Congestion of the Turkish Straits: A Market Alternative

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February, 1999

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Abstract

The paper addresses congestion of the Bosporus that could result from the Montreux Convention which states: "In times of peace merchant vessels shall enjoy complete freedom of transit and navigation in the Straits, by day or by night, under any flag and with any kind of cargo . . . ." While the Straits are not congested at present for general cargo, we can expect congestion within seven to fourteen years. There may be congestion for tankers sooner because of safety considerations. The carrying capacity of the Straits can be improved if a two-part tariff is used to ration general cargo and an auction is used to allocate tanker slots.

Key words: Bosporus, Montreux, congestion, tanker, auction, two-part tariff

I would like to thank Hikmet Sahiner and Charles Fairbanks, Jr. at the Johns Hopkins School of Advanced International Studies, William Laney Littlejohn of Littlejohn & Associates, Yasar Barut, James Joseph Barnes, Peter Hartley and Ferne Hyman at Rice, the Turkish Embassy in Washington, the Turkish Foreign Ministry, the Ministry of Maritime Affairs, and the Turkish Maritime Pilots Association for their courtesy and help in writing this paper. Support for this research came from the funds attached to the Peterkin Chair in Political Economy at Rice University. The views expressed are those of the author.

Congestion of the Turkish Straits: A Market Alternative

1. Introduction

Congestion in the Bosporus is a complicated issue: it involves economics, geography, the environment, the rights and interests of Turkey and other states and international law. This paper addresses this issue from an economic perspective. It is an attempt to show how economics and market forces can reformulate a debate that has for some time been at a stalemate because what appear to be irreconcilable points of view. Economics, and in particular the idea of using the market as a mechanism to regulate traffic in the Bosporus, suggests that it is possible to resolve this issue in a way that benefits all parties. Economics can cut the Gordian Knot.[1]

The Turkish Straits, connecting the Mediterranean with the Black Sea, consist of the Dardanelles, the Sea of Marmara and the Bosporus. The Bosporus is one of the busiest waterways in the world, handling annually 50,000 ships in addition to fishing boats and local traffic, The Bosporus is 19 miles long and is less that one half mile wide at its most narrow point. Traversing Istanbul, a city of 12 million people, the Bosporus is spanned by two bridges. Over one-half million people cross the waterway daily. The Bosporus is as central to Istanbul as the Mississippi is to New Orleans. Any accident involving hazardous cargo could endanger the lives of thousands of people. This waterway is crucial to the economies of Turkey and other countries that border the Black Sea.[2] If the Bosporus were not a trade route from the Black Sea to the Mediterranean, it would simply be regarded as Turkey's internal waters. The fact that it is an important trade route and crosses the center of Turkey's largest city creates a conflict of interests between Turkey and Black Sea commerce.

Since the eighteenth century, when the Black Sea ceased to be Turkish internal waters, transit through the Bosporus has been regulated by a series of treaties and international conven-

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[1] The key contribution is from Coase (1960). Coase, in his formulation of what came to be known as the Coase Theorem, argued that well defined property rights can lead to efficient allocations. Subsequently, Brito, Intriligator and Sheshinski (1997) show that under certain conditions the market allocation lead to allocations that improve the welfare of all parties.

[2] These countries are Bulgaria, Georgia, Moldova, Russia, Ukraine.

tions. The solutions have varied with the number of powers involved, the balance of power, and the importance of the Bosporus as a trade route and channel for the transit of warships. In 1936, the Montreux Convention allowed Turkey to regulate the passage of warships, through the Straits, but required the free passage of merchant traffic. Section I, Article 2 of the Montreux Convention states: "In times of peace merchant vessels shall enjoy *complete freedom of transit* and navigation in the Straits, by day or by night, under any flag and with *any kind of cargo*, without any formalities . . . ." .[emphasis added] The primary concern of the Montreux Convention, however, was the transit of warships through the Straits and the status of fleets in the Black Sea; very little attention was given to the regulation of merchant traffic. This is not surprising given that at the time when the Montreux Convention was signed merchant traffic was approximately 12 vessels a day. Moreover, at that time, ships were small and it was not likely that a shipwreck could pose a threat to the shore.

Sixty years later, the role of merchant traffic is more important. It now flows at a rate of 135 vessels a day. Tankers can be as large as 130 thousand tons. Furthermore, under the terms of the Montreux Convention, reporting cargo content is voluntary even with regard to hazardous cargo. So is the use of pilots. There is no mechanism in the Montreux Convention for taking special precautions for hazardous materials or for scheduling traffic.

Requiring the free passage of merchant traffic may have been trivial in 1936, but now it endangers the health and safety of the Turkish people. A question that must be addressed is whether Turkey has the power to regulate passage through the Straits to protect that health and safety. Turkey has asserted its right to regulate traffic in the Bosporus and issued regulations that went into effect on July 1, 1994.[3] The legal basis for this right is not clear, but behind international law is Turkey’s physical control of the Straits.[4] The loss of control of the Straits by Turkey is the result of a series of wars culminating in World War I. The argument can be made that duress,

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[3] The rules established a required separation of 8 cables or about one mile for normal cargo vessels; however, they restrict transit through the Bosporus to one tanker at a time. This restricts the number of tankers that can transit the Straits creating congestion for tankers even when there is adequate capacity and no congestion for normal cargo vessels. The argument is that the market can be used to ration this scarce resource. See Nitzov (1998) for a description of how the 1994 rules restrict tanker slots.

unequal bargaining power and unforseeability make these conditions unenforceable.[5] One can also make the argument that under modern conditions, unrestricted access violates Turkey's right to protect the health and safety of it citizens. The fact that the Montreux Convention changed the terms of the Lausanne Convention, which was imposed on Turkey after the First World War, suggests that the Montreux Convention itself too can be changed under new circumstances.

