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Controlling Pollution with Fixed Inspection Capacity

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In this paper I model the optimal monitoring and enforcement strategy when inspection capacity is fixed by budget or manpower constraints. I adopt a leverage enforcement structure that classifies firms into two groups with different enforcement intensities. Optimal monitoring and enforcement requires effective allocation of the fixed number of inspections to the two groups. In each period, a fixed number of firms are selected from each group for inspection, and those with the highest emissions are placed in the targeted group in which the inspection probability is higher. This transition structure induces rank-order tournaments among inspected firms. Once selected for inspection, the emissions of each firm are subject to a standard above which the firm pays a fixed penalty. I find that a regulator facing inspection capacity constraints should leverage the limited inspections by allocating more inspections to the targeted group. In addition, I show that targeting enforcement is generally superior to static enforcement. This is in accordance with findings in the literature. These results are consistent over different ranges of regulatory parameters.

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Keywords: Monitoring and Enforcement; Environmental regulation; Standard; Tournament;

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I. Introduction

The Environmental Protection Agency (EPA) is responsible for implementing environmental regulations in the United States. It has ten regional offices, each of which, cooperating with the states, conducts inspections to enforce compliance with environmental laws and regulations within its responsible areas. However, constrained fiscal budgets and limited workforce make it impossible for the EPA and the states to inspect all polluting firms every year. According to Enforcement and Compliance History Online (ECHO) data,[1] only about 40% of the firms registered with hazardous waste management programs in EPA Region 4[2] were inspected at least once from September 2006 to August 2007. The ECHO data also reveal that during the same period, about half and 3/4 of firms in EPA Region 4 registered with air programs and water programs, respectively, were inspected at least once. The inspection capacity constraints give rise to incomplete enforcement. In such circumstances, it is crucial that the limited monitoring and enforcement resources are optimally allocated. The 2004 Strategy Plan of Region 4 states, "the vast number of regulated facilities in the region dictates that Region 4 prioritize where we devote our limited resources…the region has far more areas of critical concern than resources" (chapter 2, goal 5, p. 1).

In this paper, I consider a dynamic model of monitoring and enforcement in which a regulator faces fixed inspection capacity. The regulator's objective is to determine the enforcement strategy that achieves the optimal abatement effort levels of firms. I adopt the leverage enforcement structure, also known as state-dependent enforcement or targeting enforcement, that classifies firms into two groups with different enforcement intensities. It has been shown that leverage enforcement is superior to static enforcement in terms of firm compliance or emission levels under certain conditions (see Harrington, 1988; and Harford, 1991).[3] In my model, optimal enforcement requires effectively allocating these inspections to the two groups.

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[1] The data can be found at http://www.epa-echo.gov/echo/.
[2] EPA Region 4 includes Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, and Tennessee.
[3] These conditions include: (a) there is no asymmetric information; (b) the desired compliance rate is not extremely high; (c) firms are homogeneous in their abatement cost.

The targeting model of income tax enforcement was first introduced into the environmental regulation literature by Harrington (1988). In his model, firms are placed into two groups according to their compliance status. The inspection probabilities and sanctions are higher in the targeted group than those in the other group. Firms in the non-targeted group will be placed in the targeted group if they are found in violation, and cannot move back until they are found in compliance. Harrington shows that the leverage between groups leads to partial compliance from firms that would have no incentive to comply otherwise. Russell (1990) considers a similar model in the presence of measurement errors. He concludes that a three-group model provides savings on enforcement costs even with imperfect monitoring. Using a more general social objective function, Harford (1991) shows that differentiating pollution standards yields lower social costs. More recently, Friesen (2003) suggests that moving firms randomly into the targeted group may further reduce monitoring costs. Other issues that are addressed within the framework of targeting enforcement include asymmetric information (Raymond, 1999), limitations on the superiority of state-dependent monitoring (Harford and Harrington, 1991), and self-reporting (Hentschel and Randall, 2000).

The targeting models mentioned above share one common feature—the regulator's enforcement strategy simplifies to the regulation of one representative firm with the consequence that the inspection probability of one firm is independent of that of another firm. This simplification cannot hold for a regulator facing fiscal or manpower constraints. For example, when the majority of firms end up in the targeted group, it is impossible for the regulator to target all these firms with a high inspection probability. When few firms are in the targeted group, having enforcement resources idle is neither efficient nor desirable from the regulator's viewpoint. The fluctuations in the regulator's enforcement costs stem from the assumption that the sizes of the groups vary while the inspection probabilities in the two groups are fixed. Thus the actual total number of inspections needed differs from one period to the next. I depart from the previous literature and assume that the number of inspections is fixed in any given period. By appropriately allocating the fixed number of inspections, the regulator targets firms in one of the groups with a higher inspection probability. Under such a targeting enforcement scheme, I investigate the optimal leverage of the fixed number of inspections.

To ensure fixed group sizes, the number of firms inspected in each group in the current period should be equal to the number of firms placed in that group in the next period. Making a firm's transition probability from one group to the other dependent upon its compliance status no longer satisfies that requirement. Thus I assume the inspected firms compete with each other for the chance of being placed in the non-targeted group. More specifically, of all inspected firms, if m of them are selected from the targeted group, then the m firms with the highest emissions in the current period are placed in the targeted group in the next period.

The structure of this transition process induces rank-order tournaments among inspected firms. Tournament models have been widely used in the study of labor economics and other related fields since the pioneering work by Lazear and Rosen (1981).[4] In my model, the tournaments induce competition among firms for the chance of being placed in the non-targeted group, and this competition may give firms an extra incentive to reduce emissions beyond those induced by enforcing the emission standard alone. This feature differs from other leverage enforcement models where firms do not interact with each other. In other models, the transition probability of a firm is determined solely by its own compliance status. In my model, whether a firm switches from one group to the other depends on the environmental performance of all the inspected firms. Even though a firm is in compliance, it may still be put in the targeted group if its emissions are sufficiently high for it to be ranked ahead of enough number of firms.

This paper is organized as follows. In Section II, I develop a theoretical model of firm behavior and a regulator's targeting enforcement strategies. I derive the optimal choices of abatement effort for individual firms in each group and discuss the regulator's enforcement objective—determining the optimal allocation of inspections to each group. Since the choice variables for the regulator can only be integers, the traditional first order conditions cannot be used to generalize the optimal enforcement strategy. Theoretically comparing the results from all possible inspection allocations and group sizes can be used to determine the optimal enforcement strategy. However, the complexity of the model makes it impossible to find a general solution for the purpose of comparison. Therefore, I use simulations to establish the patterns of the optimal enforcement strategy in Section III. Concluding comments are given in Section IV.

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[4] The applications of tournament models in environmental economics are quite limited. See Govindasamy, Herriges, and Shogren (1994), and Franckx, D'Amato and Brose (2004) for examples.

The main result of the model is that a regulator facing constrained monitoring budgets or manpower should leverage the limited inspections and allocate more inspections to the targeted group than to the non-targeted group. However, maximum leverage by allocating all but one inspection to the targeted group does not necessary lead to maximum total abatement effort. According to the simulations, the optimal number of inspections in the targeted group usually lies between half and three quarters of the total number of inspections.

II. The Model

A. Firm behavior under dynamic enforcement

Consider a total of n homogenous firms with identical abatement functions and abatement cost functions. Every firm faces a standard, s, above which excess emissions are penalized with a fixed fine, γ. Let a firm's measured emissions be denoted as $z = g(e) + \varepsilon$, where e is the firm's abatement effort level, $g(e)$ is the firm's abatement function such that $g'(e) < 0$ and $g''(e) \le 0$, and ε is a random error term that is independently and identically distributed across all firms with mean zero, density function $f(\varepsilon)$ and distribution function $F(\varepsilon)$Note that $g(e)$ can be regarded as the firm's intended emissions. Thus the probability that a firm with abatement effort e is found out of compliance can be written as,

$$Q(e) = \Pr(z > s) = \Pr(g(e) + \varepsilon > s) = 1 - F[s - g(e)]. \qquad (1)$$

When a firm is inspected, it also incurs a fixed cost, denoted α. The fixed cost represents the pecuniary and nonpecuniary costs borne by the firm other than the abatement costs, such as those associated with paperwork preparations for inspection.

The firm's total cost in a single period can be written as

$$\mu = c(e) + \rho[\gamma Q(e) + \alpha], \qquad (2)$$

where $c(e)$ is the abatement cost function, and ρ is the probability that the firm is inspected.

In a targeting enforcement regime, the n firms are classified into two groups, 1 and 2, where group 2 is the targeted group with tougher enforcement. To keep the model simple, I assume that the only difference in the treatment of the two groups is the probability of inspection, which is higher in group 2 than in group 1. The penalty for violation, the fixed inspection cost and the standard are the same for all firms regardless of their group status.

Let n_1 and n_2 denote group sizes, where $n_1 + n_2 = n$. In each period, a total of m ($3 \leq m < n$)[5] firms are inspected, with m_1 of them randomly selected from group 1 and m_2 from group 2. The number of inspections m is exogenously fixed by the inspection capacity. Note that $\rho_1 = m_1 / n_1$ and $\rho_2 = m_2 / n_2$ are effectively the inspection probabilities in each group. So $\rho_1 < \rho_2$ must hold for group 2 to be the targeted group. Of the $m_1 + m_2$ inspected firms, the m_1 firms with the lowest emissions in period t are placed in group 1 for period $t+1$, and the m_2 firms with the highest emissions are placed in group 2. If a firm is not inspected in a specific period, it stays in the same group.

The structure of this transition process induces rank-order tournaments among inspected firms. In a tournament, the probability that a firm wins is a function of its own effort level as well as the effort levels of other inspected firms. Even if a firm is found to be in compliance with the standard, it may nevertheless end up in group 2 in the next period if its emissions are among the m_2 highest. Similarly, a non-compliant firm may be placed in group 1 if the emission levels of other firms turn out to be higher. In equilibrium, firms in the same group should exert the same optimal effort. So the probability that an inspected firm from group i, $i = 1,2$, ends up in group 2 in the next period can be denoted as $p_i(e_i, e_{-i}, e_j)$, where e_i and e_{-i} are the effort levels of this specific firm and other firms in the same group, respectively, and e_j is the effort level of firms in the other group. As higher effort increases the probability that a firm wins in the tournament, it follows that $\partial p_i(e_i, e_{-i}, e_j) / \partial e_i < 0$.

For any firm in this regulation scheme, its decision is choosing the level of abatement effort to minimize the expected present value (EPV) of the total cost in all periods. The firm's

[5] Here m is restricted to be greater or equal to 3 because otherwise leverage between groups is impossible.

decision actually follows a Markov chain process. The transition matrix that describes the probabilities of firms moving from one group to the other is shown in Table 1 (the arguments in p_i 's are omitted).

Table 1. Markov transition matrix

	To Group	
From Group	1	2
1	$1-\rho_1 p_1$	$\rho_1 p_1$
2	$\rho_2(1-p_2)$	$1-\rho_2(1-p_2)$

Let V_{it} denote the EPV of the total cost for a firm starting from group i in period t. It follows that,

$$V_{1t} = \mu_{1t} + \delta(1-\rho_{1t} p_{1t})V_{1(t+1)} + \delta\rho_{1t} p_{1t} V_{2(t+1)}, \quad (3)$$

$$V_{2t} = \mu_{2t} + \delta\rho_{2t}(1-p_{2t})V_{1(t+1)} + \delta[1-\rho_{2t}(1-p_{2t})]V_{2(t+2)}, \quad (4)$$

where δ is the discount factor. Basically, these equations state that the EPV of the total cost for a firm is the sum of its current period cost and the discounted EPV of the total cost starting from the next period. The firm chooses the optimal effort levels to minimize V_{it}. Assuming interior solutions, the first order condition for this optimization problem is,

$$\frac{\partial \mu_i}{\partial e_i} = -\delta(V_2 - V_1)\rho_i \frac{\partial p_i}{\partial e_i}. \quad (5)$$

According to the ergodic theorem of Markov chains, the optimal strategy for a firm is stationary (Harrington, 1988; Kohlas, 1982). Therefore, the notation for time, t, is dropped from the first order condition above.

