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Warranted Skepticism: A Dynamic Model of Infant Industry Protection*

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ABSTRACT

The neo-classical model of infant industry protection has influenced both policy prescriptions in much of this century, and their empirical evaluations. This paper addresses a fundamental limitation of the neo-classical model, that agents have static expectations. Allowing agents to respond to future expectations alone reveals a previously unexplored relationship between protection and the industry's time path, and provides new policy implications. If an industry is to be protected until its good is competitive in the world market (as suggested in textbooks), its success is as likely as its failure. This explains the unreliability of protection programs in practice, and the mixed nature of empirical evaluations of their effectiveness. The industry's decline after an initial take-off can also be explained as an equilibrium. For the industry's growth to be an equilibrium, protection can be removed before the industry achieves international competitiveness. For the industry's growth to be the unique equilibrium, protection has to continue even after international competitiveness is achieved. This paper presents an analysis of how policy affects the global perfect foresight dynamics in the presence of non-linearities.

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1. Introduction

"The infant industry argument is the oldest and best known rationale for intervention,"[1] of an industry or of the manufacturing sector as a whole. Motivated at least to some extent by the argument, the U. S., Japan, and Germany all began their industrialization processes under protection, and many developing countries attempted import substituting industrialization policies in the decades following World War II.

The current state of knowledge can be summarized as follows. The "neo-classical" trade theory shows that temporary protection of an industry can be justified under the existence of market failures when the Mill-Bastable criteria are satisfied.[2] External economies of scale such as knowledge spillovers, trained-worker spillovers, and inter-industry complementarities are usually pointed out as sources of market failure,[3] and models indicate that protection should be removed once the product is competitive at world market prices. Although most economists agree on the theoretical validity of the argument, the apparent dismal performances of post-World War II interventionist policies have lead to a general skepticism over the practical significance of the infant industry argument, and to a widespread acceptance of market oriented policy stances.[4]

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[1] Krueger (1984, p. 522)

[2] Corden (1974, Chapter 9; 1997, Chapter 8) provides a comprehensive synopsis of the infant industry argument. The Mill criterion requires productivity to increase over time such that the industry can eventually be able to compete under free trade. The Bastable criterion requires the intertemporal social benefit of protection to be greater than the social cost.

[3] Helpman (1984, p. 329) states, "Explanations of external economies — economies of scale which are external to the firm but internal to the industry — rest on the argument that a larger industry takes better advantage of within-industry specialization (the division of labor is limited by the extent of the market, and so is probably the division of other factors of production), as well as better advantage of conglomeration, indivisibilities, and public intermediate inputs such as roads... ." A formulation alternative to external economies is internal economies with capital market imperfection.

[4] Some of the problems of infant industry argument that have been pointed out are: difficulty to identify infant industries, capturing of policy by special interests, lack of competitive pressure keeping firms from becoming efficient, failure of realization of economies of scale due to the small domestic market size, and time inconsistency of policy (Tornell 1991). One objective of our paper is to point out that even without these problems, protection policies can fail.

The empirical literature, however, is inconclusive in evaluating the effectiveness of infant industry protection policies.[5] Krueger and Tuncer (1982, p. 1148) report the absence of a "systematic tendency for more-protected firms or industries to have had higher growth of output per unit of input than less-protected firms and industries" in Turkish data of the 1960's and 70's, but Harrison (1994), on the other hand, finds that the tendency does exist in the same data. Bell, Ross-Larson, and Westphal (1984) report the mixed nature of evidence. Nishimizu and Page (1991) find positive correlation between export growth and TFP growth, but at the same time find negative correlation between import penetration and TFP growth. The literature is still not at ease in evaluating the validity and effectiveness of infant industry protection policies. We attempt to resolve this puzzle by addressing a fundamental shortcoming of the neo-classical infant industry model on which policy prescriptions and empirical evaluations, at least to some extent, have been based: that agents base their behavior on just the current state of the economy.

We consider a typical model of an infant industry, comprising of perfectly competitive producers (firms) with dynamic external economies of scale which are external to each producer and internal to the industry and country. One limitation of the neo-classical models is that despite the dynamic question, agents have static expectations, responding to just the current costs and prices.[6] We depart from the literature by allowing agents to make "investment" decisions responding to expectations of the future. In particular, we assume that agents have perfect foresight over the future paths of the scale of industry and the rate of production subsidy. This brings forward the possibility of multiple self-fulfilling expectations equilibria corresponding to a given subsidy scheme.[7] If the industry is not expected to grow,

[5] Rodrik (1995, pp. 2933-41) provides a survey of the empirical literature.

[6] For example, in both Ethier (1982) and Panagariya (1986), factor reallocation depends on the difference in current returns between two sectors. As with their models and the tradition in the neo-classical international trade literature, we model the external economies to be Marshallian that depend on the scale of the sector. In light of reality, this and the perfect foresight assumptions may be considered as restrictive, but are adopted to produce a benchmark model the results of which can be contrasted with those of other models.

[7] This should be distinguished from models with just internal economies for which the producer does make investment decisions but there is no room for multiple self-fulfilling equilibria since the producer internalizes the economies of scale.

then individual producers do not expect a future increase in productivity (from external economies), and it is possible for each of the producers to find investment not worthwhile even with an initial period of protection. If this is the case, no producer invests, and the expectation that the industry will not grow is fulfilled. On the other hand, under the same protection, if growth of the industry and realization of economies of scale is expected, investment can become worthwhile for individual producers. If this is the case, producers invest and the expectation of the industry's growth is fulfilled. Thus it is possible for the same protection policy to succeed as well as to fail depending on expectations. This is consistent with the unreliability of protectionist programs in practice, warranting the skepticism. This is also consistent with the mixed nature of empirical evidence. In fact, none of the empirical studies seems to take into account this possibility of multiple self-fulfilling expectations equilibria.

In this paper, we go beyond pointing out the possibility of multiplicity of equilibria. We characterize each of the equilibrium paths, and examine how the equilibrium set changes with protection of different durations and effective rates. This yields remarkably different policy implications compared to those in the literature. The neo-classical policy prescription ("textbook policy") is that protection should be applied to effectively set the domestic price (marginally) above the average cost until the industry is competitive in the world market.[8] If this protection is applied in our model, we find that there are multiple self-fulfilling equilibrium paths the industry can follow: the industry can remain in stagnation, it can take-off and grow, it can take-off but U-turn and shrink, or it can go into various cycles.[9,10] The eventual success of the industry is as likely as its eventual failure under this policy.

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[8] By becoming competitive in the world market, we mean that the average cost falls to the level of the current world price of the good. Most textbooks of international trade and economic development indicate this to be the timing of policy removal, with the presumption that agents have static expectations. For example, Krugman and Obstfeld (1997, pp. 150-155) base their discussion on the comparison of average cost and current world price.

[9] Consistent to this result is the finding by Bell, Ross-Larson, and Westphal (1984, p. 123): "... evidence does suggest that many infant firms have failed to reach international competitiveness — or if they have once reached it, have failed to maintain it." They point out cases of firms failing to reach competitiveness, firms reaching competitiveness but failing to maintain it, and firms reaching competitiveness and successfully maintaining it.

[10] Note that in our model, an equilibrium is the time path of the industry's scale.

In our model, to have growth of the industry as *an* equilibrium, protection can end before the industry is competitive in the world market. This is because given expectations that the industry will grow, even producers who are price-takers and who cannot internalize the external economies will be willing to endure current losses in exchange for expected future returns. However, growth may not be the unique equilibrium since "pessimistic" expectations can also be self-fulfilling. In order to have growth as the unique equilibrium, the most pessimistic of expectations must not be self-fulfilling, and for that, the minimal rate of protection has to be sufficiently higher than that implied by the neo-classical model, and protection has to continue even after the industry becomes competitive in the world market.

Furthermore, our model points out that even with perfect foresight expectations, policymakers must distinguish the duration and the rate of protection. We establish the result that protection policy of a shorter duration and a higher rate cannot always substitute that of a longer duration and lower rate. This is true even with perfect foresight expectations. This distinction of rate and duration, as well as the link between protection policies and multiplicity of equilibrium paths have not been addressed in a formal dynamic model before, perhaps due to the complexity of solving global perfect foresight dynamics in the presence of nonlinearities. By incorporating a fundamental behavioral assumption that agents base their behavior on expectations, we are able to expose the rich relationship between policy and outcome, the knowledge of which is vital given the importance of the question in the literature and in practice. The qualitative difference in policy implication makes the neo-classical model's results questionable even as a benchmark.

Details of the Model and Intuitions

Our model is that of a small open economy with two perfectly competitive sectors, agriculture (*A*) and manufacturing (*M*). The infant manufacturing sector is subject to Marshallian external economies: the (current) return in this sector depends positively on its size. Sector *A* has constant returns to scale. We assume that the Mill-Bastable criteria are satisfied to limit ourselves to positive analysis. For perfect foresight dynamics, we adapt the model of Matsuyama (1991).[11] Matsuyama's model is that of real time sectoral adjustment, with perfect foresight guiding the shift of resources from one sector to another. Matsuyama identifies the roles of history and expectations, and as an application considers policy. He shows how subsidies of constant rates applied for an indefinite period can make the favorable equilibrium possible. Our analysis differs in two respects. Firstly, we take a positive approach to the multiplicity of equilibria: our objective is to determine the possible ways in which the economy can behave under each given subsidy scheme. Secondly, we vary both the duration and the rate of subsidy. By varying the duration, we are able to address the issue of the timing of removal of protection. We find that the outcome depends critically on when protection is removed, and establish the aforementioned result that the duration and the rate of protection are not substitutes. We are able to contrast the timing of protection removal with that implied by the neo-classical model. Instead of subsidies of constant rates, we analyze non-linear subsidies whose effects are linear, and by doing so we are able to expose with simplicity the relationship between policy and outcome.

