "analysts disagree about the extent of this fragmentation," indicates that there may now be as many as 20 major organizations, plus more than 45 smaller regional and local groups. The ease with which synthetic drugs such as fentanyl can be manufactured may be accelerating this trend by lowering the barrier for entry into drug trafficking (Linthicum 2019). The significance for this analysis is that the lines between "large DTOs" and the peripheral "smuggling cells" they engage may be starting to blur.

- Risk Mitigation. Since each peripheral cell operates with only limited information, it is unlikely to compromise other elements of the larger organization. Similarly, a smuggling cell provides each courier only the bare minimum of information needed, so that detection and arrest of a single courier poses a minimal risk to the organization.[89]
- Resilience/Redundancy. Even if a particular cell is disrupted by law enforcement, the activities of other cells are unaffected. Redundant cells (those performing a similar function) may be able to compensate very rapidly by surging their operations, while the core organization engages another cell as a replacement for the first. Similarly, couriers who manage to leave the operation can be easily replaced.
- Agility and Adaptability. DTOs structured along multi-nodal lines have the flexibility to expand/contract as market conditions warrant, and to shift their routes as enforcement activities in a particular area may dictate. Moreover, by adding new cells with other types of focus (for example, human smuggling, arms trafficking, or oil theft), they can expand into other criminal markets. Because most major Mexican DTOs have taken advantage of this ability, they can also be characterized as TCOs (Beittel 2019, p. i; Markovic 2013, p. 119).

Smuggling Techniques

Most drug smuggling operations involve passenger vehicles and tractor trailers, although other means, such as railcars, are used as well. Drugs are typically carried in hidden compartments or locations within the vehicle; in the case of tractor trailers, they may also be concealed within a shipment of legitimate goods (DEA 2018, p. 99). Smaller loads may also be carried directly on a smuggler's person (for example, in a backpack).

Smugglers display considerable ingenuity in concealing drugs within vehicles.[90] For example, drugs may be hidden inside doors; behind vehicle panels; within truck walls and underneath floors; in false compartments; within spare tires and wheel rims; or inside vehicle batteries, axles, and drive shafts. In commercial shipments, drugs may be contained in sealed packets placed near intact containers of legitimate goods; in packets placed inside the containers; or mixed with the contents of the containers. Some drugs, such as methamphetamines, may be dissolved in liquid solution, making them harder to detect.

The vehicle in question may not even be driven by a smuggler at all. Morris (2015) reports the use of powerful magnets, surreptitiously attached to vehicle undercarriages, to turn trusted travelers into unwitting drug mules. Resendiz (2019-12) notes that U.S.-owned vehicles coming out of repair shops in Mexico often contain hidden drug loads of which the driver is unaware. (They also contain GPS trackers, which are used to recover the shipments in the United States.)

[89] Shane (2000) quotes a San Diego customs official: "Most of the mules don't know much. They're kids, homeless people, convicts. They may know only that they were paid $500 to drive this car across, leave it in this parking lot and walk away."
[90] For illustrations of the techniques described in this paragraph, see DEA (2018, pp. 19–20, 33, 52–54, 68–71, 86–87); DEA (2017, pp. 54–55, 78–80, 96–98); and San Diego's Border Busts (2019).

C. Screening at SWB LPOEs

Screening Architecture

Of the 52 LPOEs along the U.S.-Mexico border, 43 are road crossings (Rose and Davidson 2010). The exact details of screening operations at these 43 LPOEs vary somewhat from one location to another (and even from day to day at any given location). However, the basic procedure can be described as follows (GAO 2019, p. 10; Bjerk and Mason 2014, p. 6).

As vehicles approach the checkpoint, CBP uses various techniques to perform a "pre-primary" screen. These might include visual inspection of a vehicle's undercarriage using an angled mirror attached to a metal rod called a "tapper," use of a handheld density meter, or drug-detecting canines (Ludden 2019; Prendergast 2017). Vehicle license plate information is also collected. The primary inspection itself must be performed rapidly: the requirement to maintain the flow of legitimate trade and travel means that a CBP officer may have as little as 40 seconds to decide whether a particular vehicle may be carrying contraband (Solis 2017). Officers typically check passport and border crossing card information; for commercial vehicles, they may check shipment records. They also rely on their subjective assessment of crossers' behavior during a brief interview.

Based on the results of the pre-primary and primary screen, the vehicle may be referred to a secondary inspection area. (Vehicles may also be referred on a random basis.) Here, canine teams can be used to help localize the area of interest within the vehicle, which may also be subject to direct physical inspection (i.e., opening or unloading the vehicle). Fiber optic cameras are sometimes used to access difficult-to-reach areas. X-ray or gamma imaging is one of the principal tools used in secondary inspection, since it provides the ability to view the contents of the vehicle without physically accessing them (Ludden 2019; Prendergast 2017; Kerr 2019).

Figure 19 shows the corresponding screening architecture. Unlike radiological/nuclear smuggling, the effectiveness of the secondary inspection does not depend on the reason the vehicle was referred. Therefore the probability of detection for a single attempt is given by $p^1 = \rho(1-\alpha)$, just as for the simple architecture introduced in Figure 1.

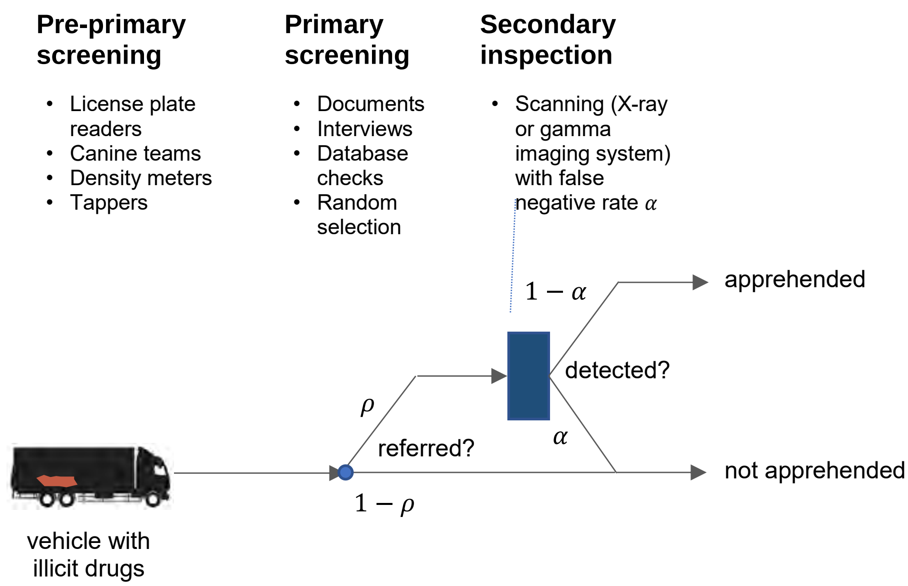

Figure 19. Screening Architecture: Drug Smuggling

Scanning Systems

Imaging systems have been in use at the SWB since the 1990s. The earliest X-ray systems relied on "transmission" imaging, which uses detectors on the far side of an object: dense objects block or absorb more of the transmitted radiation, producing shadows that indicate the objects' shape. A dense object in an unexpected location could be an indicator of contraband. Newer "backscatter" systems capture information from the radiation that is scattered away from the object, using a detector on the near side. This technique can specifically identify the presence of lower-density organic matter, such as drugs, hidden within the vehicle.[91]

CBP began using a backscatter portal at the San Ysidro, California, LPOE in 2008, to scan personally owned vehicles during secondary inspection (Bradshaw 2011, p. 1363). Within a few years, the agency had introduced 60 backscatter X-ray vans to the SWB, to complement some 150 other large-scale imaging systems in use there (Winkowski 2011). Currently, there are over 300 large-scale X-ray and gamma imaging systems in use, with the majority deployed to the SWB (Beeson 2017).