Notice that $V_2 - V_1$ is actually the cost differential between firms starting from group 1 versus group 2, and it can be solved from equations (3) and (4) to be,

$$V_2 - V_1 = \frac{\mu_2 - \mu_1}{1 - \delta\left[1 - \rho_2(1 - p_2) - \rho_1 p_1\right]} > 0.$$

In equation (5), the only negative term on the right hand side is $\partial p_i / \partial e_i$. It follows that $\partial \mu_i / \partial e_i^* > 0$, where e_i^* is a firm's optimal effort level when it is placed in group i. For a convex cost function μ_i, this implies that e_i^* is higher than the optimal effort level under static enforcement, denoted $\tilde{e}_i$, which satisfies $\partial \mu_i / \partial \tilde{e}_i = 0$. This condition reveals one of the advantages of targeting enforcement: firms in both groups have an extra incentive to increase abatement effort levels. By differentiating the EPV of the total cost in the two groups, targeting enforcement creates so-called leverage effects on a firm's emissions and abatement decisions. Firms in both groups, anticipating the threat of being in group 2 and facing the higher inspection probability in the next period, exert more effort in response than group 1 firms.

Based on the set-up of the model, it is easy to show that $e_2^* > e_1^*$ must hold. In fact, this is an expected result of targeting enforcement. When a firm is in group 2, it is at a disadvantage as the EPV of its total cost is higher than the EPV of the total cost for firms in group 1. Therefore, this firm should exert more effort to secure a higher probability of winning in the tournament. On the other hand, firms in group 1 face a lower inspection frequency and exert less effort.

Equation (5) characterizes the optimal effort level of the firms in each group, $e_i^*(m_i, n_i, \gamma, \alpha, s)$. The left-hand side of the equation is the marginal change in the current period cost. The right -hand side represents the marginal decrease in the EPV of the total cost as a higher e_i reduces the probability of being in group 2 in the next period. Even though it means incurring higher cost in the current period, a firm is nevertheless willing to exert more effort now in exchange for the expected savings as a result of decreased probability of facing tougher enforcement in the future. The optimal effort level for any firm should be the one that equates the marginal change in one-period cost to the discounted savings on the expected future cost.

B. Regulator's monitoring and enforcement strategies

Now consider a regulator who is responsible for monitoring the n firms and enforcing the standard. The potential policy instruments at his/her disposal include the inspection frequency, which is determined by the allocation of inspections, the standard and the penalty for violation.[6] However, to emphasize the structure of enforcement with fixed inspection capacity, I only consider the case in which the inspection frequency is the choice variable for the regulator.

Recall that the inspection probabilities are defined as $\rho_1 = m_1 / n_1$ and $\rho_2 = m_2 / n_2$. The regulator's objective is to optimally allocate the inspections to each group and determine the sizes of the two groups to minimize the total emissions of all firms, with the assumption that this minimum total emission level is not below the social optimal level.[7] Given that the abatement function, $g(e)$, is a decreasing function common to all firms, minimizing total emissions is equivalent to maximizing total effort. Formally, the regulator's problem is to,

$$\underset{m_i, n_i}{Max} \quad n_1 e_1^* + n_2 e_2^*$$

As mentioned previously, the traditional optimization tools—the first order conditions with respect to the choice variables—do not apply here. Since the choice variables can take integer values only, the derivatives of the objective function with respect to these variables do not exist. Analytically comparing the total effort from all possible allocations to determine the optimal enforcement strategy is not feasible due to the complexity of the firm's problem. Therefore, I briefly discuss some intuitive inferences here. In the next section I use simulations to explore the characteristics of the optimal allocation.

To simplify the exposition, I restrict attention to the case in which the number of firms in group 2 is equal to the number of inspections in that group. In other words, firms in group 2 face an inspection probability of one. This makes $n_2 = m_2$, $n_1 = n - m_2$, and $m_1 = m - m_2$. So it reduces a problem with two choice variables to a problem with one choice variable, m_2. The restriction is justified by a simulation of 4 inspections out of 10 firms. It is shown in Appendix A that an inspection probability of one in group 2 results higher total effort than any other

[6] Although the regulator may also have some influence on the fixed cost borne by the inspected firms and the variance of the error term, it is more likely that these parameters are beyond the control of the regulator.

[7] Theoretically the social optimal emission level is determined by the social benefits and social costs of emissions, which, in turn, determine the standard. Viscusi and Zeckhause (1979) and Jones (1989) address the issue of standard setting under incomplete enforcement. However, the discussion of environmental standard is beyond the scope of this paper. So I simply assume that the minimum total emissions from the optimal inspection strategy do not exceed the social optimal emission level so that the optimal leverage is desirable.

inspection probabilities of less than one in that group. The simplifying assumption is also consistent with the concept of optimal leverage to some extent. According to the comparative statics results derived in Harford (1991), increasing the inspection probability and the penalty for violation in the targeted group leads to lower emission levels from firms in both groups. As the only difference between enforcement in the two groups in this model is the frequency of inspection, a higher ρ_2 is desirable. With this restriction, the regulator chooses m_2 to maximize the total abatement effort.

Now consider a regulator allocating 10 inspections among 100 firms. To describe the trends of firm effort under different policy choices, I start with an extreme case where there is only one inspection in group 2; that is, $m_2 = n_2 = 1$, $m_1 = 9$ and $n_1 = 99$. In the tournament, nine group 1 firms and one group 2 firm are competing in period t for the chance of being placed in group 1 in period $t+1$. Basically, group 2 firms can be regarded as strong competitors as their abatement effort is high; group 1 firms are relatively weak competitors with lower abatement effort. If the regulator increases m_2 to 2, the firms in group 2 will increase their effort due to two forces. The first lies in the leverage effect. Allocating all inspections but one to group 1 results in the highest possible inspection probability in group 1 under leverage enforcement, with $\rho_1 = 0.09$. When $m_2 = 2$, the inspection probability in group 1 decreases to $\rho_1 = 0.08$, which makes the cost differential between the two groups become larger. So it is optimal for group 2 firms to abate more in order to raise their chance of winning in the tournament. The second force is a result of the competition effect. Competing with nine other group 1 firms, the only group 2 firm has a high chance of winning in the tournament. After the change in allocation, a group 2 firm has to compete with the other group 2 firm and eight group 1 firms. As a result, intensive competition drives up the effort of group 2 firms. The two forces also impose similar effects on the effort of firms in group 1. Yet the overall change in the abatement effort of group 1 firms may not necessarily increase. The reduced inspection probability in group 1 leads to a lower expected penalty for violation, which dissipates the incentive for group 1 firms to reduce emissions. Therefore, the overall change in the effort of group 1 firms is generally ambiguous.

Another extreme case is to allocate all but one inspection to group 2. This means $m_2 = n_2 = 9$, $m_1 = 1$ and $n_1 = 91$. Now the competition for being placed in group 1 in the next period is among one group 1 firm and nine group 2 firms, and only the firm with the lowest emission level wins in the tournament. If the regulator reduces m_2 to 8, two changes affect the effort levels: (1) the inspection probability in group 1 increases from 0.01 to 0.02 and the cost differential decreases with it; (2) firms in the tournament compete with one more group 1 firm and one fewer group 2 firm, and the two firms with the lowest emission levels win, so the competition becomes less intensive. For group 1 firms the smaller cost differential and less competition suggest reducing abatement effort is optimal, but the higher inspection probability induces group 1 firms to increase effort. Overall, the change in the effort of group 1 firms is ambiguous. On the other hand, group 2 firms lower abatement effort with the smaller cost differential and the reduced competition. But as a result of the interaction among firms, group 2 firms may still exert more effort in response if group 1 firms increase their effort.

In summary, assigning only one inspection in group 2 may not be optimal because reallocating one inspection from group 1 to group 2 generates more effort from firms in group 2. Although the effort of group 1 firms may decrease, with one more firm placed in group 2, it may still be optimal if the increase in the effort from group 2 firms offsets that decrement. On the other hand, increasing inspections in group 2 to the maximum may not always induce the most effort from all firms. The optimal enforcement strategy depends on the marginal changes in firm effort when the allocation changes.

C. The benchmark: static enforcement

To set a benchmark for comparison, I briefly outline a static model of enforcement. In a static model, where m of the n firms are randomly selected for inspection in each period, a representative firm chooses the optimal abatement effort to minimize its one-period cost. Specifically, a firm's problem is to,

$$\underset{e}{Min} \qquad \mu = c(e) + \frac{m}{n}\left[\gamma \; Q(e) + \alpha\right],$$

where γ, α, $c(e)$ and $Q(e)$ are defined as before. The optimal choice of effort, $\tilde{e}^*$, is determined implicitly by,

$$\frac{\partial \mu}{\partial \tilde{e}^*} = c'\left(\tilde{e}^*\right) + \frac{m}{n}\gamma\ Q'\left(\tilde{e}^*\right) = 0$$

Or

$$c'\left(\tilde{e}^*\right) + \frac{m}{n}\gamma\ Q'\left(\tilde{e}^*\right) = 0 \qquad (7)$$

III. Simulations

To characterize the optimal enforcement strategy, I use numerical techniques to show the allocations of inspections that result in the maximum total effort of all firms. First, the cost of abatement effort function is specified as $c(e) = we^2$, where w is a positive coefficient parameter; the abatement function is assumed to be linear with the form $g(e) = T - e$, wehre T is the fixed total emissions. Second, for the distribution assumptions of the error term, I consider both the normal distribution and the uniform distribution. A desirable feature of a normal distribution with mean zero is that the peak of its density function occurs at the point where the measured emissions through inspection are equal to the firm's intended emissions. To test the robustness of the model, I also analyze simulations under the assumption of uniformly distributed error terms.

For the parameters in the model, I assign the following specific numbers in the baseline examples (Table 2).

Table 2.

Total emissions, T	The standard, s	Coefficient of the abatement cost function, w	Penalty for violation, γ	Fixed inspection cost, α	Discount rate, δ
2.5	2	18	3	0.5	0.9

According to empirical statistics, the abatement costs that firms incur are fairly high compared with penalties and other sanctions.[8] Therefore, the coefficient in the abatement cost function, w, is set higher than other parameters.

A. Normally distributed errors

Assuming that the error term follows a normal distribution with mean zero and variance σ^2, I conduct four sets of simulations in this sub-section. First, I establish a baseline numerical example with a single set of parameters. By comparing the total effort of firms from all possible inspection allocations (with ρ_2 restricted to 1), I determine the optimal allocation for this specific set of parameters. Then I use the baseline parameters as a starting point and change four key parameters, s, γ, α, and σ^2. This analysis serves two purposes: (1) it is used to check if the results of optimal allocation from the first example continue to hold when parameters change; (2) it shows the effects of changing parameters on the optimal effort of individual firms and the total effort of all firms. In the third set of simulations, I increase the total number of inspections and the total number of firms being regulated. Last but not least, I fix the total number of firms and increase the number of inspections, one at a time. The last two sets of examples are used to check the robustness of the results for different inspection capacities and to characterize the pattern of the optimal inspection allocations.

In the first set of examples, I assume that the enforcement capacity for the regulator allows 4 inspections out of 10 firms. The standard deviation of the error term is set at 0.45. The equilibrium effort of firms in each group and the total effort of all firms are shown in Table 3.

Table 3. Baseline example: $m = 4$

m_2	e_1^*	e_2^*	$n_1 e_1^*$	$n_2 e_2^*$	$n_1 e_1^* + n_2 e_2^*$	ρ_1
3	0.0129	0.2317	0.0900	0.6950	0.7850	1/7
2	0.0363	0.1571	0.2906	0.3142	0.6048	1/4

[8] For example, Pollution Abatement Costs and Expenditures Survey (1999) reveals that the total abatement cost across all industries amounts to $5.8 billion. The total payment to the government, including permits/fees and charges, fines/penalties and other, is $1.0 billion according to the same survey.

1	0.0267	0.0769	0.2407	0.0769	0.3177	1/3
0	0.0166	--	0.1660	--	0.1660	4/10

Note: inconsistencies of calculation are due to rounding errors.