The economy consists of a population of agents, each endowed with one unit of the single (composite) resource called labor. Initially, all the labor is in sector *A*, and the current return on each unit of labor is less in sector *M* than in sector *A* under free trade. Due to external economies, the sector *M* current return is (strictly) increasing in its scale, and becomes greater than the sector *A* current return once past the threshold scale. At this threshold scale the private opportunity cost of *M* undercuts the world relative price of *M*. The neo-classical "textbook policy" is to raise the domestic relative price of *M* such that the sector *M* current return is effectively equal to (or marginally above) the sector *A* current return until this threshold scale is reached.

Over continuous time, agents in the population receive at random (by a Poisson process) separation opportunities to change the sector to which their labor is supplied. To

[11] Krugman (1991), Matsuyama (1992), and Kaneda (1995) also study global perfect foresight dynamics in models of sectoral adjustment.

model inertia, the sectoral choice by each agent is assumed to be irreversible until the arrival of her next separation opportunity. Therefore, it is all but natural for each agent to base the decision on future expectations. A separated agent thus chooses to invest her labor in the sector with higher asset value of labor. The asset value of investing in sector *M* depends on both the expected future path of the scale of sector *M* and the future path of the subsidy rate.

Sectoral choices of separated agents change the allocation of labor between the two sectors, and this over time maps out the time path of the scale of sector *M*. If the expectation is that every future separated agent will invest in sector *M* such that the sector *M* current return will increase over time to become greater than that in sector *A*, then the sector *M* asset value becomes equal to and surpasses that of sector *A* even while the current return is still less in sector *M*. Therefore, in terms of duration, the minimal protection is to subsidize sector *M* until this point is reached: protection can be removed before the private opportunity cost undercuts the world relative price. In terms of rate, the minimal subsidy rate is that which sets the current returns equal during the period of protection since this assures the sector *M* asset value to remain no less than that of sector *A* during this period.

However, under the same policy, all of the agents re-investing in sector *A* over time (stagnation of sector *M*) is also a self-fulfilling equilibrium. This is because if the expectation is that sector *M* remains at zero scale, its current return is less than that of sector *A* at all times except during protection when they are set equal. This means that the sector *M* asset value is less at all times, no agent invests in sector *M*, and the expectation gets self-fulfilled. By the same token, stagnation is also a self-fulfilling equilibrium even if this subsidy is extended to any finite duration. No matter how long the duration of subsidy (except infinity), if the subsidy is that which sets the current returns equal, stagnation of sector *M* is always a possible equilibrium. It follows that for stagnation to not be an equilibrium, it is necessary for the subsidy rate to be higher than that which equates the current returns, or equivalently, higher than that which equates the domestic relative price and private opportunity cost.

The take-off-U-turn-and-decline path is not an equilibrium under free trade, but can be an equilibrium if protection lasts long enough. This is because if a future U-turn and decline of sector *M* is expected, take-off will not occur in the first place unless induced by sufficient protection. Interestingly, the U-turn occurs after the sector *M* private opportunity cost has undercut its world relative price. For the U-turn to be an equilibrium, the sector *M* asset value must turn from greater than to equal to and to less than the sector *A* asset value. For the sector *M* asset value to be greater just before the U-turn, and less just after the U-turn, the sector *M* current return at the U-turn must be greater than the sector *A* current return.

To have take-off and growth as the unique equilibrium, no matter how high the subsidy rate, protection cannot stop before the sector *M* private opportunity cost undercuts its world price, because if the decline of sector *M* is expected from that point on, the sector *M* current return is less than sector *A* from that point on, the sector *M* asset value is less, and U-turn will be self-fulfilled. This also demonstrates that the rate of subsidy and the duration of subsidy are not isomorphic in the model.

The following section presents the model under free trade. Section 3 introduces policy and presents the relationship between the duration of protection and the equilibrium set. Section 4 generalizes the analysis to policies of longer durations and higher rates. Section 5 concludes, and is followed by an Appendix of proofs.

2. Model

We model a small open economy with two perfectly competitive sectors, agriculture (*A*) and manufacturing (*M*), and one factor of production called labor.[12] The economy is populated by a continuum of agents, with each agent endowed with one unit of labor. The

[12] This is the simplest setup that allows the exposition of the logic of our results. The small open economy assumption lets the time paths of the world relative price and the interest rate be exogenous. We further assume the time paths to be constants.

measure of the population of agents is normalized to one, and thus the economy's labor supply equals one.

At each given instant t within continuous time, each agent supplies her one unit of labor inelasticly to either one of the two sectors, and obtains the value of her unit labor's output as current return. The fraction of total labor supply used in sector M is represented by $n(t)$, and this will serve as our state variable since n also represents the scale of sector M. The initial state is zero scale of sector M, i.e. $n(0)=0$, and our objective is to analyze the equilibrium time path of n [0,1] as labor shifts between sectors.

Sector A has a constant returns to scale technology: each unit of labor produces one unit of good A. Sector M is subject to Marshallian external economies of scale. Each unit of labor in sector M produces $k(n)$ units of good M, where labor productivity k is a strictly increasing continuous function of the total labor input n. The difference in the current returns (sector M minus sector A) is:

$$\omega(n, p) = pk(n) - 1, \tag{1}$$

where p is the domestic relative price of good M in terms of the numeraire good A. Under free trade, p equals the world relative price, p^*. To set the stage for infant industry protection, we let $\omega(0,p^*)<0<\omega(1,p^*)$.[13] The scale of sector M that equates the current returns is determined by $\omega(n_{st}, p^*)=0$, and we call n_{st} (0,1) the static threshold.

Intersectoral labor reallocation is modeled by the random arrival of separation opportunities to agents in the population. At each instant, fraction γ of the agents, randomly chosen from the population receive the opportunity to change the sector to which their labor

[13] The sign of $\omega(n, p^*)$ also represents the relationship between the private opportunity cost and the world relative price. When $\omega>0$, we have $1/k(n)<p^*$: the private opportunity cost of M is less than the world relative price of M. When $\omega<0$, the relationship is reversed.

is supplied. Sectoral choice by an agent is irreversible until the next separation opportunity arrives.[14]

If expectations were static, intersectoral labor reallocation would be guided by the difference in current returns, ω. This corresponds to the adjustment processes seen in the literature of infant industry protection. Labor shifts from sector *M* to *A* when ω<0, and from sector *A* to *M* when ω≥0.[15] Since the initial state is *n*=0, sector *M* remains trapped there. The minimal protection policy that enables the infant to grow is to subsidize production of good *M* such that ω (*n*,*p*) is set equal to 0 until *n* becomes as large as n_{st}. Here, the timing of removal of protection is when the private opportunity cost equals the world relative price.

However, since an agent's sectoral choice affects her future returns, this choice is an investment decision which is to be based on the asset value of the sectoral choice instead of the current return difference, ω. An agent receiving a separation opportunity at time *t* decides to supply her labor to sector *M* if the following net asset value is non-negative: [16,17]

$$V(t, n(\ ), p(\ )) = \gamma \int_t^\infty e^{-r(\tau - t)} \omega(n(\tau), p(\tau)) d\tau , \tag{2}$$

where *r* is the world discount rate and agents are assumed to have perfect foresight over the expected paths of *n* and *p*. If *V*<0, labor is supplied to sector *A*.

The change in the state ($\dot{n}$) at each *t* is therefore:

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[14] The separation opportunity arrives by a Poisson process of rate γ which is constant across agents and across time. With a continuum of agents, fraction γ of the population receive the separation opportunity at any moment. The average interval of time between arrivals of two separation opportunities is $\int_t^\infty e^{-\gamma(\tau - t)} d\tau$ (=1/γ). An alternative formulation is seen in Krugman (1991). He assumes quadratic adjustment costs, rendering adjustment to take place over time.

[15] Inclusion of the equality is a tie-breaker rule.

[16] Agents can smooth consumption in the world credit market at discount rate *r*. In equilibrium, *r* can be considered as the sum of γ and the rate of time preference. This is because, in addition to discounting by time preference, future returns from a given sectoral choice need also be multiplied by the probability that the agent has not received the next separation opportunity, $e^{-\gamma(\tau - t)}$. The integral is normalized by dividing by the expected interval of time between two separation opportunities, 1/γ .

[17] What is relevant to the agent is only her future returns influenced by the current choice of a sector; the future sectoral choices after future separations are not dependent on her current sectoral choice.

$$\dot{n}(t, n(t), p(t)) \begin{cases} = -\gamma n(t) & \text{if } V(t, n(\,), p(\,)) < 0 \\ = \gamma\,(1 - n(t)) & \text{if } V(t, n(\,), p(\,)) \geq 0, \end{cases} \tag{3}$$

with a slight abuse of notation in the arguments of the $n(t)$ function. Path $n(\,)$ is a perfect foresight equilibrium if it satisfies (3).[18]

Taking the derivative of (2) with respect to t, we obtain

$$\dot{V}(t, n(t), p(t)) = rV(t, n(), p()) - \gamma\omega(n(t), p(t)). \tag{4}$$

Given that $p(\cdot)$ is at the constant value of p^* under free trade, (3) and (4) describe the global dynamics of the economy on the (n, V) plane, shown in Figure 1. We have a system of unstable spirals around the static threshold n_{st}. On this plane, $\dot{n}=0$ at points S_0 and S_1, $\dot{n}<0$ only if $V<0$, $\dot{n}>0$ only if $V\geq0$. The $\dot{V}=0$ locus is $V=\frac{\gamma}{r}\,\omega(n,p)$, which notably is a positive scalar multiple of the ω function. The value of V depends on the expected path of n, so there is a possibility of a multiplicity of perfect foresight equilibrium paths from a given initial value of n. Points S_0 and S_1 are the steady states of the system, which we call the low level and the high level steady states respectively. Only the saddle paths and the steady states are perfect foresight equilibrium paths since (2) is satisfied only on convergent paths.

