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Enforcing International Trade Agreements with Imperfect Private Monitoring: Private Trigger Strategies and the Possible Role of the WTO

by

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Abstract

International trade disputes often involve the WTO as a third party that generates impartial opinions on potential violations when countries receive *imperfect* and *private* signals of violations. To identify the role that the WTO plays in enforcing trade agreements, this paper first explores what countries can achieve without the WTO by characterizing optimal *private trigger strategies* (*PTS*) under which each country triggers a punishment phase by imposing an *explicit* tariff based on privately-observed imperfect signals of the other country's concealed trade barriers. It identifies the condition under which countries can restrain the use of concealed barriers based on *PTS* and establishes that countries will not reduce the cooperative protection level to its minimum attainable level under the optimal *PTS*. This paper then considers *third-party trigger strategies* (*TTS*) under which the WTO allows each country to initiate a punishment phase based on the WTO's judgment (i.e., its signals) about potential violations. The WTO thus changes the nature of punishment-triggering signals from *private* into *public*, enabling countries to use punishment phases of any length under *TTS*, which in turn facilitates a better cooperative equilibrium. The optimal *TTS* will involve an asymmetric and minimum punishment if the probability of a punishment phase being triggered is lower than a critical level, but it will entail punishments involving a permanent Nash tariff war if the probability of a punishment phase is higher than a certain level. A numerical comparison of the optimal *TTS* and optimal *PTS* indicates that the contribution of the WTO is likely to be significant when the signals of potential violations are relatively accurate, as this enables countries to use a more efficient punishment, such as an asymmetric and minimum punishment.

JEL Classification Code: F020; F130

Keywords: Concealed Trade Barriers; Imperfect Private Monitoring; International Trade Agreements; Repeated Game; Trade Disputes; Trigger Strategies; WTO

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1. Introduction

Enforcing international trade agreements often entails disputes in which countries present different opinions about potential deviations from the agreements. Differences in opinion may take various forms, such as disagreements over the existence of concealed trade barriers as in the disputes between the U.S. and Japan during 1980s, or disagreement over the legitimacy of antidumping duties, which is a frequent theme in the dispute settlement procedure of the World Trade Organization (WTO). These disagreements reflect the imperfectness of information about deviations from trade agreements. In addition to being *imperfect*, each country's opinion of potential violations can be *private* in the sense that the country's true opinion is not known to other countries. For example, when the United States Trade Representative (USTR) engages in a negotiation with China to curtail the piracy and counterfeiting that impede U.S. intellectual property rights, China and the USTR may not know each other's true beliefs regarding the Chinese government's effort level to curtail such practices, which in turn may contribute to a breakdown in negotiations.[1]

Trade disputes typically involve the WTO as a third party that generates impartial opinions on potential violations when countries receive imperfect private signals of violations.[2] To identify the role that the WTO plays in facilitating the enforcement of trade agreements, this paper first assumes the absence of the WTO and characterizes what countries can achieve alone in a repeated bilateral trade relationship in which each country can secretly raise its protection level through concealed trade barriers. In particular, this paper explores the possibility that countries adopt *private trigger strategies* (*PTS*) under which each country triggers a punishment phase by imposing an explicit tariff based on privately-observed imperfect signals of such barriers. The analysis identifies the condition under which countries can restrain the

[1] The signals that the USTR receives regarding potential deviations from trade agreements often come from U.S. companies with interests that are affected by deviations. Such signals may involve private information on these companies. Public revelation of this private information can be costly for those companies, forcing the signals to be private. There exist many U.S. antidumping cases in which foreign companies under investigation decide not to provide "private" costs- and sales-related information despite the fact that such nondisclosure often leads to excessive dumping duties based on "best information available."

[2] When countries bring a disputed case to the WTO and present different opinions about potential violations, the Dispute Settlement Procedure (DSP) of the WTO encourages them to solve disputes through a consultation stage prior to initiating a panel stage in which a third-party panel provides a ruling on the disputed case. Countries can appeal the panel's ruling to have the case examined by an Appellate Body. Once the case has been determined by the Appellate Body, the losing "defendant" must comply with the ruling or face the possibility of trade sanctions by the complaining side.

use of concealed trade barriers based on *simple PTS* under which each country imposes its static optimal tariff in all periods under any punishment phase. The condition is that the *sensitivity* of private signals rises in response to an increase in concealed protection. This paper, then, establishes that the equilibrium payoff of any *symmetric PTS* will be identical to the one under *simple PTS*, as long as the *initial* punishment is triggered by a static optimal tariff. Given this generality result, it characterizes the optimal *PTS* that maximize symmetric countries' expected payoffs under *simple PTS*. According to the analysis, reducing the cooperative protection level to its minimum attainable level is not optimal, implying that countries will not reduce it to the free trade level under *PTS* even when this is attainable.

To analyze a possible role that the WTO may play in enforcing trade agreements, this paper analyzes *third-party trigger strategies* (*TTS*) under which the WTO decides whether a violation has occurred and tells each country to initiate a punishment phase based on its decision as an impartial third party. Under *TTS*, the WTO changes the nature of punishment-triggering signals from *private* into *public*, enabling countries to employ punishment phases of any length, which in turn can help countries to attain a better cooperative equilibrium. The comparison between the optimal *TTS* and optimal *PTS* illustrates how and to what degree the WTO can help countries enforce international trade agreements beyond what countries can achieve under *PTS*. The analysis establishes that the optimal *TTS* involve an asymmetric and minimum punishment if the probability of a punishment phase being triggered is lower than a critical level, but the optimal *TTS* entail punishments involving a permanent Nash tariff war if the probability of a punishment being triggered is higher than a certain level. A numerical comparison of the optimal *TTS* and optimal *PTS* indicates that the contribution of the WTO is likely to be significant when signals of potential violations are relatively accurate. Under such circumstances, the WTO enables countries to adopt a more efficient punishment, such as an asymmetric and minimum punishment, facilitating a higher level of cooperation as a result.[3]

This paper contributes to the literature in two ways. First, it provides a new way of understanding the role that the WTO plays in enforcing international trade agreements in the

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[3] The WTO typically limits the degree of retaliation by authorizing commensurate retaliation, of which Schwartz and Sykes (2002) offer an interpretation based on the efficient breach theory: "the GATT system relied on unilateral retaliation and reputation to police the bargain. Toward its end, unilateral retaliation became excessive and interfered with opportunities for efficient breach. The WTO mechanism for arbitrating the magnitude of proposed sanctions is the major innovation under WTO law and ensures that sanctions are not set too high." The

presence of potential violations of which countries receive imperfect and private signals. Because the enforcement of trade agreements ultimately rely on the threat of trade sanctions against violations, previous studies have analyzed this enforcement issue using trigger strategies in a repeated game setup.[4] Earlier models developed with respect to this issue, such as Dixit (1987), Bagwell and Staiger (1990), and Riezman (1991), suggest that the WTO may serve the role of helping countries coordinate on more efficient equilibria among the multiple equilibria that typically arise in a repeated game setup. To model a more explicit role of the WTO, Kovenoch and Thursby (1993) assume that the Dispute Settlement Procedure (DSP) of the WTO has an informational superiority over trading countries in distinguishing between true violations and mistaken perceptions, which in turn enhances a reputation mechanism that supports cooperation.[5] In a multilateral trading environment, Maggi (1999) shows that the WTO may facilitate cooperation-enhancing third-country sanctions by disseminating information about deviations.[6] While these models introduce more specific roles for the WTO to play in coordinating a cooperative equilibrium, the literature has not resolved the question of why the WTO is necessary for coordination because these previous studies offer no theory of why countries could not coordinate a cooperative equilibrium in a non-WTO environment.[7]

This paper represents the emergence of the WTO as a change in the observation structure of a repeated game. The presence of the WTO changes the nature of punishment-triggering signals from *private* into *public*. In the absence of the WTO, the private nature of signals of potential violations limits the flexibility of punishment phases that countries can employ because these phases must provide countries with the incentive for truthful revelation of private signals in triggering punishments. The WTO can publicize its opinions on violations, which

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asymmetric and minimum punishment prediction under optimal *TTS* is also suggestive of this feature of WTO design, providing a different interpretation of the WTO's role in limiting the severity of punishments.

[4] Bagwell and Staiger (2002) provide a comprehensive review of studies analyzing international trade agreements as a subgame perfect equilibrium in a repeated trade relationship.

[5] Hungerford (1991) develops a model in which the WTO plays a negative role in enforcing trade agreements because the model assumes that the DSP of the WTO involves uninformative and costly investigation.

[6] As pointed out by a referee, third-party retaliation is rarely observed, and Maggi (1999) does not model information transmission directly and offers no theory as to why information could not be shared in the absence of the WTO.

[7] Bagwell and Staiger (2005) and more recently Bagwell (2008) analyze the issue of implementing trade agreements when each government is privately informed about its own domestic political pressure for protection. Their analysis differs from this paper's because it focuses on identifying the structure of trade agreements that can induce the truthful revelation of private political pressure rather than analyzing the enforcement of trade agreements when countries privately observe imperfect signals of potential deviations.

relaxes such a constraint in designing an optimal punishment scheme, enabling a better cooperative equilibrium even in the absence of any informational superiority of the WTO.[8]

More generally, this paper makes a contribution to the literature on repeated games with imperfect private monitoring. It is well known that analyzing repeated games with imperfect private monitoring is difficult because utilization of privately-observed signals in determining continuation plays can destroy the recursive structure of repeated games.[9] Kandori and Matsushima (1998) and Compte (1998) demonstrate that communication can serve as a public signal that restores a recursive structure and enables players to achieve cooperation in such a repeated game.[10] In the absence of communication, this paper shows how *PTS* can serve an alternative way for players to coordinate punishments in repeated games with imperfect private monitoring.[11] If players can choose public actions as well as concealed actions, as in the case of governments choosing particular protection levels, then players can avoid confusion between punishment phases and non-punishment phases by requiring players to signal an initiation of punishments by their public actions.[12] The analysis of *PTS* specifies the condition under which such trigger strategies can restrain the use of concealed deviant actions.[13]

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[8] Ludema (2001) emphasizes that the DSP of the WTO may require trade agreements to be renegotiation-proof by promoting communication among countries prior to starting punishments. This negatively affects cooperation by forcing countries to rely on weaker punishments. In contrast to this analysis on a repeated game with perfect monitoring, an optimal trade agreement with imperfect monitoring would not typically involve the lowest levels of protection with the most severe credible threat because punishments do occur. With imperfect private monitoring, the WTO can help countries to achieve better cooperation by enabling countries to adopt weaker punishments, as shown in this paper.

[9] Kandori (2002) discusses this point and recent developments in repeated games with private monitoring in detail.

[10] In these studies, the communication among players entails no cost (i.e., it is "cheap talk") and each player's revealed private information does not affect its own continuation payoff in order to ensure a truthful revelation of private information. As pointed out by a referee, however, they are unable to show what communication "does" though, since they are unable to show what would happen in a non-communication setting.

[11] A referee points out that communication is not illegal in the context of international trade agreements, which is different from communication in the context of price-fixing oligopolies. This suggests the possibility of using communication to achieve cooperation in the absence of the WTO. For example, one may consider applying the communication mechanism developed by Kandori and Matsushima (1998) to sustain international trade agreements. There are two reasons why such a mechanism may not work well among countries. First, in the context of an international relationship, it is not easy to allege potential violations when violations do not affect the alleging country, especially when such allegations will negatively affect the alleged country. In fact, the DSP of the WTO reduces the burden of countries having to play the third-party role of "alleging" potential wrong doings of other countries by making the DSP a kind of legal procedure primarily run by experts. Second, the use of transfers is rarely observed between countries, especially as compensation for potential violations of international trade agreements. If countries need to rely on the imposition of tariffs in punishing potential deviations as they do in practice, then communication activities will face an incentive constraint similar to the one under *PTS* because alleging a trading partner's wrong doings must be supported by the action of punishing such behavior with tariffs.

[12] In the context of collusion among firms engaging in secret price cutting, for example, firms can employ *advertised* (and thus *public*) sales to initiate a punishment phase against potential defections from collusive pricing. Similar to Green and Porter (1984), occasional *public* price wars will occur as dynamic equilibrium behaviors to

The use of *PTS*, however, necessitates a complete characterization of optimal and potentially deviant action sequences that each player may take in checking incentive compatibility for such strategies.[14] If each player triggers a punishment phase based on its private signals, as it does under *PTS*, then in any period after a cooperative phase, players must choose their actions knowing only the probability that a punishment phase may be triggered by other players. Because an action taken by each player in a current cooperative period affects the probability of a punishment being triggered in a next period, an optimal action in the next period depends on an action taken in the current period, and an optimal action in a period after the next period depends on an action taken in the next period, and so on until a punishment phase is triggered. Using a dynamic programming method, this paper establishes that countries can use *simple PTS* to achieve cooperation as long as the private signals satisfy some sensitivity constraints. With regard to the possibility of proving a folk theorem result under *PTS*, this paper generates yet another anti-folk theorem result within a class of symmetric private trigger strategies when private monitoring is far from being perfect.[15]

The paper is organized as follows. Section 2.1 develops a bilateral trade model in which each country receives imperfect private signals of the other country's use of concealed trade barriers and specifies *simple PTS*. Section 2.2 describes incentive constraints under *simple PTS*

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sustain collusion overtime. Different from the model of Green and Porter (1984) in which firms always start a price war concurrently, each firm may unilaterally initiate a price war phase by lowering its public price (and thus gaining from it in the initial period of the price war phase) under such private trigger strategies, and the lengths of the price war phases will be endogenously determined.

[13] Matsushima (2004) establishes the folk theorem for the prisoners' dilemma in two-player repeated games with imperfect private monitoring, which is a setup similar to the one analyzed in this paper, and Yamamoto (2007) generalizes the result to more general games with N players. *PTS*, however, generate on-equilibrium punishment behaviors that are different from those under the construction of Matsushima, which must "make the defective payoff vector larger than the one-shot Nash payoff vector." While both *PTS* and Matsushima's construction can be applied to the analysis of the collusion in the presence of secret price cutting (as discussed in Footnote 12), punishments under *PTS* would entail one-shot Nash actions and thus drastic price wars, which would not occur under Matsushima's construction.

[14] This aspect of *PTS* does not allow one to apply the dynamic programming technique develops by Abreu *et al*. (1986) to characterize the set of equilibrium payoffs under *PTS* because those techniques rely on the "one-stage deviation principle." For further discussion of the one-stage deviation principle, see Footnote 27 in Section 2.2.

[15] Ely and Välimäki (2002) provide a concise discussion of why many of the strategies to prove folk theorems with public monitoring fail when monitoring is private and conditionally independent. This paper also analyses the case in which monitoring is private and conditionally independent and shows that countries cannot attain the symmetric efficient frontier under *symmetric PTS* if the monitoring is far from perfect, as discussed in Footnote 41. This anti-folk theorem result, however, may rely on the use of distortional measures like tariffs to punish potential violations. For example, Horner and Jamison (2007) show that full collusion can be approximated under minimal information in *private* strategies in which punishment phases are carefully designed so that no loss collectively occurs for colluding firms. Such punishments are possible because firms can avoid collective losses as long as any

and provides conditions under which those incentive constraints are satisfied. Section 3.1 shows that countries can support *simple PTS* in the repeated protection-setting game, achieving a certain level of cooperation. It also establishes that the equilibrium payoff under any *symmetric PTS* will be identical to the payoff under *simple PTS* as long as each country starts the *initial* punishment phase by imposing its static optimal tariff. Section 3.2 then characterizes the optimal *simple PTS* under which countries maximize their joint expected discounted payoffs. To demonstrate the role that the WTO may play in enforcing international trade agreements, Section 4 characterizes the optimal *TTS* and provides a numerical comparison between the optimal *PTS* and optimal *TTS*. Section 5 discusses additional factors that may severely limit the use of *PTS* and summarizes the results. It concludes with a discussion of a possible extension of this paper's analysis towards a further understanding of the Dispute Settlement Procedure (DSP) of the WTO.

2. Private Trigger Strategies

2.1. A Trade Model with Concealed Trade Barriers and Private Trigger Strategies

The basic bilateral trade model comes from Dixit (1987), with concealed trade barriers introduced similar to Riezman (1991). There exist two countries, namely, home (H) and foreign (F), that produce and trade two products, good 1 and good 2, under perfect competition. H imports good 2, and F imports good 1. In each period, each country simultaneously chooses its action, $a^i \equiv (\tau^i, e^i) \in A^i$, with both elements of A^i being any non-negative real number. Total import protection level and explicit tariff level are given by τ^i and e^i, respectively, with i = * or none. Variables with and without superscripts * denote foreign and home variables, respectively. I assume that $\tau - e \geq 0$ and $\tau^* - e^* \geq 0$, representing the concealed protection levels of H and F, respectively. With τ and τ^* being less than prohibitive protection levels, the local prices p_1, p_2, p_1^*, and p_2^* are related as follows.[16] $p_2 = p_2^*(1+\tau)$ and

low-cost firm ends up selling its product at a monopoly price, which is a special feature that countries in a trade relationship may not be able to replicate easily in their punishment phases.

[16] An adequately high total protection level may block the importation of a good, creating an autarky equilibrium. As discussed in Section 3.1, however, there is no loss of generality in focusing on private trigger strategies that exclude the possibility of playing in such an autarky equilibrium.

$p_1^* = p_1(1+\tau^*)$.[17] Given the assumption of perfect competition, I can define each country's one-period payoff as a function of the terms of trade, represented by $\pi \; (\equiv p_1 / p_2^*)$, and its own total protection level, τ^i. Such a payoff, denoted by $w^i(\pi, \tau^i)$, induces a corresponding import demand function, $m^i(\pi, \tau^i)$.

In the absence of uncertainty (i.e., no random element) in this world, each country's amount of imports is a deterministic function of its own total protection level and the terms of trade. This implies that each country may figure out the exact level of another country's protection level based on the information about the terms of trade and the amount of imports, even in the presence of concealed trade barriers. However, when I introduce uncertainty into the model as a way of representing shocks to technology or preferences, the exact derivation of the protection levels of other countries based on the amount of imports and the terms of trade may become impossible. Uncertainty caused by random shocks can be modeled into random components in the import demand functions as follows:

(1) $$m_t^i = m^i(\pi_t, \tau_t^i, \theta_t^i, \varepsilon_t^u),$$

where $\theta_t^i \in \Theta^i$ denotes each country's random components affecting its import demand at period *t*, of which each country will privately observe their realized values at the end of period *t*, and $\varepsilon_t^u \in E^u$ denotes other random components, for which no country will observe their realized values.[18] The subscript *t* denotes the variables determined in period *t*. These random components follow a joint density function, $f(\theta_t, \theta_t^*, \varepsilon_t^u)$ that is iid across periods. In equilibrium, the following balance of payment condition should be satisfied:

(2) $$\pi_t \cdot m(\pi_t, \tau_t, \theta_t, \varepsilon_t^u) = m^*(\pi_t, \tau_t^*, \theta_t^*, \varepsilon_t^u),$$

determining the equilibrium values for π_t, m_t, and m_t^* as functions of τ_t, τ_t^*, θ_t, θ_t^*, and ε_t^u.

[17] I assume that each country cannot directly observe the other country's local market price of its export. For example, a mixture of a consumption tax and a production subsidy can replicate the effect of a tariff, as discussed by Riezman (1991). When such a tax and a subsidy are concealed through informal arrangements, each country's observation of the other country's local market price of its export becomes difficult.

[18] Assuming the existence of random components, ε^u, for which no country can observe their realized values, is reasonable given the complexity of random elements in the world economy. In addition, it allows this paper to introduce standard assumptions on the distributions of private signals in a repeated game with private monitoring, namely, *full support* and *conditional independence*.

Given that each country sets its total protection level prior to the realization of random shocks, each country's one-period expected payoff, denoted by u^i, is a function of both countries' total protection levels:

(3) $$u^i(\tau_t^i, \tau_t^j) = \iint_{(\theta_t, \theta_t^* \varepsilon_t^u) \in (\Theta, \Theta^*, E^u)} w^i\left(\pi_t(\tau_t, \tau_t^*, \theta_t, \theta_t^*, \varepsilon_t^u), \tau_t^i; \theta_t^i, \varepsilon_t^u\right) f(\theta_t, \theta_t^*, \varepsilon_t^u) d\theta_t d\theta_t^* d\varepsilon_t^u ,$$

where $w^i(\pi, \tau^i; \theta^i, \varepsilon^u)$ represents each country's one-period payoff function that is affected by random shocks, θ^i and ε^u, with $i \neq j$.