The question of traffic through the Bosporus is now getting more attention because of the emergence of Caspian oil. The two pipelines for Caspian oil now in existence end on the Black Sea as will other pipelines that are being planned or built. This production will create a burden on the Bosporus unless measures are taken. Turkey, supported by the United States, proposes to avoid the Bosporus by building a pipeline from Baku to Ceyhan on the Mediterranean. The difficulty with this solution is that pipelines are, except for very short distances, more expensive than tankers. The estimates of the cost of moving oil from Baku to Ceyhan range from $1.00 to $2.00 per barrel. The cost of moving oil from the Black Sea to the Mediterranean by tanker is less than twenty cents per barrel. The cost differential, in combination with low oil prices, is making some oil companies reluctant to invest in this pipeline. Turkey has responded with declarations that it will impose new regulations on the transit of oil through the Bosporus. The Russian government, which wants to maintain it right of free passage through the Bosporus, has opposed these regulations. Here, at the moment, the discussion appears to be deadlocked.

Congestion of the Bosporus: Executive Summary

Vessels in transit through a strait can impose two types of externalities. The first is congestion. If the traffic volume is high enough, queues form and transit is delayed. This delay imposes an economic cost on cargo. The second type of externality is risk of injury to the neighboring communities. This includes damage to the environment as well as risks from dangerous cargos.[6] Given these two externalities, the Straits can be viewed as a common property resource, subject to

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[4] Schachte and Bernhardt (1993) describe the regime of the Turkish Straits as a classic example of an article 35(c) Law of the Sea Convention that covers bodies of water governed by long-standing international conventions. The rights of transit are "clearly less that the right of transit passage and in certain facets, less that the right of non-suspendable passage." In the 1958 Convention on Territorial Sea and Contiguous Zone, these rights are subject to not being prejudicial to the "peace, good order or security of the coastal state." However, "peace, good order or security of the coastal state" is not a defined term. See also Scharfenberg (1996) and Bernhardt (1995).

[5] See Posner (1998).

congestion, that has the potential of imposing costs on surrounding communities. The question then is whether traffic in those waters creates externalities that are so substantial that it is necessary to impose some controls on passage. This paper addresses this question. The results of the paper are:

1. While the Straits are not congested at present for *general cargo*, we can expect congestion that will result in substantial delays within seven to fourteen years. In the model, delays go from 5 hours to 500 hours in the span of six months.[7] Of course, this would not happen. Freight rates would increase and the market would reach an equilibrium. Just as in the old Soviet Union, time in the queue would be the equilibrating mechanism that would ration the scarce resource. The precise time depends on the rates of growth of the economies that use the Straits as well as on some technical parameters. However, even with the most optimistic assumptions, the issue of rationing access to the Straits must be addressed very soon.

2. Tanker slots are more restricted due to safety considerations. Turkey has set the rule that only one dangerous cargo can be in the Bosporus at a time. This rule will result in congestion for tanker traffic much sooner. There is, however, sufficient capacity to carry the production of the Caspian oil fields if the slots are allocated efficiently and appropriately sized tankers are used. Such allocations would require modification of the Montreux Convention. One way to allocate tanker slots efficiently is to auction the slots. The alternative is to divert oil traffic to pipelines.

3. A key element of safety in the Straits is the separation, or distance, between vessels. As long as the required separation of traffic is sufficient to prevent vessels from having to maneuver, traffic flow is stable. However, if traffic has to maneuver to maintain separation, the flow of traffic becomes unstable, creating the potential for accidents.[8] The ability of the Straits to carry traffic is a function of separation. It may be thus be argued that, if the separation between ships is reduced,

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[6] Damage to the environment include such ongoing items as oil spill from bilges and sewerage. The risk of an accident from dangerous cargo may involve the small probability of a very large accident and is very difficult to quantify. For example, suppose the collision between *Nassia* and *Ship Broker* in 1994 had occurred next to the Topkapi Palace rather than in the Black Sea,

[7] See Table 2 on page 12 below.

[8] The distinction is between *open loop* and *close loop* control. Lags in control can make closed loop control systems unstable. Thus if vessels are spaced close enough so that they have to maneuver, the system can become unstable.

the capacity of the Straits to carry traffic will be increased. However, this can lead to unstable traffic dynamics which will increase the probability of accidents.

4. The probability of an accident in the Turkish Straits increases with the *square* of the volume of traffic if other conditions do not change. This implies that doubling traffic will increase the probability of an accident by a factor of four.

5. It is possible to reduce the volume of traffic that goes through the Straits without reducing the amount of cargo. At present, the distribution of cargo by size of vessels is such that 60 percent of the vessels are only carrying 30 percent of the cargo. A mechanism such as a two-part tariff, which makes it more economical to ship in larger vessels, could change the distribution of the size of vessels that use the Straits. A two-part tariff would consist of a fixed charge per vessel and a variable fee contingent on the size of the vessel. This result is important because it suggests that restricting access to the Straits can improve the welfare of all parties by more efficient use of its capacity.

Regulation of the use of the Bosporus is obviously very complicated. If safety is ignored, it can be argued that the Bosporus is not congested at the present time. However, if rules that space tanker traffic are enforced, then the Bosporus is or will soon be congested with respect to tankers. The Bosporus will likely be congested with respect to normal traffic in seven to fourteen years. The costs associated with traffic in the Bosporus are abstract. A large tanker accident that kills thousands of people or destroys historical treasures in Istanbul has not yet occurred. It is very difficult to create concern about an event that has not occurred and has very small probability of occurring, particularly when the danger is to others.