Our model makes a fundamental change to the neo-classical model of infant industry protection with Marshallian external economies. We allow agents to base their decisions on future expectations, and the difference in dynamics is striking. The unstable spirals around n_{st} arise due to external economies (ω increasing in n) and positive discounting ($r>0$). Where a path changes directions, the net asset value must change signs ($V=0$). It follows that between any two points of direction change, the discounted sum of current return differences is zero. For example, in Figure 1, take the path for which n

[18] Note that time consistency along an equilibrium path is assured by it being a perfect equilibrium.

increases from n_{a3} to n_{b2}, and then decreases from n_{b2} to n_{a1}. As n increases from n_{a3} to n_{b2}, ω increases as observable on the $\dot{V}=0$ locus, and the discounted sum of ω between n_{a3} and n_{b2} is zero. As n decreases from n_{b2}, since ω decreases, and the far future is discounted more than the near future, n has to decrease past n_{a3} for the discounted sum of ω between the turning points to be zero again.

Figure 1 illustrates the case in which the only free trade equilibrium starting from the initial state of n=0 is to stay there: sector M is stagnant at the low-level steady state S_0. This we take to be the case relevant to analyze infant industry protection.

An observation of Figure 1 will reveal some of our results. If sector M is protected until it grows as large as n_{a1}, the economy can then be on the saddle path towards S_1. n_{a1} is smaller than n_{st}. If protection continues until sector M is as large as n_{a2}, then the economy can be on either of two saddle paths: that which goes to S_1 and that which cycles and goes to S_0. Multiple equilibria are possible, and we provide a formal analysis in the next section.

3. Protection of Sector *M*

(a) Definitions

In Figure 1, there are two saddle paths originating from $n = n_{st}$. Points (n_{a1}, n_{a2}, n_{a3}, ...) and (n_{b1}, n_{b2}, n_{b3}, ...) are where these paths change directions. Appendix A shows how their values are determined.

Equation (3) implies that along any path, $\dot{n}$ must be either -γn or +γ(1-n). Consider now the monotonic growth path of sector M, which is n(0)=0 and $\dot{n}(t) = \gamma\left(1 - n(t)\right)$ for all t. Explicitly, this path is $n(t)=1-e^{-\gamma t}$, and using this, we can determine the times taken by this growth path to reach (n_{a1}, n_{a2}, n_{a3}, ... , n_{st}, ... , n_{b3}, n_{b2}, n_{b1}). Let these be (t_{a1}, t_{a2}, t_{a3}, ... , t_{st}, ..., t_{b3}, t_{b2}, t_{b1}) respectively. We have $0 < t_{a1} < t_{a2} < t_{a3} < \dots < t_{st} < \dots < t_{b3} < t_{b2} < t_{b1}$.

Tables 1.1 and 1.2 define and describe the potential equilibrium paths (n^L, n^H, $n^{C_1 L}$, etc.).[19] We now verify that path n^L, which is stagnation of sector *M* at zero scale, is an equilibrium under free trade.[20] If n^L is expected, then $V\left(t, n^L(\,), p^*\right)<0$ for all *t* since $\omega\left(n^L(t), p^*\right)=\omega\left(0, p^*\right)<0$ for all *t*. Equation (3) then implies that $\dot{n}=-\gamma n$ for all *t*, and such a path from $n(0)=0$ is indeed n^L, fulfilling the expectations.[21]

(b) Production Subsidy

Our policy instrument is the production subsidy given to agents supplying labor to sector *M*, financed by uniform lump sum taxation of all agents, with the government budget balanced at each *t*. We peg the rate of subsidy to be that which makes the current returns in the two sectors equal (ω=0) at each *t*. The rate path of subsidy is thus non-linear, but the resulting linearity of ω during the period of protection allows us to obtain our results with simplicity. The subsidy is applied during the time interval $[0,T]$.[22]

We can express a subsidy scheme by its effect on the current return difference:

$$\omega\left(n(t), p(t)\right) = \begin{cases} \underline{\omega} = 0 & \text{for } t \quad [0,T] \\ p^* k\left(n(t)\right) - 1 & \text{for } t \quad (T,\infty). \end{cases} \tag{5}$$

[19] Note that *n* with subscripts refer to values in [0,1] while *n* with superscripts refer to time paths.
[20] The following describes the method we use to check if a path is an equilibrium. Equation (3) requires any path of *n* to be increasing at rate $\gamma(1-n)$ or decreasing at rate γn. Given the expected paths of *n* and *p*, (2) determines the path of *V*. For this expected path of *n* to be a self-fulfilling equilibrium, it has to be increasing when $V\geq 0$ and decreasing when $V<0$.
[21] Figure 1 displays the case we consider in which n^L is the unique free trade equilibrium from $n(0)=0$. The condition for this uniqueness is $V\left(0, n^H(\,), p^*\right)<0$: even with the fastest growth expectations, n^H, $V<0$ at time 0, and take-off is not possible under free trade.
[22] Our analysis is general enough to allow other policy instruments. In this model, the production subsidy creates no static distortion, since at each *t*, the value of *n* is fixed.

T represents the duration of protection and $\underline{\omega}$ represents the value of ω to which the effect of subsidy is pegged.[23] In this section, we peg the effect of subsidy to $\underline{\omega}$=0 and vary T between 0 and t_{st} to determine how the duration of protection affects outcome.

(c) Duration of Protection versus the Equilibrium Set

Figure 2 illustrates the relationship between the duration of protection, [0,T], and (t_{a1}, t_{a2}, t_{a3}, ... , t_{st}, ... , t_{b3}, t_{b2}, t_{b1}). Table 2 is our primary result: the correspondence between the duration of protection and the set of equilibrium paths, Its derivation is Appendix B. Below, we describe how these paths become equilibria under protection of different durations, and summarize the main findings as propositions. The proofs of the propositions are in Appendix C.

(i) $0 \leq T < t_{a1}$

If the duration of protection is shorter than t_{a1}, then the only equilibrium is n^L. It can be seen in Figure 1 that even if sector M had grown during this period, its scale will be smaller than n_{a1} and thus protection is insufficient to put the economy on the saddle path to S_1. To verify that there is no other equilibrium, consider first the path n^H, along which sector M continuously grows. Note that n_{a1} is defined as the point at which V=0 given growth expectations. At time T, when protection is removed, the scale of sector M is smaller than n_{a1} and thus the net asset value (V) is negative even with growth expectations during (T,∞). Since protection makes the current return difference (ω) equal to zero during [0,T], V at time 0 is negative, and therefore n^H is not self-fulfilling. Furthermore, since ω is strictly increasing in n, V at time 0 for any other path is less than that for n^H and hence negative. Therefore, n^L is the unique equilibrium.

[23] The above restricts subsidy paths to those which are continuous in (0,T). Note that protection is terminated indefinitely once T is reached, and that the rate path will depend on which equilibrium the economy is in.

(ii) $t_{a1} \leq T < t_{a2}$

If the duration of protection is longer than t_{a1}, but shorter than t_{a2}, then n^L and n^H are the equilibria. Figure 3 shows the two equilibrium paths from n=0. Path n^L remains to be an equilibrium, since if it is expected, ω=0 during the period of protection and ω<0 thereafter, making V<0 for all t.

Figure 4 shows how n^H becomes an equilibrium under this policy. The top panel displays path n^H. The thin curves in the bottom two panels plot the free trade time paths of ω and V corresponding to the expected path n^H. The value of V at each t is the current discounted value of the future ([t,∞)) values of ω, as verifiable on the figure. For n^H to be an equilibrium, we need to have $V \geq 0$ for all $t \quad [0,\infty)$. It can be seen on the figure that under free trade, if n^H is expected, V<0 for $t \quad [0,t_{a1})$, and $V \geq 0$ for $t \quad [t_{a1},\infty)$. The production subsidy makes ω=0 during $t \quad [0,t_{a1}] \quad [0,T]$ (as shown by the bold line), letting $V \geq 0$ in this period (as shown by the bold curve) and thus $V \geq 0$ for all $t \quad [0,\infty)$.

Proposition 1.1. To have n^H (monotonic growth of sector M) as an equilibrium, protection can be removed at t_{a1} when the industry's size is n_{a1}. This duration of protection is shorter than the implication of the static model, as $t_{a1} < t_{st}$ and $n_{a1} < n_{st}$.

Proposition 1.2. At this point of protection removal, the private opportunity cost of good M is higher than its world relative price.

Proposition 1.3. The values of t_{a1} and n_{a1} depend positively on r (discount rate) and negatively on γ (rate of change).