This paper focuses on the analysis of symmetric equilibria of a repeated protection-setting game between symmetric countries. Thus, I assume that $u(\tau^1, \tau^2) = u^*(\tau^1, \tau^2)$ for all non-negative, real values of τ^1 and τ^2. Regarding derivatives of $u(\tau, \tau^*)$ and $u^*(\tau^*, \tau)$ with respect to τ and τ^*, I assume that the following standard trade-theoretic results continue to hold in the presence of random variables: $\partial u / \partial \tau > 0$ at $\tau = 0$ (i.e., each country has an incentive to raise its protection level above zero); $\partial u^* / \partial \tau < 0$ (i.e., such protection hurts the other country); and $\partial u / \partial \tau + \partial u^* / \partial \tau < 0$ (i.e., such protection also reduces the total payoff to H and F as it creates distortional losses). For analytical simplicity, I introduce the following additional assumptions: $\partial^2 u / \partial \tau^2 < 0$ (i.e., the marginal gain from protection decreases as the protection level increases); and $\partial^2 u / \partial \tau \, \partial \tau^* = 0$ (i.e., the marginal gain from protection is not affected by the other country's protection level).[19] These additional assumptions guarantee the existence of a unique static optimal protection level for H, which I denote by h (> 0). The one-shot protection-setting game between H and F then generates a Nash equilibrium in which $(\tau, \tau^*) = (h, h^*)$ with $h = h^*$ by symmetry.[20]

Private monitoring is specified as follows. At the end of period t, each country privately observes realized values of its payoff and own random variable, (u_t^i, θ_t^i), and both countries

[19] These properties of a social utility function can be derived from a two-good, partial equilibrium model of trade with linear demand and supply curves. See Bond and Park (2002) for derivation of such properties.

[20] Given these assumptions on the derivatives of $u^i(\tau^i, \tau^j)$ with respect to τ^i and τ^j, one can characterize the set of individually rational payoff vectors as follows. The set of feasible payoff vectors $Z^p \subset R^2$ is defined as the convex hull of the set $\{z^p = (z, z^*) \in R^2 \mid u(\tau, \tau^*) = z$ and $u^*(\tau^*, \tau) = z^*$ for some non-negative real values of τ and $\tau^*\}$. The minmax point $z^m \in Z^p$ is defined by $(u(\tau = h, \tau^* \to \infty), u^*(\tau^* = h, \tau \to \infty))$. The set of individually rational payoff vectors, denoted by Z^{pr}, then is the set of $z^p \in Z^p$ with $z^p \geq z^m$. It is easy to establish that $(u(0,0), u^*(0,0))$ is on the efficient frontier of Z^{pr} and $(u(h,h), u^*(h,h)) \in Z^{pr}$.

observe a pair of explicit tariffs, (e_t, e_t^*). Denote the privately observed signal by $\omega_t^i = (u_t^i, \theta_t^i)$ $\in \Omega^i$. I assume that the probability distribution of the private signal profile conditional on any action profile has *full support*, that is, $Pr(\omega_t, \omega_t^* \mid a_t, a_t^*) > 0$ for each $\omega_t \in \Omega$, $\omega_t^* \in \Omega^*$, $a_t \in A$ and $a_t^* \in A^*$. Note that while each country cannot infer the exact level of the other country's concealed protection even after observing its private signal (because it does not know the realized value of the other random variables), the privately observed information can serve as a measure for detecting the other country's potential use of concealed protection. More specifically, H can choose a subset of its private signals, $\Omega^D \in \Omega$, so that $\partial Pr(\omega_t \in \Omega^D)/\partial \tau_t^*$ > 0, with $Pr(\omega_t \in \Omega^D) \equiv Pr(\omega_t \in \Omega^D \mid a_t, a_t^*)$, which denotes the probability that H's private signal belongs to Ω^D conditional on an action profile. For example, H can assign values of u_t that are less than a critical value as the payoff part of Ω^D. This can induce $\partial Pr(\omega_t \in \Omega^D)/\partial \tau_t^*$ > 0 because $\partial u_t / \partial \tau_t^* < 0$, and the sensitivity of u_t against τ_t^* can improve if it is properly controlled for θ_t. With regard to the relationship between ω_t and ω_t^*, I assume *conditional independence*, meaning that for each action profile, the private signals of the countries are independently distributed with respect to one another. [21] This condition implies that each country cannot infer the other country's private signal based on its own private signal.[22] For symmetry between H and F, I also assume that $Pr(\omega_t \in \Omega^D) = Pr(\omega_t^* \in \Omega^D)$ for all $(\tau_t, e_t) = (\tau_t^*, e_t^*)$ $\in A = A^*$ and $\Omega^D \in \Omega = \Omega^*$.

[21] Matsushima (1991) analyzes the repeated play of stage games with a unique static Nash equilibrium and *conditionally independent* private signals, a problem that is similar to the repeated protection-setting game of this paper, and shows that any pure-strategy equilibrium other than the static Nash equilibrium should involve conditioning on payoff-irrelevant history. As discussed by Ely and Välimäki (2002), repeated games with imperfect private monitoring, especially with conditionally independent private signals, limit the use of strategies that are often useful for repeated games with public monitoring under which each player typically has a strict incentive to follow his/her equilibrium strategy after every history. Private trigger strategies considered in this paper will be subject to similar constraints, but they differ from previous works by considering the use of explicit actions, like tariffs, as a punishment coordination device.

[22] While full support and conditional independence on private signals are standard assumptions in the literature, it requires that the joint density function of random variables is specified to satisfy such assumptions. Alternatively, I can assume the existence of conditionally independent private signals of each country (of concealed barriers) that do not affect the other country's utility level, and have trigger strategies rely on such private signals.

Given this stage game and associated private monitoring depicted as above, I can describe an infinitely repeated protection-setting game between H and F as follows. A strategy for each country is defined by $s^i = (s^i(t))_{t=1}^{\infty}$ with

(4) $$s^i(t) : (A^i)^{t-1} \times (\Omega^i)^{t-1} \times (E^j)^{t-1} \rightarrow A^i,$$

where E^j denotes the set of possible explicit tariffs that each country can impose in a period with $e^j \in E^j$ and $j \neq i$. $s^i(t)$ assigns each country's current action (τ_t^i, e_t^i) based on the history of its own previous actions, $(a^i)^{t-1} \equiv (a_1^i, a_2^i \cdots, a_{t-1}^i) \in (A^i)^{t-1}$, the history of its own private information, $(\omega^i)^{t-1} \equiv (\omega_1^i, \omega_2^i \cdots, \omega_{t-1}^i) \in (\Omega^i)^{t-1}$, and the history of the other country's explicit tariffs, $(e^j)^{t-1} \equiv (e_1^j, e_2^j, \cdots, e_{t-1}^j) \in (E^j)^{t-1}$, with $j \neq i$. If each country conforms to its strategy defined in (4), then the expected discounted payoff is given by:

(5) $$V^i(s^i, s^j) = E\left[\sum_{t=1}^{\infty} u^i(\tau_t^i, \tau_t^j)(\delta^C)^{t-1} \middle| (s, s^*)\right],$$

where $E[\cdot \mid (s, s^*)]$ is the expectation with respect to the probability measure on histories induced by the strategy profile (s, s^*), and $\delta^C \in [0, 1)$ denotes the common discount factor.

To explore the possibility of supporting a cooperative protection level, denoted by l, that is lower than the one-shot Nash protection level ($h > l$) in the repeated game described above, I consider *private trigger strategies* (*PTS*) under which each country uses its private signal, ω and ω^*, as a device to trigger a punishment phase against the other country's potential use of concealed protections. Focusing on symmetric strategies with $s(t) = s^*(t)$ for all $a^{t-1} \times \omega^{t-1} \times (e^*)^{t-1} = (a^*)^{t-1} \times (\omega^*)^{t-1} \times e^{t-1}$ and $t \geq 1$, I describe H's strategy s (and, accordingly, F's strategy s^*) as follows:

(i) Given that period $t - 1$ is a *cooperative* period with $(e_{t-1}, e_{t-1}^*) = (0, 0)$, H continues cooperating by setting $(\tau_t, e_t) = (l, 0)$ if $\omega_{t-1} \notin \Omega^D$, but it initiates a *punishment* phase by setting $(\tau_t, e_t) = (h, h)$ if $\omega_{t-1} \in \Omega^D$.

(ii) Given that a *punishment* phase is initiated in period $t - 1$ with $(e_{t-1}, e_{t-1}^*) \neq (0, 0)$, H sets $(\tau, e) = (h, h)$ for the following $(T - 2)$ periods and it continues to do so for one more period with probability λ if either $e_{t-1} > 0$ and $e_{t-1}^* = 0$ or $e_{t-1} = 0$ and $e_{t-1}^* > 0$; H sets

$(\tau, e) = (h, h)$ for the following ($T^S - 2$) periods and continues to do so for one more period with probability λ^S if $e_{t-1} > 0$ and $e^*_{t-1} > 0$, where T and T^S are integer numbers that are greater than or equal to 2, and λ and λ^S belong to [0, 1]. H knows these variables (T, T^S, λ, λ^S) when it initiates a punishment phase. The actual length of the punishment phase is determined by some public randomizing device (based on values of λ and λ^S) after the punishment phase has been initiated.

(iii) In period 1 and other *initial* periods that start directly after the end of any punishment phase, H sets $(\tau, e) = (l, 0)$ with probability $(1 - Pr)$ but initiates a punishment phase by setting $(\tau^i, e^i) = (h, h)$ with probability Pr, where $Pr \equiv Pr(\omega_t \in \Omega^D)$ with $(\tau_t, e_t) = (l, 0)$ and $(\tau^*_t, e^*_t) = (l, 0)$.

The absence or presence of explicit tariffs classifies any period into either a *cooperative* period with no explicit tariffs or a *punishment* period with some positive tariffs. While H and F cannot observe each other's concealed protection levels, they use their explicit tariffs as public signals to coordinate punishment phases as described in (i) and (ii).[23] Extending a punishment phase one more period with a certain probability, as specified in (ii), is an instrument to make the expected discounted payoff from invoking a punishment phase vary smoothly, so that it can be set to equal the expected discounted payoff from not invoking a punishment phase; this is an important requirement for the incentive constraints considered in the following section. Also note that the actions for period 1 and other *initial* periods described in (iii) are designed to mimic those in a period that immediately follows a cooperative period, which in turn simplifies the analysis of the trigger strategies defined above.[24] Finally, note that the set of private signals

[23] Note that each country identifies an initiation of a punishment phase with any positive tariff (including a tariff that is not equal to h) being imposed. Once a country identifies an initiation of a punishment phase, also note that it is supposed to choose its static optimal action, $(\tau^i, e^i) = (h, h)$, in all periods under the punishment phase, regardless of tariff levels set during the punishment phase. Because each country can observe other country's deviations from the specified strategy only through explicit tariffs being set differently from h, (i), (ii), and (iii) together specify each country's strategy at every information set, except those that follow each country's private (i.e., not observable by the other country) deviations from the specified strategy.

[24] If Pr in period 1 and other *initial* periods is set to 0, for example, thus it is not equal to $Pr(\omega_t \in \Omega^D)$ with $(\tau_t, e_t) = (l, 0)$ and $(\tau^*_t, e^*_t) = (l, 0)$, then the expected one-period payoffs for period 1 and other *initial* periods will be different from those for any period immediately following a cooperative one. This will make the expected discounted payoffs along the equilibrium path more complicated than those in (6). Furthermore, having actions in period 1 and in other *initial* periods different from those in periods immediately following a cooperative period will make deviation incentives different across these periods, which in turn complicates the characterization of the optimal protection sequence in Section 2.2.2.

that trigger a punishment phase ($\mathit{\Omega}^D$), the lengths of different punishment phases ($T - 1$ if a single country triggers and $T^S - 1$ if H and F trigger simultaneously), and the corresponding probabilities of extending the punishment phases (λ, λ^S) characterize the strategy profile defined by (i), (ii) and (iii), together with the cooperative protection level, *l*. I define *simple private trigger strategies* as follows:

Definition 1. If (i), (ii), and (iii) describe a symmetric strategy profile ($\underline{s}$, $\underline{s}^*$) with $\underline{s}(t) = \underline{s}^*(t)$ for all $a^{t-1} \times \omega^{t-1} \times (e^*)^{t-1} = (a^*)^{t-1} \times (\omega^*)^{t-1} \times e^{t-1}$ and $t \geq 1$, then ($\underline{s}$, $\underline{s}^*$) are *simple private trigger strategies* (*simple PTS*) with $(l, \mathit{\Omega}^D, T, T^S, \lambda, \lambda^S)$ as characterizing parameters.

Given this definition, I can derive H's expected discounted payoff under ($\underline{s}$, $\underline{s}^*$) with $(l, \mathit{\Omega}^D, T, T^S, \lambda, \lambda^S)$, denoted by $V(\underline{s}, \underline{s}^*)$, as follows:

$$
\begin{aligned}
V(\underline{s}, \underline{s}^*) &= \frac{(1 - Pr^2)[u(l,l) - u(h,h)]}{1 - \delta^C + 2Pr(1-Pr)(\delta^C - \delta) + Pr^2(\delta^C - \delta^S)} \\
&\quad + \frac{Pr(1-Pr)[u(l,h) - u(l,l)] + Pr(1-Pr)[u(h,l) - u(l,l)]}{1 - \delta^C + 2Pr(1-Pr)(\delta^C - \delta) + Pr^2(\delta^C - \delta^S)} + \frac{u(h,h)}{1 - \delta^C},
\end{aligned} \tag{6}
$$

where $\delta^K = \lambda^K (\delta^C)^{T^K} + (1 - \lambda^K)(\delta^C)^{T^K - 1}$ with K = s or none. $(\delta^C - \delta)$ and $(\delta^C - \delta^S)$ respectively represent the relative length of the punishment phase initiated by H or F alone and by H and F simultaneously. Because $(T, T^S, \lambda, \lambda^S)$ uniquely defines (δ, δ^S) as shown above, I henceforth describe *simple PTS* using $(l, \mathit{\Omega}^D, \delta, \delta^S)$ instead of $(l, \mathit{\Omega}^D, T, T^S, \lambda, \lambda^S)$.

Note that *simple PTS* defined above are *simple* in the sense that each country imposes its static optimal tariff in all periods under any punishment phase. More generally, *PTS* may involve more complex punishment phases such as imposing lower tariffs if the signal indicates weaker violations and/or employing a stronger punishment, such as autarky, against presumably more severe violations. As shown later, the equilibrium payoff of any *symmetric PTS* will be identical to the one under *simple PTS* defined above, as long as the *initial* punishment is triggered by a static optimal tariff. From now on, I abbreviate *simple PTS* to *PTS* unless it is necessary to distinguish them. The following analysis will establish a sufficient condition under which countries can support *PTS* as a sequential equilibrium of the repeated game defined above.[25]

2.2. Incentive Constraints under Private Trigger Strategies

In this section, I analyze incentive constraints for each country to have no incentive to deviate from its specified strategy under *PTS*.[26] The private nature of signals that trigger punishments under *PTS* makes such incentive constraints different from the incentive constraints for trigger strategies under which public signals trigger punishments in two distinctive ways. First, the private nature of signals imposes restrictions on the lengths of punishment phases under *PTS*, which contrasts with the repeated game with public information in which countries can choose any length for their punishment phases. Section 2.2.1 analyzes such limits on the lengths of punishment phases under *PTS*. Second, to check the absence of $s^{/}(\neq \underline{s})$ or $s^{*/}(\neq \underline{s}^{*})$ such that $V(s^{/}, \underline{s}^{*}) > V(\underline{s}, \underline{s}^{*})$ and $V^{*}(s^{*/}, \underline{s}) > V^{*}(\underline{s}^{*}, \underline{s})$, one must check not only one-time deviations from the specified strategy, but also entire deviation paths that each country may take.[27] If private signals trigger punishments as under *PTS*, any deviant action that each country might have taken in a previous period can influence its optimal deviant action in a current period. That is, defection in a previous period affects the probability of a

[25] For a sequential equilibrium, I need to specify a strategy profile at every information set (including one that should not be reached if all countries adhere to the equilibrium strategy) and an associated system of beliefs of each country that satisfy both sequential rationality and consistency requirements. I do specify such a sequential equilibrium in the proof of *Proposition 1*, establishing that countries will follow *PTS* along the equilibrium path of the sequential equilibrium. Such specification requires a more complicated definition of *private trigger strategies* than *simple PTS* in *Definition 1*, using several theoretical results proven later in this paper. For expositional simplicity, *Definition 1* specifies the strategy profile at all information sets, except those that follow each country's private (i.e., not observable by the other country) deviations from the specified strategy.

[26] This section considers all possible deviations from *PTS*, including private deviations, to ensure the sequential rationality of *PTS* for all information sets reachable along the equilibrium path under *PTS*. Due to the existence of public deviations, the outcome equivalence result between Nash equilibrium and a sequential equilibrium by Sekiguchi (1997) is not applicable here, as a referee correctly pointed out. Once the sequential rationality of *PTS* along the equilibrium path under *PTS* is established in this section, however, establishing the sequential rationality of *PTS* for information sets that follow public deviations is not difficult. Under *PTS*, recall that each country is supposed to choose its static optimal action, $(\tau^{i}, e^{i}) = (h, h)$, in all periods under any punishment phase, regardless of whether any public deviation has occurred or not during the punishment phase. If each country believes that the other country's continuation strategy is to follow *PTS* even after observing public deviations, then following *PTS* is a sequentially rational strategy. The proof of *Proposition 1* shows that such a belief after observing public deviations does satisfy the consistency requirement of a sequential equilibrium.

[27] When a public signal triggers a punishment phase, any deviant actions that each country might have taken in any previous periods will not affect its optimal deviant action in the current period for a given history of public signals up to the current period. This is because one country's defections in the previous periods affect the other country's current and future actions only through affecting the history of public signals. Therefore, we can apply the logic of

punishment phase being initiated in the current period, which in turn influences optimal action in the current period. This necessitates a characterization of an optimal, potentially deviant protection sequence that each country may take against $(\underline{s}, \underline{s}^*)$ while analyzing the incentive constraints for *PTS*. Section 2.2.2 characterizes such a sequence for H under *PTS*, and shows that H's optimal protection sequence can be a stationary one of setting τ to l (i.e., the cooperative protection level) in all periods until a punishment phase starts, which is a prerequisite for *PTS* to be a sequential equilibrium.

2.2.1. Constraints on Lengths of Punishment Phases

In any period that immediately follows a cooperative period with (e, e^*) = (0, 0) and in any *initial* periods (i.e., period 1 and periods directly after the end of any punishment phase), each country faces the choice of whether or not to initiate a punishment phase by imposing its static optimal tariff. To eliminate the incentive to misrepresent private signals in such periods, the expected payoff from initiating a punishment phase should be identical to the expected payoff from not initiating it for each country. Denote the condition that equates those expected payoffs by *ICP* for H, with the same condition applying for F by symmetry. Then, *ICP* is

$$\text{(7)}\qquad \begin{aligned} &(1-Pr)[u(l,l)+\delta^C V_C)] + Pr[u(l,h)+(\delta^C-\delta)V_N+\delta V_C] = \\ &(1-Pr)[u(h,l)+(\delta^C-\delta)V_N+\delta V_C] + Pr[u(h,h)+(\delta^C-\delta^S)V_N+\delta^S V_C], \end{aligned}$$

where $V_C \equiv V(\underline{s}, \underline{s}^*)$ and $V_N \equiv u(h,h)/(1-\delta^C)$. The left side of the equality in (7) represents the expected discounted payoff from not initiating a punishment phase but continuing to set (τ, e) = (l, 0). The right side of the equality represents the expected discounted payoff from initiating a punishment phase, setting (τ, e) = (h, h). In calculating these expected discounted payoffs in (7), it is assumed that the other country initiates a punishment phase with a probability determined by *PTS* and is denoted by *Pr*.