If the market is used to regulate access to the Straits, then safety regulations need not be used to control the volume of traffic. It may then be possible to have a more dispassionate technical discussion on safety. Changing rights of access to the Straits by creating property rights will have distributional consequences. The economic rents that result from privatization should be sufficient to compensate the losers. An international commission can be can established to do this . This, however, is a political issue.

2. Congestion of the Straits

One of the costs that can result from free access is delay due to congestion. Congestion will be familiar to most readers from their experience on highways. Traffic on highways flows smoothly until the volume reaches a critical level, and then it slows dramatically and stops. This process has been studied by traffic engineers using queuing models, some which can be very elaborate and require numerical solutions on a computer. Traffic through the Bosporus can be modeled in a similar fashion and it is possible to construct very elaborate computer simulations. It is useful, however, to construct a relatively simple model of the flow of traffic more transparent than a computer simulation based on the assumption that the 1994 navigation rules are enforced and the separation been vessels mandated by the rules is sufficient to eliminate the dynamic interaction between vessels as they proceed through the Straits. The assumptions about parameter values are few and the solution can easily be verified. Such a model, however, must be used with care. The simplicity is gained at the expense of ignoring the dynamics of traffic through the Straits.

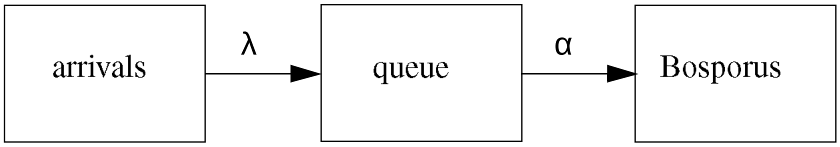

Figure 1

The process is illustrated by Figure 1 above. The arrival of vessels is assumed to be given by a Poisson process. This is equivalent to the assumption that ships arrive at random, but there is a given average arrival rate. Define the arrival rate as λ. This parameter is the average number of vessels that arrive at one of the entrances of the Bosporus in an hour. Upon arrival, vessels enter a queue for entry into the Bosporus. Vessels in the queue enter the Bosporus at an interval mandated by the navigation rules. Thus, the separation required and the speed of the vessels determine the rate at which vessels can enter the Bosporus. Define α to be the mean service time.

In 1997 traffic through the Bosporus was reported to be 50,000 vessels a year. This gives an average value of 2.85 for λ.[9] The other very important parameter in a queueing model is the rate at which vessel can enter the Bosporus denoted by α. If we assume that the 1994 navigation rules are in place, then vessels must maintain a separation of one nautical mile and a speed of 10 knots. This implies that no more than 10 vessels can enter the Bosporus in one hour in one direction. This is a very optimistic estimate of the mean service rate as it assumes that the Straits are always open to traffic. Further, maintaining a service rate of 10 vessels an hour would require that merchant vessels maneuver with the precision of a naval squadron. Ships would have to time the moment they get under way so as to maintain the required separation and speed. Weather and the skill and training of the crews of merchant vessels suggest that the effective mean service rate is likely to be less than 10 vessels an hour.[10]

The model results in a Markov process with a Poisson arrival rate, and a constant service time.[11] The waiting time of such a process is given by the equation

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[9]

month	**number of vessels**	λ
January	3551	2.47
February	3391	2.44
March	4207	2.83
April	3779	2.62
May	4813	3.23
June	4690	3.26
July	4738	3.18
August	4411	2.96
September	4272	2.87
October	4178	2.81
November	4724	3.28
December	4188	2.81

[10] The question of the correct separation between vessels involves a trade-off between the carrying capacity of the Straits and safety. Other factors that the model ignores, but must be kept in mind, are weather, local traffic and the need to close the Straits to two way traffic because of vessels that exceed 150 meters in length.

[11] For a discussion of such models see Vanags (1977).

$$W = \frac{1}{\lambda}\left(\frac{\left(\frac{\lambda}{\alpha}\right)^2}{2\left(1 - \frac{\lambda}{\alpha}\right)}\right). \tag{1}$$

where W is the mean waiting time, λ is the mean arrival rate, and α is the mean service rate.[12] In Figure 2 we plot waiting time as a function of service time for arrival rates of 3, 4.5, and 6 vessels an hour.