(iii) $t_{a2} \le T < t_{a3}$

If the duration of protection is longer than t_{a2}, then the orbital path, n^{C_1L}, for which sector *M* takes off, grows to n_{b1}, makes a U-turn there, and contracts back to n=0 becomes an equilibrium. Figure 5 shows the three equilibria, { n^L, n^H, n^{C_1L} }, from n=0. Figure 6 shows how n^{C_1L} becomes an equilibrium under this policy. Under free trade (thin curves), if n^{C_1L} is expected, then V<0 for t (t_{b1},∞), V≥0 for t [t_{a2}, t_{b1}], and V<0 for t [0, t_{a2}]. Since V<0 at t=0, take-off does not take place, and n^{C_1L} is not a free trade equilibrium. If a future downturn is expected, then there will be no investments to that sector in the first place. However, a sufficiently long protection will make the sector take off even with expectations of a future downturn. In the figure, as shown by bold, protection sets ω=0 during [0,T] and this makes V≥0 during [0, t_{a2}]. Now we have V<0 for t (t_{b1},∞), and V≥0 for t [0, t_{b1}], making n^{C_1L} an equilibrium. Intuitively, if a "bad" outcome is expected, then sector *M* will not take off unless protected initially. Paths n^L and n^H are also equilibria by the same reasons as those in (ii) above. The following holds if we confine policy to $\underline{\omega}$ =0 and T [0, t_{st}].

Proposition 2.1. Path n^{C_1L} is an equilibrium iff $t_{a2} \le T \le t_{st}$, where $t_{a2} > t_{a1}$.

Interpretation: The orbital path n^{C_1L}, in which sector *M* takes off but U-turns and contracts towards the low level steady state, is an equilibrium if protection lasts longer than t_{a2}, where $t_{a2} > t_{a1}$. This equilibrium is not possible under free trade. Too long a protection, even if it lasts shorter than t_{st}, makes a growing Sector *M* to contract towards stagnation a possible equilibrium.

Proposition 2.2. $\omega\left(n_{b1}, p^*\right) > 0$.

Interpretation: At n_{b1}, the U-turn point of path n^{C_1L}, the private opportunity cost of *M* is less than its world relative price. Even with that, if the expectation is that sector M will decline, then V<0 and the expectation will be fulfilled. It must be the case that ω>0 at n_{b1}, because V>0 (V<0) just before (after) the U-turn at n_{b1} and V is the discounted sum of future ω's.

Proposition 2.3. For $t \in (T, t_{b1})$: $\dot{n}^{C_1 L}(t) > 0$.

Interpretation: Along path $n^{C_1 L}$, after the removal of protection at time *T*, sector *M* continues to grow until the U-turn point at time t_{b1}. Even though an eventual U-turn is perfectly foresighted and protection is no longer being applied, sector *M* continues to grow until the U-turn point. Since *V*=0 and ω>0 at the U-turn point, *V*>0 and $\dot{n}$>0 just before it.

(iv) $t_{a3} \le T < t_{a4}$

If the duration of protection is longer than t_{a3}, then the orbital path $n^{C_1 H}$, for which sector *M* takes off, grows to $n=n_{b2}$, turns and contracts to $n=n_{a1}$, and then turns again and grows to *n*=1 becomes an equilibrium. The equilibrium set becomes $\{n^L, n^H, n^{C_1 L}, n^{C_1 H}\}$. Figure 7 shows how $n^{C_1 H}$ becomes an equilibrium under this policy.

(v) $t_{a4} \le T < t_{a5}$

The equilibrium set becomes $\{n^L, n^H, n^{C_1 L}, n^{C_1 H}, n^{C_2 L}\}$. Path $n^{C_2 L}$ is that in which the economy cycles twice prior to heading to the low-level steady state. Sector *M* takes off, grows to $n=n_{b3}$, turns and contracts to $n=n_{a2}$, turns and grows to $n=n_{b1}$, and then turns and contracts to *n*=0.

(vi) $T = t_{st}$

As the duration of protection is extended further to ($[t_{a5}, t_{a6})$, $[t_{a6}, t_{a7})$, $[t_{a7}, t_{a8})$, $[t_{a8}, t_{a9})$, ...), equilibrium paths, ($n^{C_2 H}$, $n^{C_3 L}$, $n^{C_3 H}$, $n^{C_4 L}$, ...) are consecutively included in the equilibrium set, where C_i in the superscripts indicate the number of cycles made prior to heading to the low or the high steady state indicated by *L* or *H* in the superscripts. At $T = t_{st}$ the cardinality of the equilibrium set becomes countable infinity; the set consisting of n^L, n^H, countably many cyclical paths leading to the low level steady state, and countably many cyclical paths leading to the high level steady state. Note that under static expectations, this protection is the minimum that enables sector M to take-off and grow, and the equilibrium is unique. If each equilibrium is as likely, then the likelihoods of the eventual success and the eventual failure of sector M are the same.

Proposition 3. If the minimal policy implied by the static model (setting $\omega=0$ until t_{st}) is applied to this model, then there is an infinite number of equilibria leading to either steady state. The eventual success of the industry is as likely as its eventual failure.[24]

4. Policies of Longer Durations and Higher Pegged Rates

We next examine the possible equilibria under subsidizations of durations $0\leq T<\infty$, and pegged effective rates $\underline{\omega}\geq 0$. We express a subsidy scheme in terms of the path of ω:

$$\omega(n(t),p(t)) = \begin{cases} \max\{\underline{\omega},\ p^{*}k(n(t))-1\} & \text{for } t \in [0,T] \\ p^{*}k(n(t))-1 & \text{for } t \in (T,\infty), \end{cases} \qquad (6)$$

where $T \in [0,\infty)$ and $\underline{\omega} \in [0,\infty)$. We obtain the following propositions, the proofs of which are in Appendix C.

Proposition 4. If $\underline{\omega}=0$, then for any $T \in [0,\infty)$, n^{L} is an equilibrium.

Interpretation: If the effect of subsidy is pegged to that which makes the current returns in the two sectors equal (or the private opportunity cost of M equal to its world relative price), then stagnation of sector M is an equilibrium for any duration of protection.

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[24] In this paper, we place no restriction on expectation formation such that every perfect foresight equilibrium is considered equally likely. It is hoped that this will serve as a benchmark for more restrictive and realistic assumptions on expectation formation.

Proposition 5. If $T<t_{a1}$, then for any $\underline{\omega} \geq 0, n^H$ is not an equilibrium.

Interpretation: If the duration is shorter than t_{a1}, then no matter how high the pegged effective rate of subsidy, growth of sector M cannot be an equilibrium. This implies that changing the duration of protection is not isomorphic to changing the rate of protection.

Proposition 6. If $t_{a2} \leq T < t_{b1}$, then for any $\underline{\omega} \geq 0$, $n^{C_1 L}$ is an equilibrium.

Interpretation: If the duration is $t_{a2} \leq T < t_{b1}$, no matter how high the pegged effective rate of subsidy, the orbital path $n^{C_1 L}$ cannot be removed from the equilibrium set.

Proposition 7. A necessary condition for n^H to be a unique equilibrium is $T \geq t_{b1}$.

Interpretation: To make the growth path unique, protection cannot last shorter than t_{b1}, for any $\underline{\omega} \geq 0$. For uniqueness, policy needs to continue even after the private opportunity cost undercuts the world relative price at t_{st}.

Proposition 8. A sufficient condition for n^H to be the unique equilibrium is $V\left(t_{b1}, n^L(), p()\right) \geq 0$.

Interpretation: If the subsidy lasts long enough beyond t_{b1} and the pegged rate is high enough, such that at t_{b1} the value of V is non-negative even with the most pessimistic of expectations $n^L()$, then the only equilibrium is n^H. Such a policy is sufficient for uniqueness of n^H. It is possible to make n^H unique, but both the associated duration and pegged rate must be large compared to the neo-classical policy implication.[25]

5. Concluding Remarks

Despite the theoretical rationale for infant industry protection, the effectiveness of protection programs in practice has been observed to be questionable leading to a general

[25] For practical purposes, such an extensive protection may be difficult and costly to administer.

skepticism over infant industry protection policies and import-substituting industrialization. We have addressed a fundamental aspect of the decision making process of agents, namely expectations. By doing so, we were able to disclose the rich relationship between policy and outcome, which was found to differ starkly from that of the neo-classical models and to be more consistent with the practical experience and the mixed nature of the empirical evaluations. To the extent that economic agents base their behavior on the expected future, the results of our model should have validity.

If expectations matter, then a policy prescription based on the static model results in a multiplicity of equilibria where the industry's success is as likely as its failure. We have shown that even without the "problems" inherent in the practice of protection policy (listed in Footnote 4), and even if the government can commit to the future policy path, protection may not work.

In this paper, we have focused on the positive issues by assuming that the Mill-Bastable criteria are satisfied, by analyzing production subsidies which do not create static distortion, and by abstracting from the administrative cost of policy. Having obtained the positive results, it becomes possible to discuss some welfare implications. Suppose now that there is a welfare cost to impose protection. Our model indicates that to have the industry's success as one of the equilibria, protection can be removed before the industry is competitive in the world market. For the industry's success to be the unique equilibrium, the rate of protection has to be sufficiently high and protection needs to continue after the industry is competitive in the world market. Therefore, if the sentiment of the private sector is of optimism, or if the government can influence expectation formation through measures such as propaganda, and if the cost of policy imposition is high, the former policy is more favorable. On the other hand, if the cost of policy imposition is low and the government cannot hope expectation to coordinate to the industry's success, the latter policy becomes more favorable.