Using $u(l, l) - u(l, h) = u(h, l) - u(h, h)$ implied by $\partial u/\partial\tau\partial\tau^* = 0$, I simplify (7) into

$$\textbf{(ICP)}\qquad u(l,l)-u(h,l)+(\delta^C-\delta)(V_C-V_N) = Pr[(\delta^C-\delta)-(\delta-\delta^S)](V_C-V_N).$$

For any given cooperative protection level (l) and any given range of private signals that trigger punishment phases (Ω^D), I determine two variables (δ, δ^S) with one equation (*ICP*),

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the "one-stage deviation principle" proved by Theorem 4.1. and Theorem 4.2 in Fudenberg and Tirole (1991) for the subgame perfect equilibrium, to the perfect public equilibrium with unobservable actions.

potentially generating infinite combinations of (δ, δ^S) that satisfy *ICP*. However, *Lemma 1* (a) below establishes that $\delta^C - \delta^S = 2(\delta^C - \delta)$ and *ICP* are the necessary conditions for each country to truthfully represent its private signals under *PTS*.

Lemma 1.

(*a*) $\delta^C - \delta$ = [$u(h, l) - u(l, l)$]/($V_C - V_N$) and $\delta^C - \delta^S = 2(\delta^C - \delta)$ are necessary conditions for each country to truthfully represent its private signals under *PTS*, triggering a punishment phase *iff* its private signal belongs to Ω^D.

(*b*) If H and F value their future payoffs adequately highly ($\delta^C \approx 1$) and the probability of a punishment phase being triggered along the equilibrium path is adequately low ($Pr \approx 0$), then for any given combination of (l, Ω^D) with $l < h$, there exists a unique combination of (δ, δ^S) that satisfies the necessary condition for the truthful revelation of private signals in *Lemma 1* (*a*). (See the appendix for proof.)

Recall that $\delta^C - \delta$ and $\delta^C - \delta^S$ respectively represent the length of a punishment phase that H or F can initiate alone and the length of a punishment phase that H and F initiate concurrently, with $\delta = \lambda(\delta^C)^T + (1-\lambda)(\delta^C)^{T-1}$ and $\delta^S = \lambda^S(\delta^C)^{T^S} + (1-\lambda^S)(\delta^C)^{T^S-1}$. Thus, for a given combination of (l, Ω^D), *ICP* with $\delta^C - \delta^S = 2(\delta^C - \delta)$ determines $\delta^C - \delta$ = [$u(h, l) - u(l, l)$]/($V_C - V_N$). Note that the length of a punishment phase that each country initiates by itself ($\delta^C - \delta$) increases in its expected gain in the initial period of the punishment phase by imposing a static optimal tariff unilaterally ($u(h, l) - u(l, l)$) but decreases in its expected loss in the following tariff-war periods ($V_C - V_N$). The expected gain in the initial period of a punishment phase provides each country with the incentive to start a punishment phase despite the expected loss from engaging in a tariff war that follows under a punishment phase. Thus, the larger is the expected gain in the initial period, the longer is the punishment phase that H can tolerate (without violating *ICP*); meanwhile the larger is the expected loss from a tariff war, the shorter is the punishment phase that H can tolerate (without violating *ICP*).

Even when *ICP* is satisfied so that each country has no (strict) incentive to untruthfully represent its private signal after a *real* cooperative period, it may still have an incentive to misrepresent its private signal after a *pseudo* cooperative period under which it deviates by setting $\tau \neq l$ (or $\tau^* \neq l$), with its explicit tariff being zero. The proof of *Lemma 1* (*a*) in the appendix shows that $\delta^C - \delta^S = 2(\delta^C - \delta)$ is indeed a necessary condition for each country not to misrepresent its private signals in a period following a *pseudo* cooperative period. For example, if $\delta^C - \delta^S < 2(\delta^C - \delta)$, so that the length of the punishment phase that H and F initiate concurrently is shorter than what it is supposed to be, then each country will have an incentive to set its protection level higher than l in a cooperative period and then initiate a punishment phase in the following period, regardless of its private signal. Such a deviation strategy may pay off because an increase in the protection level in a cooperative period raises the probability of a punishment phase being triggered by the other country in the following period, which would then lead to a short punishment phase (with $\delta^C - \delta^S$ being small) when the deviating country initiates a punishment, regardless of its private signals.

2.2.2. The Optimal Protection Sequence and the Existence of a Stationary Protection Level

To characterize the optimal protection sequence, I analyze the dynamic optimization problem in which H maximizes its expected discounted payoff by choosing a protection sequence $\{\tau_{d+1}\}_{d=0}^{\infty}$, given that F follows its specified strategy under *PTS*. The dynamic optimization problem for H is

$$(8) \qquad \underset{\{\tau_{d+1}\}_{d=0}^{\infty}}{Sup} \sum_{d=0}^{\infty} \left\{ (\delta^C)^d \cdot \left[\prod_{t=0}^{d-1} [1 - Pr(\tau_t)] \right] \cdot F(\tau_d, \tau_{d+1}) \right\}$$

where $\prod_{t=0}^{d-1}[1-Pr(\tau_t)] = [1-Pr(\tau_0)] \times [1-Pr(\tau_1)] \times \cdots \times [1-Pr(\tau_{d-1})]$ with $\prod_{t=0}^{-1}[1-Pr(\tau_t)] = 1$; $Pr(\tau_t) \equiv Pr(\omega_t^* \in \Omega^D)$, given (τ_t, e_t) = (l, 0), (τ_t^*, e_t^*) = (l, 0), and $\tau_0 = l$; and $F(\tau_d, \tau_{d+1}) \equiv Pr(\tau_d)[u(\tau_{d+1}, h) + (\delta^C - \delta)V_N + \delta V_{CO}] + [1 - Pr(\tau_d)]u(\tau_{d+1}, l)$, with $V_{CO} = V_C$. Note that the protection sequence $\{\tau_{d+1}\}_{d=0}^{\infty}$ in (8) specifies protection levels only until F triggers an initial punishment phase. The optimization in (8) assumes that H will follow its specified strategy under *PTS* once F triggers an initial punishment phase with $V_{CO} = V_C \equiv V(\underline{s}, \underline{s}^*)$. The *full* optimization problem should characterize the optimal protection sequence after the end of each punishment phase that may occur in future periods. Characteristics of the optimal protection sequence derived from (8), however, will be qualitatively identical to those of the full optimization problem. This is because the optimal sequence resulting from (8) will be identical to the one resulting from the full optimization problem if V_{CO} in (8) is set equal to the maximized expected discounted payoff of the full problem, with H facing an identical optimization problem in determining the protection sequence after the end of each punishment phase in the future.[28] Also note that the optimal protection sequence considered in (8) excludes the possibility of using explicit tariffs as a part of its path. Once the lengths of punishment phases satisfy the necessary conditions for truthful revelation of private signals given in *Lemma 1* (*a*), however, one can show that H cannot increase its payoff by using explicit tariffs along its deviation path.[29] Hence, there is no loss of generality in analyzing the optimal protection sequence for H (and for F by symmetry) through the problem defined in (8).

Having the full details to solve the problem in (8) provided in the one-line technical appendix, this subsection characterizes an optimal protection sequence that each country may take against *PTS*, $(\underline{s}, \underline{s}^*)$, and shows that each country's optimal protection sequence can be a stationary one that sets τ to l in all periods until a punishment phase starts. Given solution $V(\cdot)$ to the following dynamic programming problem:

(9) $$V(\tau_{-1}) = \underset{\tau \in [0,h]}{Sup} \left\{ F(\tau_{-1}, \tau) + \delta^C [1 - Pr(\tau_{-1})] V(\tau) \right\} \text{ for all } \tau_{-1} \in [0, h],$$

where τ_{-1} and τ respectively denote previous-period and current-period protection levels of H, define the optimal policy correspondence G: $[0, h] \rightarrow [0, h]$ as:

(10) $$G(\tau_{-1}) = \{ \tau \in [0, h]: V(\tau_{-1}) = F(\tau_{-1}, \tau) + \delta^C [1 - Pr(\tau_{-1})] \cdot V(\tau) \}.$$ [30]

Based on an equivalence result between (8) and (9),[31] I can characterize the optimal protection sequence of H by characterizing $G(\cdot)$ because any protection sequence generated by G with

[28] The discounted payoff of the full optimization problem can be obtained by applying the following iterative process to the optimization problem in (8). Initially set V_{CO} in (8) to be V_C as defined in (6) and solve the optimization in (8), obtaining a discounted payoff as an outcome of this initial optimization problem. Then, set the value of V_{CO} in (8) to have the value of this initially generated discounted payoff, supposedly higher than (or equal to) the initial V_{CO} (= V_C), which redefines the optimization problem in (8). This redefined optimization problem will generate another discounted payoff as an outcome of this second optimization problem. Then, set V_{CO} in (8) at the value of this newly-generated discounted payoff and continue this iterative process until the discounted payoff generated through this process reaches its limit. As the sequence of the discounted payoffs generated through this process is monotonically increasing and bounded, there exists such a limit. This limit will be equal to the discounted payoff of the full optimization problem.

[29] The proof for this statement can be found in *Lemma 4* (*b*) in the online technical appendix.

[30] Note that limiting H's protection choice to be equal to or less than h as in (9) does not affect the generality of the optimization problem because H has no incentive to raise τ above its static optimal protection level, h.

initial τ_{-1} set at l is an optimal protection sequence that solves (8). $V(\tau_{-1})$ is strictly decreasing in $\tau_{-1} \in [0, h]$ and $G(\tau_{-1})$ is strictly increasing in τ_{-1} in the sense that $g(\tau''_{-1}) > g(\tau'_{-1})$ for all $\tau''_{-1} > \tau'_{-1} \in [0, h]$, with $g(\tau''_{-1}) \in G(\tau''_{-1})$ and $g(\tau'_{-1}) \in G(\tau'_{-1})$.[32]

The fact that $G(\tau_{-1})$ is strictly increasing in τ_{-1} may entail both an increasing protection sequence and a decreasing one, as shown in Figure 1.[33] If $\tau_0 = \tau_S$, however, the resulting optimal protection sequence will be stationary with $\tau_0 = \tau_1 = \tau_2 = \cdots$. If there exists such a stationary protection level, $\tau_S \in [0, h)$ under *PTS* with $G(\tau_S) = \tau_S$ and $l = \tau_S$, then H would continue to set its protection level at l until a punishment phase begins, satisfying a prerequisite for *PTS* to be a sequential equilibrium of the repeated game. An increasing optimal policy correspondence itself, however, does not rule out the possibility that the only stationary protection level of the dynamic problem in (9) is h, as demonstrated by $G'(\tau_{-1})$ in Figure 1.

If there exists a stationary protection level $\tau_S \in [0, h)$ with $G(\tau_S) = \tau_S$, such a τ_S should satisfy the following first-order condition for a stationary equilibrium, denoted by *IC*:

(11) **(*IC*)** $\partial F(\tau_S, \tau_S)/\partial\tau + \delta^C[1 - Pr(\tau_S)]\cdot[\partial V(\tau_S)/\partial\tau] = 0,$

where $\partial F(\tau_S, \tau_S)/\partial\tau = \partial u(\tau_S, l)/\partial\tau$ and $\partial V(\tau_S)/\partial\tau = -[\partial Pr(\tau_S)/\partial\tau]\{u(\tau_S, l) + \delta^C V(\tau_S) - [u(\tau_S, h) + (\delta^C - \delta)V_N + \delta V_C]\}$.[34] For τ_S to be a stationary protection level for H, the static incentive to raise the protection level, $\partial F(\tau_S, \tau_S)/\partial\tau > 0$ in (11), must be balanced by the dynamic incentive to avoid a costly punishment phase in the future, $\delta^C[1 - Pr(\tau_S)]\cdot[\partial V(\tau_S)/\partial\tau] < 0$ in (11). If $\partial^2 Pr(\tau)/(\partial\tau)^2 > 0$ with $[\partial^2 Pr(\tau)/(\partial\tau)^2][1 - Pr(\tau)] - \{1 + \delta^C[1 - Pr(\tau)]\}[\partial Pr(\tau)/\partial\tau]^2 > 0$ for all τ

[31] Even though the optimization problem in (8) does not take a standard form for which a dynamic programming method is typically applied, *Lemma 2* in the online technical appendix establishes the equivalence between (8) and (9) as well as proves other standard dynamic programming results for V and G.

[32] *Lemma* 3 in the online technical appendix proves these results on characterizing V and G.

[33] If the cooperative protection level is set too low under *PTS* with $l = \tau_0'$, then H would keep raising the protection level above the cooperative one until it reaches a stationary level, τ_S, and the opposite is true if the cooperative protection level is too high with $l = \tau_0''$. Blonigan and Park (2004) identify that a similar dynamic behavior emerges in the context of an exporting firm's dynamic pricing problem in the presence of antidumping policy; once an exporting firm becomes subject to an antidumping duty, it would either continue to decrease its export price (thus, having the duty increase over time) or continue to increase its export price (thus, having the duty lowered over time) depending on whether initial export pricing is higher or lower than a stationary pricing.

[34] While I cannot assume differentiability of $V(\tau)$ on $\tau \in [0, h]$, $V(\tau)$ is differentiable on any $\tau \in G(\tau_{-1})$ and $\tau \in (0, h)$ for each $\tau_{-1} \in [0, h]$, according to the generalized differentiability result of Cotter and Park (2006). Therefore, (11) is indeed a necessary condition for any stationary protection level that belongs to $(0, h)$. Thus it serves as an incentive constraint (*IC*) for H to sustain the cooperative protection level, $l = \tau_S$ under *PTS*.

$\in [0, h]$ and $\partial Pr(\tau)/\partial\tau \approx 0$ at $\tau = 0$, then I can show that there exists a unique stationary equilibrium protection level $\tau_S \in (0, h)$ with $G(\tau_S) = \tau_S$, using the first-order condition in (11).[35]

According to this result, it is possible to have *IC* in (11) satisfied for some $\tau_S < h$ if the sensitivity of F's private information in detecting a rise in H's concealed protection, $\partial Pr(\tau_S)/\partial\tau$, increases as H's concealed protection level rises with $\partial^2 Pr(\tau)/(\partial\tau)^2 > 0$. On the one hand, H's static incentive to raise its protection level, $\partial F(\tau_S, \tau_S)/\partial\tau = \partial u(\tau_S, l)/\partial\tau$ in (11), diminishes as τ_S increases with $\partial^2 u(\tau_S, l)/\partial\tau^2 < 0$, reaching zero at $\tau_S = h$. On the other hand, H's dynamic incentive to avoid a future punishment phase, $\delta^C[1 - Pr(\tau_S)]\cdot[\partial V(\tau_S)/\partial\tau]$ in (11), may diminish or intensify in response to an increase in τ_S, depending on the value that $\partial^2 Pr(\tau_S)/\partial\tau^2$ takes. The absolute value of $\delta^C[1 - Pr(\tau_S)]\cdot[\partial V(\tau_S)/\partial\tau]$ rises in response to a rise in τ_S if $[\partial^2 Pr(\tau)/(\partial\tau)^2][1 - Pr(\tau)] - \{1 + \delta^C[1 - Pr(\tau)]\}[\partial Pr(\tau)/\partial\tau]^2 > 0$ for all $\tau \in [0, h]$. This in turn guarantees the existence of a unique $\tau_S \in (0, h)$ that satisfies *IC* in (11) with $\partial Pr(\tau)/\partial\tau \approx 0$ at $\tau = 0$.[36]

While the above result specifies the condition under which H (and F) would follow *PTS* by keeping its protection at *l* until a punishment phase is triggered, this result assumes that the lengths of punishment phases satisfy the conditions in *Lemma 1* (*a*). Because such lengths of punishment phases vary with the cooperative protection level to be sustained under *PTS*, it still remains to be shown whether there exist *PTS* that simultaneously satisfy the conditions in *Lemma 1* (*a*) and *IC*. The following section provides an affirmative answer.

3. Optimal Private Trigger Strategies

This section establishes that symmetric countries can sustain a symmetric cooperative protection level under *simple PTS* as defined in the previous section if the sensitivity of their private information satisfies certain conditions. In addition, this section establishes that any equilibrium payoff under *symmetric PTS* that start an *initial* punishment phase by imposition of

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[35] *Lemma 4* (*a*) in the online technical appendix proves the existence of a unique stationary protection level. It also proves that such a τ_S is also a globally stable equilibrium with $G(\tau) > \tau$ for $\tau \in [0, \tau_S)$ and $G(\tau) < \tau$ for $\tau \in (\tau_S, h)$, which is a contributing factor to the stability of *PTS* as an equilibrium of the repeated game. This is because H will eventually return to its globally stable behavior of setting $\tau = \tau_S$ (= l) after any arbitrary perturbations (which are possibly caused by errors) in its protection level choices.

[36] Having $\partial^2 Pr(\tau_S)/\partial\tau^2 > 0$ can be crucial in discouraging the use of concealed protection under *PTS*. If $\partial^2 Pr(\tau)/(\partial\tau)^2 = 0$, for example, $\delta^C[1 - Pr(\tau_S)]\cdot[\partial V(\tau_S)/\partial\tau]$ in (11) decreases as τ_S increases, creating the possibility that *IC* in (11) is not satisfied for any $\tau_S < h$.

a static optimal tariff should be identical to the payoff under *simple PTS*. After proving the existence and uniqueness (in terms of payoffs, among a certain class of trigger strategies) of *symmetric PTS* as a sequential equilibrium in Section 3.1, I characterize optimal *simple PTS* under which H and F maximize their joint expected discounted payoffs in Section 3.2.

3.1. Private Trigger Strategies and Uniqueness Results

I can derive an implicit function of a cooperative protection level, denoted by $I(l)$, such that $I(l) = 0$ guarantees the existence of *simple PTS* that simultaneously satisfy the conditions in *Lemma 1* (*a*) and *IC*. To derive such a function, first assume that there exists τ_S that satisfies *IC* in (11) with $\tau_S = l$. This implies that $V(\tau_S) = V_C$, and I can rewrite *IC* in (11) as follows:

(12) $\partial u(\tau_S, l)/\partial\tau = \delta^C[\partial Pr(\tau_S)/\partial\tau][1 - Pr(\tau_S)][u(\tau_S, l) - u(\tau_S, h) + (\delta^C - \delta)(V_C - V_N)]$.

Now, assume that the lengths of punishment phases are determined by the conditions in *Lemma* 1 (*a*); $\delta^C - \delta = [u(h, l) - u(l, l)]/(V_C - V_N)$ and $\delta^C - \delta^S = 2(\delta^C - \delta)$. By substituting $\delta^C - \delta$ with $[u(h, l) - u(l, l)]/(V_C - V_N)$, (12) can be rewritten as the following implicit function, $I(l)$:

(13) $I(l) \equiv \partial u(l, l)/\partial\tau - \delta^C[\partial Pr(l)/\partial\tau][1 - Pr(l)][u(h, l) - u(l, h)] = 0$.

If there exists l satisfying $I(l) = 0$, note that such l will also satisfy *IC* in (11) with $\tau_S = l$, $\delta^C - \delta = [u(h, l) - u(l, l)]/(V_C - V_N)$, and $\delta^C - \delta^S = 2(\delta^C - \delta)$. Using $I(l)$, *Proposition 1* provides a sufficient condition for the existence of *simple PTS* that countries can sustain along the equilibrium path of a sequential equilibrium of the game:

Proposition 1. If $\partial^2 Pr(l)/(\partial l)^2 > 0$ with $[\partial^2 Pr(l)/(\partial l)^2][1 - Pr(l)] - \{1 + \delta^C[1 - Pr(l)]\}[\partial Pr(l)/\partial l]^2 > 0$ for all $l \in [0, h]$, $\partial Pr(l)/\partial l \approx 0$ at $l = 0$, and there exists at least one protection level, $l_s < h$, such that $I(l_s) = 0$, then H and F can employ *simple PTS* with $l = l_s$, $\delta^C - \delta = [u(h, l_s) - u(l_s, l_s)]/(V_C - V_N)$, and $\delta^C - \delta^S = 2(\delta^C - \delta)$ along the equilibrium path of a sequential equilibrium of the repeated protection-setting game. (See the appendix for proof)

The sufficient condition in *Proposition 1* does not necessarily imply that the second term of $I(l)$ in (13), $\delta^C[\partial Pr(l)/\partial\tau][1 - Pr(l)][u(h, l) - u(l, h)]$, representing H's dynamic incentive to avoid a tariff war, increases in response to a rise in l.[37] Thus, one may consider the case in which multiple values of l satisfy $I(l) = 0$ as illustrated in Figure 2; $l = l_{\max}$ as well as $l = l_{min}$

satisfy $I(l)$ = 0. Denoting the minimum of such l by l_{min}, then *simple PTS* with $l = l_{min}$ will Pareto-dominate the others when $Pr(l)$ is small enough.[38]

While the above result establishes that symmetric countries may employ *simple PTS* characterized by *Proposition 1* (and *Definition 1*) in restraining the use of concealed trade barriers, one may wonder whether there exist other (symmetric) private trigger strategies that may outperform this simple one. Surprisingly, there is no loss of generality in focusing on this *simple PTS* to characterize the optimal *symmetric private trigger strategies* as long as the explicit tariff that starts an *initial* punishment phase is the static optimal tariff of each country.