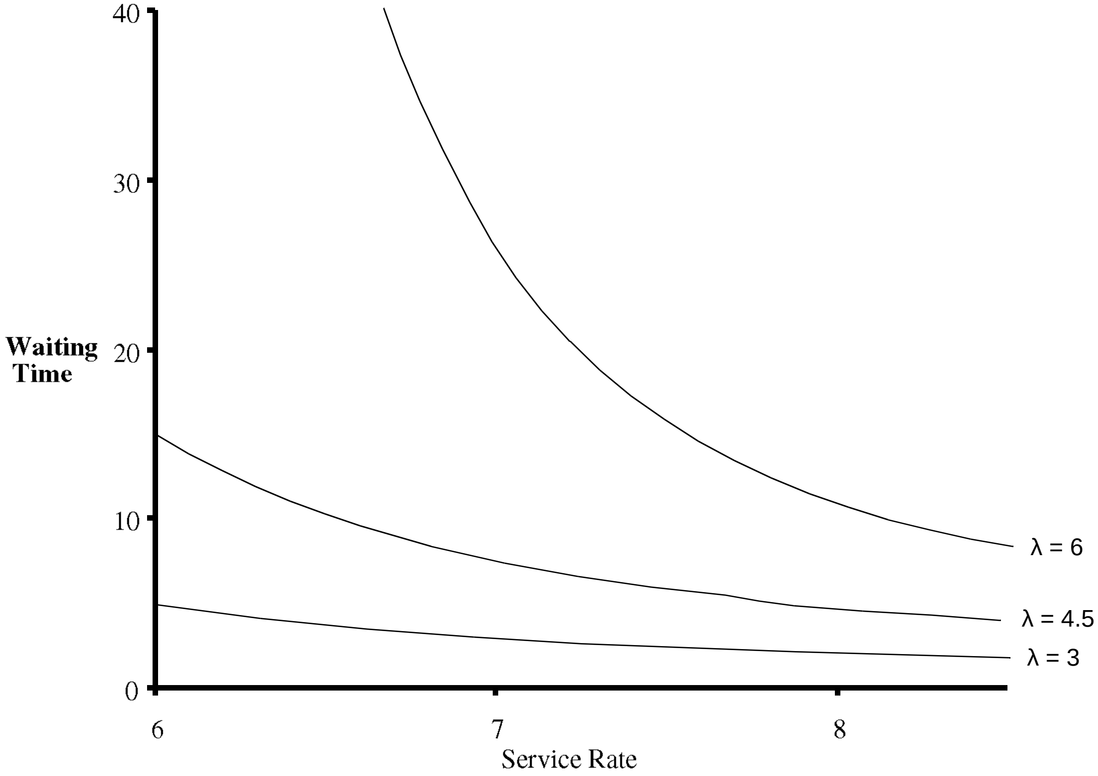

Figure 2

These calculations suggests that under normal circumstances, delays due to congestion are negligible for arrival rates less than 4.5 vessels an hour and service rates greater that 7 vessels an hour. This is consistent with current experience.

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[12] See Hillier, F. S. and G. J. Lieberman, (1967) p. 302.

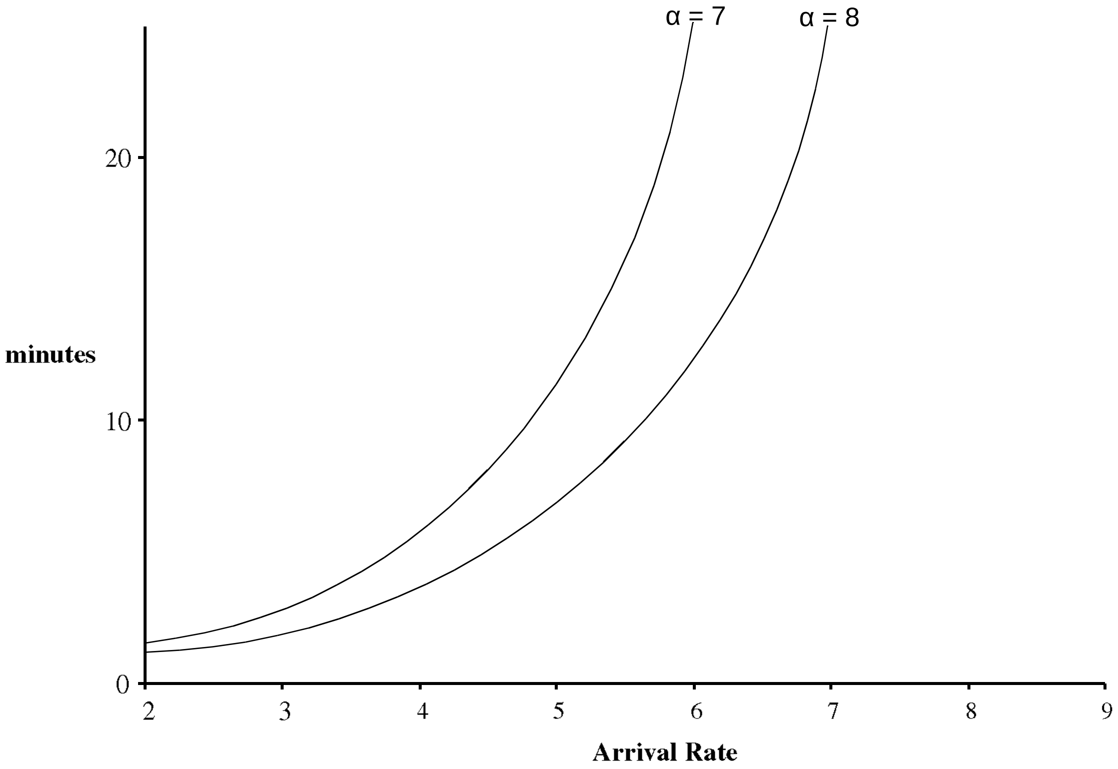

Figure 3

In Figure 3 above, we see that as the mean arrival time approaches the mean service time, the mean waiting time becomes very large. Traffic levels can be partitioned into three regions: First, a region where traffic is not congested and additional traffic does not create delays; second, a region where traffic is congested and additional traffic creates substantial delays; and third, a region where traffic through the Bosporus is not feasible. The points of partition between the congested and the uncongested region is somewhat arbitrary and the exact level of traffic where the Straits become congested is to some degree subjective. A measure that has been used to define congestion is the flow rate.[13] The flow rate, φ, is the ratio of the flow of traffic divided by the time it takes to use the facility. Thus, in the case of the Bosporus, this number is given by

$$\varphi = \frac{\lambda}{W + \tau} \qquad (2)$$

where τ is the time it take a vessel to transit the Bosporus, approximately 1.8 hours.

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[13] See Johnson (1965).