The model indicates that graduation of industries from protection cannot be defined by the comparison of the private opportunity cost and the world relative price. The static notion of the uniqueness of outcomes, and the "textbook policy" that protection should continue until the industry achieves international competitiveness, may have misled actual policy prescriptions and empirical evaluations of the infant industry argument. We await an empirical evaluation of the significance of future expectations in this important problem.

APPENDIX

A. Obtaining $(n_{a1}, n_{a2}, n_{a3}, \ldots)$ *and* $(n_{b1}, n_{b2}, n_{b3}, \ldots)$*:*

Below, we obtain the values of n at which the spirals change directions. We make use of V being equal to 0 at these points given the expected future path. Under our assumptions, $\lambda \equiv \frac{r}{\gamma} - 1 > 0$.

n_{a1}: Consider the path $n^{a1}(\,)$ that starts from n_{a1} and increases monotonically to n=1 (i.e. $n^{a1}(0) = n_{a1}$ and $\dot{n} = \gamma\,(1 - n)$ for all n). This path is $n^{a1}(\tau) = 1 - (1 - n_{a1})e^{-\gamma\tau}$. Our n_{a1} is defined by $V(0, n^{a1}(), p^*) = \gamma \int_0^\infty e^{-r\tau}\omega(n^{a1}(\tau), p^*)d\tau = 0$. Substituting by $\nu = n^{a1}(\tau)$, this becomes $\int_{n_{a1}}^1 (1-\nu)^\lambda \omega(\nu, p^*)d\nu = 0$.

n_{b1}: Consider the path $n^{b1}(\,)$ that starts from n_{b1} and decreases monotonically to n=0 (i.e. $n^{b1}(0) = n_{b1}$ and $\dot{n} = -\gamma n$ for all n). This path is $n^{b1}(\tau) = n_{b1}e^{-\gamma\tau}$. Our n_{b1} is defined by $V(0, n^{b1}(), p^*) = \gamma \int_0^\infty e^{-r\tau}\omega(n^{b1}(\tau), p^*)d\tau = 0$. Substituting by $\nu = n^{b1}(\tau)$, this becomes $\int_0^{n_{b1}} \nu^\lambda \omega(\nu, p^*)d\nu = 0$.

n_{b2}: Consider the path $n^{b2}(\,)$ that starts from n_{b2}, $\dot{n} = -\gamma n$ until it reaches n_{a1}, and $\dot{n} = \gamma\,(1 - n)$ after that. This path is $n_{b2}e^{-\gamma\tau}$ as n decreases from n_{b2} to n_{a1}, and $n^{a1}(\,)$ after that. Our n_{b1} is defined by $V(0, n^{b2}(), p^*)$ =0. Since the value of V at n_{a1} when the path changes directions is 0, this condition is: $\gamma \int_0^{(n^{b2})^{-1}(n_{a1})} e^{-r\tau}\omega(n^{b2}(\tau), p^*)d\tau$ =0, which after substitution by $\nu = n^{b2}(\tau) = n_{b2}e^{-\gamma\tau}$ becomes $\int_{n_{a1}}^{n_{b2}} \nu^\lambda \omega(\nu, p^*)d\nu = 0$.

n_{a2}: Consider the path $n^{a2}(\,)$ that starts from n_{a2}, $\dot{n} = \gamma\,(1-n)$ until it reaches n_{b1}, and $\dot{n} = -\gamma n$ after that. This path is $1-(1-n_{a2})e^{-\gamma\tau}$ as n increases from n_{a2} to n_{b1}, and $n^{b1}(\,)$ after that. Our n_{a2} is defined by $V(0, n^{a2}(), p^*)$ =0. Since the value of V at n_{b1} when the path changes directions is 0, this condition is: $\gamma \int_0^{(n^{a2})^{-1}(n_{b1})} e^{-r\tau}\omega(n^{a2}(\tau), p^*)d\tau$ =0, which after substitution by $\nu = n^{a2}(\tau) = 1-(1-n_{a2})e^{-\gamma\tau}$ becomes $\int_{n_{a2}}^{n_{b1}} (1-\nu)^{\lambda}\omega(\nu, p^*)d\nu = 0$.

Recursively, the values of n_{ai} and n_{bi} for i=3,4,5,... can be obtained.

B. Proof: Duration of Protection versus the Equilibrium Set

Policy as defined by equation (5) is applied to the economy. Note that ω=0 while policy is applied. Policy starts at time t=0, is applied continuously, and ends at $t=T$ [0,t_{st}].

The proof proceeds in three steps. Lemma 1 first proves that for any duration of policy within T [0,t_{st}], all equilibrium paths converge to either n=0 or n=1. Lemma 2 shows that for any T [0,t_{st}], the equilibrium set is a subset of $\tilde{N} = \left\{n^L, n^H, \left(n^{C_iL}, n^{C_iH}\right)_{i=1}^{\infty}\right\}$. Given the lemmata, we then obtain the necessary and sufficient durations of policy for each path in $\tilde{N}$ to be an equilibrium.

LEMMA 1. All equilibrium paths converge to either n=0 or n=1.

In our system, this is equivalent to the non-existence of closed orbits. Suppose that there exist a closed orbit, $n(\,)$. Then, there exist t_1, t_2 and t_3 such that:

$t_3 > t_2 > t_1 > T$,

$n(t_1) = n(t_3) < n(t_2)$, and

$V(t_1, n(\,), p^*) = V(t_2, n(\,), p^*) = V(t_3, n(\,), p^*) = 0$.

These imply $\gamma \int_{t_1}^{t_2} e^{-r\tau}\omega(n(\tau), p^*)d\tau = \gamma \int_{t_2}^{t_3} e^{-r\tau}\omega(n(\tau), p^*)d\tau = 0$. But since ω is strictly increasing in n, $\gamma \int_{t_1}^{t_2} e^{-r\tau}\omega(n(\tau), p^*)d\tau = 0$ implies that $\gamma \int_{t_2}^{t_3} e^{-r\tau}\omega(n(\tau), p^*)d\tau > 0$, and we have a contradiction.

LEMMA 2. For any T [0,t_{st}], the equilibrium set is a subset of $\tilde{N} = \left\{n^L, n^H, \left(n^{C_iL}, n^{C_iH}\right)_{i=1}^{\infty}\right\}$.

(a) If an equilibrium is not n^L, then $\dot{n} = \gamma\,(1-n) > 0$ at t=0.
(If take-off path is an equilibrium, then take-off is at t=0.)

Consider a trajectory that leaves n=0. Let n^{t_0} represent a path that stays at n=0 until t=t_0≥0 and then starts to follow the given trajectory. If an equilibrium is not n^L, then the path leaves n=0 at some t_0≥0, and $V\left(t_0, n^{t_0}(), p()\right)$≥0. Since our policy is such that ω≤0 during [0,t_0], we have $V\left(0, n^0(), p()\right) \geq V\left(t_0, n^{t_0}(), p()\right)$≥0. Thus $\dot{n} = \gamma\,(1-n) > 0$ at t=0.

(b) If $\dot{n} = \gamma\,(1-n) > 0$ at t=0, then $\dot{n} = \gamma\,(1-n) > 0$ for t [0,t_{st}].

(If take-off is to take place at t=0, then n increases strictly during the period it takes to reach n_{st}). Suppose that the path turns back at t<t_{st}. This means $V\left(t, n(), p()\right)$ =0, which implies that $V\left(0, n(\,), p(\,)\right)$<0, since our policy is such that ω≤0 during [0,t), and thus $\dot{n} = -\gamma n < 0$ at t=0.

Given (a) and (b) above, if an equilibrium is not n^L, then the equilibrium path has $\dot{n} = \gamma\,(1-n) > 0$ for t [0,t_{st}], which is $n(t) = 1 - e^{-\gamma t}$ as n increases from 0 to n_{st}. From n_{st}, given Lemma 1, the equilibrium paths are those on the cycles tending to n=0 or n=1. Such paths are $\{n^H, n^{C_1 L}, n^{C_1 H}, n^{C_2 L}, \ldots\}$, as defined in Table 1.2.

Therefore, the superset of the set of equilibrium paths corresponding to a policy duration T is: $\tilde{N} = \left\{n^L, n^H, \left(n^{C_i L}, n^{C_i H}\right)_{i=1}^{\infty}\right\}$.

We now proceed to obtain the correspondence between durations of policy and the equilibrium set.

(i) n^L is an equilibrium ⇔ T [0,t_{st}]

( ) For any T [0,t_{st}],

$$\omega\left(n^L(t), p(t)\right) = \begin{cases} 0 & \text{for } t \ \ [0,T] \\ p^* k_0 - 1 < 0 & \text{for } t > T. \end{cases}$$

This obtains $V\left(t, n^L(\,), p()\right) < 0$ for all t≥0, and thus n^L is an equilibrium.

( ) trivial (T is always in [0,t_{st}].)