Denote the level of τ that initiates the first (or *initial*) punishment phase with $e > 0$ by d_0 and the cooperative protection level for the *initial* cooperative periods (prior to any punishment being triggered) by l_0, thus focusing on *symmetric PTS* where the cooperative protection level and the protection level that starts an *initial* punishment phase are stationary at least prior to an *initial* punishment phase.[39] Then, I can show that the equilibrium payoff of such *symmetric PTS*, denoted by $V(l_0; d_0)$, is a function of only l_0 and d_0 with

$$V(l_0;d_0) = \frac{u(l_0,l_0)}{1-\delta^C} - Pr(l_0)\frac{u(d_0,l_0)-u(l_0,d_0)}{1-\delta^C}, \tag{14}$$

where $Pr(l_0) = Pr(\omega_t^* \in \Omega^D)$ given $(\tau_t, e_t) = (l_0, 0)$ and $(\tau_t^*, e_t^*) = (l_0, 0)$.[40] Thus, this result establishes that one can fully characterize the equilibrium payoff of any *symmetric PTS* only with information on l_0 and d_0, which are incentive-compatible.[41] If $l_0 = l$ and $d_0 = h$, note that the equilibrium payoff of any *symmetric PTS* is identical to the payoff of *simple PTS*

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[37] For the proof of this claim, see the proof of *Proposition 1* in the appendix.

[38] Note that $u(l_{min}, l_{min}) > u(l_{max}, l_{max})$ and $Pr(l_{min}) < Pr(l_{max})$ imply a higher cooperative-period payoff and a lower probability of punishment phases with $l = l_{min}$ than with $l = l_{max}$. While the lengths of punishment phases may be longer with $l = l_{min}$ than with $l = l_{max}$, an increase in l will lower the expected discounted payoff under *simple PTS* if $Pr(l)$ is close enough to 0, as shown in (16) of the following subsection.

[39] While *symmetric PTS* under consideration require that the expected discounted payoff of a country after an initial punishment has been triggered by a single country does not depend on the identity of the punishment-triggering country, *symmetric PTS* do not require $s(t) = s(t^*)$ for all $t \geq 1$. In fact, *symmetric PTS* do encompass all symmetric strategies subject only to the constraints described here. The online technical appendix provides a formal definition of so-called "*almost strongly*" *symmetric PTS* under consideration in *Definition 3*.

[40] The online technical appendix provides a proof of this result in *Proposition 4*.

[41] The above result remarkably simplifies the task of characterizing the payoff frontier attainable under any *symmetric PTS*; one only needs to identify l_0 and d_0 that are incentive-compatible, which in turn maximize the payoff in (14). Using this, the online technical appendix establishes that countries cannot attain the symmetric efficient frontier with $V_C = u(l_0, l_0)/(1 - \delta^C)$ and $l_0 = 0$ as their equilibrium payoffs if their private signals entail non-negligible errors in detecting concealed trade barriers with $Pr(l_0) > 0$; thus, this corollary to *Proposition 4* is an anti-folk theorem result.

characterized in *Proposition 1* with $V(l; h) = u(l, l)/(1 - \delta^C) + Pr(l)[u(h, l) - u(l, h)]/ (1 - \delta^C)$.[42] With regard to the issue of characterizing the efficient frontier among this subset of *symmetric PTS* with $d_0 = h$, one can thus focus on *simple PTS* characterized in *Proposition 1*.

3.2 Optimal Private Trigger Strategies

Up to this point, I have assumed that the range of private signals that trigger a punishment phase, Ω^D, is fixed. Countries can change the cooperative protection level by changing the range of private signals that trigger punishment phases, Ω^D, because this affects the probability of a punishment phase being triggered in response to the potential use of concealed trade barriers. This section characterizes the optimal *simple PTS*, or equivalently, the optimal *symmetric PTS* with $l_0 = l$ and $d_0 = h$ as defined in the preceding section, by focusing analysis on the choice of Ω^D that maximizes the expected discounted payoffs of countries. I abbreviate optimal *simple PTS* to optimal *PTS* hereafter, unless it is necessary to distinguish them.

The private signal $\omega \in \Omega$ has two distinctive yet related quality dimensions as a measure that detects the potential use of concealed protection. One is the *sensitivity* of the signal in detecting possible defections, which links a higher protection to a higher probability that a punishment phase is triggered. The other is the *stability* of the signal that rewards cooperative behaviors with a lower probability of a punishment phase. I can represent the sensitivity by $Pr^{\prime}(\tau) \equiv \partial Pr(\tau)/\partial\tau > 0$ and the stability by $1 - Pr(\tau)$ measured at $\tau = l$.

A change in the range of private signals that trigger a punishment phase may affect these qualities of signals in different directions. In particular, countries may raise the sensitivity by properly expanding the range of private signals that trigger punishment phases, Ω^D, but at the cost of undermining the stability. By denoting the degree of such expansion with a parameter ω^D, which is termed a *trigger control variable*, I can formalize this trade-off that countries face in choosing ω^D by assuming $\partial Pr^{\prime}(\tau)/\partial\omega^D > 0$ and $\partial Pr(\tau)/\partial\omega^D > 0$.

The analysis of optimality in this section focuses on *simple PTS* identified in *Proposition 1*, with the cooperative protection level determined by the choice of ω^D. Assuming that ω^D uniquely determines l with $I(l) = 0$, I can represents l as a function of ω^D, $l = l(\omega^D)$. Using $V(l_0; d_0)$ in (14), the expected discounted payoff under *simple PTS* is

[42] One can derive the same expected discounted payoff of H under the *simple PTS* from (6) using $\delta^C - \delta = [u(h, l) - u(l, l)]/(V_C - V_N)$ and $\delta^C - \delta^S = 2(\delta^C - \delta)$.

(15) $$V_C \equiv V(\underline{s}, \underline{s}^*) = V(l_0 = l; d_0 = h) = \frac{u(l,l)}{1-\delta^C} - Pr(l)\frac{u(h,l)-u(l,h)}{1-\delta^C},$$

where ($\underline{s}$, $\underline{s}^*$) are *simple PTS* defined in *Definition 1*. Note that the expected discounted payoff in (15) no longer depends on the lengths of punishment phases. Therefore, I can describe the optimal choice for ω^D using the following first-order condition:

(16) $$\frac{\partial V_C}{\partial \omega^D} = \frac{\partial V_C}{\partial l}\frac{\partial l(\omega^D)}{\partial \omega^D} + \frac{\partial V_C}{\partial Pr}\frac{\partial Pr(l)}{\partial \omega^D} = 0, \text{ with}$$

$$\frac{\partial V_C}{\partial l} = \frac{\partial u(l,l)}{\partial l}\frac{1}{1-\delta^C} - Pr^{/}(l)\frac{u(h,l)-u(l,h)}{1-\delta^C}$$
$$- Pr(l)\frac{\{\partial u(l,l)/\partial\tau^* - \partial u(l,l)/\partial\tau\}}{1-\delta^C} < 0 \text{ for } Pr(l) \text{ being close to 0,}$$

$$\frac{\partial l(\omega^D)}{\partial \omega^D} = -\frac{\partial I/\partial\omega^D}{\partial I/\partial l} < 0 \text{ iff } \frac{\partial Pr^{/}(l)}{\partial \omega^D}[1-Pr(l)] - \frac{\partial Pr(l)}{\partial \omega^D}Pr^{/}(l) > 0, \text{ and}$$
$$\frac{\partial V_C}{\partial Pr}\frac{\partial Pr(l)}{\partial \omega^D} = -\frac{\partial Pr(l)}{\partial \omega^D}\frac{[u(h,l)-u(l,h)]}{1-\delta^C} < 0,$$

where $I \equiv I(l)$ is the implicit function defined in (13). The first-order condition is informative regarding the trade-off that countries face in choosing an optimal ω^D. Raising the trigger control variable, ω^D, will have a positive effect on the expected discounted payoff by lowering the cooperative protection level since $\partial l/\partial\omega^D < 0$ and $\partial V_C/\partial l < 0$, but it also has a negative effect on the expected payoff by raising the probability that a punishment phase is invoked, as shown by $\partial V_C/\partial\omega^D < 0$ in (16). Thus, the optimal ω^D should balance the gain from raising the sensitivity of the private signal (and thus achieving a lower l) against the loss from reducing the stability of the cooperative equilibrium with a higher probability of a punishment phase.

When the initial ω^D is at a very low level, it is generally possible to lower l by raising the trigger control variable. For example, if $\Omega^D = \varnothing$, then $l = h$ and $Pr(l) = Pr^{/}(l) = 0$, implying $\partial l/\partial\omega^D < 0$ with $\partial Pr^{/}(l)/\partial\omega^D > 0$ from (16). Once I assume that $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$, which makes the effect of a higher ω^D on $Pr(l)$ constant, it is possible show that $\partial l/\partial\omega^D = 0$ for an adequately high ω^D.[43]

[43] $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$ implies $\partial^2 Pr^{/}(l)/\partial(\omega^D)^2 = 0$ by Young's theorem; $\partial^2 Pr^{/}(l)/\partial(\omega^D)^2 = \partial[\partial^2 Pr(l)/\partial(\omega^D)^2]/\partial l = 0$. This in turn implies that $[\partial Pr^{/}(l)/\partial\omega^D][1 - Pr(l)] - [\partial Pr(l)/\partial\omega^D]Pr^{/}(l) = 0$ for an adequately high value of ω^D. Note that $\partial l/\partial\omega^D = 0$ for such a value of ω^D because $[\partial Pr^{/}(l)/\partial\omega^D][1 - Pr(l)] - [\partial Pr(l)/\partial\omega^D]Pr^{/}(l) = 0$ implies $\partial l/\partial\omega^D = 0$, as their relationship identified in (16) entails.

Even when it is possible to raise ω^D to such a point that countries would no longer be able to lower the cooperative protection level any further with $\partial l/\partial\omega^D = 0$, note that it is never optimal to do so. If countries were to raise ω^D in this way, then the first order condition for the optimal ω^D in (16) will be violated with $\partial V_C/\partial\omega^D = (\partial V_C/\partial Pr)(\partial Pr(l)/\partial\omega^D) < 0$, implying that countries can increase their payoffs by lowering the trigger control variable. One can use a similar argument to show that setting $l = 0$ cannot be optimal when $\partial u(l, l)/\partial l = 0$ at $l = 0$ and $\partial Pr(l)/\partial l \approx 0$ at $l = 0$, as assumed in *Proposition 1*. I summarize these characterizations of the optimal *PTS* in the following proposition.

Proposition 2. Assume that the sufficient conditions for the existence of equilibrium *simple PTS* in *Proposition 1* are satisfied. In addition, assume that $\partial Pr^{/}(l)/\partial\omega^D > 0$, $\partial Pr(\tau)/\partial\omega^D > 0$, and $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$, where ω^D denotes the *trigger control variable* associated with an expansion of Ω^D. Then, under the optimal *PTS*, countries do not raise ω^D to the level that reduces the cooperative protection level to its minimum attainable level where $\partial l/\partial\omega^D = 0$. In particular, the optimal *PTS* will not set $l = 0$, with $\partial u(l, l)/\partial l = 0$ at $l = 0$.

The characterization of the optimal *PTS* in *Proposition 2* emphasizes the need for tolerating some level of concealed trade barriers under *PTS*. For example, setting the concealed trade barriers to zero in the cooperative period is not optimal; a slightly higher cooperative protection level obtained by choosing a slightly lower ω^D would cause no first-order loss as free trade is efficient with $\partial u(l, l)/\partial l = 0$ at $l = 0$; rather, it would decrease the likelihood that a costly punishment phase is triggered.[44] One cannot directly apply *PTS* for understanding Section 301 of the U.S. Trade Law under which the United States Trade Representative (USTR) follows an elaborate procedure prior to initiating a punishment against potential deviant actions of other countries. However, Special Section 301, which is aimed at protecting U.S. intellectual property rights (IPR) in foreign markets, does illustrate the U.S. government's willingness to tolerate some level of deviations from agreements, reserving retaliatory sanctions mainly for considerable deviations. In applying Special Section 301, the USTR specifies not only "Priority Foreign Countries" who are "pursuing the most onerous or egregious policies that have the greatest adverse impact on U.S. right holders or products, and are subject to accelerated investigations and possible sanctions" but also a "Priority Watch List" of countries "who do not provide an adequate level of IPR protection or enforcement, or market access for persons relying on intellectual property protection."[45] Such a practice may not lead to the maximal protection of U.S. IPR, but it may reduce the probability of costly tariff wars.

4. A Possible Role for the WTO: Optimal Third-Party Trigger Strategies

Regarding the issue of enforcing international trade agreements, this paper focuses on a phenomenon that the trade literature has not fully explored: Countries may form diverse opinions about potential violations of trade agreements. In the absence of a third party like the WTO that can generate supposedly impartial opinions about such violations, Section 2 and 3 of this paper explore the possibility that countries adopt *private trigger strategies*, under which each country initiates punishment phases based on its own imperfect private signals of the other country's potential use of concealed trade barriers. In particular, this paper characterizes optimal *PTS* in an attempt to describe what countries can achieve with regard to trade policy coordination in the absence of the WTO, which is a prerequisite for analyzing how the WTO can facilitate improved coordination, especially given that the WTO can only supply an opinion on potential violations without any coercive power to impose its opinions upon countries.

To understand a possible role that the WTO can play under imperfect private monitoring of potential violations of international trade agreements, this section analyzes *third-party trigger strategies* under which a third party, such as the WTO, decides upon whether a violation has occurred and asks each country to initiate a punishment phase based on its decision. Given the characterization of optimal *PTS* in the previous section, the comparison between the optimal *third-party trigger strategies* and optimal *PTS* illustrates how and to what degree the WTO can help countries to enforce trade agreements beyond what countries can do alone.

This paper does not attempt to build a model that can proxy the actual operation of the WTO in addressing potential violations and associated trade disputes; however, as I discuss in the conclusion, this in itself would be a meaningful research project. Instead, this section considers *third-party trigger strategies* under which the only role that the WTO plays is that of providing an impartial third-party (and thus *public*) opinion of violations, so that trigger

[44] A similar characterization has been developed for optimal cartel trigger price strategies by Porter (1983).

strategies are no longer subject to the constraints imposed by the *private* nature of signals of violations under *private triggers strategies* such as *ICP*. This analysis thus illustrates a minimum role that the WTO can play in helping countries improve their trade policy coordination.

In order to directly compare *third-party trigger strategies* and *PTS* characterized in Section 3, I make the following assumptions in this section. The stage-game payoffs and action variables of H and F are the same as those described in Section 2. In addition to these two players, there exists the WTO, a third party supposedly neutral with regard to the issue of enforcing international trade agreements. At the end of period *t*, the WTO obtains $\omega_t \in \Omega$ and $\omega_t^* \in \Omega^*$, which are the same private signals that each country receives regarding the other country's potential violations. One may model a mechanism under which each country truthfully reports its private signals to the WTO in a non-public manner if the WTO can verify the reported signals. For simplicity, this section simply assumes that the WTO has access to such signals. While the WTO's information on τ_t and τ_t^* would still be imperfect due to the existence of non-observable random components, $\varepsilon_t^u \in E^u$, the WTO has an informational superiority over countries given this access to the private signals of both countries. The analysis of how the WTO may utilize such informational superiority, which itself is attributable to the WTO's neutrality, is an interesting topic. As mentioned earlier, this paper assumes that this possibility does not exist and instead simply focuses on the possible role of the WTO in relaxing the constraints on the lengths of punishment phases imposed by the private nature of signals that trigger punishments, namely the conditions specified in *Lemma 1* (*a*).[46] Therefore, the following analysis will characterize how changing *private trigger strategies* into *third-party trigger strategies* with the help of the WTO may improve the enforcement of international trade agreements, controlling for the quality of available information about potential deviations.

Once again, Ω^D denotes the range of private signals that triggers H (or F) to initiate a punishment phase by imposing an explicit tariff, but it is the WTO that tells each country to initiate such a punishment phase in *third-party trigger strategies*. The infinitely repeated

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[45] These quoted definitions come from the USTR website (http://www.ustr.gov).

[46] Among the two roles that the WTO can play, namely, a *coordinating* role (i.e., publicly announcing when and who must initiate a punishment) and an *information-pooling* role (i.e., utilizing its informational superiority), this

protection-setting game between H and F stays the same as before, except that now the WTO tells (or does not tell) each country to initiate a punishment phase by imposing an explicit tariff based on its own (that is, the WTO's) signals of potential deviations. Note that these signals are not made public unless the WTO decides to make them public. For simplicity, I denote the WTO's decision to tell H to initiate a punishment phase in period t based on its signals received at the end of period $t-1$ by $\mu_{t\text{-}1} \in M \equiv \{1, 0\}$, with $\mu_{t\text{-}1}$ equal to 1 *iff* $\omega_{t\text{-}1} \in \Omega^D$; a similar decision to tell F to initiate a punishment phase is denoted by $\mu^*_{t\text{-}1} \in M^* \equiv \{1, 0\}$. Then, a strategy for each country is defined by $s^{W^i} = (s^{W^i}(t))_{t=1}^{\infty}$, similarly to the ones in Section 2, with

$$(17) \qquad s^W(t) : A^{t-1} \times M^{t-1} \times M^{*^{t-2}} \times E^{*^{t-1}} \to A \text{ and } s^{W^*}(t) : A^{*^{t-1}} \times M^{*^{t-1}} \times M^{t-2} \times E^{t-1} \to A^*$$

where M^{t-1} and $M^{*^{t-1}}$, respectively denote the history of the WTO's decision to tell H and F to initiate a punishment phase up to period $t-1$. Note that strategies defined in (17) allow each country to observe the WTO's decision for the other country to initiate a punishment phase only afterwards. This strategy specification, under which each country chooses its current action without knowing the WTO's current decision on the other country's initiation of a punishment phase, may seem unnatural. However, it enables a direct comparison between *third-party trigger strategies* and *PTS* of Section 2 by making these two types of strategies differ only in their ability to select the lengths of punishment phases. Henceforth, the analysis will focus on *third-party trigger strategies* defined in *Definition 2* below.

(i) Given that period $t-1$ is a *cooperative* period with $(e_{t-1}, e^*_{t-1}) = (0, 0)$, each country keeps cooperating by setting $(\tau^i_t, e^i_t) = (l, 0)$ as long as the WTO does not tell it to initiate to a punishment phase with $\mu_{t\text{-}1}{}^i = 0$ with $i = *$ or none.

(ii) Given that period $t-1$ is a *cooperative* period with $(e_{t-1}, e^*_{t-1}) = (0, 0)$, the WTO tells H to initiate a punishment phase by setting $(\tau_t, e_t) = (h, 0)$ *iff* $\omega_{t-1} \in \Omega^D$ and it tells F to initiate a punishment phase by setting $(\tau^*_t, e^*_t) = (h, 0)$ *iff* $\omega^*_{t-1} \in \Omega^D$.

(iii) Given that a *punishment phase* is initiated in period $t-1$ by only one country, countries set $(\tau, e) = (h, h)$ and $(\tau^*, e^*) = (h, h)$ for the following $(T-2)$ periods, and they continue to

paper exclusively focuses on the *coordinating* role of the WTO. As discussed later in Footnote 63, these two roles can be complementary with each other.

do so for one more period with probability λ. Given that a *punishment phase* is initiated in period $t - 1$ by both countries simultaneously, countries set $(\tau, e) = (h, h)$ and $(\tau^*, e^*) = (h, h)$ for the following $(T^S - 2)$ periods, and they continue to do so for one more period with probability λ^S. T and T^S are integers that are greater than or equal to 2, and λ and λ^S belong to [0, 1]. Each country knows these variables (T, T^S, λ, λ^S) when it initiates a punishment phase, and the actual length of a punishment phase is determined by some public randomizing device (based on values of λ and λ^S) after a punishment phase being initiated.