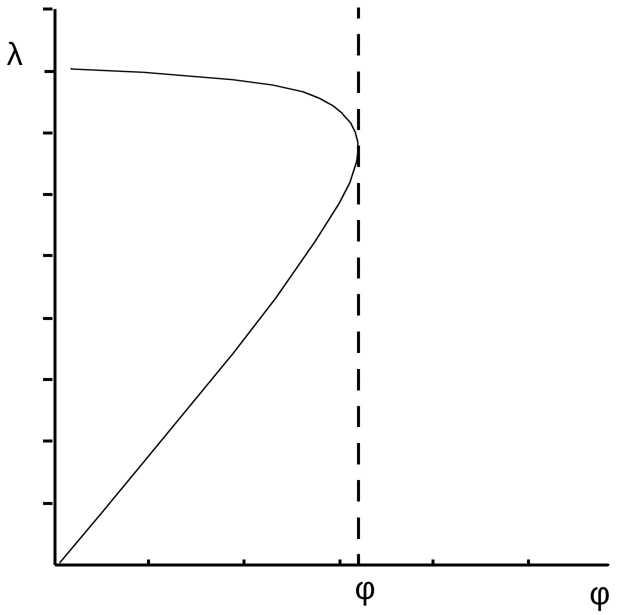

Figure 4

The relationship between λ and φ is depicted in Figure 4. Congestion is defined as the point where additional traffic reduces the flow, or equivalently, as the point where $\frac{d\varphi}{d\lambda} = 0$. φ is the maximum feasible flow of traffic. If we assume the service rate is 7, then the Bosporus becomes congested at 83 percent of capacity.

The date at which the Bosporus become congested depends on two parameters, the service rate and the rate at which traffic will increase. Predicting the rate at which the traffic will increase requires a prediction of the rate at which the economies that border the Black Sea will grow. Under normal circumstances, such predictions are difficult. In this case, the difficulties in prediction are further complicated by the fact that the economies of the countries that border the Black Sea are undergoing structural change. Further, the economic activity associated with the exploitation of the Caspian oil fields will generate additional traffic. The exploitation rate of these resources is still uncertain. Thus, it is probably a fool’s errand to attempt to predict when the Bosporus will become congested. It is not difficult, however, to compute a contingency table which can be used to put bounds on the problem.

A key parameter of the model is the arrival rate, λ. This parameter will vary by time of year and time of day. The seasonal variation in the reported data in 1997 was 134 percent. There appears to be variation the arrival rate over the day.[14] For example, if 60 percent of the traffic was during the twelve hours between six in the morning and six in the evening, then the arrival rate for July, 1997 would increase from 3.26 to 3.91 during the daylight hours. Table 1 below gives the time until the Bosporus becomes congested for general cargo under such conditions.

Table 1:

	service rate		
growth rate	7	8	9
3	13.0	17.9	22.2
3.5	11.2	15.3	19.0
4	9.8	13.4	16.7
4.5	8.7	11.9	14.8
5	7.8	10.7	13.3
5.5	7.1	9.8	12.1
6	6.5	8.9	11.1
6.5	6.0	8.3	10.3
7	5.6	7.7	9.5
7.5	5.2	7.2	8.9
8	4.9	6.7	8.3

The economic cost of congestion can be calculated. Define C_w as the cost of waiting, H as the average tonnage of a vessel, and β as the cost per ton per day. Then the cost of waiting is given by

$$C_w = \beta W H \tag{3}$$

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[14] I could not find published data of the use of the Straits by time of day. Casual observation suggests that traffic decreases a night. Collecting this data from primary sources should not be difficult. Whether time-of-day congestion will change arrival times is an interesting question.

The elasticity of cost with respect to traffic is given by

$$\eta = \frac{\partial C_w}{\partial \lambda} \frac{\lambda}{C_w} = \frac{\lambda}{\alpha - \lambda} \tag{4}$$

A modern 25-thousand ton container vessel costs approximately $1.00 per ton per day. The cost of tankers and bulk carriers are more on the order of $.50 a ton. The cost of holding cargo ranges from $.04 per ton per day for oil to $5.00 per ton per day for automobiles.[15] If we assume a service rate of 7 ships per hour, the delay of the average vessel at the point where the Bosporus becomes congested is about 20 minutes. The cost of delay under the assumptions that the average vessel is 4,500 tons and the cost per ton day is $1.00 at the point where the Bosporus becomes congested is about $70.

Table 2:

cost of delay

arrival rate (ships/hour)	**elasticity**	**delay (hours)**	**cost (dollars)**
6.000	7.00	0.43	$80
6.900	70.00	4.93	$924
6.990	700.00	49.93	$9,362
6.999	7000.00	499.93	$93,737

Table 2 above illustrates the dramatic increase in delay that occurs after the Bosporus becomes congested. Note that at a growth rate of 4.5 percent a year, it would take just over three years from the point where the Bosporus becomes congested to the point where delays are about 5 hours. It would take less than six months more to reach the point where the use of the Bosporus becomes economically infeasible. Of course this would not happen because freight rates would increase and the market would reach an equilibrium. Just as in the former Soviet Union, time in the queue would be the equilibrating mechanism that would ration the scarce resource. An explicit market for access is a more efficient way of allocating this resource.

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[15] Ship operating costs can be found in Noer (1996) and Tusiani(1996). Cargo hold cost can be calculated.

The separation between vessels and the regulations as to speed were assumed to be those of the 1994 regulations. There is a clear trade-off between the level of traffic the Turkish Straits can handle and the value of these parameters. This is a safety question that hinges on technical issues as well as judgments as to the value of human life. Telling the Turks that they must accept the risks associated with smaller separation distance between vessels is in fact telling the Turks that they must risk their population for the benefit of the economies of the Black Sea countries.