Several patterns can be observed in Table 3. First, the random inspection strategy without leverage (corresponding to $m_2 = 0$) induces the least total effort. Therefore targeting is superior to static enforcement. Second, if an inspection is moved from group 1 to group 2, the effort of each group 2 firm increases while the effort of group 1 firms may increase or decrease. When m_2 increases, it creates more competition among firms in both groups, because a group 1 firm is replaced by a group 2 firm in the tournament. In this example, the effort of a group 2 firm increases steadily when m_2 increases from 1 to 3. However, group 1 firms may exert less effort because the increase in m_2 lowers the inspection probability in group 1 (shown in the last column in Table 3). Thus the overall change in the effort of group 1 firms depends on the relative magnitude of two effects: increased competition and decreased inspection probability. For example, the effort of each group 1 firm increases when m_2 increases from 1 to 2 because the effect of the increased competition outweighs that of the decreased inspection probability. When m_2 increases from 2 to 3, group 1 firms lower their effort, as the effect of the decreased inspection probability dominates. Although firms in group 1 decrease their effort when m_2 increases from 2 to 3, setting $m_2 = 3$ yields the highest total effort because the increased effort by group 2 firms ($n_2 e_2$) outweighs the decreased effort by group 1 firms ($n_1 e_1$).

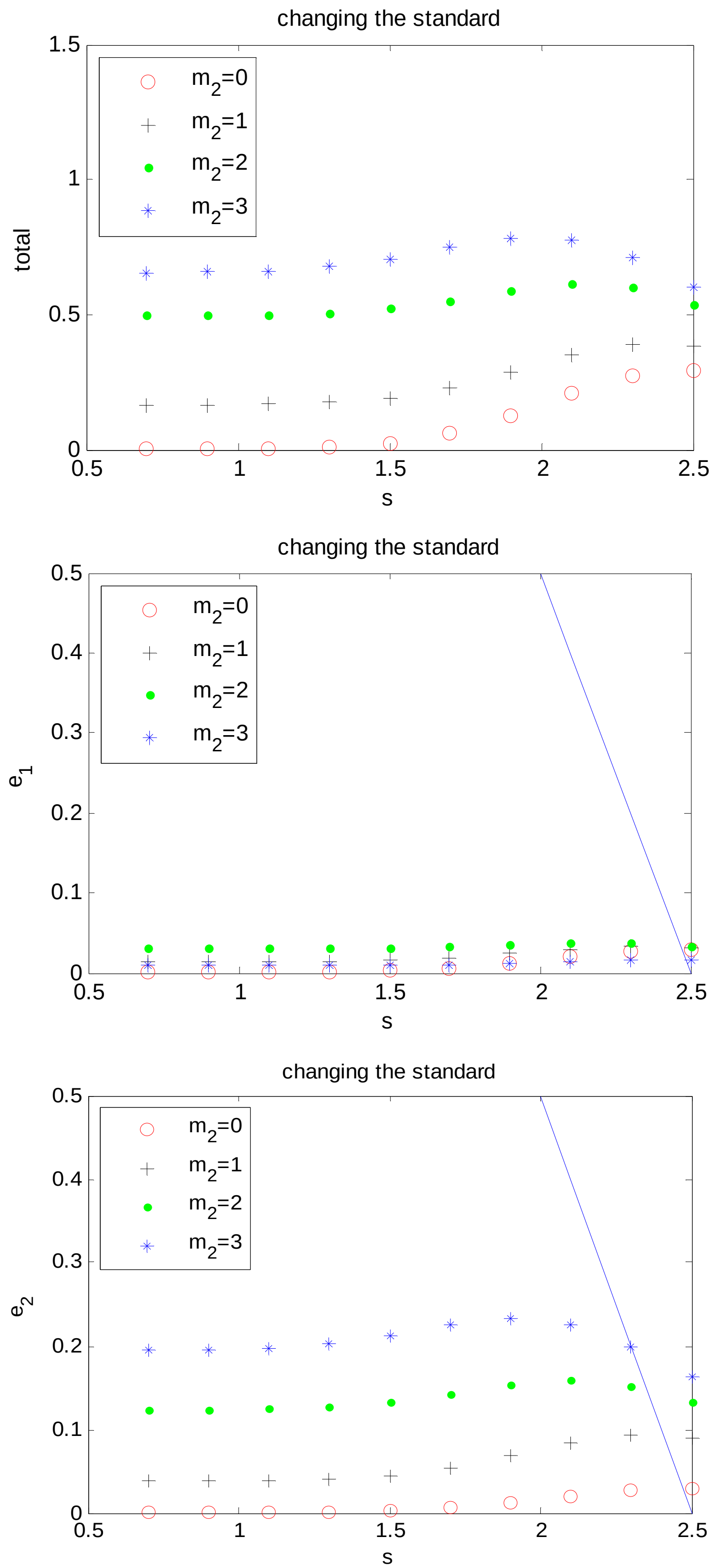
The key result from this example is that the regulator minimizes total emissions when it leverages its limited inspections by allocating most of them to the targeted group. Next, I change the four key parameters in the model, including s, γ, α, and σ^2, to test the robustness of this result.

Figures 1-4 show the results of all possible inspection allocations when s, γ, α, or σ^2 changes. Each figure consists of three graphs, showing the total effort of all firms, the effort level of individual firms in group 1 and group 2, respectively. A straight line representing the difference between T and s is added to the last two graphs in each figure. In expectation, a firm is in compliance if its effort is sufficient to eliminate the excess emissions above the standard (in the absence of random errors), which is $T-s$. Thus, effort levels above this line suggest that firms are over-complying in expectation. That is, without the random errors, a firm's intended emissions are below the standard. Similarly, effort levels below this line imply under-compliance in expectation.

Several results can be concluded from Figures 1-4. First of all, over the ranges of the four parameters, inspecting three firms in group 2 and one firm in group 1 ($m_2 = 3$) always results in the highest total effort in these examples. Therefore allocating most of the resources to monitoring firms in group 2 is an optimal enforcement strategy for the case of 4 inspections. Second, firms in group 1 exert much less effort than firms in group 2. It is an expected result of leverage since firms in group 2 face tougher enforcement. Third, the trend of the total effort is dominated by the changes in the effort of group 2 firms. This is a consequence of the previous result since the effort level of any single firm in group 2 is much higher than the effort level of every group 1 firm. Last, the total effort from the static enforcement ($m_2 = 0$) is always lower than the total effort level from targeting enforcement. Even a small leverage ($m_2 = 1$) adds incentives for firms to increase effort.

As mentioned earlier, firms are over-complying with the standard in expectation if their effort levels are above the straight line. According to the graphs in Figures 1-4, firms in group 1 almost never over-comply. Instead, they under-comply in expectation substantially. An exception is: group 1 firms over-comply when the standard is equal to a firm's actual emissions. The expected compliance status of firms in group 2 depends on the magnitude of the parameters. Specifically, firms in group 2 tend to over-comply in expectation when the penalty for violation and the fixed inspection cost are high, as a higher penalty or inspection cost induces more effort. The firms in group 2 also over-comply when the standard is high. Notice that when the standard is equal to a firm's actual emissions, firms in both groups over-comply despite that the expected penalty is zero. These over-complying behaviors of firms are driven by their intention to avoid or reduce the expected inspection costs.

Figure 1



changing the standard
total
s
m_2=0
m_2=1
m_2=2
m_2=3
changing the standard
e_1
s
m_2=0
m_2=1
m_2=2
m_2=3
changing the standard
e_2
s
m_2=0
m_2=1
m_2=2
m_2=3

Figure 2

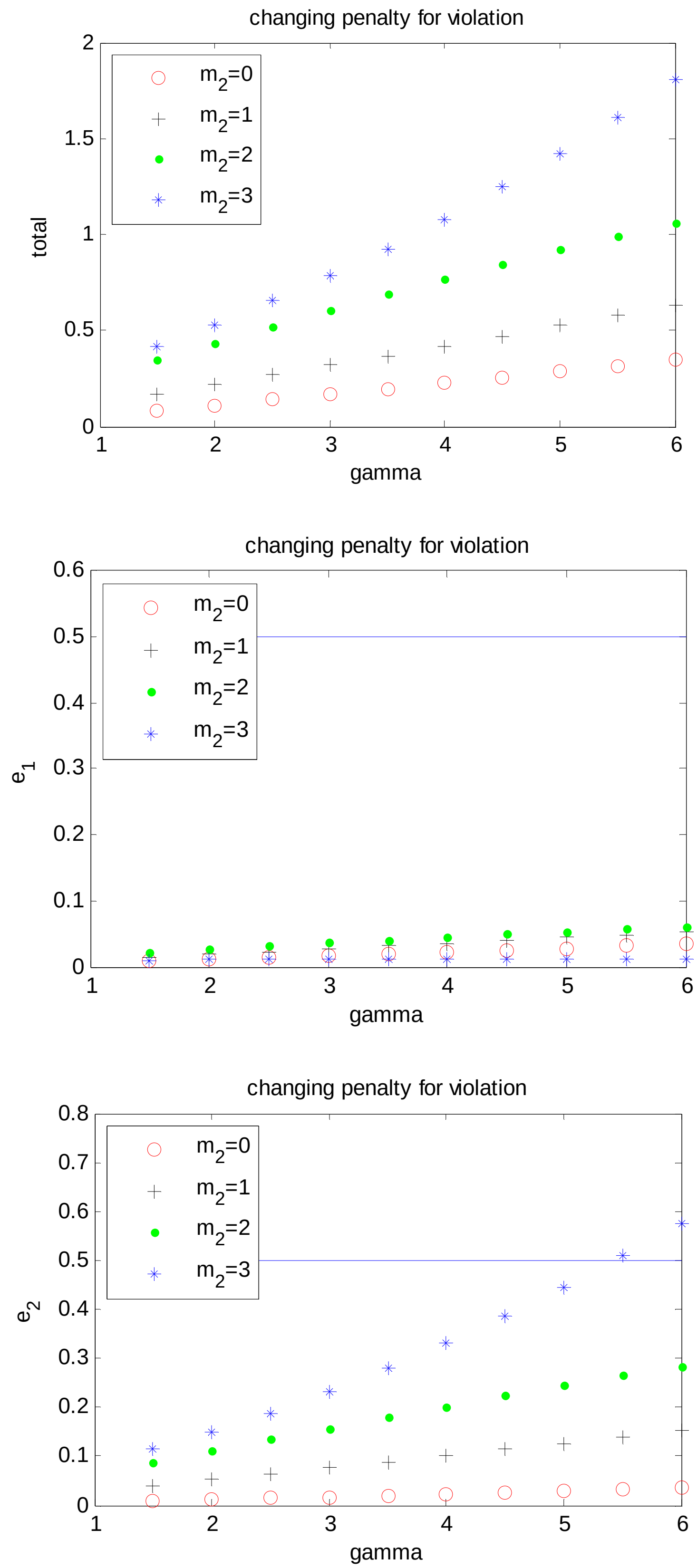

changing penalty for violation
total
gamma
m2=0
m2=1
m2=2
m2=3
2
1.5
1
0.5
0
1
2
3
4
5
6
changing penalty for violation
e1
gamma
m2=0
m2=1
m2=2
m2=3
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
changing penalty for violation
e2
gamma
m2=0
m2=1
m2=2
m2=3
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6