In practice, the use of these systems is constrained by their size, cost, and throughput. Large mobile and/or drive-through portal versions of backscatter systems, for instance, carry a price tag of several million dollars each and can scan approximately 250 trucks and/or 400 passenger vehicles per hour (Bradshaw 2011, p. 1362; Rapiscan n.d.-1; Rapiscan n.d.-2). They are currently used only in secondary inspection. Given the volume of traffic entering the United States from

[91] For a more extended description, see Bradshaw (2011, pp. 1359–64).

Mexico (approximately 70 to 90 million passenger vehicles and 5 to 10 million trucks per year)[92] and the time required for secondary inspection,[93] the percentage of vehicles scanned is necessarily small. Currently, about one to two percent of passenger vehicles and 16 percent of commercially owned vehicles are scanned (Horwitz and Higham 2019; Overacker 2019). CBP has conducted more aggressive referral and scanning, but only on a local and/or temporary basis (Pietsch 2018).

D. Screening and Scanning: Effectiveness

Effectiveness of Primary Screen

The effectiveness of the primary screen, ρ, is difficult to measure, given the varied techniques employed, including the use of CBP officer judgment, and the fact that "ground truth" (i.e., which vehicles really are carrying drugs) cannot realistically be known. CBP's Operational Field Testing Division conducts covert tests at LPOEs to assess the effectiveness of its equipment and procedures; however, the results of these tests are considered sensitive and are not available to the public (GAO 2019).

On the one hand, it seems likely that the primary screen is at least somewhat more effective than referring an equal number of vehicles to secondary inspection on a purely random basis. Under a random selection strategy, approximately 1 out of every 600 vehicles entering secondary inspection might be carrying concealed drugs.[94] Assuming that approximately 10 percent of these loads are large enough to be detected with a very high probability by the scan (see the following subsection), roughly one of every 6,000 scans would result in a seizure. For comparison, the actual ratio of scans to narcotics seizures is roughly 4,000 to 1.[95] Under the most pessimistic assumptions,[96] these figures suggest that primary screening is more accurate than random selection (i.e., that the actual screening effectiveness ρ is higher than the current referral rate).

On the other hand, section IV.B pointed out that drug smugglers tend to underestimate detection probabilities. They may well believe that their chances of being referred to secondary inspection are no different than those of any other border crosser, particularly at low referral rates. If so, the perceived effectiveness of the primary screen $\bar{\rho}$ would be approximately equal to the current rate of referral to secondary inspection. Accordingly, this analysis uses the value $\bar{\rho} = 0.02$ for

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[92] Author's analysis of data from BTS (n.d.). See also BTS (2017, Table 1.2011).

[93] The amount of time varies; however, secondary inspections can easily last 8 minutes (Resendiz 2019-12).

[94] The figure 1/600 is derived from the estimated annual average of 150,000 illegal to 90,000,000 total crossings. The probability that a vehicle entering secondary is carrying drugs can be written as $p(vehicle\ is\ carrying\ drugs | vehicle\ is\ referred\ to\ secondary)$. Under a purely random strategy, the decision to refer to secondary inspection is independent of what the vehicle is carrying, and this term becomes simply $p(vehicle\ is\ carrying\ drugs)$.

[95] The ratio of scans to subsequent narcotics seizures is given as 87 million to 20,000 over the period 2003–18 (McAleenan 2018); 32 million to 7,600 over the period 2008–11 (Winkowski 2011); and 6.5 million to 2,600 in 2016 (Owen et al. 2017). Note that these figures are for all CBP imaging systems, not only those at SWB LPOEs.

[96] Namely, that all these scans were for narcotics (in fact, many were performed to detect other types of contraband, such as weapons and bulk currency) and that each seizure is associated with a single scan.

personal vehicles and $\bar{\rho} = 0.16$ for commercial vehicles. Section IV.B also showed that DTOs and smuggling cells can test their estimates by observing the results of successive attempts. The high volume of smuggling activity suggests that these organizations could collect 20 or even 200 observations fairly quickly; therefore, this analysis considers a range of values, from a "high" underestimate $\rho = \bar{\rho} + 0.15$ to a "low" underestimate $\rho = \bar{\rho} + 0.05$.

Effectiveness of Scanning Systems

It is not easy to develop meaningful estimates of detection probabilities for scanning systems, given the complexity of the operating environment and the number of variables at play (including the type of drug, the size of the load, the way it is packaged, the way it is concealed within the vehicle, and the ability of the operator to interpret the image) (Crane 1997). Receiver operating curves, operational test results, and other such data for these systems are not available in the open literature (cf. the market survey conducted by Koslover et al. (2017)). CBP's covert testing specifically includes tests of its imaging systems; however, those results are not available to the public.[97]

Some information on very specific and well-defined scenarios is available. For example, the ability of SAIC's Vehicle and Cargo Inspection System (VACIS®), a gamma imaging system, to determine whether or not a truck is empty has been estimated at 97 percent (Orphan et al. n.d.). Other lower-contrast scenarios would be more challenging; still, it is reasonable to believe that a "large"[98] load of drugs might be difficult to conceal from imaging systems currently in use. Accordingly, this analysis focuses on loads large enough to be readily detectable by current imaging systems and uses the value $(1 - \alpha) = 0.95$.

Under these assumptions, a smuggler's estimate of p^1—in other words, the perceived probability of a single "large" drug shipment being detected at an SWB LPOE—would be approximately $0.02 * 0.95 \cong 0.02$ if using a passenger vehicle and $0.16 * 0.95 \cong 0.15$ if using a truck.

How many of the total estimated number of smuggling attempts carry loads large enough to be readily detected by imaging systems? One estimate might be the number of seizures that actually result from the use of such systems. Based on the number of scans and seizures reported by CBP, this number is on the order of 2,000 per year.[99] Although the locations of these particular seizures are not specified, it is reasonable to assume—based on the information presented in section VI.A—that the majority (perhaps 1,500) occur at the SWB.[100] This would suggest that

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[97] GAO (2019, p. 28) indicates that of the 213 LPOE tests conducted during the period 2013–18, several dozen were designed specifically to test imaging systems.

[98] The term is used here in relation to the size of the vehicle, the benign material used as camouflage, and/or the size of a typical shipment of that particular drug.