(iv) In period 1 and other *initial* periods directly after the end of any punishment phase, the WTO tells each country with probability Pr to initiate a punishment phase by setting $(\tau^i, e^i) = (h, h)$, while the WTO does not tell each country with probability $(1 - Pr)$ to initiate a punishment phase, so that each country continues to set $(\tau^i, e^i) = (l, 0)$, where $Pr = Pr(\omega_t^i \in \Omega^D)$ with $(\tau_t, e_t) = (l, 0)$ and $(\tau_t^*, e_t^*) = (l, 0)$.

Definition 2. If (i), (ii), (iii), and (iv) describe ($\underline{s}^W$, $\underline{s}^{W*}$), then ($\underline{s}^W$, $\underline{s}^{W*}$) are *third-party trigger strategies* (*TTS*) with (l, Ω^D, T, T^S, λ, λ^S) as characterizing parameters.

Given this definition, it is easy to check that the expected discounted payoff under ($\underline{s}^W$, $\underline{s}^{W*}$) with (l,Ω^D, T, T^S, λ λ^S), denoted by $V^W(\underline{s}^W, \underline{s}^{W*})$, is identical to $V(\underline{s}, \underline{s}^*)$ in (6). Once again, I have $(\delta^C - \delta)$ and $(\delta^C - \delta^S)$ respectively represent the relative length of the punishment phase initiated by one country and by both countries simultaneously.

While the expression for the expected discounted payoff under *TTS* defined above is the same as the one under *PTS* defined in *Definition 1*, there exists an important distinction between these two types of trigger strategies. The WTO has no incentive to lie about its private signals so that *TTS* are not subject to the *ICP*. This implies that one can choose any values for the lengths of punishment phases, $(\delta^C - \delta)$ and $(\delta^C - \delta^S) \in [0, \delta^C]$. Recall that $\delta^C - \delta = [u(h, l^c) - u(l^c, l^c)]/(V_C - V_N)$ and $(\delta^C - \delta^S) = 2(\delta^C - \delta)$ under *PTS*. To make the comparison between *TTS* and *PTS* even simpler, I make one more assumption that $(\delta^C - \delta^S) = 2(\delta^C - \delta)$ holds under *TTS*, thus allowing full flexibility only over the choice of $(\delta^C - \delta)$, which is the length of a punishment phase initiated a single country. This enables one to ascertain whether the lengths of punishment phases under optimal *PTS* are too short or too long relative to optimal *TTS* by comparing the endogenously determined value for $(\delta^C - \delta)$ under optimal *PTS* with the optimal choice of $(\delta^C - \delta)$ under *TTS*. Given this assumption of $(\delta^C - \delta^S) = 2(\delta^C - \delta)$, one can simplify $V^W(\underline{s}^W, \underline{s}^{W*})$ into $V_C{}^W \equiv V^W(\underline{s}^W, \underline{s}^{W*}) = (1 - Pr)[u(l, l) - u(h, h)]/[1 - \delta^C + 2Pr(\delta^C - \delta)] + V_N$ with $V_N = u(h, h)/(1 - \delta^C)$.

In order that *TTS* is an equilibrium of the repeated protection-setting game between H and F, *TTS* must satisfy the following incentive constraint, denoted by IC^W:

$$(\boldsymbol{IC^W}) \qquad I^W(l) \equiv \partial u(l, l)/\partial\tau - \{\delta^C[\partial Pr(l)/\partial\tau][1 - Pr(l)][u(l, l) - u(l, h) + (\delta^C - \delta)(V_C{}^W - V_N)]\} = 0.$$

Note that IC^W is identical to IC in (12) under *PTS* as long as δ under *TTS* is the same as under *PTS*. This equivalence results from constructing *TTS* in a way that it may only differ from *PTS* in its flexibility to allow a single-country-initiated punishment phase to last for any length. The intuition behind this equivalence between *IC* under *PTS* and IC^W under *TTS* is quite simple. Each country chooses its protection level during cooperative periods, knowing that raising the protection level increases the probability of a punishment phase being triggered in the same manner under both trigger strategies.

In addition to IC^W, there is one more incentive constraint that *TTS* must satisfy: Each country has an incentive to follow the WTO's decision to initiate a punishment phase. Because the WTO's decision becomes *public* (i.e., known to all players) with a one period lag, one may construct a punishment strategy off equilibrium path in response to the behavior of not following the WTO's decision. While it is easy (and, standard in the literature) to show that each country has an incentive to follow the WTO's decision under a permanent Nash tariff war punishment as long as the discount factor, δ^C, is high enough, it might be more natural to posit that a violation of the WTO decision would leave to the unraveling of the WTO and a return to the private trigger strategy equilibrium. If the expected discounted payoff under *TTS* is strictly greater than the payoff under *PTS*, then such a punishment scheme of reverting to the *PTS* equilibrium (possibly forever) would also work.[47] In the following analysis, I assume that each

[47] Because *TTS* defined in this section differ from *PTS* only in the length of punishment phases on the equilibrium path, it is possible to have the expected discounted payoff under *TTS* be identical to that under *PTS*. As shown in the following numerical analysis, the length of punishment phases under the two optimal strategies may become identical with imperfect signals having certain parameter values. Under more general *TTS*, such as those allowing $(\delta^C - \delta^S) \neq 2(\delta^C - \delta)$ or those utilizing the potential informational superiority of the WTO, I conjecture that the expected discounted payoff under such *TTS* would be strictly greater than under *PTS*.

country has an incentive to follow the WTO's decision under the punishment of reverting to the *PTS* equilibrium or to the static Nash tariff war given an adequately high value for δ^C.

For analytical simplicity, one can represent a choice of (T, λ) by a real number $T^W \in [1, \infty)$, with $\delta^C - (\delta^C)^{T^W} = (\delta^C - \delta)$. $T^W = 1$ (which is equivalent to the case of $T = 2$ and $\lambda = 0$) is the case in which any country's initiation of a punishment phase by imposing its static optimal tariff is not followed by any punishment period in which countries play a Nash tariff war, thereby representing the shortest possible punishment phase. $T^W \to \infty$ is the case in which a permanent Nash tariff war is followed by an initiation of a punishment phase, representing the longest possible punishment phase.[48] Then, the problem of finding the optimal *TTS* is equivalent to solving the following maximization problem:

$$\text{(18)} \qquad \underset{\omega^D \text{ and } T^W \in [1,\infty)}{Max} \left\{ \frac{[1-Pr(l)][u(l,l)-u(h,h)]}{1-\delta^C + 2Pr(l^c)[\delta^C - (\delta^C)^{T^W}]} + V_N \right\} \text{ subject to}$$
$$\frac{\partial u(l,l)}{\partial \tau} = \delta^C \frac{\partial Pr(l)}{\partial \tau}[1-Pr(l)]\{u(l,l)-u(h,h)+[\delta^C - (\delta^C)^{T^W}](V_C^W - V_N)\},$$

where ω^D represents a *trigger control variable*, defined in the same way as in Section 3.2.

Because the problem of finding the optimal *PTS* in Section 3.2 is to choose only ω^D to maximize the same payoff function as in (18) subject to the same incentive compatibility condition but with T^W (or equivalently, corresponding T and λ) determined by $\delta^C - (\delta^C)^{T^W}$ = $[u(h, l^c) - u(l^c, l^c)]/(V_C{}^W - V_N)$, it is obvious that the optimal *TTS* involved in solving the maximization problem in (18) will yield an expected discounted payoff that is greater than (or at least equal to) that under the optimal *PTS*. The question is how and to what degree the less-constrained optimal *TTS* will outperform the optimal *PTS*.

Analyzing the first-order conditions of the maximization problem for optimal *TTS* in (18) can provide some insight into the factors that determine the optimal choice of ω^D and T^W as follows:

[48] Under *TTS*, it is not impossible to choose $T^W \in (0, 1)$ by setting $T = 1$ and $\lambda \in (0, 1)$. For example, the WTO uses its own randomizing device in determining whether to tell each country to impose its static optimal tariff for one period with probability λ if $\omega \in \Omega^D$ or $\omega^* \in \Omega^D$. To make a direct comparison between *PTS* and *TTS*, once again I limit the choices of T^W, with $T^W \in [1, \infty)$.

$$\frac{dV_C^W}{d\omega^D} = \frac{\partial V_C^W}{\partial l}\frac{\partial l}{\partial \omega^D} + \frac{\partial V_C^W}{\partial Pr}\frac{\partial Pr(l)}{\partial \omega^D} = \left(-\frac{\partial V_C^W / \partial l}{\partial I^W(l)/\partial l}\right)\frac{\partial I^w(l)}{\partial \omega^D} + \frac{\partial V_C^W}{\partial Pr}\frac{\partial Pr(l)}{\partial \omega^D} = 0,$$

$$\frac{dV_C^W}{dT^w} = \frac{\partial V_C^W}{\partial l}\frac{\partial l}{\partial T^w} + \frac{\partial V_C^W}{\partial T^W} = \left(-\frac{\partial V_C^W / \partial l}{\partial I^W(l)/\partial l}\right)\frac{\partial I^W(l)}{\partial T^W} + \frac{\partial V_C^W}{\partial T^W} = 0$$

with

(19) $$\frac{\partial V_C^W}{\partial Pr} = -\frac{\{[1-\delta^C + 2[\delta^C - (\delta^C)^{T^W}]\}[u(l,l) - u(h,h)]}{\{1-\delta^C + 2Pr[\delta^C - (\delta^C)^{T^W}]\}^2} < 0 \text{ and}$$

$$\frac{\partial V_C^W}{\partial T^w} = \frac{2\ln(\delta^C)(\delta^C)^{T^W} Pr(1-Pr)[u(l,l) - u(h,h)]}{\{1-\delta^C + 2Pr[\delta^C - (\delta^C)^{T^W}]\}^2}$$

$$= \frac{-2\ln(\delta^C)(\delta^C)^{T^W} Pr(1-Pr)}{1-\delta^C + 2[\delta^C - (\delta^C)^{T^W}]}\frac{\partial V_C^W}{\partial Pr} < 0,$$

where $I^W(l)$ represents the implicit function defining IC^W above, while $\partial l/\partial\omega^D = -(\partial I^W/\partial\omega^D)/(\partial I^W/\partial l)$ and $\partial l/\partial T^W = -(\partial I^W/\partial T^W)/(\partial I^W/\partial l)$ generate the second equality for $dV_C{}^W/d\omega^D$ and $dV_C{}^W/dT^W$, respectively. The expression after the second equality for $\partial V_C{}^W/\partial T^W$ is obtained using the expression for $\partial V_C{}^W/\partial Pr$ in (19). As explained in Section 3.2, the optimal choice of ω^D involves a balance between its positive effect of lowering the cooperative protection and its negative effect of increasing the probability of costly punishment phases. Similarly, increasing the length of a punishment phase has a positive effect of lowering the cooperative protection level by strengthening punishment, but it also entails a negative effect of increasing the cost of punishment with a costly punishment phase being longer. The optimal choice of T^W also involves balancing between these counteracting forces.

This section focuses on the analysis of an optimal choice of T^W because Section 3.2 provides an analysis of the optimal choice over ω^D; thus, a similar characterization should apply to the one under *TTS*.[49] For a further characterization of an optimal choice of T^W, I assume that the optimal ω^D is an interior solution, and thus, $dV_C{}^W/d\omega^D = 0$.[50] Using $dV_C{}^W/d\omega^D = 0$ together with the second expression for $\partial V_C{}^W/\partial T^W$ in (19), I can rewrite $dV_C{}^W/dT^W$ as follows:

[49] For any given level of T^W, the optimal choice over ω^D under *TTS* should be the same kind of balancing choice as the one under *PTS*. See the above discussion on the choice of ω^D in relation with (19). Therefore, the characterization of an optimal ω^D of *Proposition 2* should apply to the optimal ω^D under *TTS*.

(20)
$$\frac{dV_C^W}{dT^W}=\left(-\frac{\frac{\partial V_C^W}{\partial l}}{\frac{\partial I^W}{\partial l}}\right)\left[\frac{\partial I^W}{\partial T^W}+A\frac{\partial I^W}{\partial \omega^D}\right], \text{ where } A=\frac{2\ln(\delta^C)(\delta^C)^{T^W}Pr(1-Pr)}{1-\delta^C+2[\delta^C-(\delta^C)^{T^W}]}\left(\frac{\partial Pr(l)}{\partial \omega^D}\right)^{-1},$$
$$\text{with } \left(-\frac{\frac{\partial V_C^W}{\partial l}}{\frac{\partial I^W}{\partial l}}\right)<0, \frac{\partial I^W}{\partial T^W}<0, \frac{\partial I^W}{\partial \omega^D}<0, \text{ and } A\frac{\partial I^W}{\partial \omega^D}>0.$$

The above first-order condition for an optimal choice of T^W, which also embodies the first-order condition for the choice of ω^D, reveals the potentially competing nature of these two choice variables in restraining the use of concealed trade barriers. The inequalities $\partial I^W/\partial T^W < 0$ and $\partial I^W/\partial\omega^D < 0$ demonstrate that both of these choice variables can relax IC^W, enabling countries to lower the cooperative protection level, l. For example, consider the case in which the effectiveness of ω^D in relaxing IC^W rises so that the absolute value of $\partial I^W/\partial\omega^D$ (and $A\partial I^W/\partial\omega^D$) increases. Then, the optimal choice of T^W may involve a decrease in T^W and an increase in ω^D to sustain $dV_C{}^W/dT^W = 0$ if $\partial^2 I^W/(\partial T^W)^2 > 0$ and $\partial(A\partial I^W/\partial\omega^D)/\partial\omega^D < 0$.[51] In fact, the following result establishes that the optimal T^W may take corner solutions depending on the probability of a punishment being triggered in the equilibrium, which in turn may depend on the accuracy of information about potential deviations, as shown through a numerical analysis that follows the following *Proposition 3*.

Proposition 3. Given that $\partial Pr^{/}(l)/\partial\omega^D > 0$, $\partial Pr(\tau)/\partial\omega^D > 0$, and $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$ as assumed in *Proposition 2* for the characterization of the optimal *PTS*,

(*a*) the length of a punishment phase initiated by a single country, T^W, equals 1 under the optimal *TTS* if $Pr(l) < \overline{Pr}$, where

$$\overline{Pr}=\frac{-3(1-\delta^C)+\sqrt{[3(1-\delta^C)]^2+16\delta^C(1-\delta^C)}}{8\delta^C},$$

with $\partial\overline{Pr}/\partial\delta^C < 0$ and $\lim_{\delta^C\to 0}\overline{Pr}/\partial\delta^C = 1/3$ so that $\overline{Pr}\in(0,1/3)$ for $\delta^C\in(0,1)$, and

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[50] It is reasonable to assume that $dV_C{}^W/d\omega^D = 0$ for any *TTS* that attains improvement over a one-shot Nash equilibrium because a corner solution for ω^D implies either no punishment for any contingency ($\Omega^D = \emptyset$) or punishment for all contingencies ($\Omega^D = \Omega$).

[51] One can show that $\partial^2 I^W/(\partial T^W)^2 > 0$ but it is difficult prove that $\partial(A\partial I^W/\partial\omega^D)/\partial\omega^D < 0$ given the highly non-linear nature of A in ω^D, unless one introduces stringent assumptions on Pr.

(*b*) the length of a punishment phase initiated by a single country, T^W, goes to ∞ under the optimal *TTS* if $Pr(l) > \underline{Pr}$, where

$$\underline{Pr} = \frac{2 - [u(l,l) - u(h,h)]/[u(l,l) - u(l,h)]}{4 - [u(l,l) - u(h,h)]/[(u(l,l) - u(l,h)]},$$

with $[u(l,l) - u(h,h)]/[u(l,l) - u(l,h)] \in (0,1)$ for $l \in [0,h)$ so that $\underline{Pr} \in (1/3, 1/2)$.

(See the appendix for proof)

According to *Proposition 3*, the length of a punishment phase initiated by a single country under the optimal *TTS* takes its minimum value of $T^W = 1$ if the probability of a punishment phase being triggered is below a critical level, denoted by $\overline{Pr}$. With $T^W = 1$, note that no tariff war period (under which both countries impose their static optimal tariffs) will follow the initiation of any punishment phase.[52] This implies an *asymmetric* punishment in the sense that only the potential deviator is punished, with the punishing country being rewarded by imposing its static optimal tariff, as well as a *minimum* punishment in the sense that the punishment length takes a minimum value.[53]

I first provide a mechanical derivation of this result before an intuitive explanation. The proof for *Proposition 3* in the appendix shows that

$$(21) \qquad \frac{dV_C^W}{dT^W} < BC\left(\frac{\partial Pr}{\partial \omega^D}\right)^{-1} \frac{\partial Pr}{\partial l} \frac{1}{\omega^D} \frac{Pr}{1+\delta^C}\left[(1-Pr)(1+\delta^C) + 2(2Pr-1)(1+Pr\delta^C)\right],$$

where $B \equiv -[(\partial V_C^W / \partial l)/(\partial I^W / \partial l)]\delta^C (\delta^C)^{T^W} ln(\delta^C)(1-Pr) > 0$ and $C \equiv [u(l, l) - u(h, h)]/\{1 - \delta^C + 2Pr[\delta^C - (\delta^C)^{T^W}]\} > 0$, with $Pr \equiv Pr(l)$. The sign of the term on the right side of the inequality in (21) depends on the sign of the terms inside the bracket. If $Pr < \overline{Pr}$, the entire expression in this bracket will take a negative value for any $T^W \geq 1$, implying the optimality of choosing the minimum possible value for T^W, and thus, $T^W = 1$.

While $Pr(l)$ in (21) is endogenously determined by the optimal choice of ω^D, T^W, and the resulting value for *l*, $Pr(l)$ is likely to approach zero when the private signals become very accurate, inducing $Pr(l) < \overline{Pr}$. Thus, $T^W = 1$. If countries can set *l* to be close to 0 with

[52] Note that countries cannot use $T^W = 1$ under *PTS* because countries will have an incentive to initiate such a punishment phase regardless of their private signals.

adequately accurate private signals, then they will have little reason to choose ω^D so that Pr is significantly higher than 0 because a tariff war is costly for them and little is gained by lowering l any further.[54] Even as Pr dips below $\overline{Pr}$ with adequately accurate private signals, it is not intuitively clear why setting $T^W = 1$ is optimal; a lower Pr reduces the cost associated with raising T^W due to less frequent tariff wars, improving the effectiveness of T^W in relaxing IC^W. One can understand this result by looking at how a change in Pr, possibly caused by a change in the accuracy of private signals, affects the relative effectiveness of T^W and ω^D in relaxing the incentive constraint, IC^W. Note that $(1 - Pr)(1 + \delta^C)$ and $2(2Pr - 1)(1 + Pr\,\delta^C)$ inside the bracket in (21) correspond to $-\,\partial I^W/\partial T^W$ and $A\partial I^W/\partial\omega^D$ in (20), thus respectively representing the relative effectiveness of T^W and ω^D in relaxing IC^W. While the absolute values of both terms in this bracket rise in response to a decrease in Pr (<1/2), the second one increases faster than the first one. If $Pr < \overline{Pr}$, the absolute value of the second term (i.e., the effectiveness of ω^D) dominates the first one (that is, the effectiveness of T^W) for any $T^W \geq 1$, necessitating the minimization of T^W under the optimal *TTS*.[55]

Proposition 3 (*b*) shows that $T^W \rightarrow \infty$ may also emerge as an optimal punishment length choice under *TTS* if the probability that a punishment phase is triggered is above a critical level, denoted by $\underline{Pr}$. This maximum punishment of playing the Nash tariff war forever once a punishment is triggered is a surprising result because the main reason for countries to coordinate their trade policies is to avoid playing the Nash tariff war, and countries can choose any length for the duration of a punishment phase under *TTS*. Again, it is possible to

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[53] This kind of asymmetric action is often an important characteristic of optimal strategies of repeated games under various applications, such as in Kandori and Matsushima (1998), Compte (1998), and Athey and Bagwell (2001), because such asymmetry allows players to avoid costly actions, at least heavy with dead-weight losses.