(ii) n^H is an equilibrium ⇔ T [t_{a1},t_{st}]

( ) For any T [t_{a1},t_{st}],

$$\omega\left(n^H(t), p(t)\right) = \begin{cases} 0 & \text{for } t \ \ [0,T] \\ p^* k\left(n^H(t)\right) - 1 & \text{for } t > T. \end{cases}$$

For t>T, $V\left(t,n^H(),p()\right) \;>\; V\left(T,n^H(),p()\right) \geq V\left(t_{a1},n^H(),p()\right) \geq V\left(t_{a1},n^H(),p^*\right) \geq 0.$

For t [0,T], $V\left(t,n^H(),p()\right) = \gamma\int_t^T e^{-r(\tau-t)}\omega\left(n^H(\tau),p(\tau)\right)d\tau + \gamma\int_T^\infty e^{-r(\tau-t)}\omega\left(n^H(\tau),p(\tau)\right)d\tau$

$$= 0 + e^{rt}\gamma\int_T^\infty e^{-r\tau}\omega\left(n^H(\tau),p^*\right)d\tau \;\; \geq \;\; 0.$$

Therefore $V\left(t,n^H(),p()\right) \geq 0$ for all $t \geq 0$, and n^H is an equilibrium.

( ) Suppose T [0,t_{a1}). Then,

$$V\left(0,n^H(),p()\right)$$

$$= \gamma\int_0^T e^{-r\tau}\omega\left(n^H(\tau),p(\tau)\right)d\tau + \gamma\int_T^{t_{a1}} e^{-r\tau}\omega\left(n^H(\tau),p(\tau)\right)d\tau + \gamma\int_{t_{a1}}^\infty e^{-r\tau}\omega\left(n^H(\tau),p(\tau)\right)d\tau$$

$$= 0 + \gamma\int_T^{t_{a1}} e^{-r\tau}\omega\left(n^H(\tau),p^*\right)d\tau + \gamma\int_{t_{a1}}^\infty e^{-r\tau}\omega\left(n^H(\tau),p^*\right)d\tau$$

$$= 0 + \gamma\int_T^{t_{a1}} e^{-r\tau}\omega\left(n^H(\tau),p^*\right)d\tau + 0 \;\; < \;\; 0,$$

which means that n^H is not an equilibrium.

(iii) n^{C_1L} is an equilibrium $\Leftrightarrow$ T [t_{a2},t_{st}]

( ) For any T [t_{a2},t_{st}],

$$\omega\left(n^{C_1L}(t),p(t)\right) = \begin{cases} 0 & \text{for } t \;\; [0,T] \\ p^*k\left(n^{C_1L}(t)\right) - 1 & \text{for } t > T. \end{cases}$$

For t>t_{b1},

$$V\left(t,n^{C_1L}(),p()\right) = V\left(t,n^{C_1L}(),p^*\right) < V\left(t_{b1},n^{C_1L}(),p^*\right) = 0.$$

For t (T,t_{b1}],

$$V\left(t,n^{C_1L}(),p()\right) = \gamma\int_t^{t_{b1}} e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau + \gamma\int_{t_{b1}}^\infty e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau$$

$$= \gamma\int_t^{t_{b1}} e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau + e^{rt}\gamma\int_{t_{b1}}^\infty e^{-r\tau}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau$$

$$= \gamma\int_t^{t_{b1}} e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau + 0 \;\; > \;\; 0.$$

For t [0,T],

$$V\left(t,n^{C_1L}(),p()\right) = \gamma\int_t^T e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p(\tau)\right)d\tau + \gamma\int_T^{t_{b1}} e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau$$

$$+ \gamma\int_{t_{b1}}^\infty e^{-r(\tau-t)}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau$$

$$= 0 + e^{rt}\gamma\int_T^{t_{b1}} e^{-r\tau}\omega\left(n^{C_1L}(\tau),p^*\right)d\tau + 0 \;\; \geq \;\; 0.$$

Therefore n^{C_1L} is an equilibrium.

( ) Suppose T [0,t_{a2}). Then,

$$V\left(0, n^{C_1L}(), p()\right)$$
$$= \gamma \int_0^T e^{-r\tau}\omega\left(n^{C_1L}(\tau), p(\tau)\right)d\tau \ + \gamma \int_T^{t_{a2}} e^{-r\tau}\omega\left(n^{C_1L}(\tau), p^*\right)d\tau \ + \gamma \int_{t_{a2}}^{\infty} e^{-r\tau}\omega\left(n^{C_1L}(\tau), p^*\right)d\tau$$
$$= 0 + \gamma \int_T^{t_{a2}} e^{-r\tau}\omega\left(n^{C_1L}(\tau), p^*\right)d\tau \ + 0 \ < \ 0,$$

which means that n^{C_1L} is not an equilibrium.

Recursively, it can be shown that:

n^{C_1H} is an equilibrium $\Leftrightarrow$ $T \quad [t_{a3}, t_{st}]$,
n^{C_2L} is an equilibrium $\Leftrightarrow$ $T \quad [t_{a4}, t_{st}]$,
n^{C_2H} is an equilibrium $\Leftrightarrow$ $T \quad [t_{a5}, t_{st}]$, ...

Therefore, the following are the correspondences between the duration of policy and the equilibrium set.

$T \quad [0, t_{a1})$	$\leftrightarrow$	$\{n^L\}$
$T \quad [t_{a1}, t_{a2})$	$\leftrightarrow$	$\{n^L, n^H\}$
$T \quad [t_{a2}, t_{a3})$	$\leftrightarrow$	$\{n^L, n^H, n^{C_1L}\}$
$T \quad [t_{a3}, t_{a4})$	$\leftrightarrow$	$\{n^L, n^H, n^{C_1L}, n^{C_1H}\}$
$T \quad [t_{a4}, t_{a5})$	$\leftrightarrow$	$\{n^L, n^H, n^{C_1L}, n^{C_1H}, n^{C_2L}\}$
	.	
	.	
	.	
$T = t_{st}$	$\leftrightarrow$	$\tilde{N}$

C. Proofs of Propositions

Propositions 1.1 and 1.2

These follow from the correspondence established in Appendix B.

Proposition 1.3

t_{a1} depends positively on n_{a1}, and the definition of n_{a1} in Appendix A shows that n_{a1} depends positively on r and negatively on γ.

Proposition 2.1

This follows from the correspondence established in Appendix B.

Proposition 2.2

Since $n_{b1} > n_{st}$, we have $\omega\left(n_{b1}, p^*\right) > \omega\left(n_{st}, p^*\right) = 0$.

Proposition 2.3

This follows from (5) and the definition of path n^{C_1L}.

Proposition 3

This follows from the correspondence established in Appendix B.

Proposition 4. For path n^L, we have

$$\omega\left(n^L(t), p(t)\right) = \begin{cases} 0 & \textit{for } t \quad [0, T] \\ p^* k_0 - 1 < 0 & \textit{for } t \quad (T, \infty). \end{cases}$$

This implies that $V\left(t, n^L(\ ), p(\ )\right) < 0$ for all $t \geq 0$, and therefore, n^L is an equilibrium.

Proposition 5. For path n^H, we have

$$\omega\left(n^H(t), p(t)\right) = \begin{cases} \underline{\omega} \geq 0 & \textit{for } t \quad [0, T] \\ p^* k\left(n^H(t)\right) - 1 & \textit{for } t \quad (T, \infty). \end{cases}$$

For t $[T, t_{a1})$,

$$\begin{aligned} V\left(t, n^H(\ ), p(\ )\right) &= \gamma \int_t^{t_{a1}} e^{-r(\tau - t)} \omega\left(n^H(\tau), p(\tau)\right) d\tau + \gamma \int_{t_{a1}}^{\infty} e^{-r(\tau - t)} \omega\left(n^H(\tau), p(\tau)\right) d\tau \\ &= \gamma \int_t^{t_{a1}} e^{-r(\tau - t)} \left(p^* k\left(n^H(t)\right) - 1\right) d\tau + 0 \quad < \quad 0. \end{aligned}$$

Therefore, n^H is not an equilibrium.

Proposition 6. For path n^{C_1L}, we have

$$\omega\left(n^{C_1L}(t), p(t)\right) = \begin{cases} \max\left\{\underline{\omega}\ ,\ p^* k\left(n^{C_1L}(t)\right) - 1\right\} & \textit{for } t \quad [0, T] \\ p^* k\left(n^{C_1L}(t)\right) - 1 & \textit{for } t \quad (T, \infty). \end{cases}$$

For t (t_{b1}, ∞), $V\left(t, n^{C_1L}(\ ), p(\ )\right) < 0$.

For t $[T, t_{b1}]$, since $t \geq t_{a2}$,

$$\begin{aligned} V\left(t, n^{C_1L}(\ ), p(\ )\right) &= \gamma \int_t^{t_{a1}} e^{-r(\tau - t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau + \gamma \int_{t_{a1}}^{\infty} e^{-r(\tau - t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau \\ &= \gamma \int_t^{t_{a1}} e^{-r(\tau - t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau + 0 \quad \geq \quad 0. \end{aligned}$$

For t $[0, T)$, since $T \geq t_{a2}$,

$$
\begin{aligned}
V\left(t, n^{C_1L}(\,), p(\,)\right) &= \gamma \int_t^T e^{-r(\tau-t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau \\
&\quad + \gamma \int_T^{t_{a1}} e^{-r(\tau-t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau + \gamma \int_{t_{a1}}^{\infty} e^{-r(\tau-t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau \\
&= \gamma \int_t^T e^{-r(\tau-t)} \max\left\{\underline{\omega}, p^* k\left(n^{C_1L}(t)\right) - 1\right\} d\tau \\
&\quad + \gamma \int_T^{t_{a1}} e^{-r(\tau-t)} \omega\left(n^{C_1L}(\tau), p(\tau)\right) d\tau + 0 \quad > \quad 0.
\end{aligned}
$$

Therefore, n^{C_1L} is an equilibrium.

Proposition 7. This follows from Propositions 5, 6, and Lemma 3 below.