[99] Imaging scans are said to have resulted in 20,000 seizures over a 15-year period (McAleenan 2018); 7,600 seizures over a three-year period (Winkowski 2011); and 2,600 in a single year (Owen et al. 2017).

[100] As a point of comparison, a review of press releases over a recent 54-day period (Bump 2019) shows 65 "large" seizures occurring at SWB LPOEs (specifically, 14 seizures involving more than 12 pounds of cocaine, two involving more than three pounds of heroin, 15 with more than 125 pounds of marijuana, 33 with more than eight pounds of methamphetamines, and one involving over seven pounds of fentanyl). Extrapolating this small sample (and thereby ignoring seasonal variation) would yield a figure of 400–500 large seizures per year.

roughly 10 percent of all loads (1,500 out of 15,000 total SWB LPOE seizures per year) are large enough to be readily detected. The corresponding number of attempts is 15,000 (based on the estimate, presented in section VI.A, that seizures represent approximately 10 percent of attempts).

E. Implications for Deterrence: Large DTOs/TCOs

For DTOs, gains are measured purely in terms of proceeds received from smuggling. The organizational model ensures that detection of a smuggling attempt poses almost no risk to the organization; therefore, prospective losses are simply the costs of doing business, including costs that are unrecovered when a shipment is seized. In other words, the ratio of benefit to punishment $B/|P|$ is based on the organization's level of profitability.[101]

A single DTO might attempt over 1,000 large shipments per year (based on 15,000 such attempts and six to nine such organizations), which can be taken as the value of A. How many of these attempts must avoid detection—i.e., how many entries, E, are needed to achieve an acceptable level of profitability? Unfortunately, there are no independent estimates of this number.[102] It is tempting to assume that the number cannot be greater than 900, since roughly 10 percent of shipments are currently seized. Unfortunately, this line of reasoning is specious. For example, it might be that the "real" number is greater than 900, and some degree of deterrence is already taking place. Even the knowledge that no more than 900 per 1,000 attempts is sufficient provides no information about deterrence, as long as data are drawn solely from baseline conditions. It is easy to show that using baseline data in Equation 11 yields the result $p^* \cong 0$, which, per Equation 14, tells us only that $\tau_2 \geq 0$. In other words, the threshold for absolute deterrence must be greater than zero—neither a surprising nor useful result.

[101] This particular expression is the inverse of the cost-to-income ratio, a widely-used profitability measure.

[102] OAS (2013, p. 24) points out that confiscated accounting records are available for certain "franchises" (i.e., smuggling cells), but not for DTOs' central operations.

The Effect of Increased Scanning

If the baseline conditions were changed (say, by significantly increasing smugglers' perceived probability of being scanned $\bar{\rho}$), would there be a deterrent effect? One challenge is that deterrence is unlikely to be the first result of such a change. Instead, DTOs could simply redefine "success" (without incurring any additional risk) by modifying their business model in various ways: by increasing production (along with the number of smuggling attempts A) and/or accepting a smaller number of undetected entries E; by raising prices; or by accepting a slightly lower level of profitability. Unless the increase in $\bar{\rho}$ is extreme (i.e., for values approaching 1), some combination of these strategies is probably quite viable. The price elasticity of demand for illegal drugs is believed to be fairly modest (ONDCP 2012)[103] and the "markup" for crossing the border can double or triple the sales price (Kurrle 2013, p. 60; Keefe 2012), suggesting that there may be ample margin for adjustments. This view is broadly consistent with the conclusion reached by many researchers: namely, that at the macroscopic level, an increase in the rate of seizure of drugs at the border is unlikely to have either a deterrent effect or a significant impact on the total quantity of drugs smuggled into the United States (Keck and Correa 2015; Layne et al. 2001, p. 80).

To illustrate the ability of DTOs to maintain profitability without incurring additional risk, consider any arbitrary starting values of the extended model variables $A, E,\ B,\ P,$ and τ, along with the starting value $p^1 = 0.10$. At a very simplistic level, the DTO's profitability $B/|P|$ can be expressed as:

$$\frac{B}{|P|} = \frac{price \times min(demand, E)}{A \times (smuggling\ cost + other\ cost)} \tag{24}$$

where "price" and "cost" are expressed on a per-shipment basis, and "demand" is expressed in equivalent number of shipments. For any given number of attempts A and required entries E, an increase in the scanning rate $\Delta\rho$ increases the probability of detection for a single attempt p^1 and thus, per Equation 11, increases the organization's probability p^* of failing to achieve the baseline level of profitability. It also raises smuggling costs by requiring higher payments to couriers. The increased payment can be estimated from Equations 20 and 22 as the increase in benefit to the courier necessary to maintain a constant decision threshold τ, given an increase in his or her probability of failure (i.e., the increased probability of detection and apprehension Δp^1). To compensate for these increased costs,[104] the DTO can increase the sales price; however, there will be a reduction in demand and therefore in the number of shipments that can be sold. For a demand elasticity of -0.5, if price is increased by a multiplicative factor of ($\Delta\ price$), demand will be changed by a factor of ($\Delta\ demand$), where

[103] Price elasticity is defined as the change in demand that would result from a 1 percent increase in price. ONDCP (2012, p. 96) cites a body of prior research indicating that elasticity is less than one in absolute value and most likely in the vicinity of -0.5: a if the price of the drug is increased to 1.01 times the previous price, the new demand will be 0.995 times its previous value.

[104] For purposes of illustration, smuggling costs are arbitrarily assumed to be equal to 20 percent of total costs. Cf. OAS (2013, p. 20), which found that approximately $5.3 out of $35.3 billion gross profits in the U.S. cocaine trade accrued to processing, trafficking, and wholesaling outside the United States.

$$\Delta\, demand = 1 - (1 - 0.005)^{ln(\Delta\, price)/ln(1.01)} \tag{25}$$

Under these assumptions, there are many possible ways to choose values for price, number of attempts A, and required number of entries E, such that the level of profitability $B/|P|$ is maintained with a more or less constant probability of success $1 - p^*$. Figure 20 shows just one of many strategies that could be used. In this example, $B/|P|$ is approximately 80 percent or more of its baseline value over the range $0.10 < p^1 < 0.50$.[105] If these levels of profitability were acceptable to the DTO, there would be no deterrent effects over this range of values for p^1.