[54] If the private signal improves both its sensitivity (i.e., a higher Pr') and stability (i.e., a lower Pr) for any given ω^D, it will decrease l toward 0 to satisfy IC^W. With a sufficiently large improvement in the private signals that induces such l to be close enough to 0 (resulting in $\partial V_C^W / \partial l \approx 0$), the optimal ω^D is likely to decrease to meet the first-order condition, which in turn reduces Pr further toward 0. If the private signals are *almost perfect* and δ^C is adequately high, countries can attain efficient payoffs with $l \rightarrow 0$ and $Pr \rightarrow 0$ even under *PTS*, as shown by Park (2002). Thus, I conjecture that $Pr(l)$ under the optimal *TTS* will approach 0 when the private signals are *almost perfect*.

[55] $\partial\overline{Pr} / \partial\delta^C < 0$ in *Proposition 3* implies that the optimal *TTS* is less likely to involve $T^W = 1$ when countries' relative valuations of future payoffs increase with higher values for δ^C. Once again, one can understand this result by examining how a change in δ^C affects the relative effectiveness of T^W and ω^D in relaxing the incentive constraint, IC^W, measured by the terms in the same bracket in (21). One can show that the effectiveness of T^W increases faster than that of ω^D in response to an increase in δ^C so that the optimal *TTS* is less likely to set $T^W = 1$

understand this sufficient condition for $T^W \to \infty$ by looking at how a change in $Pr(l)$ affects the relative effectiveness of T^W and ω^D in relaxing the incentive constraint, IC^W. From the proof for *Proposition 3* in the appendix,

$$(22)\qquad \frac{dV_C^W}{dT^W} > BD\frac{\partial Pr}{\partial l}\frac{1}{\omega^D}Pr\left[(1-Pr)\frac{u(l,l)-u(h,h)}{u(l,l)-u(l,h)}+2(2Pr-1)\right],$$

where $D \equiv [u(l, l) - u(l, h)]/\langle\{1 - \delta^C + 2Pr[\delta^C - (\delta^C)^{T^W}]\}(\partial Pr/\partial\omega^D)\rangle > 0$, with the first and second terms inside the bracket on the right side of the inequality of (22) respectively representing the relative effectiveness of T^W and ω^D in relaxing IC^W, similarly to those in (21). In response to an increase in Pr possibly caused by deteriorated signal quality, the second term in this bracket decreases faster than the first term. If $Pr(l) > \underline{Pr}$, the effectiveness of ω^D gets smaller than that of T^W even when $T^W \to \infty$, thus generating $dV_C^W/dT^W > 0$ even when $T^W \to \infty$.

Proposition 3 provides a characterization of the optimal *TTS* that depends on the probability of a punishment phase being triggered directly after a cooperative period. One may find that such a characterization is not satisfactory because the characterization relies on $Pr(l)$, a variable that countries choose indirectly by choosing ω^D.[56] One may also wonder about the possibility of more directly comparing the optimal *PTS* and optimal *TTS* in order to understand when they differ from each other and how.[57] In response to such demands, one may try to introduce more structures to the private signals, thus making $Pr(l)$ depend on some accuracy measure of private signals, then characterizing the optimal *TTS* as well as optimal *PTS* depending on such a fundamental variable. Because of the highly non-linear nature of the maximization problem involving two choice variables (T^W and ω^D), as shown through the first-order conditions in (19), pursuing such a characterization is extremely difficult, if not infeasible.

While it might not be possible to derive complete analytical results regarding the characterization of the optimal *TTS* and optimal *PTS* in the way the preceding paragraph discusses, one can conduct a numerical analysis for such a characterization. The following

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when δ^C is higher. If $\delta^C = 1/2$, for example, $\overline{Pr} = 1/4$, implying that $T^W = 1$ is optimal under *TTS* when the probability of a punishment being triggered is less than 1/4. $\overline{Pr}$ will decrease toward zero if δ^C approaches 1.

[56] A positive side of the characterization of optimal *TTS* in *Proposition 3* is that it imposes relatively weak assumptions on private signals and is still able to derive a relatively sharp prediction regarding when corner solutions will emerge as an optimal choice for T^W, depending on the values of $Pr(l)$.

[57] *Proposition 3* does provide results that show how and when the optimal *TTS* would differ from the optimal *PTS* because neither $T^W = 1$ nor $T^W \to \infty$ occur under *PTS*. What is missing is a more continuous comparison of the two strategies, possibly depending on some fundamental variables, such as a measure for the accuracy of signals.

numerical analysis does precisely this, revealing several interesting numerical results. To conduct a numerical analysis, I use the same partial equilibrium trade model as in Bond and Park (2002) in which H exports good 1 and F exports good 2, with $\sigma \in [1, \infty)$ denoting the size of H's markets relative to F's.[58] Demand for good i in H is $D_i = \sigma(A - Kp_i)$, and supply of good i in H is $X_i = \sigma(\alpha_i + \kappa p_i)$, where p_i is the price of good i in H with i = 1 or 2. For F, demand and supply are given by $D_i^* = A - Kp_i^*$ and $X_i^* = \alpha_i^* + \kappa p_i^*$. To ensure that H will export good 1 and import good 2 and that the countries are symmetric, I assume that $\sigma = 1$, $\alpha_1 - \alpha_1^* = \alpha_2^* - \alpha_2 > 0$ and $\alpha_1 = \alpha_2^*$. In addition, I assume that $Pr(l)$ takes the following functional form:

$$
\begin{aligned}
Pr(l) = Pr(l \mid \omega^D; \rho, \chi) &= \omega^D[l^2/(2\chi) + \rho] \quad for \ \ l \le \underline{l}/2, \\
&= \omega^D[(\underline{l} \times l)/\chi - l^2/(2\chi) + \rho - \underline{l}^2/(4\chi)] \quad for \ \ \underline{l}/2 < l \le \underline{l}, \\
&= 1 \quad for \ \ l > \underline{l},
\end{aligned} \tag{23}
$$

where $\bar{l} \equiv 2\sqrt{\chi/\omega^D - \chi\rho}$, $1/\chi \in (0,\infty)$ represents the sensitivity of the signal in detecting an increase in the level of concealed trade barriers, and $\rho \in [0, \infty)$ represents the level of errors in detecting concealed trade barriers (hence, the instability of the signals), making $Pr(l) > 0$ even when $l = 0$ with $\rho > 0$ and ω^D ($\in[0, 1/\rho)$) > 0. While the complicated expression for $Pr(l)$ with $l > \underline{l}/2$ is used to make the probability density function to be symmetric around $\underline{l}/2$ and $Pr(l) = 1$ when $l = \underline{l}$, the equilibrium values for l are all less than $\underline{l}/2$ in the following numerical analysis, thus making this part of the probability definition redundant. $Pr(l)$ as defined in (23) is one of the simplest functional forms for $Pr(l)$, with parameters representing both the sensitivity and instability of private signals, and with $\partial Pr(l)/\partial l > 0$, $\partial^2 Pr(l)/\partial(l)^2 > 0$, $\partial Pr'(l)/\partial\omega^D > 0$, $\partial Pr(\tau)/\partial\omega^D > 0$, and $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$ for $l \le \underline{l}/2$, as assumed in *Proposition 3*.[59]

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[58] As a previous version of this paper, Park (2006) provides an analysis of *PTS* in the presence of asymmetry in the size of trading countries. The following concluding section briefly discusses the effect of introducing such asymmetry on *PTS* as a factor that may limit the use of *PTS* in restraining concealed trade barriers.

[59] One may find $Pr(l) = 1$ for $l > \underline{l}$ not satisfying, especially when $\underline{l} < h$. Thus, one can consider using an adjusted Rayleigh distribution, $Pr(l) = Pr(l \mid \omega^D; \rho, \chi) = 1 - \exp[-(\omega^D l)^2/(2\chi^2) - \rho\omega^D]$, for the numerical analysis because $Pr(l) < 1$ for all $l \in [0, \infty)$. The problem associated with using this Rayleigh distribution is that $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$ is no longer true, and this assumption is what enables the simplification of the first-order condition for T^W in (20), which in turn leads to the analytical results in *Proposition 3*. As a robustness check, I have done a numerical analysis using this probability function and found that the characteristics of optimal *PTS* and optimal *TTS* are qualitatively identical to those shown in the numerical analysis of this section using $Pr(l)$ in (23).

I assume that $\alpha_1 - \alpha_1^* = 3$, $\kappa + K = 1$, which induces $h = 1$ for simplicity.[60] To illustrate how the optimal *TTS* change as the instability of the private signal changes as measured by ρ, Figure 3 shows the outcome of the numerical analysis with $\chi = 1$ and $\delta^C = 0.5$. This indicates each of the following changes in response to an increase in the instability of the signal, ρ, from 80(×0.00005) to 130.2(×0.00005), including (i) the expected percentage payoff gain under the optimal *TTS* as compared with playing the static Nash tariff war forever, $(V_C^W - V_N)/V_N$; (ii) the cooperative protection level, l; (iii) the probability of a punishment phase being triggered, $Pr(l)$; (iv) the length of a punishment phase, T^W; and (v) the trigger control variable choice, ω^D.

As predicted by *Proposition 3*, $T^W = 1$ when $Pr(l) < \overline{Pr} = 1/4$ (using $\delta^C = 0.5$), and $T^W \to \infty$ when $Pr(l) > 4/9$, drawing on the fact that the maximum value that $\underline{Pr}$ can take is 4/9.[61] It also confirms the conjecture that the probability of a punishment phase being triggered in the equilibrium would depend on the accuracy of information about potential deviations (at least in the limits), thus generating $T^W = 1$ for adequately low values of ρ and $T^W \to \infty$ for adequately high values of ρ. Another notable aspect of this numerical result is that when the optimal *TTS* utilize both ω^D and T^W (> 1), $Pr(l)$ decreases in response to an increase in ρ, which is the instability (or inaccuracy) measure of private signals. A possible explanation for this phenomenon once again can be based on the relative effectiveness of ω^D and T^W in relaxing IC^W. If the effectiveness of T^W relative to ω^D improves as ρ increases, then countries will substitute ω^D with T^W, implying a lower ω^D and a higher T^W as shown in the bottom two graphs in Figure 3, which in turn may lead to a decrease in $Pr(l)$ because $\partial Pr(l)/\partial\omega^D > 0$.[62]

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[60] In deriving this result, I assume that each country's welfare function (as a function of τ and τ^*) derived from demand and supply functions with no uncertainties is identical to the ones derived with uncertainties described in Section 2.1. This is a strong assumption but justifiable given the fact that what one really needs are $u(\tau, \tau^*)$ and $u^*(\tau^*, \tau)$ with $\partial u(\tau, \tau^*)/\partial\tau > 0$ at $\tau = 0$, $\partial u^*(\tau^*, \tau)/\partial\tau < 0$, $\partial[u(\tau, \tau^*) + u^*(\tau^*, \tau)]/\partial\tau < 0$, $\partial^2 u(\tau, \tau^*)/\partial\tau^2 < 0$, and $\partial^2 u(\tau, \tau^*)/\partial\tau\partial\tau^* = 0$, properties of welfare functions of the trade model of Bond and Park (2002).

[61] $[u(l, l) - u(h, h)]/[u(l, l) - u(l, h)]$ reaches its minimum at 2/5 with $l = 0$ given the parameter values of the trade model under consideration. I use this minimum value to calculate the maximum value that $\underline{Pr}$ can take.

[62] This explanation presuming that the effectiveness of T^W relative to ω^D improves as ρ increases seems to be in conflict with the explanation for *Proposition 3* (*b*) that in response to an increase in *Pr*, possibly caused by deteriorated signal quality, the second term (the effectiveness of ω^D) in this bracket decreases faster than the first term (the effectiveness of T^W). That is because *Pr* decreases in response to an increase in ρ in the 3rd graph of Figure 3 for $T^W \in (1, \infty)$. However, note that the explanation for *Proposition 3* (*b*) does not exclude the possibility of *Pr* falling in response to deteriorated signal quality as a result of readjusting ω^D in response to an increase in ρ, which would result in an increase in *Pr* if ω^D were held constant. *Proposition 3* (*b*) focuses on how the corner solution of $T^W \to \infty$ may arise for large values of *Pr* (> $\underline{Pr}$), despite the fact that the absolute effectiveness of T^W in relaxing IC^W decreases when the quality of private signals deteriorates, eventually causing $Pr > \underline{Pr}$.

One interesting exercise related to this numerical analysis involves comparing the optimal *TTS* with optimal *PTS*. Continuing to assume the same parameter values, except setting χ at 100 instead of 1 and thus lowering the sensitivity of private signals, Figure 4 compares the optimal *TTS* and optimal *PTS* across the same five variables as in Figure 3 when ρ increases from 30(×0.000005) to 61.9(×0.000005). Note that the bold lines represent variables for the optimal *TTS* and the dotted lines depict variables for the optimal *PT*S. The graphs on the right column in Figure 4 provide zoomed graphs of the same five variables for high values of ρ, from 59(×0.000005) to 61.9(×0.000005) because the variables for *TTS* and *PTS* are very similar for these high values of ρ. One obvious result is that the gains from cooperation under the optimal *TTS* are higher than those under the optimal *PTS*; gains are identical only when $\rho = 60.5$ in Figure 4 with all other variables identical as well. One less obvious but potentially important result is that the gains from moving from the optimal *PTS* to optimal *TTS* are significant when the signals are relatively accurate with low values for ρ. As one can easily tell from the top graphs in Figure 4, such gains can become negligible for high values of ρ. It is important to note that the significant gains from shifting from the optimal *PTS* to optimal *TTS* come from the ability of countries to reduce the length of the punishment phase and substitute it with a higher value for ω^D under *TTS*. The probability that a punishment phase is triggered is higher under *TTS* than under *PTS* for all $\rho < 60.5$ due to a higher value for ω^D. This higher value for ω^D enables countries to support a lower protection level under *TTS* than under *PTS*, as shown in Figure 4 for $\rho < 60.5$.

Given the analytical results in *Proposition 3* as well as the numerical results shown in Figures 3 and 4, I can highlight the main potential benefit of the WTO's presence in enforcing international trade agreements as follows. Even when the (private) signals of violations are relatively accurate, it may be hard for countries to be responsive against potential violations under *PTS* by choosing a higher value for ω^D because initiating a punishment should and will accompany a rather long and costly phase of a tariff war between countries in order to eliminate the incentive to abuse the punishment. Once countries can utilize opinions of an impartial third party, such as the WTO, then countries can employ a more effective punishment, possibly an *asymmetric* and *minimum* punishment with $T^W = 1$, which in turn enables countries to be less tolerant of potential violations, thereby attaining a higher level of cooperation.[63]

5. Concluding Remarks

In the presence of concealed trade barriers of which each country has imperfect private signals, the WTO can facilitate a better cooperative equilibrium in a repeated trade relationship. This is established by comparing optimal *private trigger strategies* (*PTS*) in which each country triggers a punishment phase based on its own private signals with optimal *third-party trigger strategies* (*TTS*) in which the WTO tells a country to start a punishment phase based on its own (i.e., the WTO's) signals, abstracting away any informational advantage or disadvantage of the WTO over trading countries. Prior to discussing the role of the WTO, the analysis first establishes that symmetric countries may restrain the use of concealed trade barriers under *simple PTS* if the sensitivity of their private signals rises in response to an increase in such barriers. The analysis also shows that any equilibrium payoff under *symmetric PTS* will be identical to that under *simple PTS* as long as the initial punishment is triggered by a static optimal tariff, justifying the focus on *simple PTS*. The analysis of optimal *simple PTS* reveals that it is not optimal to reduce cooperative protection to its minimum level due to the cost associated with increasing the probability of costly punishments.

To illustrate how and by what degree the WTO may facilitate countries in enforcing international trade agreements beyond what they can achieve alone under *PTS*, this paper conducts both an analytical analysis of the optimal *TTS* and a numerical comparison of the optimal *PTS* and optimal *TTS*. If the probability of a punishment phase being triggered is lower than a critical level, possibly because of adequately accurate signals of potential violations, the analytical analysis establishes that the optimal *TTS* entail an *asymmetric* and *minimum* punishment. In fact, the opposite result of using a punishment involving a permanent Nash tariff war will emerge under the optimal *TTS* if the probability of a punishment being triggered is higher than a certain level, possibly because of highly inaccurate signals of violations. The

[63] While the optimal *TTS* exclusively focus on the *coordinating* role of the WTO, its *information-pooling* role can be complementary to its *coordinating* role in the following way. The *information pooling* of the WTO can improve the accuracy of signals of potential deviations, which in turn may enable countries to choose a more efficient punishment, such as an *asymmetric* and *minimum* punishment.

presence of the WTO under *TTS* changes the nature of signals that trigger punishments from *private* to *public*, thus enabling countries to employ punishment phases of any length, which in turn, can help countries to attain a better cooperative equilibrium. The numerical analysis illustrates that the WTO's contribution is likely to be more significant when its private signals are relatively accurate so that the lengths of punishment phases are shorter than those under the optimal *PTS*, possibly enabling countries to employ an *asymmetric* and *minimum* punishment.

With regard to the effectiveness of *PTS*, there exist other factors that may severely limit the use of *PTS* so that countries cannot support any level of cooperation, as analyzed in Park (2006), a previous version of this paper. One is a reduction in each country's time lag in readjusting its tariff protection level in response to another country's initiation of a punishment phase by imposing an explicit tariff. The other is asymmetry among countries. Both of these factors may limit the level of cooperation attainable under *PTS* by reducing the lengths of punishment phases that countries can employ against potential deviations.

Recall that each country is willing to initiate a punishment phase involving costly tariff war periods under *PTS* because it can realize some gains in the initial period of a punishment phase by imposing its static optimal tariff unilaterally. If countries can readjust their tariff levels faster so that countries play the static Nash tariff war (almost) instantaneously in response to the initiation of a punishment, then no length of a punishment phase would satisfy the incentive compatibility condition for the truthful revelation of private information, *ICP*.[64] This is because countries will only lose from initiating a punishment, thus making it impossible to support any cooperation under *PTS*.[65] If there exists a large enough asymmetry among trading countries, a similar problem will rise under *PTS*. When the size of one of two trading countries become very small compared to the other one's, then the small country's static optimal tariff

[64] It is sometimes argued that enforcement constraints cannot be relevant in the trade policy setting, since a government can retaliate almost immediately whenever another government defects. This result suggests that such an argument is based on a public-action model and requires substantial modification in a private monitoring setting, as pointed out by a referee of this paper.

[65] Abreu, Milgrom and Pearce (1991) and more recently Sannikov and Skrzypacz (2007) show that shortening the period over which actions are held fixed can hurt the possibilities for cooperation under imperfect public monitoring, possibly making cooperation impossible. While this outcome from shortening the period over which actions are held fixed is similar to that under *PTS*, the driving forces behind these results regarding impossible cooperation are different. Under imperfect public monitoring, shorter periods of fixed action multiply the ways that a player can deviate from the equilibrium, leading to the impossibility of cooperation. Under *PTS*, the impossibility of cooperation arises not because countries can deviate more effectively but because the punishments that countries can use become weakened. Note that only the period that allows tariff levels to be readjusted in

approaches zero because its ability to change the terms of trade by imposing tariff becomes negligible.[66] This implies that there is no length of punishment phase that satisfies the incentive compatibility condition for the small country, eliminating the possibility of supporting any cooperation under *PTS*.[67]

In the presence of factors that may limit the credibility of initiating strong punishments against potential deviations under *PTS*, once again the WTO may facilitate cooperation by changing the nature of information that triggers punishments from *private* into *public*, which in turn restores the credibility of punishments. For example, the WTO mandates a regular review of its members under the Trade Policy Review Mechanism (TPRM), generating public reports that consist of detailed chapters examining the trade policies and practices of its members. According to the WTO's website, "surveillance of national trade policies is a fundamentally important activity running throughout the work of the WTO. At the centre of this work is the TPRM."

Another activity that the WTO does to enforce trade agreements is to settle disputes through its Dispute Settlement Procedure (DSP). When countries form different opinions of potential violations based on their imperfect and private information, the DSP of the WTO may generate third-party rulings on disputed cases and thus public signals about potential deviations. As emphasized in this paper in the analysis of the optimal *TTS*, the availability of an impartial third party's opinion may enable countries to adopt a more efficient punishment, such as an *asymmetric* and *minimum* punishment. This in turn enables countries to be more responsive to

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response to the initiation of punishment phases shortens, while the period over which concealed trade barriers are held fixed remains constant, thus assuming no change in the way that countries can deviate from *PTS*.