Lemma 3: If $t_{a1} \leq T < t_{a2}$, then for any $\underline{\omega} \geq 0$, either n^L or a one cycle U-turn path to stagnation which is distinct from n^{C_1L} is an equilibrium.

Proof of Lemma 3:

(i) If $V\left(0, n^L(\,), p(\,)\right) < 0$, then $V\left(t, n^L(\,), p(\,)\right) < 0$ for all $t \geq 0$, and n^L is an equilibrium.

(ii) If $V\left(0, n^L(\,), p(\,)\right) \geq 0$, then n^L is not an equilibrium, and there exists n_U $[0, n_T)$ such that the path n^U defined by $\dot{n} = \gamma(1-n)$ as n increases from 0 to n_U and $\dot{n} = -\gamma n$ as n decreases from n_U to 0 is an equilibrium.

Proposition 8. (i) If policy is such that $V\left(t_{b1}, n^L(\,), p(\,)\right) \geq 0$, then $T > t_{b1} > t_{a1}$ and $\underline{\omega} > 0$. Then, $V\left(t, n^H(\,), p(\,)\right) > 0$ for all $t \geq 0$, and n^H is an equilibrium.

(ii) If $V\left(t_{b1}, n^L(\,), p(\,)\right) \geq 0$, then n^L is not an equilibrium.

(iii) There does not exist t_U such that $V\left(t_U, n(\,), p(\,)\right) = 0$.

Take a $t_U \leq t_{b1}$. Let n^U be the path with $\dot{n} = \gamma(1-n)$ during $[0, t_U]$ and $\dot{n} = -\gamma n$ during (t_U, ∞).

Then, $V\left(t_U, n^U(\,), p(\,)\right) > V\left(t_U, n^L(\,), p(\,)\right) \geq V\left(t_{b1}, n^L(\,), p(\,)\right) \geq 0$.

Take a $t_U > t_{b1}$. Then, $V\left(t_U, n^U(\,), p(\,)\right) > V\left(t_{b1}, n^{C_1L}(\,), p(\,)\right) > V\left(t_{b1}, n^L(\,), p(\,)\right) \geq 0$.

Therefore the only equilibrium path is that which monotonically increases, which is n^H.

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FIGURE 1: Global Dynamics

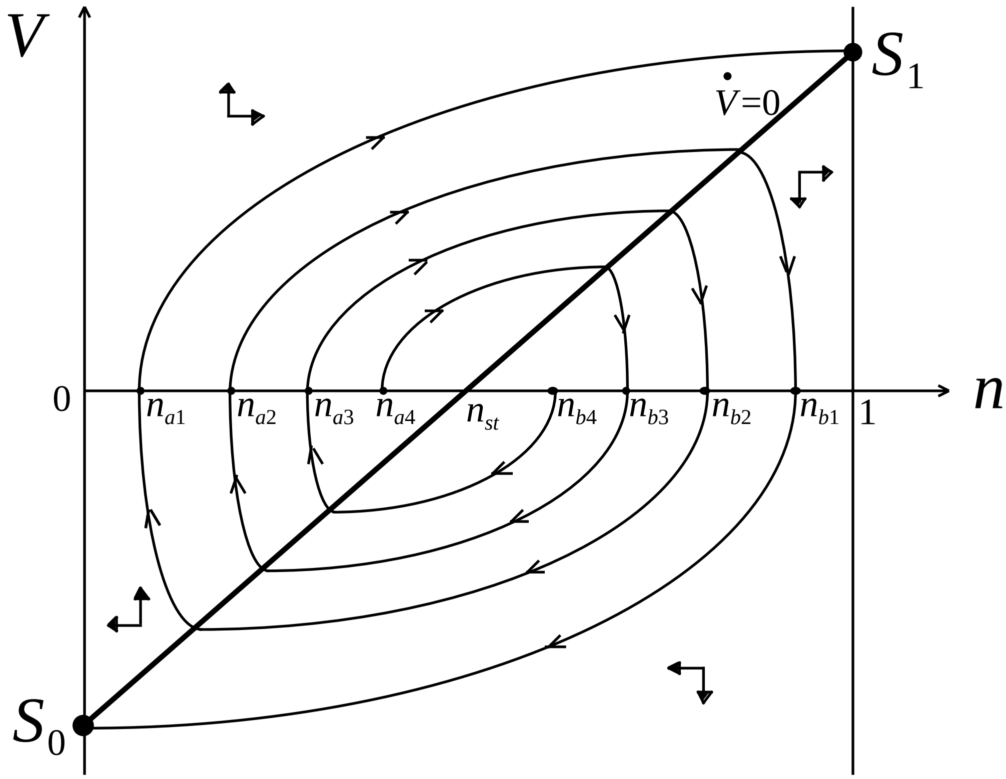

TABLE 1.1: Path Descriptions (initial state: *n*=0)

path	description	how *n* changes
$n^{L}(t)$	stagnation at S_0	0
$n^{H}(t)$	monotonic growth to S_1	$0 \xrightarrow{+} 1$
$n^{C_1 L}(t)$	1-cycle path to S_0	$0 \xrightarrow{+} n_{b1} \xrightarrow{-} 0$
$n^{C_1 H}(t)$	1-cycle path to S_1	$0 \xrightarrow{+} n_{b2} \xrightarrow{-} n_{a1} \xrightarrow{+} 1$
$n^{C_2 L}(t)$	2-cycle path to S_0	$0 \xrightarrow{+} n_{b3} \xrightarrow{-} n_{a2} \xrightarrow{+} n_{b1} \xrightarrow{-} 0$
$n^{C_i L}(t)$	*i*-cycle path to S_0	
$n^{C_i H}(t)$	*i*-cycle path to S_1	

note: $\xrightarrow{+}$ indicates the period during which $\dot{n} = +\gamma(1-n)$

$\xrightarrow{-}$ indicates the period during which $\dot{n} = -\gamma n$

TABLE 1.2: Explicit Forms of Paths

explicit form
$n^L(t) = 0$
$n^H(t) = 1\text{-}e^{-\gamma t}$
$n^{C_1L}(t) = \begin{cases} 1-e^{-\gamma t} & \text{for } t \quad [0, t_{b1}] \\ \frac{n_{b1}}{1-n_{b1}} e^{-\gamma t} & \text{for } t \quad (t_{b1}, \infty) \end{cases}$
$n^{C_1H}(t) = \begin{cases} 1-e^{-\gamma t} & \text{for } t \quad [0, t_{b2}] \\ \frac{n_{b2}}{1-n_{b2}} e^{-\gamma t} & \text{for } t \quad \left(t_{b2}, \frac{1}{\gamma} \ln \frac{n_{b2}}{n_{a1}(1-n_{b2})}\right) \\ 1-\frac{(1-n_{a1})n_{b2}}{n_{a1}(1-n_{b2})} e^{-\gamma t} & \text{for } t \quad \left[\frac{1}{\gamma} \ln \frac{n_{b2}}{n_{a1}(1-n_{b2})}, \infty\right) \end{cases}$
$n^{C_2L}(t) = \begin{cases} 1-e^{-\gamma t} & \text{for } t \quad [0, t_{b3}] \\ \frac{n_{b3}}{1-n_{b3}} e^{-\gamma t} & \text{for } t \quad \left(t_{b3}, \frac{1}{\gamma} \ln \frac{n_{b3}}{n_{a2}(1-n_{b3})}\right) \\ 1-\frac{(1-n_{a2})n_{b3}}{n_{a2}(1-n_{b3})} e^{-\gamma t} & \text{for } t \quad \left[\frac{1}{\gamma} \ln \frac{n_{b3}}{n_{a2}(1-n_{b3})}, \frac{1}{\gamma} \ln \frac{(1-n_{a2})n_{b3}}{(1-n_{b1})n_{a2}(1-n_{b3})}\right] \\ \frac{n_{b1}(1-n_{a2})n_{b3}}{(1-n_{b1})n_{a2}(1-n_{b3})} e^{-\gamma t} & \text{for } t \quad \left(\frac{1}{\gamma} \ln \frac{(1-n_{a2})n_{b3}}{(1-n_{b1})n_{a2}(1-n_{b3})}, \infty\right) \end{cases}$

FIGURE 2: Duration of Protection ($t_{a1} \leq T < t_{a2}$ case illustrated)

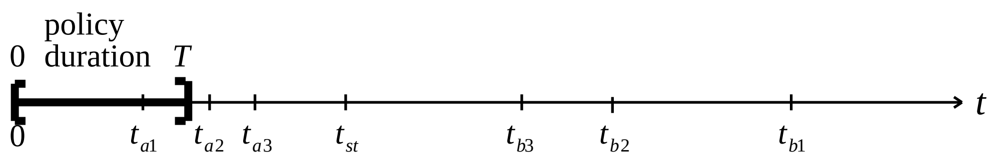

TABLE 2: Correspondence Between Duration of Protection and Equilibria

note: Tables 1.1 and 1.2 define and describe the paths

duration of protection, [0,*T*]	**equilibrium set**
$0 \leq T < t_{a1}$	n^L
$t_{a1} \leq T < t_{a2}$	n^L, n^H
$t_{a2} \leq T < t_{a3}$	n^L, n^H, n^{C_1L}
$t_{a3} \leq T < t_{a4}$	$n^L, n^H, n^{C_1L}, n^{C_1H}$
$t_{a4} \leq T < t_{a5}$	$n^L, n^H, n^{C_1L}, n^{C_1H}, n^{C_2L}$
...	...
$T = t_{st}$	$n^L, n^H, \left(n^{C_iL}\right)_{i=1,2,..,\infty},$