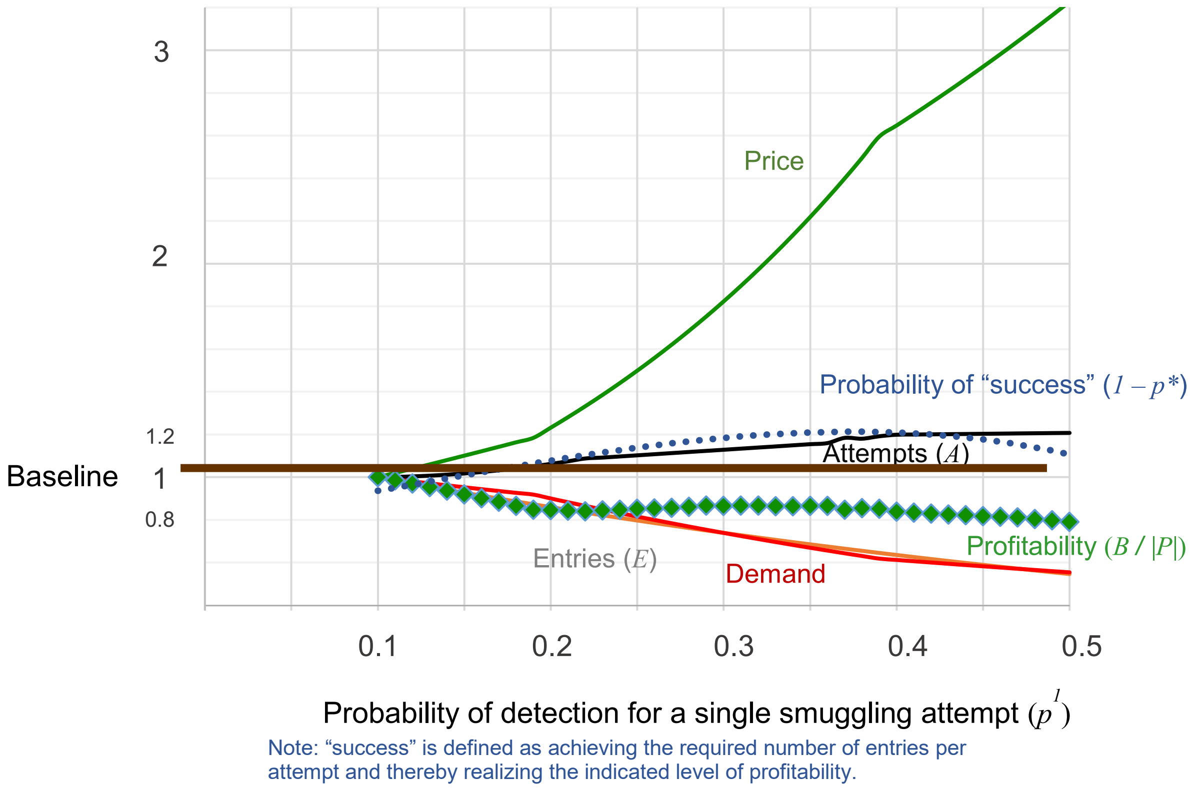

Figure 20. Example DTO Strategy for Maintaining Profitability Despite Increased Probability of Detection/Seizure

Even if a DTO were faced with increased risk, in the form of a lower probability of success $1 - p^*$, deterrence (e.g., a shift from drug smuggling to other types of criminal activity or, at the least, a shift from SWB LPOEs to other avenues of entry) is not the only possible result.

- DTOs can and do change smuggling pathways to maintain the most favorable results (Medel et al. 2015).[106] Thus, if the increase in referral/scanning is temporary (e.g., a

[105] As $p^1 \to 1$, $B/|P| \to 0$ or $p^* \to 1$ regardless of the strategy adopted; thus, for $p^1 \geq 0.50$ it becomes much more difficult to sustain the baseline level of profitability with anything like the same probability.

[106] Cf. Che and Benson (2013, p. 18): "Drug smugglers clearly can and do respond to changes in law-enforcement activity, but entry and exit are not likely to be the dominant responses. Instead changes in behavior occur, like moving to a different route when law-enforcement threats increase on one route relative to another, to eliminate or at least mitigate the law-enforcement effort."

"surge" or limited-duration campaign) or localized (i.e., it occurs at some LPOEs but not others), it is likely to have no effect on the organization's ability to achieve success (Caulkins et al. 1993; Layne et al. 2001, pp. 3, 44, 82).

- There is evidence that DTOs actually view enhanced enforcement as a signal or stimulus to improve their operations—by forming or finding smuggling cells that are more effective, for instance, or by promoting the development of new smuggling methods and tools. In the latter case, DTOs have adopted the role of "deviant entrepreneurs," using illicit venture capital to fund the development of innovative smuggling technologies (Nieto-Gomez 2013, pp. 153–58).
- DTOs can simply accept the increased risk. The DTO organizational model is geared to this type of response (Farfán-Méndez 2019). Behavioral economic models such as CPT (see section IV.B) also predict that DTOs will respond to increased enforcement by engaging in more risky behavior (for example, increasing load sizes) in an attempt to recapture lost profits (Caulkins and MacCoun 2003).

Summary (DTOs)

Developing independent quantitative estimates for deterrence thresholds and predicted seizures requires detailed knowledge of DTOs' business models, including ranges for the number of attempts and entries (A and E) required to generate an acceptable level of profitability ($B/|P|$), as well as the organizations' likely response(s) to increased levels of detection and seizure. Lacking such information, the author was unable to develop testable predictions of deterrent effects at the level of large DTOs.

F. Implications for Deterrence: Smaller Drug-Smuggling Cells

The collection of smaller drug-smuggling cells employed by DTOs forms a volatile landscape, with organizational lifetimes of months to years (Beittel 2019; Kurrle 2013; Wilson and Stevens 2016, p. 4).[107] The motivations, perceptions, and behaviors of these organizations are similar to those of the larger DTOs, with success measured in terms of profitability. The scale of operations is smaller, perhaps by an order of magnitude; that is, the value of A may be on the order of 100 large-scale attempts per year.

As with DTOs, detection of a shipment at the border poses minimal risk to the employees of these cells[108]; rather, apprehension and seizure represent part of the organizations' "cost of doing business." Two types of cost are involved: the effect of courier apprehensions on costs for recruitment/replacement and payment, and the direct cost of losing a shipment due to seizure.

[107] Layne et al. (2001, pp. 86–89, 94) interviewed "high-level" cocaine smugglers, defined as U.S. citizens charged with smuggling more than 15kg (approximately 33 lbs.) of cocaine and who either had a prior conviction or were responsible for supervising five or more people. Since many of these individuals functioned in leadership and planning roles (versus acting as mules or couriers), they correspond to leaders of "smuggling cells" in this analysis. The 32 individuals who were interviewed averaged 14 years' involvement (excluding 5 first-time offenders).

[108] These employees are well compensated: OAS (2013, p. 24) indicates they earn an average of about $20,000 per year, "about 1.3 times the mean formal sector wage in Mexico and 6 times the minimum wage."

There is some evidence that a 2 percent or greater chance of arrest has a deterrent effect on individual smugglers[109]; above this level, smuggling organizations must presumably work harder to recruit and/or increase the prices paid for smuggling a load of drugs. Current experience, however, suggests that this type of cost has remained well within organizations' ability to tolerate (see section VI.G). Therefore, with respect to smuggling cells, we cannot necessarily conclude that $\tau_1 = 0.02$.