3. Stability of traffic and Safety

A key assumption of the analysis is the assumption that the navigation rules are being enforced so that the mandatory separation distance between vessels determines the service rate of the Straits. As the Straits become congested, there may be pressure to increase the service rate by decreasing the separation. Thus, it is useful to investigate the implications of separation on the stability of the traffic and safety.

The assumption that the service rate, α, is constant implies that once a vessel enters the Bosporus, it proceeds without any interaction with other traffic. Even at low volumes of traffic this assumption is probably not valid because vessels going through the Straits must deal with local traffic such as ferries. The problem becomes much more difficult, however, when the volume of traffic increases to the point where there is substantial interaction.

Traffic engineers have studied the dynamics of traffic systems and model such systems as coupled second order differential equations with lag responses. Consider *N* vessels trying to maintain a distance Δ from the vessel ahead and assume that there is a lag T between a disturbance and the time a vessel responds. This lag is due to lags in recognition, transmission of commands, and response of the machinery. Such interaction can be described by a second order differential equation

$$\frac{d^2 x_i}{dt} = \rho_i [x_{i-1}(t-T) - \Delta - x_i(t-T)] \tag{5}$$

Define a Δn -platoon as a group of n vessels following at a distance of Δ apart. The dynamics are described by the system of differential equations, where $\ddot{x}_1$ is the second derivative of x_1 with respect to time and ξ is a forcing function.

$$\begin{bmatrix} \ddot{x}_1 \\ \ddot{x}_2 \\ \\ \ddot{x}_N \end{bmatrix} = \begin{bmatrix} -\rho_1 & 0 & 0 & 0 \\ \rho_2 & -\rho_2 & 0 & 0 \\ \\ 0 & 0 & \rho_N & -\rho_N \end{bmatrix} \begin{bmatrix} x_1(t-T) \\ x_2(t-T) \\ \\ x_N(t-T) \end{bmatrix} - \begin{bmatrix} \xi \\ \Delta \\ \\ \Delta \end{bmatrix} \tag{6}$$

This system of lagged differential equations can be solved using Laplace transforms. Represent the Laplace transform of $x_i(t)$ by $X_i(s) = \Lambda(x_i(t))$ and recall that $\Lambda(x_i(t-T)) = e^{-sT} X_i(s)$, The system of differential equations given by (6) can be written as

$$\begin{bmatrix} s^2 + \rho_1 e^{-sT} & 0 & 0 & 0 \\ -\rho_2 & s^2 + \rho_2 e^{-sT} & 0 & 0 \\ \\ 0 & 0 & & s^2 + \rho_3 e^{-sT} \end{bmatrix} \begin{bmatrix} X_1(s) \\ X_2(s) \\ \\ X_N(s) \end{bmatrix} = \begin{bmatrix} \xi \\ -\Delta \\ \\ -\Delta \end{bmatrix} \tag{7}$$

The stability of the system is determined by the roots of

$$\det \begin{bmatrix} s^2 + \rho_1 e^{-sT} & 0 & 0 & 0 \\ -\rho_2 & s^2 + \rho_2 e^{-sT} & 0 & 0 \\ \\ 0 & 0 & & s^2 + \rho_N e^{-sT} \end{bmatrix} = 0 \tag{8}$$

If the lags are zero, the roots of the system are given by $\chi_i = \pm\sqrt{-\rho_i}$. The real roots are zero, so this is the equation of an undamped oscillator. Formally, it is a stable, but not asymptotically stable, system. However, if $T>0$, the system is unstable. If $T>0$, the characteristic equation is a transcendental function and there are an infinite number of roots. The stability properties can be investigated by looking at a linear approximation of the characteristic equation. This results in $\chi_i = \frac{\rho_i T \pm \sqrt{(T^2 - 4)\rho_i}}{2}$. The system will have positive real roots and is unstable. Since the real roots are positive, the transfer function does not give a defined response to a perturbation. The roots are independent of the size of the system which runs counter to the intuition and observations that an increase in the length of the platoon will increase the instability of the platoon. Furthermore, the stability properties are independent of the separation which goes counter to observations that gaps in traffic dampen disturbances. Observations of traffic in tunnels have suggested that as density increases there are discontinuities in the flow of traffic.[16] We can construct a model that addresses such questions. Assume that vessels are initially separated by a distance Δ and as long as the separation exceeds Δ_0 the vessel maintains the prescribed speed, v_0. If the separation is sufficient so that vessels do not have to respond to minor variations, most disturbances should cancel and the system can run open loop. As long as the disturbances are minor, the dynamics of the system are stable. If, however, there is a disturbance of sufficient magnitude to reduce the separation to less than Δ_0, vessels will maneuver to maintain separation. Since an unstable system will amplify disturbances, a disturbance to the *i*-th vessel in a platoon will be transmitted to all following vessels.

Calculating the probability that a disturbance will create instability is a special case of calculating the probability that a disturbance can lead to an accident. If we assume that the probability of a disturbance is small enough so that we can ignore second order terms, then the probability of a disturbance to a platoon will deviate sufficiently to lead to an accident is:

$$\xi_n = n\int_{\Delta}^{\infty} \phi(s))ds. \tag{9}$$

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[16] See Gazis (1973), pp. 76-103.

A Δn -platoon can have an accident if the platoon ahead has an accident or a platoon of oncoming traffic has an accident and is close enough to transmit the disturbance. To compute the probability of an accident it is necessary to first compute the distribution of platoons.