Figure 3

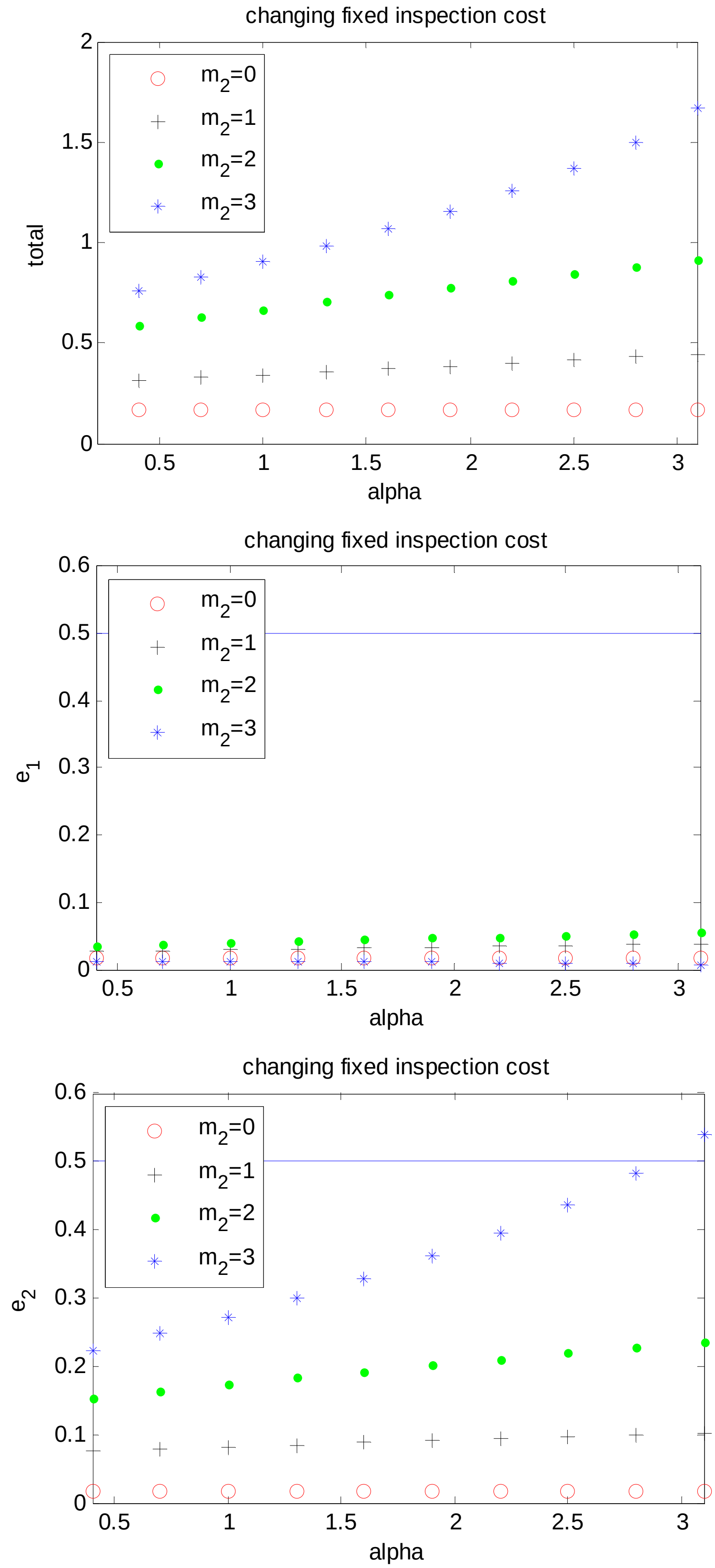
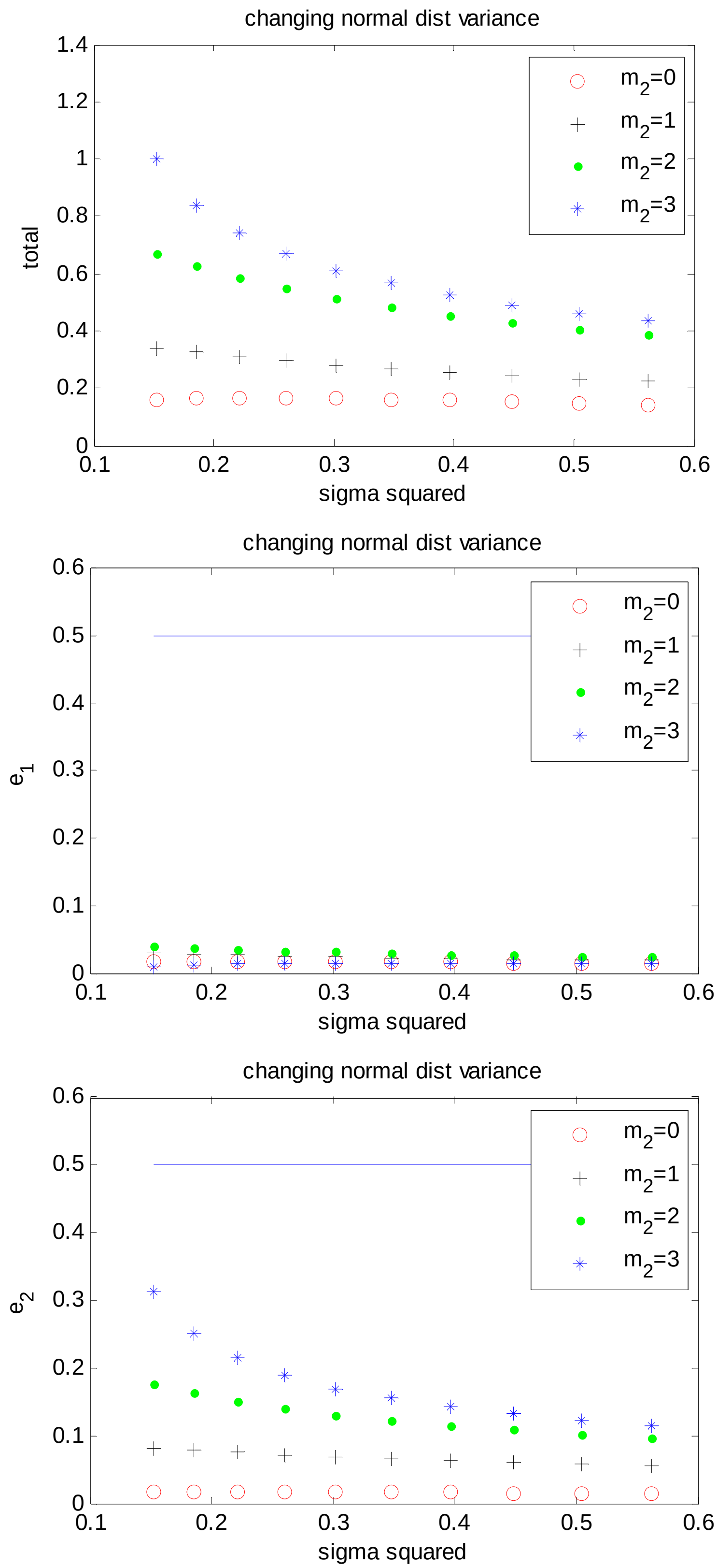

changing fixed inspection cost
total
alpha
m2=0
m2=1
m2=2
m2=3
changing fixed inspection cost
e1
alpha
m2=0
m2=1
m2=2
m2=3
changing fixed inspection cost
e2
alpha
m2=0
m2=1
m2=2
m2=3

Figure 4


changing normal dist variance
total
sigma squared
m2=0
m2=1
m2=2
m2=3
changing normal dist variance
e1
sigma squared
m2=0
m2=1
m2=2
m2=3
changing normal dist variance
e2
sigma squared
m2=0
m2=1
m2=2
m2=3

The numeric examples shown in Figures 1-4 also describe the trends in the effort of individual firms when the parameters changes. Overall, the effort of firms in group 2 is more responsive to the changes in parameters, according to the shapes of the curves. The four key parameters, s, γ, α, and σ^2, are related to the inspection probability: the higher the probability, the more likely that a firm incurs sanctions or inspection costs and the more likely that a firm is involved in the tournament. Since firms in group 2 are inspected in every period, changes in these parameters have more effect on their choices of effort.

In Figure 1, the effort of group 1 firms increases with s, and the effort of group 2 firms originally increases with s and then decreases when s approaches a firm's total emissions, T. Although one would expect that relaxing the standard leads to a lower effort level in general, in this model the changes in a firm's effort actually depend on the distribution of the error term, the firm's expected compliance status, and the effect of the standard on $V_2 - V_1$. Under the assumption of a normally distributed error term with mean zero, the derivative of the marginal probability of violation, $Q''(e_i^*) = f'[s - g(e_i^*)]$, is positive if $s - g(e_i^*)$ is below zero. This implies when the firm's intended emissions, $g(e_i^*)$, exceed the standard, relaxing the standard makes the probability of violation decrease at an increasing rate with more effort. So firms are willing to exert more effort to take the advantage of the decreased expected penalty. If a firm's expected emissions are below the standard, increasing the allowed emissions only results in lower effort, because exerting more effort reduces the probability of a violation at a decreasing rate. The changes in the standard affect the cost differential, $V_2 - V_1$, through the one period cost μ_i. When the standard is relaxed, μ_i declines for firms in both groups since the probability of violation, $Q(e_i^*)$, decreases. However, it is more likely that μ_2 declines fast than μ_1 because $Q(e_i^*)$ is multiplied by the inspection probability, which is higher in group 2. Thus the cost differential between the two groups decreases when the standard is relaxed and firms in both group reduce effort.

Figures 2-4 show that γ and α are positively related to the effort level while σ^2 exhibits a negative relationship with the effort level. First, γ represents sanctions on a firm's violation of the standard, no matter to which group the firm belongs. As γ increases, the expected penalty for any given level of effort is higher. With an unchanged cost of abatement effort function, the firm should increase effort to eliminate the increase in the expected penalty caused by the higher γ. Meanwhile, changing γ also affects $V_2 - V_1$. If the cost differential increases with higher γ, firms in both groups increase effort. Next, whether a firm incurs the fixed inspection cost, α, depends on the probability that the firm is inspected. With unchanged inspection probabilities, increasing α effectively magnifies the leverage of targeting because the cost differential between the two groups becomes larger. Thus the benefits of staying in group 1 are more significant and firms in both groups increase their optimal abatement effort. Third, although the variance of the error term is not explicitly involved in the equations, the intuition is straightforward. According to the tournament literature, when the randomness associated with the measurement of players' performance is small, the players tend to exert more effort. Similarly, a smaller variance means that a firm's intended emissions, $g(e_i^*)$, are more accurately measured. As a result, the firm increases its effort.

Those previous sets of simulations show that allocating more inspections to the targeted group is optimal. For an inspection capacity with $m = 4$, the optimal allocation is $m_2 = 3$. The three inspections allocated to group 2 can be interpreted as $1 + m/2$, $3m/4$, or $m - 1$. The simple example of 4 inspections does not provide sufficient information to draw a conclusion whether the optimal number of inspections in group 2 should be around $m/2$, $3m/4$ or $m-1$ for higher values of m. In the next set of simulations, I address this issue and check the consistency of other relevant results in the previous analysis as well. It is assumed that 10 out of 100 firms are inspected in each period. The standard deviation of the error term is set at 0.8 to ensure the existence of solutions.[9] Under these assumptions, I first set the baseline for the example of 10 inspections and then change the four enforcement parameters, s, γ, α, and σ^2.

The optimal effort of individual firms and the total effort in the baseline example are shown in Table 4. As m_2 increases, e_1^* increases gradually until $m_2 = 5$, after which e_1^* begins to fall. Similarly, e_2^* and the total effort both increase with m_2 until m_2 reaches 7, then e_2^* and the total effort decrease. The intuition behind these patterns is similar to that in the example with 4 inspections. Focusing on the total effort, it is clear that allocating $m - 1 = 9$ inspections to

[9] The existence of solutions requires that the variance is sufficiently large. See Lazear and Rosen (1981), footnote 2, p. 845.

group 2 is not optimal. The optimal allocation is $m_2 = 7$, which is between $m/2$ and $3m/4$. Also, consistent with the previous results, the random inspection strategy without leverage results in the lowest total effort.

To present the patterns of firm effort with the changes in allocation, the same baseline results are shown in Figure 5. In comparison, the effort levels of group 1 firms are extremely low and firms in group 2 exert much higher effort, especially when 6 or 7 inspections are allocated to that group. Consequently, the changes in the total effort are closely related to the changes in the effort of group 2 firms.

Table 4. Baseline example: $m = 10$

m_2	e_1^*	e_2^*	$n_1 e_1^*$	$n_2 e_2^*$	$n_1 e_1^* + n_2 e_2^*$
9	0.0005	0.0462	0.0413	0.4158	0.4572
8	0.0015	0.1160	0.1390	0.9280	1.0668
7	0.0030	**0.2774**	0.2790	**1.9418**	**2.2207**
6	0.0063	0.2465	0.5906	1.4790	2.0696
5	**0.0084**	0.1623	**0.7933**	0.8115	1.6046
4	0.0072	0.1021	0.6951	0.4084	1.1034
3	0.0050	0.0627	0.4851	0.1881	0.6732
2	0.0035	0.0423	0.3477	0.0846	0.4324
1	0.0031	0.0359	0.3106	0.0359	0.3465
0	0.0034	--	0.3428	--	0.3428

Notes: 1. inconsistencies of calculation are due to rounding errors;
2. bold numbers indicate the maximum within each column.

Next, I change the enforcement parameters in the example of 10 inspections to examine the consistency of the optimal allocations and the effects on the effort of individual firms. Figure 6 shows the total effort associated with the optimal inspection allocations when s, γ, α, or σ^2 change. The effort levels of individual firms in each group are shown in Appendix B.