Regarding direct losses from seizure, smuggling organizations are believed to be able to operate successfully despite the loss of as many as 3 of every 10 shipments[110] (that is, $E = 70$ undetected entries per 100 attempts). Since successful smuggling is currently taking place, baseline values of the extended model parameters, by themselves, provide no useful information regarding deterrence thresholds. This is indeed the case: once again, Equations 11 and 14 yield only the results $p^* \cong 0$ and $\tau_2 \geq 0$.

The Effect of Increased Scanning

What if referral and scanning rates were to increase? Analyses of limited-scope enforcement crackdowns suggest that increased enforcement and seizures can alter the behavior of a smuggling organization, and that this may include a deterrent effect. Based on analysis of multiple enforcement operations and interviews with apprehended members of smuggling organizations, Crane (1999, p. III-5) estimated that deterrent effects would begin to occur when the probability of detection for a single attempt p^1 reached approximately 0.30 and would increase linearly thereafter, with absolute deterrence requiring p^1 approximately equal to 1.0 (near certainty of detection).[111] Using these values, along with the above values of A and E, in Equation 11, the corresponding values of failure probability p^* are 0.32 and 1.00, respectively. Accordingly, this analysis uses $\tau_1 = 0.32$ and $\tau_2 = 1.00$ as the range of deterrence thresholds.[112]

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[109] For example, Layne et al. (2001, p. 80) concluded that detection/arrest rates greater than 2 percent "[get] the attention of" individuals; Crane (1999, pp. 2, III-1 through III-5) states that "based upon the responses of captured drug traffickers and confirmation by several successful operations," the threshold for deterrence was estimated to occur at an apprehension rate of 2 to 4 percent.

[110] Feyerick (2009), in describing Mexican smuggling organizations, quotes the former DEA chief of global enforcement operations as follows: "They'll line up 10 loads, and if you pick off two or three, well, that's the cost of doing business, 'I got seven across.' So it's that shotgun mentality."

[111] The rationale for taking the upper limit at 1.0 is not given. Presumably, it is based on the statement (drawn from interviews) that absolute deterrence would require the seizure and loss of four consecutive loads—an event that would happen with high probability over for extremely high values of p^1.

[112] Layne et al. (2001, p. 16) found that none of the planners who were interviewed would be deterred if the rate of detection/apprehension were 0.01; 6 percent would be deterred if it were 0.10, and 37 percent if it were 0.50. These results are roughly consistent with the behavior that would be seen if deterrence operated linearly as a function of detection probability p^1 (as opposed to failure probability p^*) over the interval $[0.32, 1.00]$. For example, at a 50 percent rate of apprehension, the linear model shown in Equation 13 would predict that $1 - 0.50/(1.00 - 0.32)$, or 26 percent of planners would be deterred. If deterrence is instead measured with respect to failure probability p^*, the data are consistent with the non-linear model proposed by Jacobson et al. (2005) (see sections IV.A and C), using p^* in place of ρ in Equation 6, taking A = 4, E = 1 in Equation 11 (avoidance of 4 consecutive seizures, per Crane (1999, p. III-5)), and setting the deterrence exponent η equal to 0.4. These values yield the prediction that a 50 percent detection rate would deter $(1 - 0.05^4)\left(1 - \sum_{i=1}^{4} \binom{4}{i} [0.5]^4\right)^{2.5}$, or 33 percent of planners.

Combining these results and applying Equations 1, 2, and 13 (with the baseline number of intentionally illicit attempts I_0 in Equation 1 set equal to the value of A; that is, 100 attempts) yields the predictions shown in Figure 21. Recall that deterrence (and hence the number of attempts actually made) depends on the *perceived* effectiveness of the primary screen (that is, $\bar{\rho}$), whereas the number of seizures depends on the *true* effectiveness of the screen (that is, ρ). Accordingly, the figure shows different results corresponding to "low" and "high" degrees to which smugglers might underestimate the value of ρ. For comparison, the figure also shows an underestimation rate of "none"; that is, the case in which smugglers have perfect knowledge regarding primary screening and therefore $\bar{\rho} = \rho$.

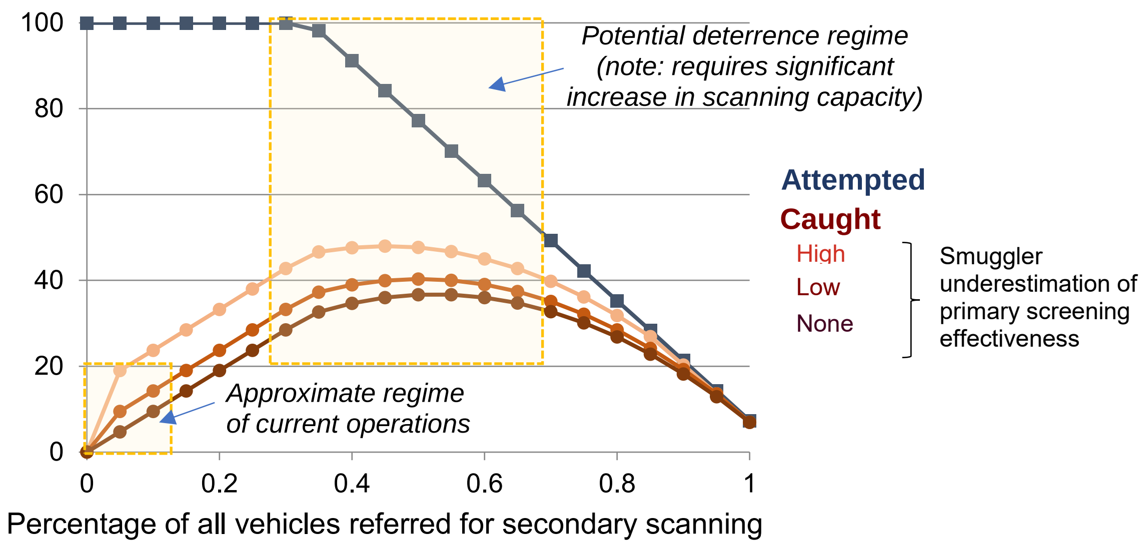

Figure 21. Predicted Deterrence as a Function of Referral/Scanning Rate (Smuggling Cells)

The shaded rectangle in the lower left-hand corner of the graph depicts the current operating regime, with less than 15 percent of all vehicles referred for scanning and less than 20 percent of all attempts caught. As the figure shows, deterrence (indicated by a decreasing number of attempts) is predicted to occur well outside this operating regime (i.e., toward the central portion of the graph).

The figure points out one other important caveat. Recall that time and resources limit the number of vehicles that can be referred for scanning. Increasing the scanning rate indiscriminately will result in a large increase in the total number of vehicles scanned (since many more "innocent" vehicles will be referred), and thus is not possible without a significant increase in resources. Lacking such resources, an increased rate will necessarily be temporary or localized, making it difficult to measure deterrent effects on the basis of aggregated data.

Potential Enhancements

Recent technology developments indicate that it may be possible in the future to scan a much larger percentage of all vehicles at SWB LPOEs. For example, the year 2018 saw the introduction of relatively affordable handheld backscatter systems, which could potentially increase throughput (CT Strategies 2018). In theory, a large enough increase could enable operations in the deterrence regime—although other constraints (such as the impact on legitimate trade and travel) would still have to be taken into account.