FIGURE 3: Policy $t_{a1} \leq T < t_{a2}$ and Equilibrium Set $\{n^L, n^H\}$

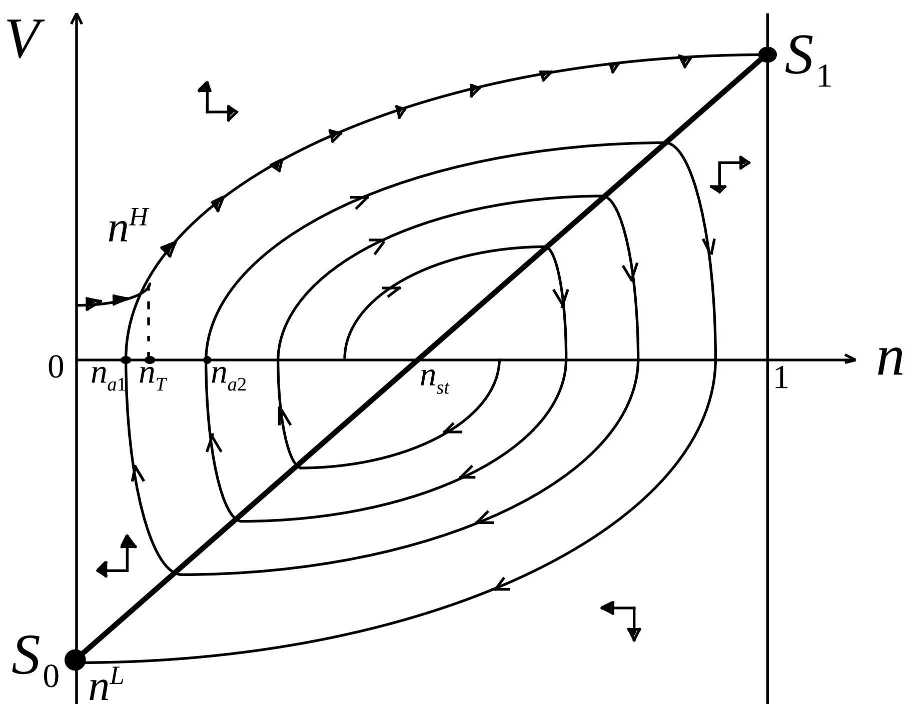

FIGURE 4: How Path n^H Becomes an Equilibrium

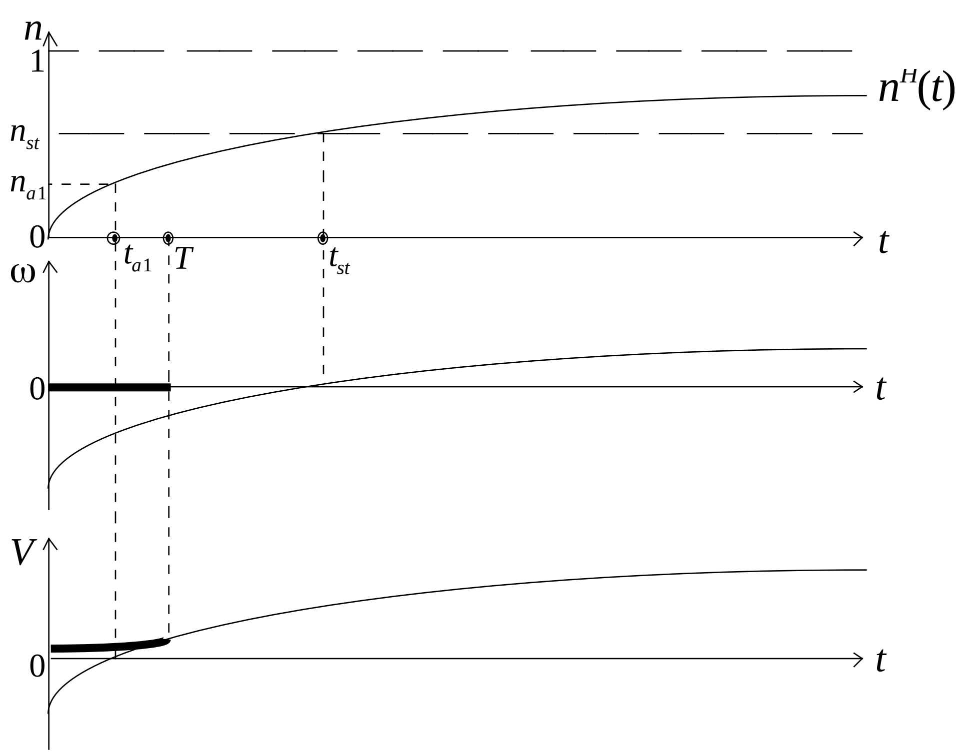

FIGURE 5: Policy $t_{a2} \leq T < t_{a3}$ and Equilibrium Set $\{n^L, n^H, n^{C_1L}\}$

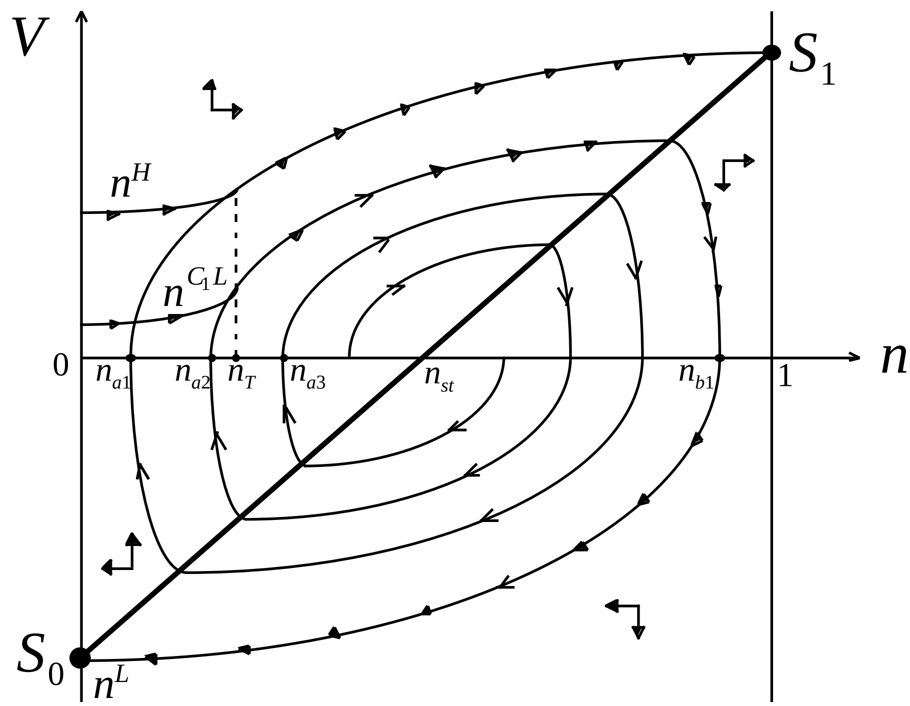

FIGURE 6: How Path n^{C_1L} Becomes an Equilibrium

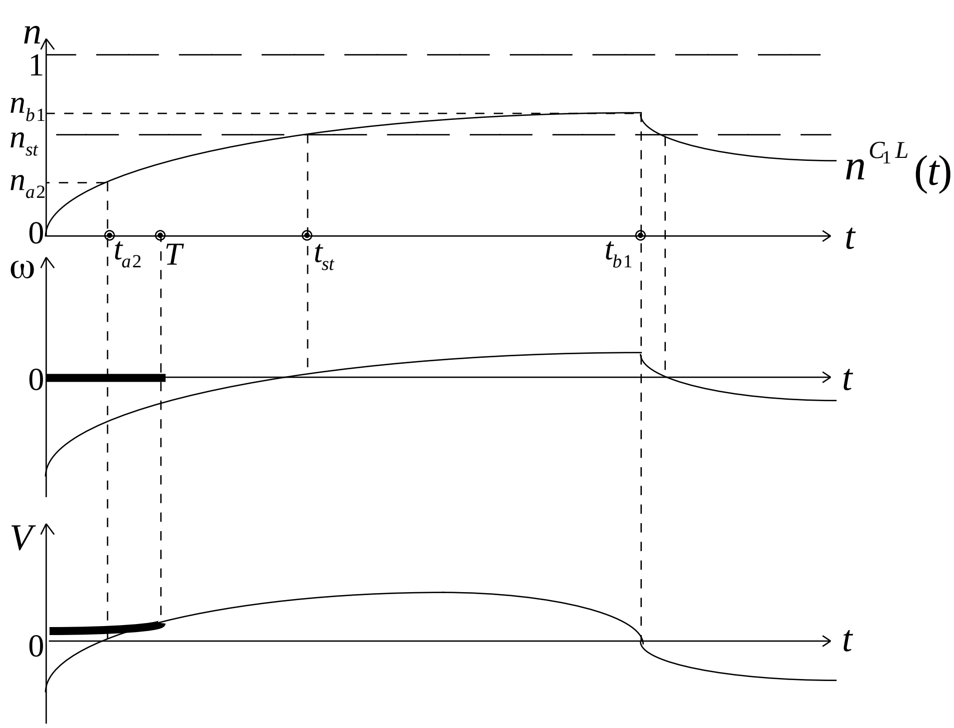

FIGURE 7: How Path n^{C_1H} Becomes an Equilibrium