Figure 5

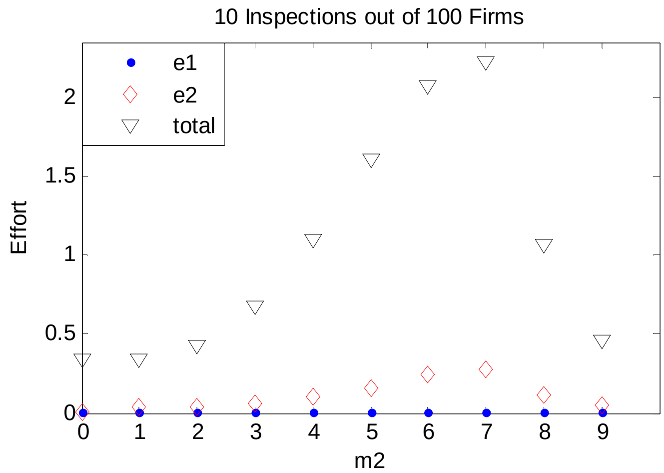
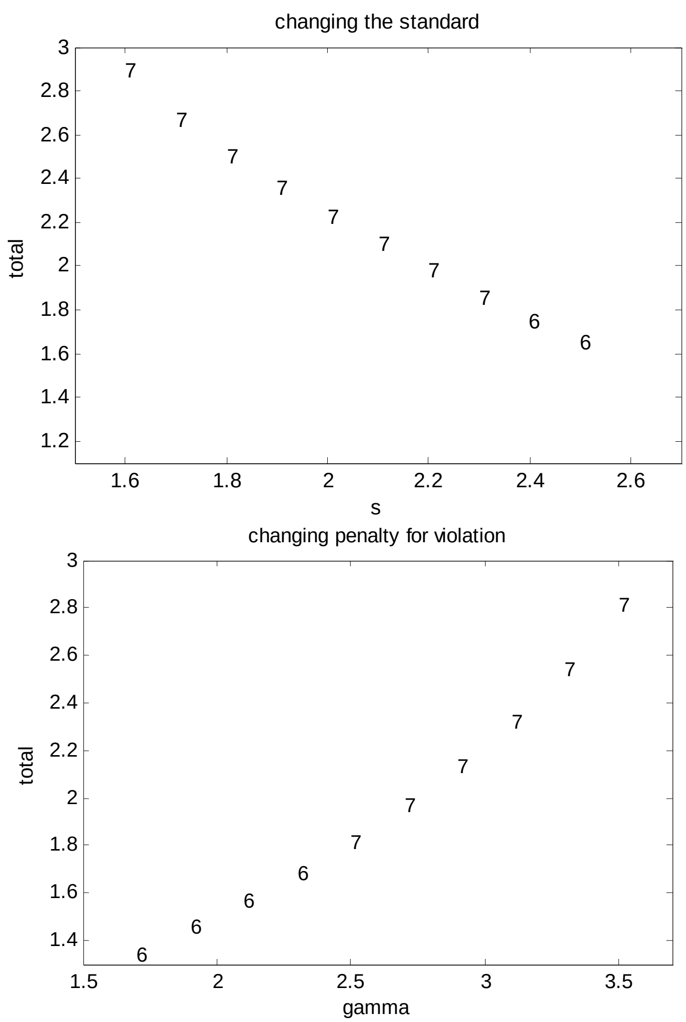
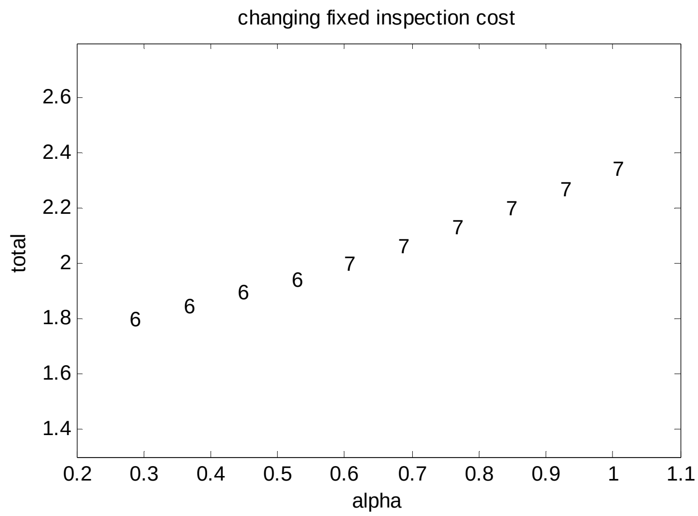
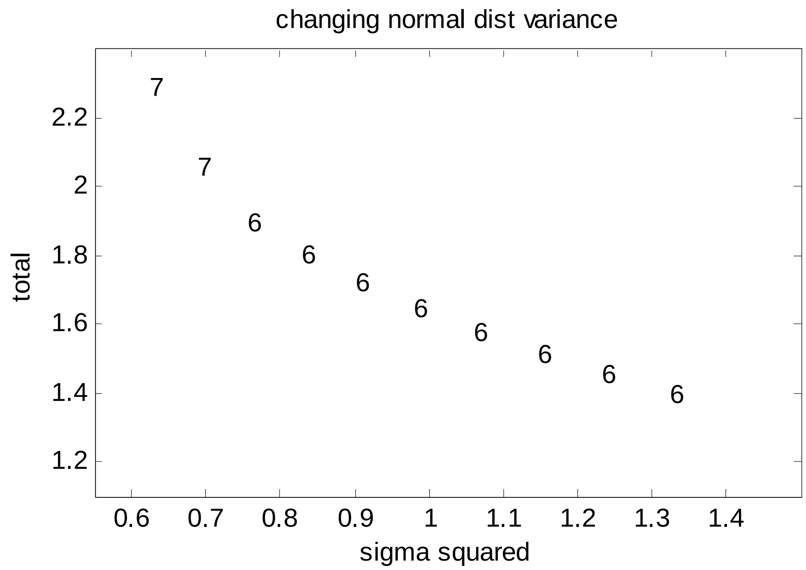


Figure 6.







When the enforcement parameters change, the optimal allocation is 6 or 7 inspections in group 2, depending on the magnitude of the parameters. Inspecting 7 firms in group 2 is optimal for higher γ and α, or lower s and σ^2 (the numbers in the graphs indicate the optimal number of inspections in group 2); otherwise, allocating 6 inspections to group 2 is optimal. The shifts in the effort of group 1 firms in the graphs of s, γ, α and σ^2 (Appendix B) reflect this change in the optimal inspection allocation.

The relationships between the total effort and the four parameters s, γ, α, and σ^2 presented in Figure 7 confirm the results from the first set of examples. While increasing s and σ^2 reduces total effort, higher γ and α induce more total effort. Other similar results include: (1) the optimal effort of firms in group 1 is substantially lower than that of firms in group 2; (2) the shape of the total effort curve is closely related to the shape of the effort curve of the group 2 firms.

According to the numerical analyses of 4 inspections and 10 inspections, the optimal number of inspections in group 2 seems to lie between $m/2$ and $3m/4$. To further confirm this conclusion, it is worthwhile examining the optimal inspection allocations when the number of total inspections takes other integer values between 4 and 10, while holding the total number of firms constant. The next set of examples fulfills this purpose.

In the last set of examples, the total number of firms is fixed at 25, 50, and 100, respectively, and the number of inspections is increased from 4 to 10. The standard deviation of the error term is still 0.8. Detailed results are shown in Tables 5-7. The comparison among the bold numbers within each table (which represent the total effort from the optimal allocation in each row) reveals that increasing the number of inspections induces more total effort from the optimal enforcement when the total number of firms is held constant. So the extra inspection capacity is desirable for the regulator. Also, allocating more inspections to group 2 remains to be optimal. When the total number of inspections is small, inspecting only one firm in group 1 and putting all other inspections in group 2 results in the maximum total effort. Yet, it is not always optimal to allocate this extra inspection to group 2 when extra budget allows one more inspection. Whether the regulator should put the extra inspection in group 1 or 2 depends on the marginal change in the effort of firms in each group ($n_i e_i^*$). For example, with 7 inspections out of 25 firms, the optimal allocation is $m_2 = 6$, and the effort levels of firms in group 1 and 2 are 0.0014 and 0.0854, respectively. When the number of inspections increases to 8, the effort levels of firms in group 1 and group 2 decrease by 0.0002 and by 0.02, respectively, if the regulator still allocate all but one inspection in group 2. In comparison, for the allocation $m_2 = 6$ with 8 total number of inspections, the effort levels of firms in group 1 and 2 increase to 0.0042 and 0.1712, respectively. Thus inspecting 2 firms in group 1 and 6 firms in group 2 is optimal for a total of 8 inspections. Overall, this set of examples confirm that the optimal number of inspections in group 2 should lie between $m/2$ and $3m/4$.

Table 5. $n = 25$

	Number of inspections in group 2								
Total number of inspections	1	2	3	4	5	6	7	8	9
4	0.2345	0.4383	**0.5356**						
5	0.2454	0.4542	**0.6727**	0.5970					
6	0.2606	0.4450	0.7191	**0.8735**	0.5696				
7	0.2653	0.4273	0.7288	0.8588	**0.9772**	0.5117			
8	0.2972	0.4123	0.7338	0.4206	**1.1813**	0.9468	0.4613		
9	0.3237	0.4055	0.6269	0.9602	1.2481	**1.2753**	1.2408	0.4314	
10	0.3480	0.4087	0.584	0.8986	1.2428	**1.4297**	1.2408	0.7361	0.4218

Table 6. $n = 50$

	Number of inspections in group 2								
Total number of inspections	1	2	3	4	5	6	7	8	9
4	0.2420	0.4627	**0.5832**						
5	0.2528	0.4822	**0.7339**	0.6694					
6	0.2656	0.4743	0.7874	**1.0062**	0.6455				
7	0.2686	0.4555	0.8039	1.0597	**1.2021**	0.5764			
8	0.3006	0.4373	0.8254	0.4377	**1.4409**	1.2122	0.5105		
9	0.3256	0.4263	0.6949	1.1030	1.4976	1.6951	**1.7722**	0.4663	
10	0.3470	0.4248	0.6450	1.0394	1.4907	**1.8439**	1.7722	0.9389	0.4454

Table 7. $n = 100$

	Number of inspections in group 2								
Total number of inspections	1	2	3	4	5	6	7	8	9
4	0.2457	0.4747	**0.6082**						
5	0.2564	0.4957	**0.7645**	0.7087					
6	0.2681	0.4883	0.8203	**1.0782**	0.6866				
7	0.2701	0.4689	0.8394	1.1593	**1.3413**	0.6110			
8	0.3023	0.4492	0.8695	0.4451	**1.5842**	1.3862	0.5363		
9	0.3266	0.4361	0.7264	1.1688	1.6193	1.9827	**2.2207**	0.4842	
10	0.3465	0.4324	0.6732	1.1034	1.6046	2.0696	**2.2207**	1.0668	0.4572