An even more dramatic change would be the ability to scan all vehicles during the pre-primary phase. In 2019, CBP acquired, as part of a pilot program, four in-ground X-ray systems designed to scan the undercarriage of every vehicle during the pre-primary screen. Since the scan takes less than one minute, it can be performed at high-volume LPOEs with little or no additional impact on vehicle wait times. Other drive-through scanners designed for more extensive pre-primary screening will be also be tested in 2020 (Bernstein 2019; Biesecker 2019; Resendiz 2019-12).

If the probability of being scanned by such a device were 1.0, the probability of being detected during pre-primary screening would depend only on the added effectiveness (and the perceived effectiveness) provided by this scanning system. Such a system is likely to be less effective than the scanners used in secondary inspection, largely because the duration of the measurement will be shorter. Nevertheless, the net result would be to increase the probability that a vehicle carrying contraband will be referred to secondary inspection—without anything more than a modest increase in the number of innocent referrals.

Figure 22 shows the modified screening architecture corresponding to the introduction of this type of system. If the pre-primary scan does not yield a detection, the vehicle is checked with canines, density meters, and/or tappers as before. The effectiveness of the primary screening process is $\rho = max(\rho_P,\ \rho_0)$, where ρ_P is the effectiveness of the primary scanner and ρ_0 is the effectiveness of the primary screen without the scanner. (At worst, the new system will yield no improvement over current methods.)

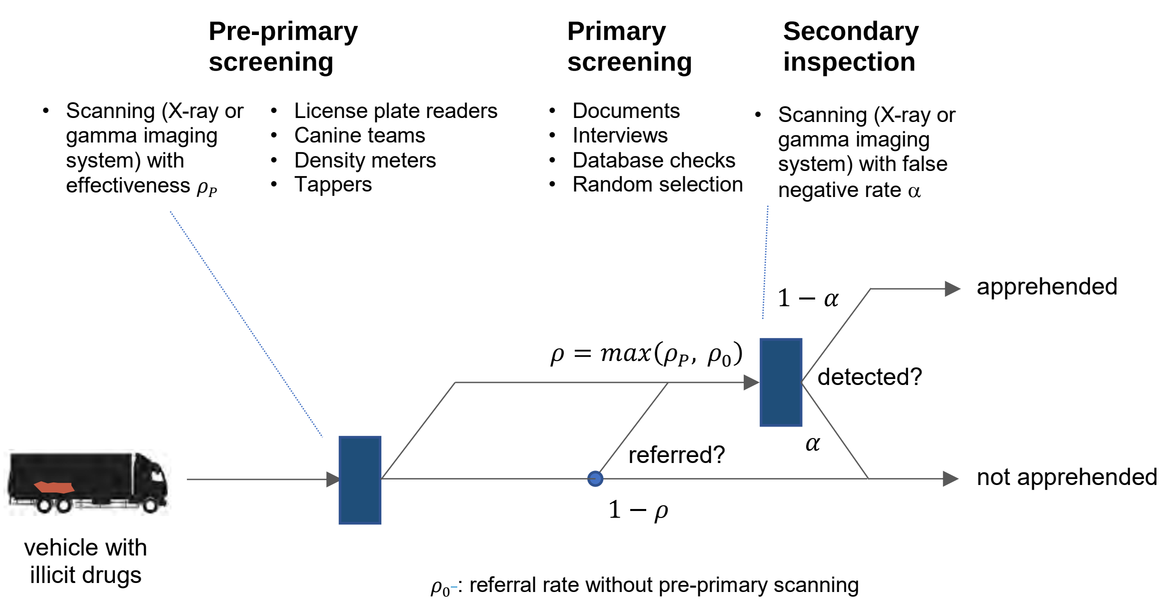

Figure 22. Modified Screening Architecture (with Pre-Primary Scanning): Drug Smuggling

Figure 23 shows the resulting predictions for attempts and seizures, as a function of the effectiveness ρ_P of the new pre-primary scanning system. Note that the horizontal axis represents the *true* value of the primary scan effectiveness (in contrast to Figure 21, where the axis represented the *perceived* effectiveness of the primary screening process); smuggler underestimation of this value would affect the number of attempts as well as the number subsequently caught. The figure shows the effectiveness of the pre-primary scanning system ranging from zero to 0.95: the upper bound corresponds to the assumption that this system is no more effective than the secondary scanning system.

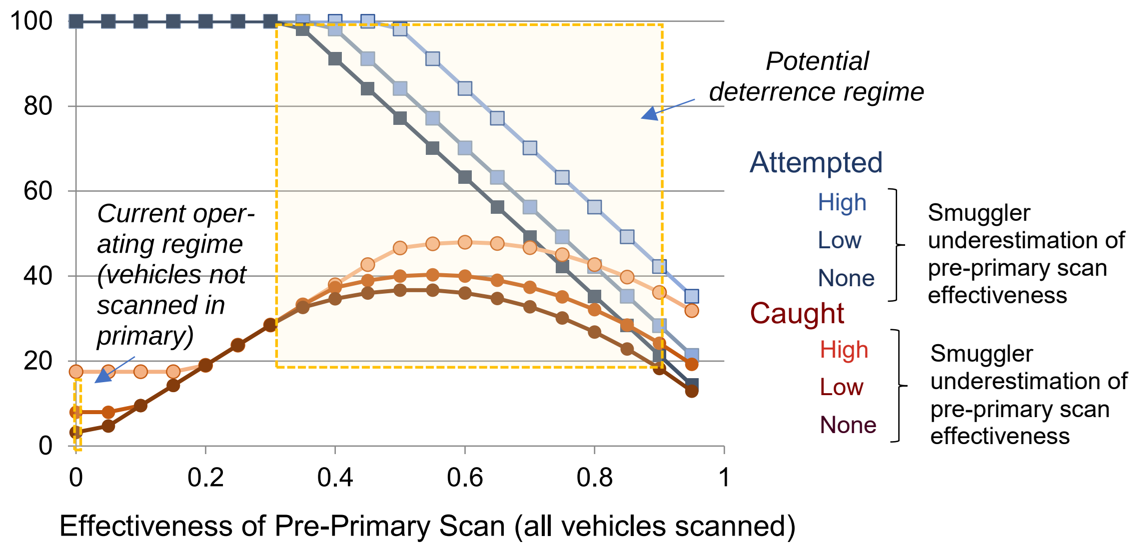

Figure 23. Predicted Deterrence as a Function of Pre-Primary Scanning Effectiveness (Smuggling Cells)

Summary (Smuggling Cells)

The advent of new systems and screening architectures may make it possible to test their deterrent effects, which are predicted to occur when the probability of detection exceeds approximately 30 percent for a single smuggling attempt. However, there are several challenges and caveats. First, impacted smuggling organizations may be able to counter these improvements by changing their tactics—a common response (cf. Che and Benson 2013, pp. 17–18 and note 28; NDIC 2007). Second, if the improvements are localized, the parent DTO may develop a new set of smuggling paths, as discussed previously; if improvements are temporary, they may wait out the change.[113] In either case, it would be difficult to document an effect from open-source, aggregated data. Third, some of the data on which these predictions are based was derived from experience with Colombian (as opposed to Mexican) smuggling organizations, and is a decade or more old; the extent to which those data can be safely generalized is not known.