Let *v* be the required speed though the Bosporus and *D* be the length of the Strait. The time necessary to transit the strait is $\frac{D}{v}$. In a steady state, average rate must be equal to the rate at which vessels are going though the Strait. Thus, the average number of vessels in the strait is $\lambda\frac{D}{v}$. Assume the separation distance is Δ, then there are $\frac{D}{\Delta}$ slots and the probability that any of the slots is occupied is $p = \frac{\lambda\frac{D}{v}}{\frac{D}{\Delta}} = \frac{\lambda\Delta}{v}$.

The probability that a vessel is in a Δn -platoon is $n(1-p)^2p^{n-1}$. Let $M = \lambda\tau_o$ be the number of vessels that transit the Straits in a given time period, τ_0. The expected number of vessels in a Δn -platoon is $Mn(1-p)^2p^{n-1}$ and the number Δn -platoons is $\frac{Mn(1-p)^2p^{n-1}}{n} = M(1-p)^2p^{n-1}$. The total number of platoons is $\Theta = M(1-p)$.

Let *N* be the size of the largest platoon, for a very large *N*, the distribution of Δn -platoons is then given by

$$\pi(\Delta, n) = \frac{(1-p)^2p^{n-1}}{(1-p)^2\sum_{n=1}^{N}p^{n-1}} = \frac{p^{n-1}}{\sum_{n=1}^{N}p^{n-1}} \quad p^{n-1}(1-p). \tag{10}$$

Define $G_1(\lambda, \Delta)$ as a function that gives the conditional probability that a platoon will have an accident caused by the platoon ahead of it and $G_2(\lambda, \Delta)$ as a function that gives the conditional probability that a platoon will have an accident caused by the platoon adjacent to it. It will be assumed that $\frac{\partial G_1(\lambda, \Delta)}{\partial \lambda} \geq 0$ and $\frac{\partial G_2(\lambda, \Delta)}{\partial \lambda} \geq 0$. That is, increased traffic does not decrease the probability of an accident.

Assume that both streams of traffic are symmetrical. Let $\Omega_{\Delta n}$ be the probability that a Δn -platoon will have an accident. Then

$$\Omega_{\Delta n} = \xi_n + G_1(\lambda, \Delta) \sum_{i=1}^{N} \pi(\Delta, n) \Omega_{\Delta i} + G_2(\lambda, \Delta) \sum_{i=1}^{N} \pi(\Delta, n) \Omega_{\Delta i} . \tag{11}$$

Define

$$\Omega_{\Delta} = \sum_{i=1}^{N} \pi(\Delta, n) \Omega_{\Delta i} \tag{12}$$

and

$$G(\lambda, \Delta) = G_1(\lambda, \Delta) + G_2(\lambda, \Delta) . \tag{13}$$

Equation (11) can be approximated by a system of linear equations

$$\begin{bmatrix} 1 & 0 & -G(\lambda, \Delta) \\ 0 & & -G(\lambda, \Delta) \\ & & \\ -\pi(\Delta, 1) & -\pi(\Delta, 2) & 1 \end{bmatrix} \begin{bmatrix} \Omega_{\Delta 1} \\ \Omega_{\Delta 2} \\ \\ \Omega_{\Delta} \end{bmatrix} = \begin{bmatrix} \xi_1 \\ \xi_2 \\ \\ 0 \end{bmatrix} \tag{14}$$

For N large, $\sum_{i=1}^{N} \pi(\Delta, i) \quad 1$, so

$$\Omega_{\Delta n} = \xi_n + G(\lambda, \Delta)\left[\frac{\sum_{i=1}^{N} \pi(\Delta, i)\xi_i}{1 - G(\lambda, \Delta)}\right] \tag{15}$$

$$\Omega_{\Delta} = \left[\frac{\sum_{n=1}^{N} \pi(\Delta, i)\xi_i}{1 - G(\lambda, \Delta)}\right] = \left[\frac{(1-p)\sum_{n=1}^{N} np^{n-1}}{1 - G(\lambda, \Delta)}\right]\int_{\Delta}^{\infty} \phi(s))ds \tag{16}$$

or

$$\Omega_{\Delta} = \left[\frac{p}{(1-p)[1 - G(\lambda, \Delta)]}\right]\int_{\Delta}^{\infty} \phi(s))ds \tag{17}$$

Recall that $\Theta = \tau_0\lambda(1-p)$ is the number of platoons. The expected number of Δn -platoons that have an accident is $\pi(\Delta, n)\Omega_{\Delta n}\Theta$. Using equation (12), the total number that have an accident can be written as

$$Z(\Delta, \lambda) = \Theta\Omega_{\Delta} = \tau_0\lambda\left[\frac{\frac{\lambda\Delta}{v}}{[1 - G(\lambda, \Delta)]}\right]\int_{\Delta}^{\infty} \phi(s))ds\,. \tag{18}$$

Now consider some base period $Z(\bar{\Delta}, \bar{\lambda})$. The number of accidents relative to this base period is given by

$$R(\Delta, \lambda) = \frac{Z(\Delta, \lambda)}{Z(\bar{\Delta}, \bar{\lambda})} = \frac{\lambda^2[1 - G(\bar{\lambda}, \bar{\Delta})]}{1 - G(\lambda, \Delta)}\,. \tag{19}$$

As long as the probability of a transmitted accident is not decreasing with the volume of traffic, the number of accidents increases with the *square* of the flow of traffic.

4. The Economics of Restricting Passage

Because the Bosporus is a common property resource, its congestion is not unexpected. The argument that restricting access to a congested common property resource will increase efficiency is also not novel. Until recently, however, it had been accepted that the wealth transfer associated with privatizing a common property resource was from the user to the new holder of the resource. Recent research, however, has shown that if the users of the common property resource are heterogeneous, then the creation of property rights to a common property resource can lead to a market allocation that will benefit both the owner of the common property resource and the user.