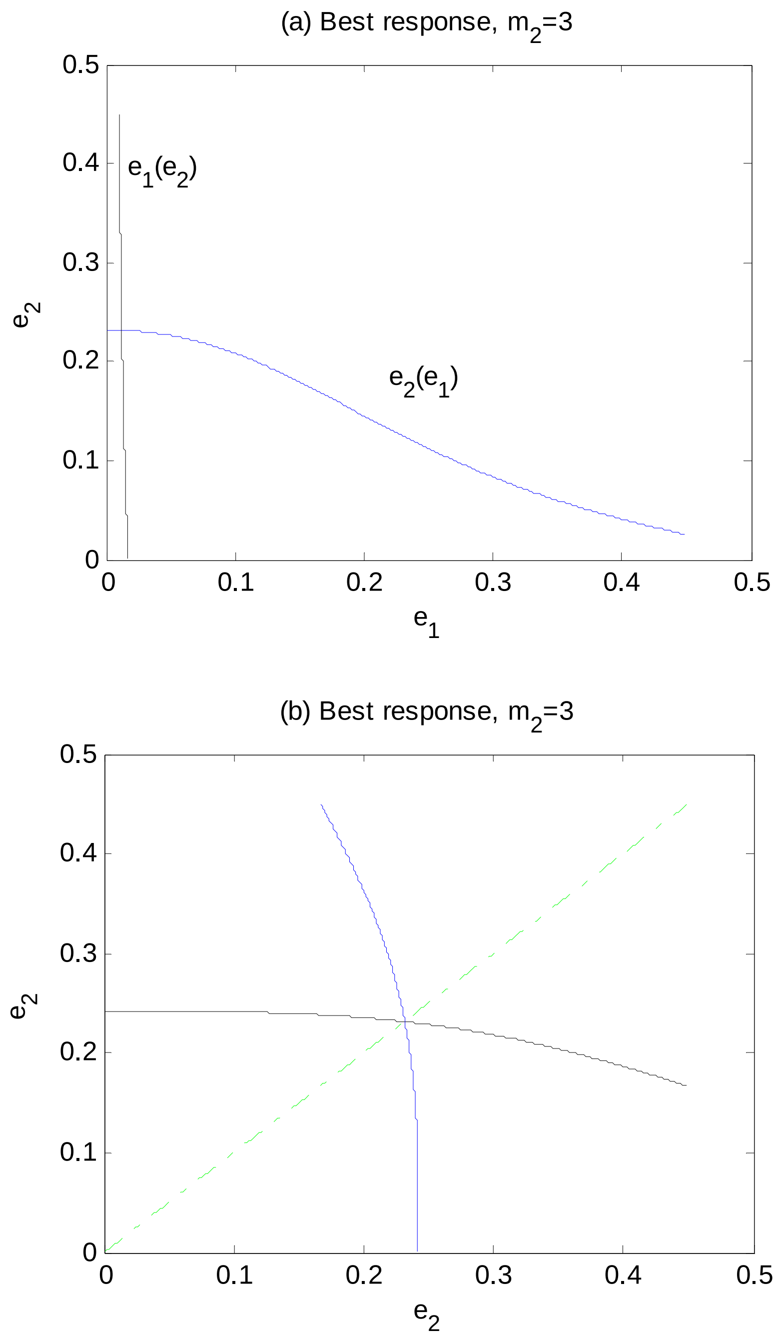
Note: bold numbers represent the total effort from the optimal allocations

B. Firms' Best Responses

In the theoretical model developed in this paper, the inspected firms compete with each other in tournaments. The interactions among firms can be summarized using best response curves, which describe one firm's best response to the changes in the effort of another firm. In this section, I discuss the best response curves for the optimal allocation, $m_2 = 3$, when there are 4 inspections.

Figure 7 shows: (1) the best response between the only group 1 firm and one of the group 2 firms while holding the other two group 2 firms' effort at their equilibrium levels; (2) the best response between two group 2 firms while holding the group 1 firm and the third group 2 firm at their respective equilibrium levels.

Figure 7.



In Figure 7 (a), the best response curve of the group 1 firm is fairly flat with a slightly decreasing trend, indicating that the changes in the effort of one group 2 firm have little impact on the group 1 firm. The best response curve of the group 2 firm exhibits an apparent decreasing trend, except at the beginning where the curve is almost flat. Since the effort of the other two group 2 firms is fixed at their equilibrium levels, the intersection of the two curves represents the equilibrium effort levels of the group 1 firm and the group 2 firm in this numerical example. Around the equilibrium point, the effort of the group 1 firm decreases with that of the group 2 firm, and vice versa. The best response curves of the two group 2 firms, shown in Figure 7 (b), are symmetric with the same pattern: increasing at the beginning and then decreasing. The intersection of the two curves is the equilibrium effort level of the group 2 firms, around which the effort of one group 2 firm decreases with that of the other group 2 firm.

C. Uniformly distributed errors

In this section, I test the robustness of the results in Section III (A) using uniformly distributed errors on the support [-0.5, 0.5]. Following the first set of examples in Section III (A), it is assumed that the inspection capacity allows 4 inspections out of 10 firms. The effort levels in the baseline treatment are listed in Table 8. The basic results from the normal distribution assumption are confirmed: among all possible allocations (with ρ_2 restricted to 1), $m_2 = 3$ is the optimal enforcement strategy; the static enforcement induces the least total effort; the trends in the effort of individual firms when m_2 increases from 1 to 3 can be explained by the same intuition discussed in the previous sub-section.

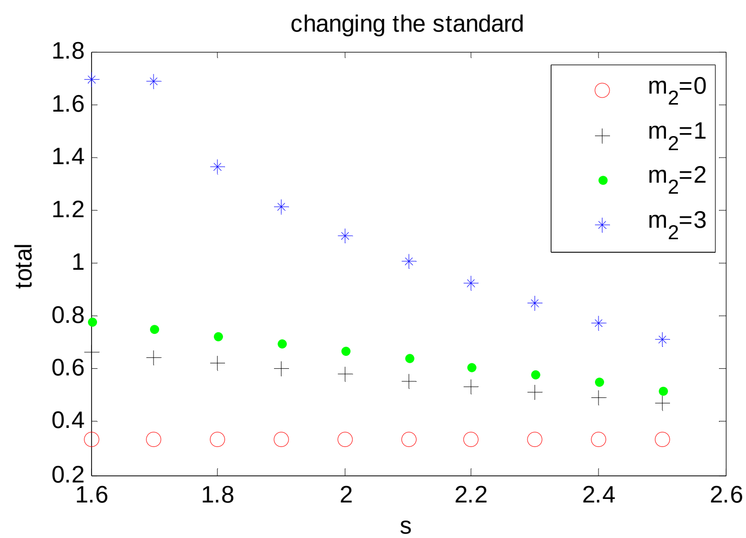
Table 8. Baseline example: $m = 4$

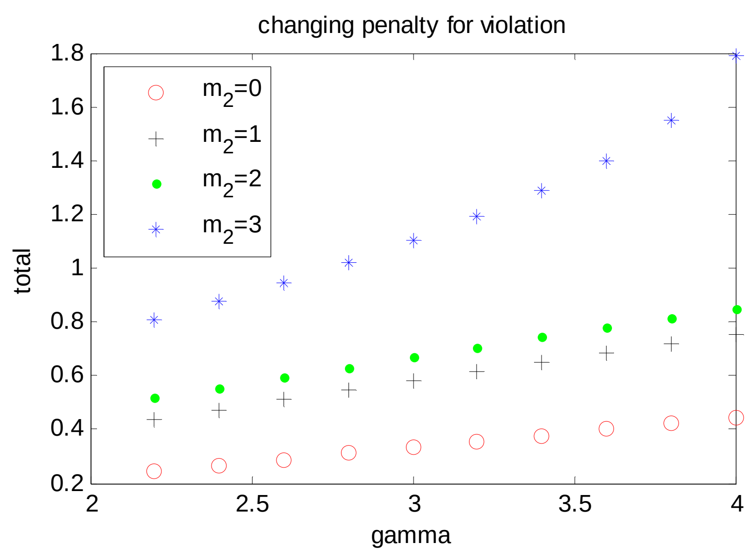
m_2	e_1	e_2	n_1e_1	n_2e_2	$n_1e_1 + n_2e_2$
3	0.0216	0.3173	0.1511	0.9518	1.1029
2	0.0418	0.1674	0.3348	0.3348	0.6696
1	0.0498	0.1308	0.4481	0.1308	0.5788
0	0.0333	--	0.3333	--	0.3333

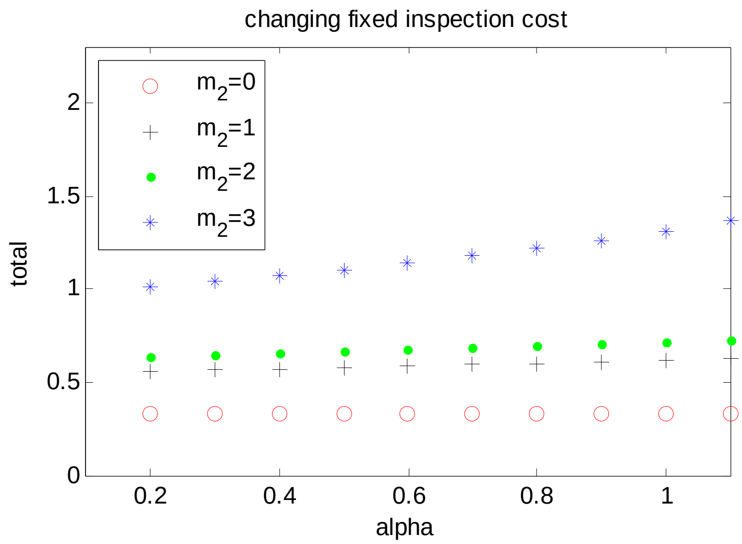
Note: inconsistencies of calculation are due to rounding errors.

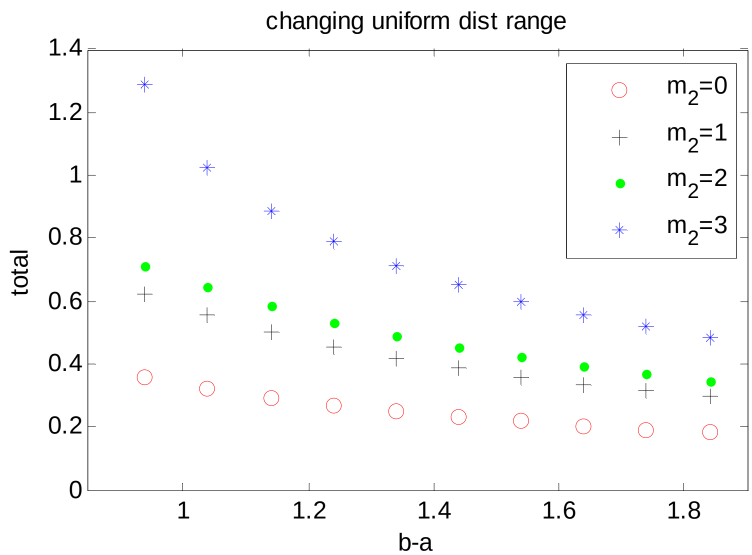
Figure 8 shows the total effort from all possible allocations when the enforcement parameters change. The results under the assumption of normally distributed errors are largely confirmed by the examples with uniformly distributed errors. Over the ranges of the parameters considered in the analysis, assigning three inspections to group 2 is generally optimal and static enforcement leads to the least total effort. Results regarding effort of individual firms (shown in Appendix C) also agree with the corresponding results from the examples with normally distributed errors: the effort of group 1 firms is always much lower than that of group 2 firms; firms in group 1 almost never over-comply in expectation while firms in group 2 over-comply in expectation with higher s, γ or α.

Figure 8.









IV Conclusion

In environmental regulations, optimally allocating limited enforcement resources is crucial for effective pollution controls. In this paper, I develop a model of monitoring and enforcement with an environmental standard when a regulator faces fixed inspection capacity.

Based on the theoretical analysis, I characterize the optimal allocation of a fixed number of inspections with the aid of simulations. The major conclusion is that a regulator facing fixed inspection capacity should leverage the limited inspections by allocating more inspections to the targeted group. The optimal number of inspections in the targeted group usually lies between $m/2$ and $3m/4$, where m is the number of inspections fixed by the inspection capacity. The numerical examples also confirm the superiority of leveraged enforcement such that static enforcement induces the least total effort from all firms. These results are robust to the distribution assumptions of the error term, and to different ranges of enforcement parameters, such as the number of inspections, the penalty for violations, the fixed inspection cost, and the standard.

The model presented in this paper is based on the assumption that a regulator faces fixed inspection capacity in every period. How restrictive the inspection capacity is depends on the time horizon one considers. From a short-run perspective, the enforcement budget and the inspection personnel for a regulator are unlikely to change. The effectiveness of the enforcement is confined by the limited number of inspections. In the long-run, the regulator may be able to adjust the budget or inspection staff according to actual firm behaviors.

This model can be extended in several directions in future work. For simplification purposes, I have assumed that the penalty for violation and the standard are constant across firms. One possible modification to the model is to set such parameters at different levels for the two groups. Harford (1991) points out that differentiating the standard, in addition to the inspection probabilities across groups, may be optimal. Furthermore, it is assumed that firms are homogeneous in this model. In the real world, a regulator may face the task of monitoring firms with different abatement costs. Raymond (1999) points out that with asymmetric information or firm heterogeneity, the optimal regulatory policy depends on the distribution of costs among firms. Adding firm heterogeneity will complicate the model, but it may provide further insights.

Like other targeting enforcement models, the model developed in this paper is subject to critiques. For instance, a direct result of the targeting regulation is the different abatement effort and emission levels from homogenous firms. Hence, the marginal abatement costs are not equal across firms, which violates the condition for minimizing the social costs of emission controls (Harford and Harrrington, 1991).