[113] As Che and Benson (2013, p. 19) note: "prospect theory predicts that due to loss-aversion, a smuggler is likely to be prepared to accept large and continuing losses for some time before exit is considered. If there is a deterrence impact, it is likely to be lagged substantially after considerable investment in risk mitigation."

G. Implications for Deterrence: Individual Smugglers

Although committed smugglers may continue their activities for an extended period of time, most couriers or mules can be classified as "adventurers" characterized by "low permanence levels (weeks or months)" (Wilson, p. 4). For these individuals, each attempt is a separate undertaking and "success" consists in avoiding detection and arrest during a particular crossing. In other words, using the terminology of the extended model (section IV.B), $A = E = 1$ and $p^* = p^1$. The benefits B from smuggling are the payments they receive for carrying a load of drugs across the border. The punishments P result from apprehension (and subsequent conviction and sentencing).

Payments can be substantial, relative to legitimate income: Bjerk and Mason (2014) report a mean payment of $1,600 per load (with 10th and 90th percentiles at approximately $500 and $3,000, respectively), compared with average per capita wages of $30,000 to $35,000 in U.S. and $13,500 in Mexican border counties. Moreover, punishments can be light: even a large load of cocaine can draw a sentence of just three years in prison for a first-time offender, and sentences average less than two years for marijuana loads as large as 200 pounds (Bjerk and Mason 2014, p. 2; Davis 2018). Smugglers under 18 years of age may face nothing more than a fine—perhaps paid by their parents—and a few weeks or months in a juvenile detention center (Davis 2018).

Because this analysis uses aggregated data rather than case studies, deterrence must be viewed in terms of the collective behavior of the entire population of couriers and potential couriers. In other words, deterrence thresholds will be distributed on the interval $[\tau_1, \tau_2]$. As noted earlier, Layne et al. (2001) and Crane (1999) found that deterrent effects for individual smugglers begin when the probability of arrest reaches 2 percent, which may therefore be taken as an estimate of the threshold τ_1. However, the effects of increasing detection and apprehension rates beyond that level are not well understood. Aggregated data would be impacted by higher detection rates only if such increases made it difficult to find willing mules or couriers. This has not been the case to date, for at least two reasons.

Risk-Based Courier Payments

First, greater risk can be offset simply by increasing the price paid for carrying a given load of drugs. There is clear evidence that smuggling cells adjust the level of payment based on courier perceptions of risk. Bjerk and Mason (2014) analyzed statistics derived from statements of probable cause filed following federal smuggling arrests at Mexico-California LPOEs. The results demonstrated that payments rates varied substantially, with a strong degree of correlation to load size and associated risk.[114] Davis (2018) reports a practice of incentive payments ($1,000, rather than the usual $500) to first-time mules, presumably to help them overcome their inhibitions. This practice is consistent with one of the predictions of the CPT decision-making

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[114] For cocaine and methamphetamines, increased payments were correlated with the expected sentence *if caught*; for marijuana, the authors argue that the correlation is instead driven primarily by the effect of load size on likelihood of detection. They speculate that this may be because the expected sentence length for marijuana smuggling is relatively limited regardless of quantity.

model: namely, that the decision to start smuggling requires a greater inducement than the decision to continue[115] (cf. section IV.B).

Consider the hypothetical case of a single individual whose income is $12,490—the Federal poverty level (HHS 2019). Suppose this individual is offered the opportunity to smuggle drugs via personally owned vehicle for a payment of $500 (i.e., $B = 500$). Suppose further that he or she monetizes the potential punishment of three years' imprisonment strictly in terms of lost income (i.e., $P = -37{,}500$). Then the ratio of benefit to punishment $B/|P| \cong 0.013$. For a scanning system with a false negative rate $\alpha = 0.05$, Equations 20 and 22 (with $p^* = p^1 = \bar{\rho}(1 - \alpha)$) predict that the deterrence threshold τ_0 corresponds to $\bar{\rho} \cong 0.02$—typical of current operations—and that the deterrent effect of a 50 percent increase in the scanning rate, from $\bar{\rho} \cong 0.02$ to $\bar{\rho} \cong 0.03$, could be overcome by a 38 percent increase in the level of payment offered, from $500 to less than $700.

Under these circumstances, it is not surprising that recruiting couriers is literally as simple as posting a job ad on Facebook, and that there is no shortage of willing applicants (Rohrlich and Kozlowska 2019).

Risk Tolerance of Smugglers

The second reason that increased scanning and detection does not necessarily result in deterrence is that smuggling cells target individuals who are more risk-seeking than average, and thus for whom the deterrent effects of increased enforcement are correspondingly less effective. For example, individuals are known to become more risk averse with age (Che and Benson 2013, p. 27, note 27); thus, it is not surprising that smuggling organizations devote considerable energy to recruiting young adults and teenagers, including those who are impoverished, involved in gang-related activity, or otherwise susceptible (Davis 2018; Fajardo 2018). In the words of Che and Benson,

> "At least some individuals who get involved in drug smuggling are risk seekers … [which] suggests that deterrence effects of increased law enforcement will be relatively small, particularly if the gains from smuggling are also increasing as they may with increased enforcement" (Che and Benson 2013, p. 17).

Limiting Cases

For very large changes in the probability of detection p^1 such as those that might result from the introduction of comprehensive pre-primary scanning, deterrent effects on individual smugglers may be more dramatic. Based on Figure 4, it appears that increasing the detection probability p^1 from 0.02 to approximately 0.50 might drive couriers to seek payments multiplied by a factor of 50 or more (for example, from $500 to $25,000). It is hard to imagine that smuggling organizations would be willing to accommodate such a change. The extent to which such effects are incorporated into the deterrence predictions of section VI.F is not clear.

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115 Other factors may also make it more difficult to discontinue smuggling: for example, the threat of violence or reprisal against an individual who decides to quit (Campbell and Hanson 2012; Davis 2015).

Summary

It is difficult to develop quantitative predictions regarding activity levels for the set of individual drug smugglers on the basis of the aggregated data. Modeling deterrence for this population would require detailed knowledge regarding the pool of current and potential smugglers (size and composition, including potentially relevant factors such as age, income, gang involvement, and so on); the rate at which individuals currently enter and leave the pool; these individuals' attitudes toward potential incarceration (i.e., how they monetize punishment); and the degree to which their employers are willing/able to offer increased payments to offset an increased risk of apprehension.

Another unknown is whether individuals base their perceptions of detection probabilities on the shared knowledge and experience of all fellow drug smugglers within the organization, on the experience of a particular group of individuals (e.g., family members and friends), or strictly on their own experience. The answer could greatly impact a smuggler's perception of the scanning rate (that is, $\bar{\rho}$) relative to its true value ρ.