[66] McLaren (1999) and Park (2000) analyze trade agreements between countries of asymmetric size in which a small country has no ability to change the terms of trade by its tariff so that its static optimal tariff is zero.

[67] Formal proofs for these results can be found in Park (2006) which is an earlier version of this paper. As correctly pointed out by one of referees of this paper, a proper way to introduce a change in the speed of readjusting tariff protection levels is to make the model into one in which information arrives continuously over time and to shorten the period under which tariff levels are held fixed. The ad-hoc approach of changing the payoff function to some convex combination of the payoff before and after the readjustment of tariffs is adopted to introduce a change in the readjustment speed of tariffs without any change in the basic structure of the model as well as without any change in the readjustment speed of concealed trade barriers. This reflects that the readjustment of concealed trade barriers may take longer than readjusting tariffs because concealed trade barriers often rely on customary practices or implicit agreements, but each country may readjust its tariff level by simply issuing an executive order. Given the logic of the proof, the result regarding the impossibility of cooperation should be still valid even when one properly introduces a change in the readjustment speed of tariffs into the model. A referee's question regarding the focus on symmetry in the triggering event, $\Omega^P = \Omega^{P*}$, in the presence of asymmetry among countries is also legitimate, but the result regarding the impossibility of cooperation given adequately large asymmetry among countries should be valid even when one considers asymmetric triggering events with $\Omega^P \neq \Omega^{P*}$.

potential violations and as a result attain a higher level of cooperation as compared to a situation with no DSP.

While this paper provides a new way of understanding the role that the WTO plays in enforcing international trade agreements, there is still much to be done before a more complete understanding of its role in dispute settlements is reached.[68] One possible way to extend the current analysis of the WTO is to consider a more general punishment scheme that allows countries to engage in non-static Nash actions during the punishment.[69] It is also worthwhile to note that the DSP of the WTO encourages settlements through consultations among disputing parties as a preferred way to address trade disputes. According to the official website of the WTO, "The priority is to settle disputes, through consultations if possible. By July 2005, only 130 of the nearly 332 WTO's dispute cases had reached the full panel process. Most of the rest have either been notified as settled "out of court" or remain in a prolonged consultation phase — some since 1995."[70] This indicates that the DSP plays a role that goes beyond simply generating public signals of potential deviations. Carefully analyzing the role that the DSP of the WTO plays in the context of imperfect private monitoring of potential violations, especially regarding settlements through consultations, would be a meaningful extension of this paper.

[68] Maggi and Stagier (2008) analyze the possible role that the DSP of the WTO plays in completing an incomplete contract and characterize the optimal choice of contractual incompleteness and the DSP design. In a related study, Maggi and Staiger (2009) characterize optimal remedies for breaches of trade agreements in the presence of uncertain political pressure for protection, for which the DSP may generate noisy signals. Assuming similar uncertainty and private political pressure for protection, Beshkar (2008) analyzes how the rulings of the DSP can affect renegotiation of trade agreements in the context of designing a direct revelation bargaining mechanism. However, they do not introduce imperfect private signals of potential deviations into their models, and so such signals play no role in their analyses of the DSP of the WTO.

[69] Even though the current analysis of the WTO focuses on its role of relaxing the constraint on the length of punishments, it already emphasizes the possibility that the guilty party might not be expected to engage in static Nash actions during the punishment by *Proposition 3* (*a*). An asymmetric and minimal punishment, $T^W = 1$, may rise as a part of the optimal *TTS* under which only the punishing party engages in a static Nash action with the guilty party being simply punished in one period with no chance to play a static Nash action in that or following periods as a part of the punishment against its behaviors as determined by the WTO.

[70] This quote comes from the following website: http://www.wto.org/english/thewto_e/whatis_e/tif_e/disp1_e.htm.

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Appendix

Proof of Lemma 1 (a)

It is obvious that *ICP* is a necessary condition and that *ICP* becomes $\delta^C - \delta = [u(h, l) - u(l, l)]/(V_C - V_N)]$ if $\delta^C - \delta^S = 2(\delta^C - \delta)$. Therefore, I only need to show that $\delta^C - \delta^S = 2(\delta^C - \delta)$ is also a necessary condition for each country to truthfully represent its private signals under *PTS*. Note that *ICP* only provides the incentive for each country to truthfully initiate a punishment phase given that it follows the equilibrium strategy of setting $\tau = l$ in a previous, cooperative period. Even when *ICP* is satisfied, there is the deviant possibility of setting $\tau \neq l$ in a current period and starting a punishment phase in a following period, regardless of its private signal, on the contingency that no punishment phase is initiated in the current period. In an equilibrium of the repeated game, there should be no such deviation incentive; the following argument proves that $\delta^C - \delta^S = 2(\delta^C - \delta)$ is necessary for eliminating such an incentive.

For *PTS* defined in *Definition 1* to be equilibrium strategies, each country should have no incentive to set $\tau \neq l$ in any period following a cooperative one or in any *initial* period unless it desires to initiate a punishment phase by setting $\tau = e = h$, regardless of whether it would initiate a punishment or continue cooperating in the following period, on the contingency that no punishment phase is initiated. To derive the necessary condition for such an equilibrium behavior, first note that the expected discounted payoff of setting a total protection level to equal τ in any period following a cooperative period is

$$Pr[u(\tau,h) + (\delta^C - \delta)V_N + \delta V_C]$$
$$+ (1-Pr)\{u(\tau,l) + \delta^C Pr(\tau)[u(l,h) + (\delta^C - \delta)V_N + \delta V_C] + \delta^C[1-Pr(\tau)][u(l,l) + \delta^C V_C]\},\text{ or}$$

$$Pr[u(\tau,h) + (\delta^C - \delta)V_N + \delta V_C]$$
$$+ (1-Pr)\{u(\tau,l) + \delta^C Pr(\tau)[u(h,h) + (\delta^C - \delta^S)V_N + \delta^S V_C] + \delta^C[1-Pr(\tau)][u(h,l) + (\delta^C - \delta)V_N + \delta V_C]\},$$

depending on whether H continues to cooperate (by setting its total protection level equal to *l*) or choose to initiate a punishment phase (by setting its total protection level equal to *h*), respectively, in the following period on the contingency that no punishment phase is initiated after setting its total protection level equal to τ. To be able to support the action of setting $\tau = l$ as an equilibrium action, the following first-order conditions must be satisfied for each expected discounted payoff expressions described above: $\partial u(l, l)/\partial\tau = \delta^C (1 - Pr)[\partial Pr(l)/\partial l][u(l, l) - u(l, h) + (\delta^C - \delta)(V_C - V_N)]$ for the first expression, and $\partial u(l, l)/\partial\tau = \delta^C (1 - Pr)[\partial Pr(l)/\partial l][u(h, l) - u(h, h) + (\delta - \delta^S)(V_C - V_N)]$ for the second one. Using $u(l, l) - u(l, h) = u(h, l) - u(h, h)$, these two-first order conditions imply that $\delta^C - \delta = \delta - \delta^S$, or equivalently $\delta^C - \delta^S = 2(\delta^C - \delta)$.

Proof of Lemma 1 (b)

I prove *Lemma 1* (*b*) in the following way. First, I assume the existence of (δ, δ^S) that satisfies $\delta^C - \delta$ = $[u(h, l) - u(l, l)]/(V_C - V_N)]$ and $\delta^C - \delta^S = 2(\delta^C - \delta)$ such that $V_C \equiv V(\underline{s}, \underline{s}^*)$ in (6) can be rewritten in a simpler form. Given $\delta^C \approx 1$ and $Pr \approx 0$, I show that there indeed exists a unique combination of (δ, δ^S) that satisfies these necessary conditions.

Using $\delta^C - \delta^S = 2(\delta^C - \delta)$, I can simplify $V(\underline{s}, \underline{s}^*)$ in (6) into $V_C = k/[1-\delta^C + 2Pr(\delta^C - \delta)] + V_N$ with $k = (1-Pr^2)[u(l,l) - u(h,h)] + Pr(1-Pr)[u(l,h) - u(l,l)] + Pr(1-Pr)[u(h,l) - u(l,l)]$. To denote the value of δ that satisfies *ICP* with $V_C = V_C(\delta_0) \equiv k/[1-\delta^C + 2Pr(\delta^C - \delta_0)] + V_N$, define $\delta_e(\delta_0) \equiv$ $\delta^C - (1-\delta^C)[u(h,l) - u(l,l)]/[(1-\delta^C)V_C(\delta_0) - u(h,h)] = \delta^C - [u(h,l) - u(l,l)][1-\delta^C + 2Pr(\delta^C - \delta_0)]/k$. If there exists a unique value of $\delta_0 \in (0, \delta^C)$ such that $\delta_e(\delta_0) = \delta_0$ and $\delta^S = 2\delta_0 - \delta^C \in (0, \delta^C)$ when $\delta^C \approx 1$ and $Pr \approx 0$, then the proof is complete for *Lemma 1* (*b*). First, note that $\partial\delta_e(\delta_0)/\partial\delta_0$ $= 2Pr[u(h,l) - u(l,l)]/k > 0$ approaches zero if $Pr \approx 0$. Second, note that $\delta_e(\delta_0)$ approaches δ^C with $\delta_e(\delta_0) < \delta^C$ when $\delta^C \approx 1$ and $Pr \approx 0$, including the case when $\delta_0 = 0$. These two facts together imply that there exists a unique value of $\delta_0 \in (0, \delta^C)$ such that $\delta_e(\delta_0) = \delta_0$ when $\delta^C \approx 1$ and $Pr \approx 0$. If δ^C ≈ 0 and $Pr \approx 0$, $\delta_0 < \delta^C$ and $\delta_0 \approx \delta^C$ for δ_0 that satisfies $\delta_e(\delta_0) = \delta_0$, thus $\delta^S = 2\delta_0 - \delta^C \in (0, \delta^C)$.

Proof of Proposition 1

With $\delta = \delta^C - [u(h, l_s) - u(l_s, l_s)]/(V_C - V_N)$ and $\delta^C - \delta^S = 2(\delta^C - \delta)$, setting $\tau_S = l_s$ satisfies *IC* in (11). Thus, l_s is the unique stationary protection level from which H (and F by symmetry) does not have any incentive to deviate, as shown in *Lemma 4* in the online technical appendix. If $l = l_s$, then *simple PTS* satisfy *ICP*, $\delta^C - \delta^S = 2(\delta^C - \delta)$, and *IC*. This ensures the sequential rationality of *simple PTS* for all information sets reachable along the equilibrium path under *simple PTS*: No country has any incentive to deviate on such information sets given its consistent (i.e., following Bayes' rule) belief that the other country's continuation strategy is to follow the specified strategy under *simple PTS*.

To establish that countries follow *simple PTS* along the equilibrium path of a sequential equilibrium, I first define a sequence of strategy profiles that generate positive probabilities for all possible histories of publicly observable actions, denoted by (s^N, s^{*N}), and associated systems of beliefs that follow Bayes' rule, denoted by (β^N, β^{*N}). By properly constructing (s^N, s^{*N}), I ensure that $(\underline{s}, \underline{s}^*)$ is the limit of (s^N, s^{*N}) with $N \to \infty$. Each country's system of beliefs associated with $(\underline{s}, \underline{s}^*)$, denoted by $(\underline{\beta}, \underline{\beta}^*)$, is defined to be the limit of (β^N, β^{*N}). Given $(\underline{\beta}, \underline{\beta}^*)$, I establish that *simple PTS* is a sequentially rational strategy even for information sets that follow public deviations.

I define (s^N, s^{*N}) to be a strategy profile that is identical to $(\underline{s}, \underline{s}^*)$, except that in any punishment phase each country sets its explicit tariff (e^i) with a mixed strategy that induces e^i to be a random variable, having $e^i = h$ with probability $1 - 1/N$ and other e^i $(\neq h)$ follow a positive probability density function with $Pr(e^i \geq 0) = 1$. As an example of such (s^N, s^{*N}), one can consider a strategy of having $e^i = h$ with probability $1 - 1/N$ and other e^i $(\neq h)$ follow the probability density function, $1/(e^i + N)^2$ (thus, of a Pareto distribution), which in turn generates the following probabilities: $Pr(e^i = h) = 1 - 1/N$, $Pr(e^i > e^p) = 1/(e^p + N) + 1 - 1/N$ for $e^p \in [0, h)$, and $Pr(e^i > e^p) = 1/(e^p + N)$ for $e^p \geq h$. Note that every possible history of explicit tariff combinations may emerge as a part of its equilibrium path under (s^N, s^{*N}). This implies that any country's information set off the equilibrium path mush follow that country's own deviation(s), enabling each country to form its system of beliefs based on Bayes' rule. Denote such a consistent system of beliefs of each country associated with (s^N, s^{N*}) by (β^N, β^{N*}).

Given the construction of (s^N, s^{N*}), it is obvious that $(\underline{s}, \underline{s}^*) = \lim_{N\to\infty} (s^N, s^{N*})$. There remain two things to do: (i) showing that following *simple PTS* is a sequentially rational strategy for information sets that follow public deviations, and (ii) characterizing each country's sequentially rational continuation strategies for information sets that follow its own private deviations. For the first task, recall that *simple PTS* require each country to choose its static optimal action, $(\tau^i, e^i) = (h, h)$, in all periods under any punishment phase, regardless of whether any public deviation has occurred or not during the punishment phase. After observing any public deviation, under $(\underline{\beta}, \underline{\beta}^*)$, note each country would believe that the other country's continuation strategy is to follow *PTS*. This is because $(\underline{\beta}, \underline{\beta}^*)$ is the limit of (β^N, β^{N*}), under which each country develop such a belief based on Bayes' rule. With this consistent belief, following *simple PTS* after observing any public deviation is a sequentially rational strategy, as already shown by the sequential rationality of *simple PTS* along its equilibrium path. For the final task, recall that any total protection level sequence generated by $G(\tau_{-1})$ with τ_{-1} being the previous period's protection level (and e^i being zero in such a sequence) is an optimal pure continuation strategy until a punishment phase is triggered. By defining each country's continuation strategy for any information that follows its own deviation of choosing $\tau \neq l$ to be such an optimal protection sequence generated by $G(\cdot)$, I complete the description of a sequential equilibrium strategy profile even for information sets that follow each country's own private deviations. For deviations that set $\tau > h$, note that the standard dynamic programming results on $V(\tau)$ and $G(\tau)$ for $\tau \in [0, h]$ of *Lemma 2* in the online technical appendix are readily extendable to the case where τ is any non-negative real number.

What is the relationship between the condition for *Lemma 4* (*a*) in the online technical appendix and the existence of l $(< h)$ that satisfies $I(l) = 0$ in (13)? For example, does the condition for *Lemma 4*

(a), $\partial^2 Pr(l)/(\partial l)^2 > 0$ with $[\partial^2 Pr(l)/(\partial l)^2][1 - Pr(l)] - \{1 + \delta^C[1 - Pr(l)]\}[\partial Pr(l)/\partial l]^2 > 0$ for all $l \in [0, h]$ and $\partial Pr(l)/\partial l \approx 0$ at $l = 0$, guarantee the existence of such an l? To address this issue, I show that the second term of $I(l)$ in (13), $\delta^C[\partial Pr(l)/\partial \tau][1 - Pr(l)][u(h, l) - u(l, h)]$, representing H's dynamic incentive to avoid a punishment phase, may not necessarily increase in l when the condition for *Lemma 4* (a) is satisfied. $\partial\{[\partial Pr(l)/\partial l][1 - Pr(l)][u(h, l) - u(l, h)]\}/\partial l = \langle[\partial^2 Pr(l)/(\partial l)^2][1 - Pr(l)] - [\partial Pr(l)/\partial l]^2\rangle[u(h, l) - u(l, h)] + [\partial Pr(l)/\partial l][1 - Pr(l)]\{\partial[u(h, l) - u(l, h)]/\partial l\} = \langle[\partial^2 Pr(l)/(\partial l)^2][1 - Pr(l)] - \{1 + \delta^C[1 - Pr(l)]\}[\partial Pr(l)/\partial l]^2\rangle [u(h, l) - u(l, h)] + \langle\{\delta^C[1 - Pr(l)]\} [\partial Pr(l)/\partial l]^2[u(h, l) - u(l, h)] + [\partial Pr(l)/\partial l][1 - Pr(l)]\{\partial[u(h, l) - u(l, h)]/\partial l\}\rangle$. Because $[\partial Pr(l)/\partial l][1- Pr(l)]\{\partial[u(h, l) - u(l, h)]/\partial l\} < 0$, one cannot rule out the possibility that $\{\delta^C[1 - Pr(l)]\}[\partial Pr(l)/\partial l]^2[u(h, l) - u(l, h)] + [\partial Pr(l)/\partial l][1 - Pr(l)]\{\partial[u(h, l) - u(l, h)]/\partial l\} < 0$. Thus $\partial\{[\partial Pr(l)/\partial l][1 - Pr(l)][u(h, l) - u(l, h)]\}/\partial l < 0$ even when $[\partial^2 Pr(l)/(\partial l)^2][1 - Pr(l)] - \{1 + \delta^C[1 - Pr(l)]\}[\partial Pr(l)/\partial l]^2 > 0$. Therefore, the condition for *Lemma 4* (a) does not necessarily guarantee the existence of $l\,(< h)$ that satisfies $I(l) = 0$, validating the insertion of an additional condition to guarantee the existence of such an l in *Proposition 1*.

<u>Proof of Proposition 3</u>

For (a): It is sufficient to show that dV_C^W/dT^W in (20) is less than 0 for all values of $T^W \geq 1$ if $Pr(l) < \overline{Pr}$. Using

$$\frac{\partial I^W}{\partial T^W} = \delta^C \delta^{C^{T^W}} \ln(\delta^C)\frac{\partial Pr}{\partial l}(1 - Pr)\left\{(V_C^W - V_N) - \frac{2(\delta^C - \delta^{C^{T^W}})Pr(1-Pr)[u(l,l) - u(h,h)]}{[1 - \delta^C + 2Pr(\delta^C - \delta^{C^{T^W}})]^2}\right\}, \text{ and}$$

$$\text{(A1)}\quad \frac{dI^W}{d\omega^D} = \delta^C\left[-\frac{\partial^2 Pr}{\partial l \partial \omega^D}(1 - Pr) + \frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}\right]\left[u(l,l) - u(l,h) + (\delta^C - \delta^{C^{T^W}})(V_C^W - V_N)\right]$$
$$+\frac{\delta^C(\delta^C - \delta^{C^{T^W}})(\partial Pr/\partial l)(1 - Pr)}{[1 - \delta^C + 2Pr(\delta^C - \delta^{C^{T^W}})]^2}\frac{\partial Pr}{\partial \omega^D}[1 - \delta^C + 2(\delta^C - \delta^{C^{T^W}})][u(l,l) - u(h,h)],$$

I can rewrite dV_C^W/dT^W in (20) as

$$\frac{dV_C^W}{dT^W} = \left(-\frac{\dfrac{\partial V_C^W}{\partial l}}{\dfrac{\partial I^W}{\partial l}}\right)\left\{\begin{array}{l}\delta^C \delta^{C^{T^W}} \ln(\delta^C)\dfrac{\partial Pr}{\partial l}(1 - Pr)(V_C^W - V_N) \\ + \delta^C A\left[-\dfrac{\partial^2 Pr}{\partial l \partial \omega^D}(1 - Pr) + \dfrac{\partial Pr}{\partial l}\dfrac{\partial Pr}{\partial \omega^D}\right]\begin{bmatrix}u(l,l) - u(l,h) \\ + (\delta^C - \delta^{C^{T^W}})(V_C^W - V_N)\end{bmatrix}\end{array}\right\}, \text{ with}$$

$\left[-\dfrac{\partial^2 Pr}{\partial l \partial \omega^D}(1 - Pr) + \dfrac{\partial Pr}{\partial l}\dfrac{\partial Pr}{\partial \omega^D}\right] < 0,$ to have $dV_C^W/d\omega^D = 0$. Using $V_C^W - V_N = \dfrac{(1 - Pr)[u(l,l) - u(h,h)]}{1 - \delta^C + 2Pr(\delta^C - \delta^{C^{T^W}})}$,

$$\frac{dV_C^W}{dT^W} =$$

$$B\left\langle \begin{array}{l} \frac{\partial Pr}{\partial l}\frac{(1-Pr)[u(l,l)-u(h,h)]}{1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})}+ \\ 2Pr\left(\frac{\partial Pr}{\partial \omega^D}\right)^{-1}\left[-\frac{\partial^2 Pr}{\partial l \partial \omega^D}(1-Pr)+\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}\right]\left\{\begin{array}{l} \frac{[1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})][u(l,l)-u(l,h)]}{[1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})][1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]} \\ +\frac{(1-Pr)(\delta^C-\delta^{C^{T^W}})[u(l,l)-u(h,h)]}{[1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})][1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]} \end{array}\right\} \end{array}\right\rangle,$$

with $B \equiv -[(\partial V_C^W / \partial l)/(\partial I^W / \partial l)]\delta^C(\delta^C)^{T^W} \ln(\delta^C)(1-Pr)$.