Appendix

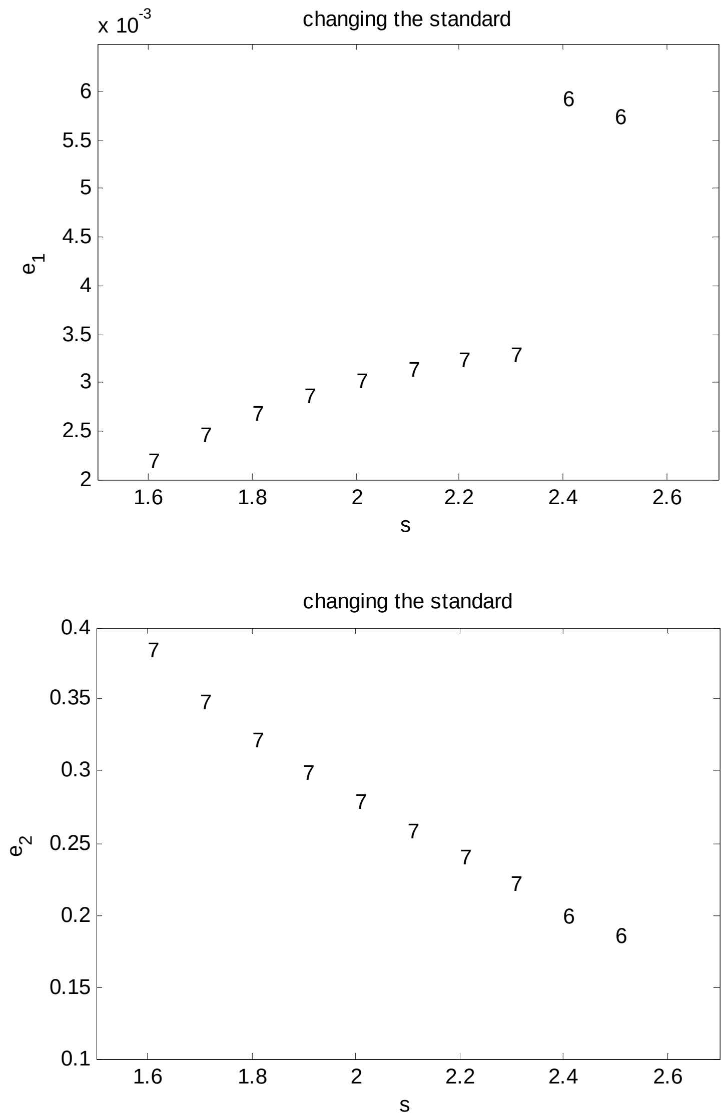
A. Simulation results of all possible allocations: 4 inspections out of 10 firms.

	$m_1 = 1,\ m_2 = 3$			$m_1 = 2,\ m_2 = 2$			$m_1 = 3,\ m_2 = 1$		
n_1	Total efforts	ρ_1	ρ_2	Total efforts	ρ_1	ρ_2	Total efforts	ρ_1	ρ_2
3	0.1880	1/3	3/7	--	2/3	2/7	--	1	1/7
4	0.2330	1/4	1/2	--	1/2	1/3	--	3/4	1/6
5	0.2928	1/5	3/5	--	2/5	2/5	--	3/5	1/5
6	0.4028	1/6	3/4	0.2426	1/3	1/2	--	1/2	1/4
7	0.7850	1/7	1	0.3600	2/7	2/3	--	3/7	1/3
8	--	--	--	0.6048	1/4	1	0.1930	3/8	1/2
9	--	--	--	--	--	--	0.3177	1/3	1

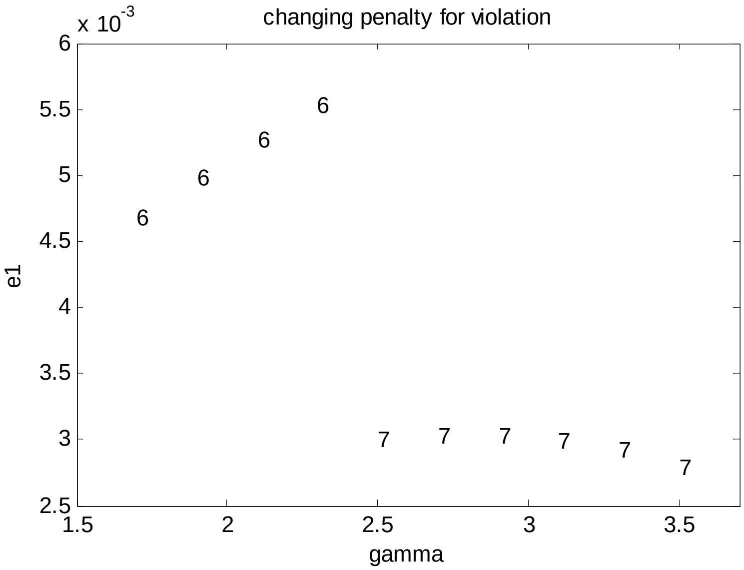
Notice that the inspection probability in group 1 should be less than the inspection probability in group 2 for targeting enforcement to be effective. Thus the number of firms in group 1 can only take certain numbers. Under each inspection and firm allocation, as the number of firms allocated in group 1 increases, the total effort increases continuously and reaches the maximum when the inspection probability in group 2 becomes one.

B. Effort of individual firms in group 1 and 2 when there are 10 inspections out of 50 firms. (The numbers in the graphs indicate the optimal number of inspections in group 2)

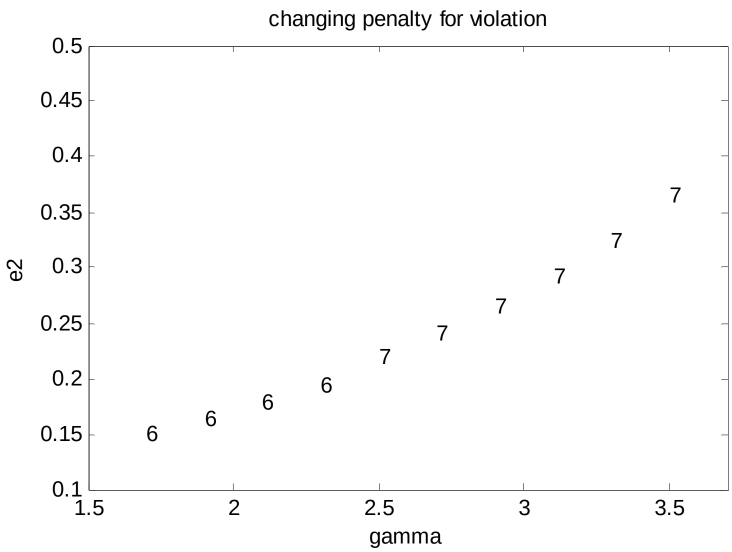
(a)



(b)

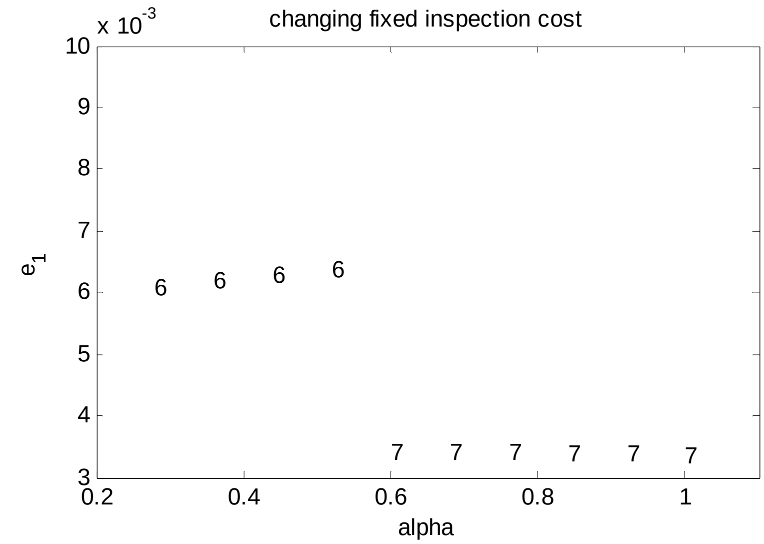


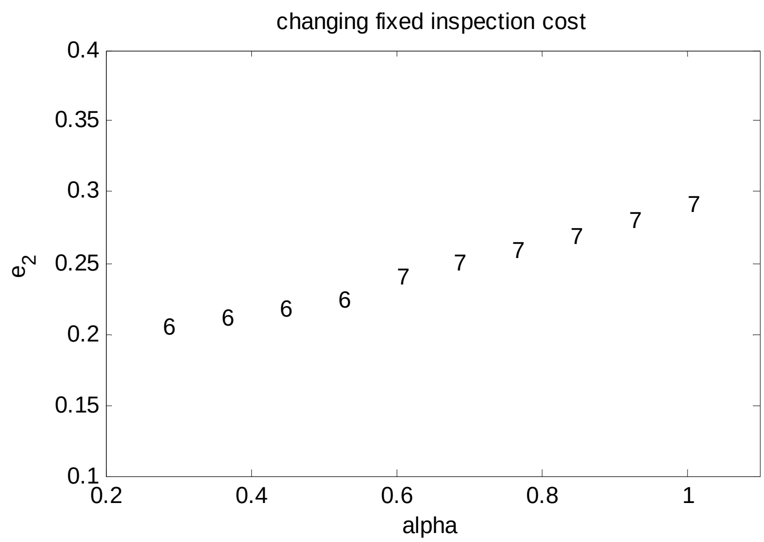
changing penalty for violation
x 10^-3
e1
gamma



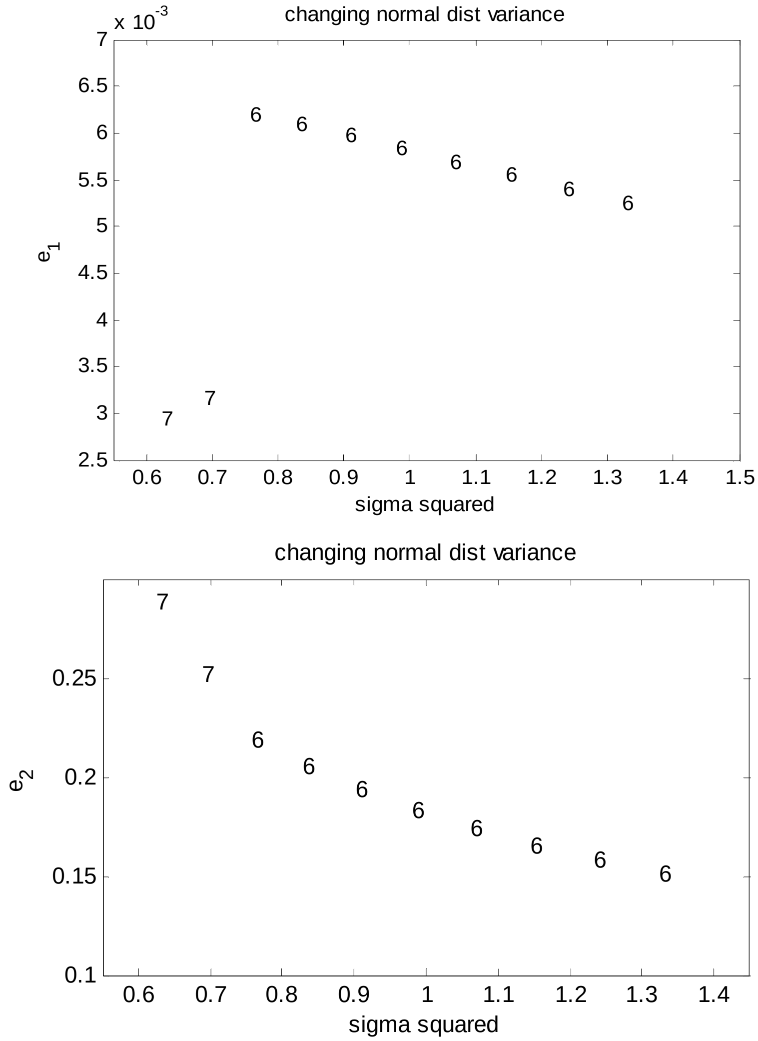
changing penalty for violation
e2
gamma

(c)


changing fixed inspection cost
x 10^-3
10
9
8
7
6
5
4
3
e_1
6
6
6
6
7
7
7
7
7
7
0.2
0.4
0.6
0.8
1
alpha


changing fixed inspection cost
0.4
0.35
0.3
0.25
0.2
0.15
0.1
e_2
6
6
6
6
7
7
7
7
7
7
0.2
0.4
0.6
0.8
1
alpha