VII. Conclusions

This study sought to measure the deterrent effect of large-scale scanning systems with respect to two different types of smuggling: the worldwide smuggling of radiological and/or nuclear materials and the smuggling of illicit drugs through LPOEs at the SWB. As Figure 24 shows, these two types of activity are fundamentally different in several respects that bear on deterrence.

	Radiological/Nuclear Smuggling	Drug Smuggling at SWB LPOEs
Level of activity (incidents per year)	• ~2	• ~150,000
Nature of activity	• Isolated incidents	• Ongoing enterprise with established supply chain
Smuggling populations	• Individuals/opportunists and small groups of criminals	• Large DTOs/TCOs • Smuggling cells • Individual mules
End users/demand	• Unknown	• Distributors, dealers, drug users
Type of scanning system	• Passive radiation detection (portal monitors, mobile vans)	• Active imaging (X-ray and gamma)
Role of scanning systems within checkpoint screening/detection architecture	• Primary phase	• Secondary phase (note: may expand to include primary phase in the future)
Key determinants of scanning system effectiveness	• Material type, mass, activity, and configuration • Source-detector geometry • Presence of benign emitters • Shielding/masking • Vehicle speed • Effectiveness of secondary inspection	• Size and density of package • Presence of other, similar objects • Duration of scan • Operator interpretation of image • Effectiveness of primary screen

Figure 24. Radiological/Nuclear Smuggling versus Drug Smuggling

One of the few similarities concerns the individuals who actually carry the illicit material through a checkpoint. Both radiological/nuclear smugglers and drug mules tend to be impoverished individuals with few prospects for advancement—in other words, individuals for whom the potential gains of engaging in criminal activity represent a powerful inducement.

With respect to radiological/nuclear smuggling specifically, the study found that:

- Potential gains from smuggling appear to be on the order of tens to hundreds of thousands of dollars for a single attempt.
- Potential losses may involve sentences of roughly 2 to 4 years' imprisonment for an individual with a limited role, or 7 to 10 years for an individual with a larger role. These sentences are not always served in full.
- In most areas where radiological/nuclear smuggling has been observed, average incomes are only a few thousand dollars per year. As a result, the ratio of perceived smuggling gains to losses is likely quite large, and deterrence is correspondingly difficult.

- Before the mid-2000s, radiation portals were not widely prevalent and most apprehensions resulted from intelligence and law enforcement operations. Smugglers believed (no doubt correctly, in most cases) that their chances of being detected at a border checkpoint were less than 10 percent.
- The subsequent widespread deployment of portal monitors and vans increased the probability of detection at border checkpoints; however, smuggling attempts have continued.
- It is possible that at least a few of these more recent incidents represent deliberate challenges (i.e., attempts in which the presence of scanning systems and the increased risk of detection were known beforehand). Alternative explanations include lack of prior knowledge, exploitation of specific gaps in coverage, or the ability to evade a functioning detector by bribing one or more border officials.
- A full diagnosis of these incidents is not possible within the bounds of publicly available, open-source data.
- Considering all these factors, a tentative and very rough estimate from available information is that at least some radiological/nuclear smugglers may not be deterred unless the probability of detection is quite high—perhaps 50 percent or greater.
- Depending on the effectiveness (and perceived effectiveness) of the secondary inspection process, achieving such a probability of detection may require a near-certain probability that the material will be scanned in the primary phase and that the system will alarm; the latter stipulation is notoriously difficult in the case of shielded HEU.
- The above estimate comes with several important caveats: in addition to the limitations imposed by the use of open-source information, these include the relatively small number of documented radiological/nuclear smuggling cases, the use of very rough estimates for certain intermediate variables, and the application of decision-making theories and models that have not been validated for this specific population of smugglers.

With respect to drug smuggling at Mexico-U.S. LPOEs, the study found that:

- Deterrence is difficult … not only because current detection rates (as a percentage of attempts) are low, but also because DTOs and smuggling cells employ organizational constructs that encourage risk taking, recruit risk-seeking individuals, and react to increased interdiction by adapting their methods and/or engaging in more risky behavior to recoup their losses.
- Metrics for success, failure, gains, and losses depend on the level of organization being considered.
- It is not possible to develop quantitative estimates of deterrent effects for large-scale DTOs/TCOs without a more complete picture of their business model(s), including current and minimum-acceptable levels of profitability, risk tolerance, and preferred strategies.
- It is also difficult (on the basis of aggregated data) to quantify deterrent effects for individual smugglers. A more in-depth analysis would require detailed information on the

pool of potential smugglers (by age, income, gang affiliation, etc.), their attitudes toward the risk of fine/imprisonment, their sources of information regarding detection risk, and many other factors.

- Some existing evidence points to a deterrent effect for small-scale smuggling cells, provided that a vehicle's probability of being scanned is greater than approximately 30 percent—almost certainly much greater than what is experienced under current operations.
- A large increase in the rate of referral to secondary inspection is not feasible under the existing screening/detection architecture due to the increased number of innocent vehicles that would be referred, along with the corresponding impacts on required resource levels and/or the flow of legitimate commerce.
- New systems being developed by CBP may allow all vehicles to be scanned during the pre-primary phase. Such systems could increase the probability that a smuggler is scanned in the secondary phase without increasing referral rates for innocent vehicles.
- It is possible to predict the deterrent effect of these new systems in terms that are directly observable (i.e., the net impact on the number of seizures), provided that their effectiveness is known, they are deployed to all SWB LPOEs, and they are not susceptible to countermeasures such as changes in smuggling tactics.
- Some of the intermediate variables used to develop these predictions are based on very rough estimates; moreover, much of the data on deterrent effects is derived from experience with Colombian smuggling organizations circa 2000, and may not be generalizable.

Many of the caveats and limitations noted above point to areas for further research and analysis. One example is the need to test behavioral economics models such as CPT on populations of actual and/or potential cross-border smugglers. Widening the scope of analysis to include intelligence and/or law-enforcement sensitive information could also impact some of the conclusions of this report.

References

Because this report deals with widely different subject areas, the list of references is organized into the following groups:

- **Screening, Scanning, and Deterrence.** This group includes sources dealing with screening processes and scanning technologies in general, as well as applications outside the realm of either radiological/nuclear smuggling or drug smuggling. It also includes works that focus on the subject of deterrence, along with related topics such as behavioral economics, decision-making, and criminal psychology.
- **Radiological/Nuclear Smuggling.** In addition to works that deal broadly with nuclear proliferation and radiological/nuclear terrorism and smuggling, this group also includes incident chronologies and descriptions of specific smuggling incidents, reports of portal monitor deployments, assessments of detection effectiveness, and sources that provide relevant background material on the regions and populations of interest.
- **Drug Smuggling.** This group includes sources that describe drug smuggling activity and the nature of the drug smuggling enterprise, including its organization, tactics, and behaviors. It also includes works that describe models of drug smuggling networks, flows, and supply chains; data on seizures; and descriptions of the screening and scanning systems used at the Mexico-U.S. border.

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