By replacing $u(l, l) - u(l, h)$ with $u(l, l) - u(h, h)$ in the above expression and using $u(l, l) - u(l, h) > u(l, l) - u(h, h)$, I obtain the first inequality in the following expressions:

$$\frac{dV_C^W}{dT^W} < BC\left\{\frac{\partial Pr}{\partial l}(1-Pr)+2Pr\left(\frac{\partial Pr}{\partial \omega^D}\right)^{-1}\left[-\frac{\partial^2 Pr}{\partial l \partial \omega^D}(1-Pr)+\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}\right]\left[\frac{1-\delta^C+(1+Pr)(\delta^C-\delta^{C^{T^W}})}{1-\delta^C+2(\delta^C-\delta^{C^{T^W}})}\right]\right\}$$

$$< BC\left\{\frac{\partial Pr}{\partial l}(1-Pr)+2Pr\left(\frac{\partial Pr}{\partial \omega^D}\right)^{-1}\left[-\frac{\partial^2 Pr}{\partial l \partial \omega^D}(1-Pr)+\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}\right]\left(\frac{1+Pr\delta^C}{1+\delta^C}\right)\right\}$$

$$= BC\left(\frac{\partial Pr}{\partial \omega^D}\right)^{-1}\frac{\partial (Pr/\omega^D)}{\partial l}\frac{Pr}{1+\delta^C}\left[(1-Pr)(1+\delta^C)+2(2Pr-1)(1+Pr\delta^C)\right],$$

with $\mathrm{C} \equiv [u(l,l)-u(h,h)]/\{1-\delta^C+2\mathrm{Pr}[\delta^C-(\delta^C)^{T^W}]\}$.

To obtain the second inequality, I use $\partial\{[1-\delta^C+(1+Pr)(\delta^C-\delta^{C^{T^W}})]/[1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]\}/\partial T^W$ < 0 and set $T^W \to \infty$ for $[1-\delta^C+(1+Pr)(\delta^C-\delta^{C^{T^W}})]/[1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]$, the last bracketed term in the expression that precedes the second inequality. To obtain the final equality in the above expressions, I use the assumption that $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$; that is $Pr(l)$ is linear in ω^D. With this assumption, I can rewrite $Pr(l) = \omega^D Pr^D(l)$, which in turn implies that $\partial Pr(l)/\partial l = \omega^D[\partial Pr^D(l)/\partial l]$, $\partial Pr(l)/\partial\omega^D = Pr^D(l)$, $\partial^2 Pr(l)/\partial l\partial\omega^D = \partial Pr^D(l)/\partial l$, and $[\partial Pr(l)/\partial l][\partial Pr(l)/\partial\omega^D] = Pr[\partial Pr^D(l)/\partial l]$. Once I rewrite the corresponding terms in the expression that precedes the last equality in this way, I can obtain the last equality. As a result of these transformations, I obtain the following inequalities:

(A2) $$\frac{dV_C^W}{dT^W} < BC\left(\frac{\partial Pr}{\partial \omega^D}\right)^{-1}\frac{\partial (Pr/\omega^D)}{\partial l}\frac{Pr}{1+\delta^C}\left[(1-Pr)(1+\delta^C)+2(2Pr-1)(1+Pr\delta^C)\right] < 0,$$

with the last inequality holding for all values of $T^W \geq 1$ if $(1-Pr)(1+\delta^C)+2(2Pr-1)(1+Pr\delta^C) < 0$, which in turn holds if $Pr(l) < \overline{Pr}$.

For (b): It is sufficient to show that dV_C^W/dT^W in (20) is greater than 0 for all values of $T^W \geq 1$ if $Pr(l) > \underline{Pr}$. As shown above, I can rewrite dV_C^W/dT^W (20) into the following expression, using (A1):

$$\frac{dV_C^W}{dT^W} =$$

$$B\left\langle \begin{array}{l} \dfrac{\partial Pr}{\partial l}\dfrac{(1-Pr)[u(l,l)-u(h,h)]}{1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})}+ \\ 2Pr\left(\dfrac{\partial Pr}{\partial \omega^D}\right)^{-1}\left[-\dfrac{\partial^2 Pr}{\partial l \partial \omega^D}(1-Pr)+\dfrac{\partial Pr}{\partial l}\dfrac{\partial Pr}{\partial \omega^D}\right]\left\{\begin{array}{l} \dfrac{[1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})][u(l,l)-u(l,h)]}{[1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})][1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]} \\ +\dfrac{(1-Pr)(\delta^C-\delta^{C^{T^W}})[u(l,l)-u(h,h)]}{[1-\delta^C+2Pr(\delta^C-\delta^{C^{T^W}})][1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]} \end{array}\right\} \end{array}\right\rangle .$$

By replacing $u(l, l) - u(h, h)$ with $u(l, l) - u(l, h)$ in the above expression and using $u(l, l) - u(l, h) > u(l, l) - u(h, h)$, I obtain the first inequality in the following expressions:

$$\frac{dV_C^W}{dT^W}$$

$$> BD\left\{\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}(1-Pr)\frac{u(l,l)-u(h,h)}{u(l,l)-u(l,h)}+2Pr\left[-\frac{\partial^2 Pr}{\partial l \partial \omega^D}(1-Pr)+\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}\right]\left[\frac{1-\delta^C+(1+Pr)(\delta^C-\delta^{C^{T^W}})}{1-\delta^C+2(\delta^C-\delta^{C^{T^W}})}\right]\right\}$$

$$> BD\left\{\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}(1-Pr)\frac{u(l,l)-u(h,h)}{u(l,l)-u(l,h)}+2Pr\left[-\frac{\partial^2 Pr}{\partial l \partial \omega^D}(1-Pr)+\frac{\partial Pr}{\partial l}\frac{\partial Pr}{\partial \omega^D}\right]\right\}$$

$$= BD\frac{\partial (Pr/\omega^D)}{\partial l}Pr\left[(1-Pr)\frac{u(l,l)-u(h,h)}{u(l,l)-u(l,h)}+2(2Pr-1)\right],$$

with $D \equiv [u(l,l)-u(l,h)]/\left\langle\{1-\delta^C+2Pr[\delta^C-(\delta^C)^{T^W}]\}(\partial Pr/\partial\omega^D)\right\rangle$,

where $[1-\delta^C+(1+Pr)(\delta^C-\delta^{C^{T^W}})]/[1-\delta^C+2(\delta^C-\delta^{C^{T^W}})]<1$ for the last bracketed term in the expression preceding the second inequality is used to obtain the second inequality. To obtain the last equality in the above expressions, once again I use the assumption that $\partial^2 Pr(l)/\partial(\omega^D)^2 = 0$ in the same manner that I used it to obtain the last equality in the corresponding expressions in the proof for *Proposition 3* (*a*). As a result of these transformations, I obtain the following inequalities:

(A3) $$\frac{dV_C^W}{dT^W} > BD\frac{\partial (Pr/\omega^D)}{\partial l}Pr\left[(1-Pr)\frac{u(l,l)-u(h,h)}{u(l,l)-u(l,h)}+2(2Pr-1)\right] > 0$$

with the last inequality holding for all values of $T^W \geq 1$ if $(1 - Pr)[u(l, l) - u(h, h)]/[u(l, l) - u(l, h)] + 2(2Pr - 1) > 0$, which in turn holds if $Pr(l) > \underline{Pr}$.

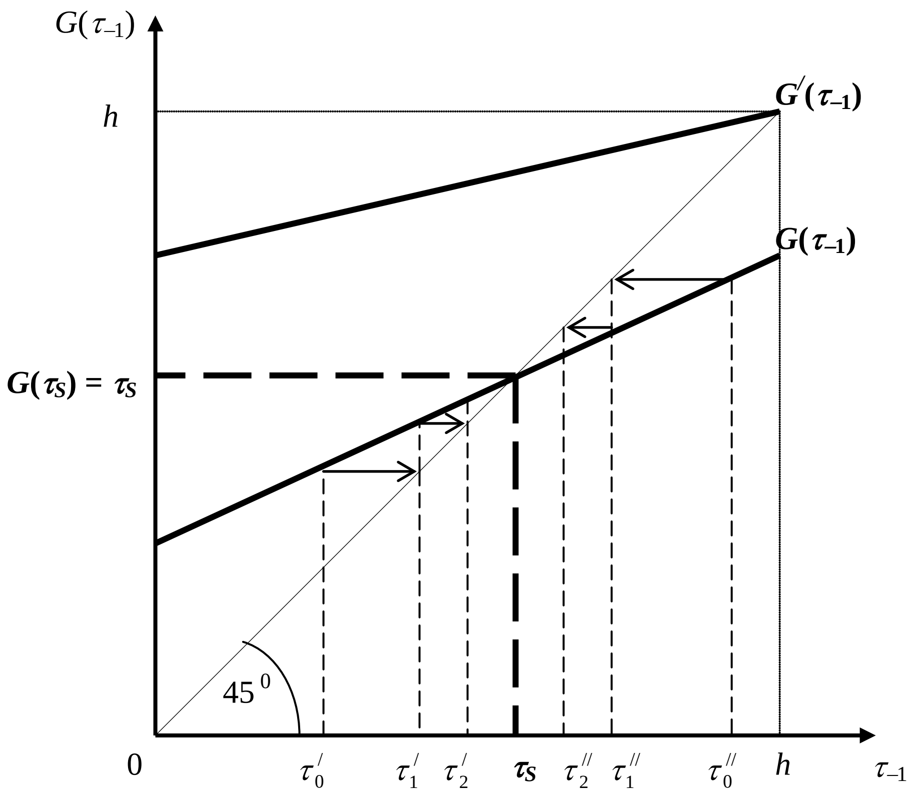

Figure 1. The Existence of a Stationary Protection Sequence at τ_S

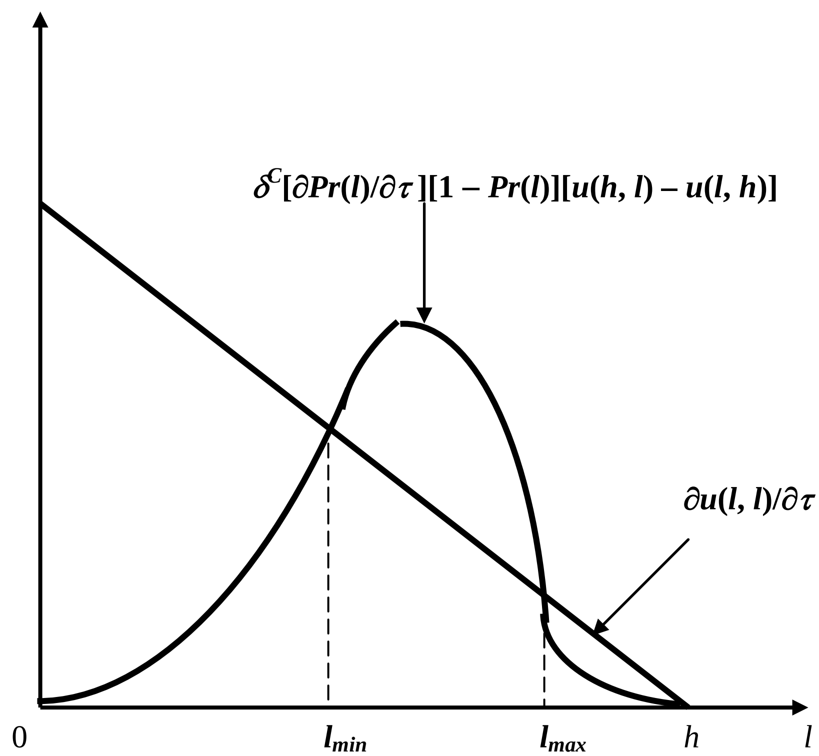

Figure 2. Multiple *l* satisfying *I*(*l*) = 0

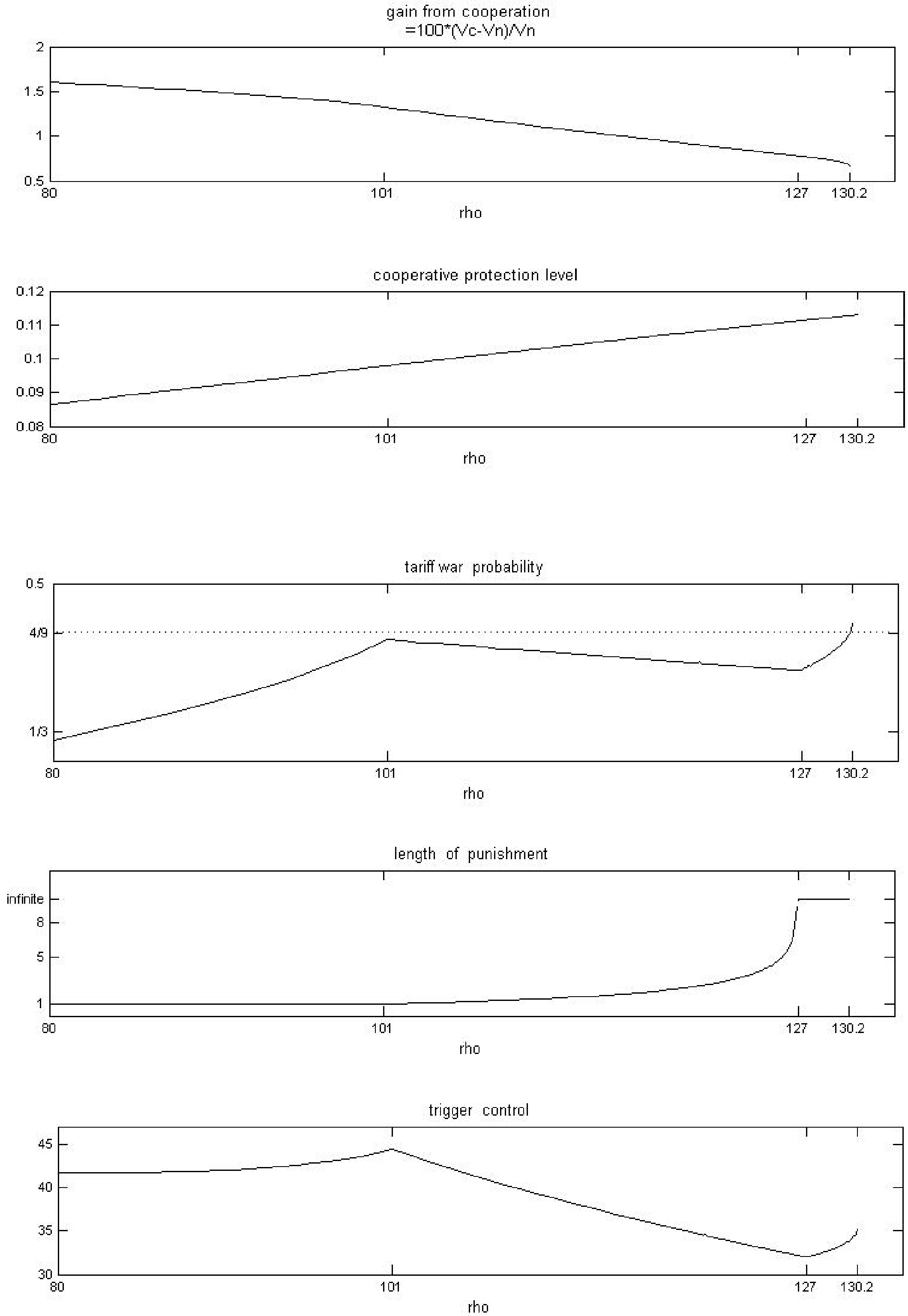

Figure 3. A numerical analysis of the optimal *TTS* for different values of ρ (rho) with $\chi = 1$, $\alpha_1 - \alpha_1^* = 3$, $\kappa + K = 1$ (so, $h = 1$), and $\delta^C = 0.5$

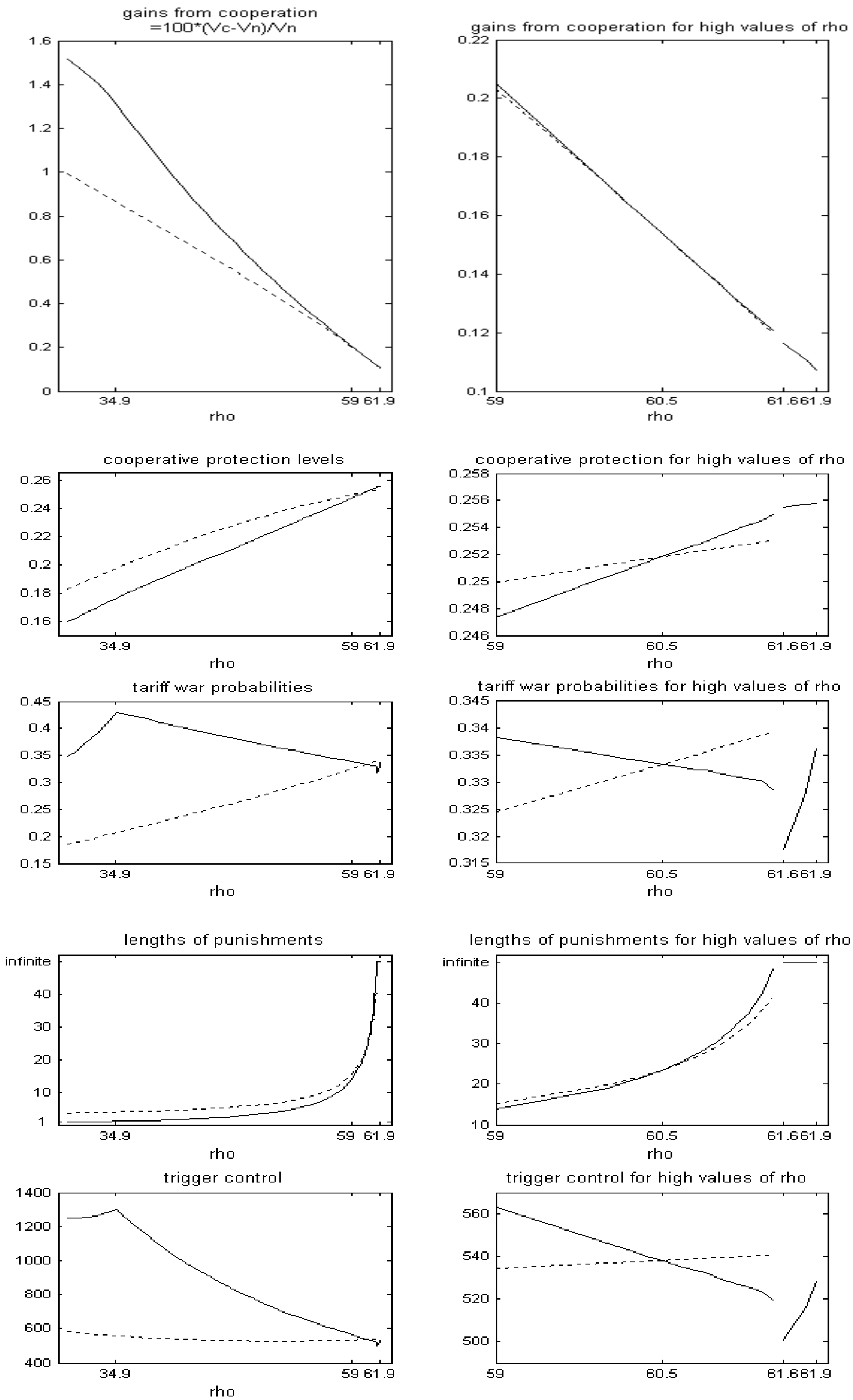

Figure 4. A numerical analysis of the optimal *TTS* and optimal *PTS* for different values of ρ (rho) with $\chi = 100$, $\alpha_1 - \alpha_1^* = 3$, $\kappa + K = 1$ (so, $h = 1$), and $\delta^C = 0.5$