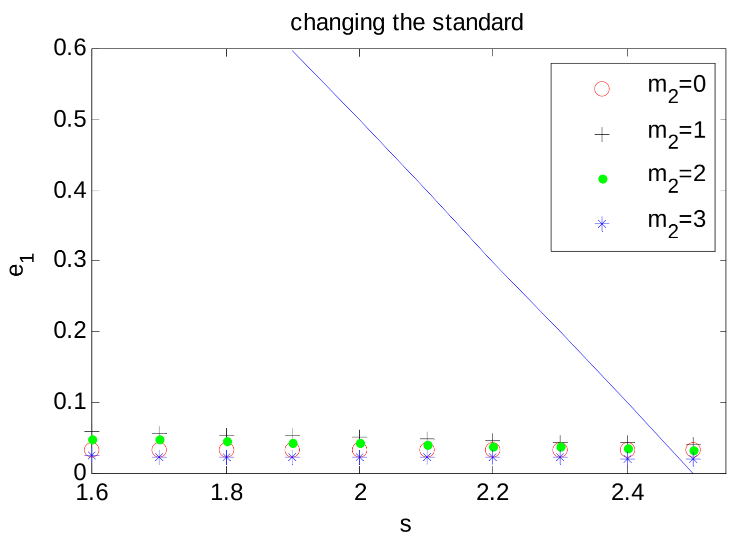
(d)

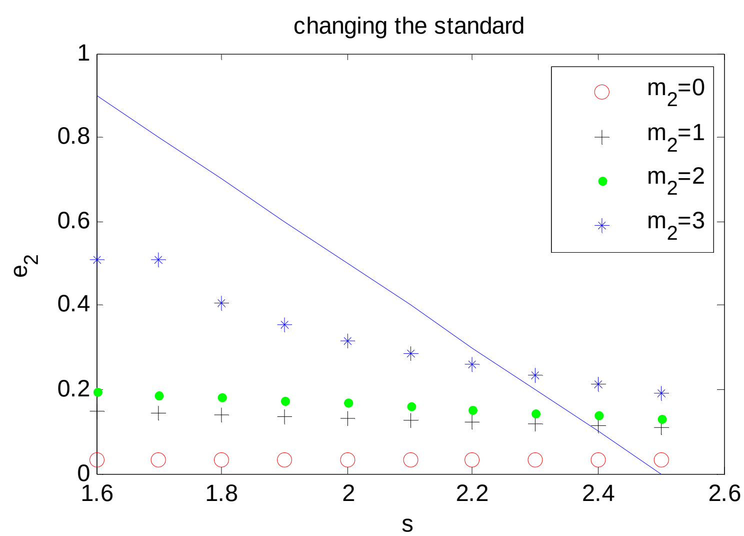


Note that when $\gamma \geq 2.5$ or $\alpha \geq 0.6$, the effort level of group 1 firms slightly decreases with these two parameters. In a static enforcement regime, increasing the penalty for violation or the fixed inspection cost should result in firms increasing their abatement effort. However, in this dynamic model where firms interact with each other, the changes in the effort of one firm also reflect its best response to that of other firms. Here the decrease in the effort of group 1 firms may suggest that those firms responds to the increased effort of group 2 firms by exerting less effort, and this reduction outweighs the increase in the effort of the group 1 firms due to the direct effect of higher sanctions. Similar intuition can be used to explain the result that group 1 firms exert more effort with higher variance when $\sigma^2 \leq 0.7$.

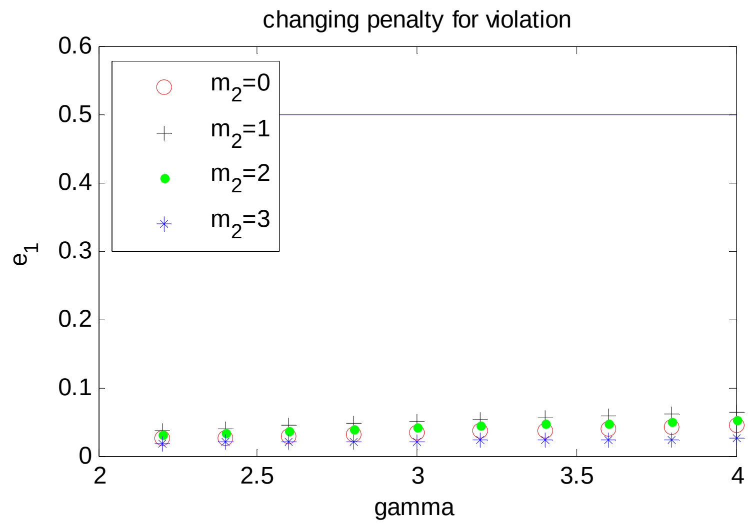
C. Effort of firms in group 1 and 2 under uniformly distributed error terms

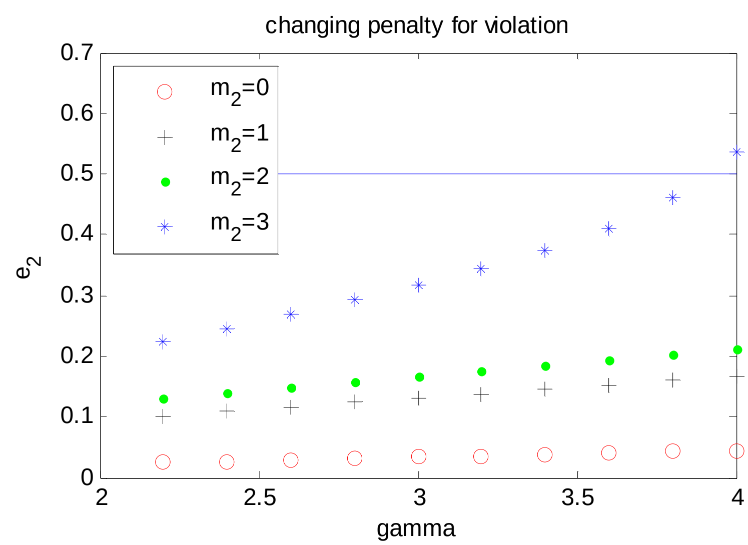
(a)



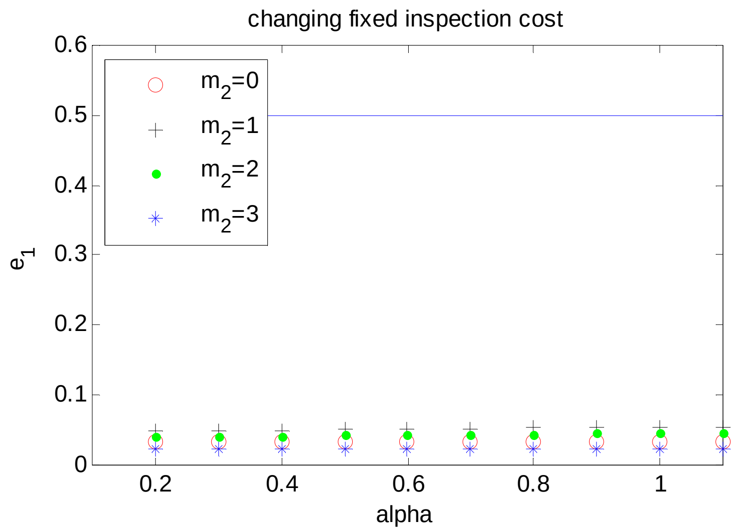


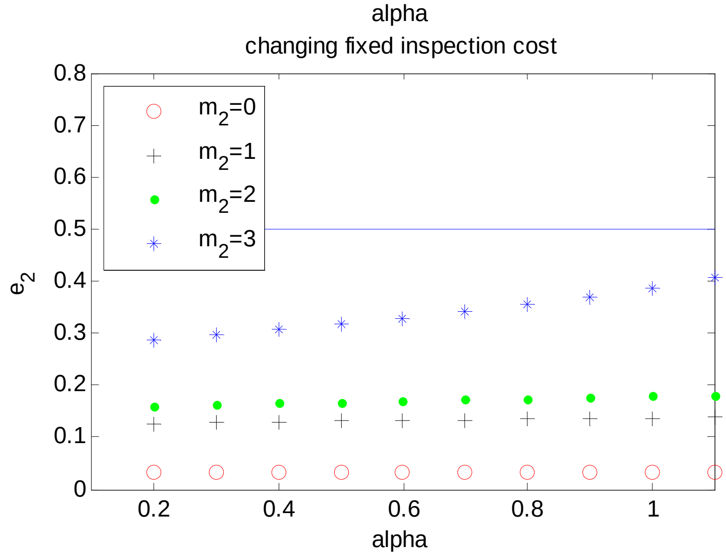
(b)


changing penalty for violation
0.6
0.5
0.4
0.3
0.2
0.1
0
2
2.5
3
3.5
4
gamma
e1
m2=0
m2=1
m2=2
m2=3

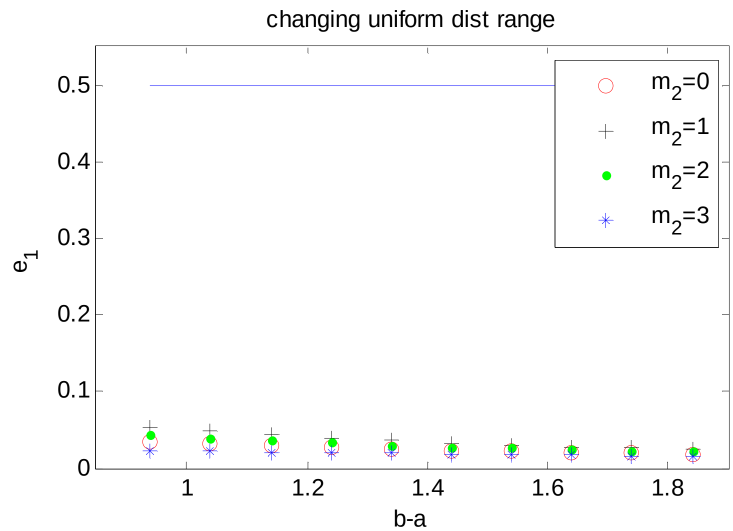

changing penalty for violation
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
2
2.5
3
3.5
4
gamma
e2
m2=0
m2=1
m2=2
m2=3

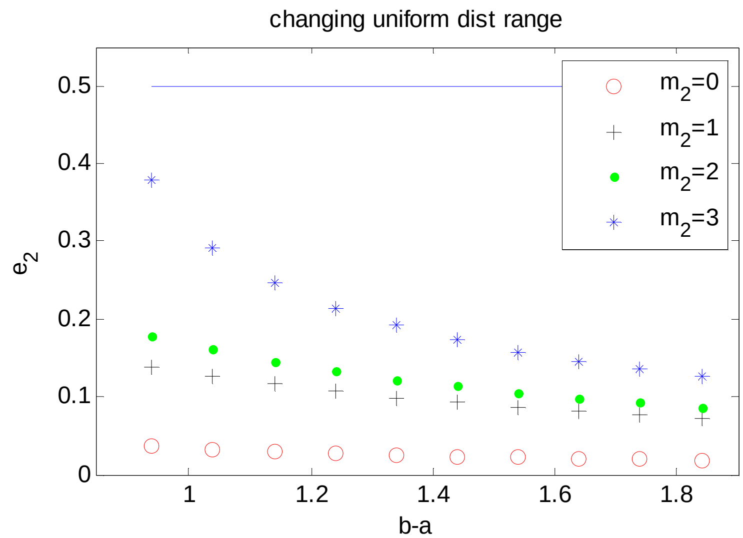
(c)


changing fixed inspection cost
e1
alpha
m2=0
m2=1
m2=2
m2=3
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1


changing fixed inspection cost
e2
alpha
m2=0
m2=1
m2=2
m2=3
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.2
0.4
0.6
0.8
1

(d)


changing uniform dist range
0.5
0.4
0.3
0.2
0.1
0
e1
1
1.2
1.4
1.6
1.8
b-a
m2=0
m2=1
m2=2
m2=3


changing uniform dist range
0.5
0.4
0.3
0.2
0.1
0
e2
1
1.2
1.4
1.6
1.8
b-a
m2=0
m2=1
m2=2
m2=3

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