The argument is that a solution to the problem of congestion of the Bosporus is to recognize Turkish property rights to this Strait. If the Bosporus is congested, this allocation of rights will lead to an increase in the welfare of the Black Sea states that depend upon the Bosporus for access to the Mediterranean.

A key element in establishing this argument is to show that it is feasible to reduce the volume of traffic without reducing the cargo that transits the Bosporus. Data on the distribution of tonnage of vessels that transit the Straits are not available, but there are data on the distribution of length of vessels that cross the Dardanelles.[17] This data can be used to construct a distribution of tonnage given some technical assumptions. The data are presented in the histogram in Figure 5 below.

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[17] This data is courtesy of the Turkish Embassy in Washington.

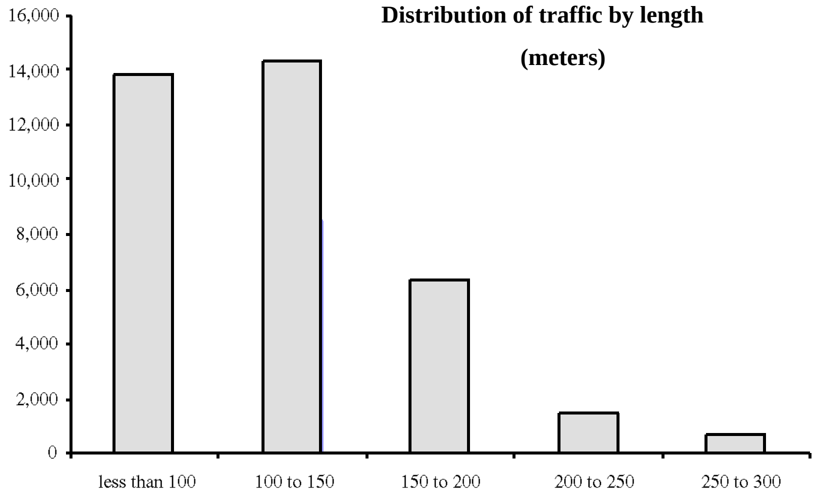

Figure 5

The data can be used to construct a cumulative density function. I will assume that all merchant vessels are at least 75 meters in length. Inasmuch as there are vessels that are reported that are less than 75 meters in length, this assumption will bias the data against the argument I am making.

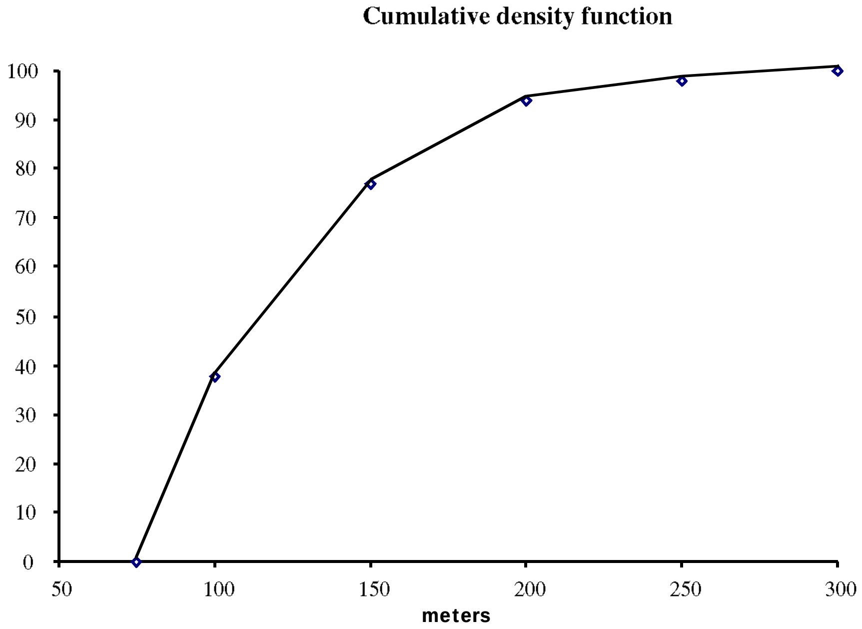

Figure 6

To calculate the distribution of the traffic by tonnage, approximate the cumulative density function by piece-wise linear segments. Define N_0 as the total number of ships that pass through the Straits and $N(L)$ as the total number of ships under L meters in length. The density function is defined by equation (20), below.

$$N(300) = N_o \int_0^{300} A(s)ds. \qquad (20)$$

Where

$$\int_0^{300} A(s)ds = \int_{75}^{100} a_1 ds + \int_{100}^{150} a_2 ds + \int_{150}^{200} a_3 ds + \int_{200}^{250} a_4 ds + \int_{250}^{300} a_5 ds \qquad (21)$$

and $a_i \quad i = 1, 5$ are the parameters of the piece-wise linear density function.

The next step is to relate the data on length of vessels to tonnage. If vessels are similar in shape, tonnage is a function of the cube of the length, thus

$$Y = \theta L^3 \qquad (22)$$

where θ is a parameter.[18] The amount of cargo capacity of vessels of length L or less is given by

$$\int_0^{L} \theta N_0 A(s) s^3 ds \qquad (23)$$

and total cargo capacity is given by

$$\int_0^{300} \theta N_0 A(s) s^3 ds. \qquad (24)$$

The fraction of cargo capacity of vessels of length less than or equal to L is given by

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[18] John H. Noer at the Center for Naval Analyses reports finding this relationship between length of vessel and tonnage.

$$F(L) = \frac{\int_0^L A(s)s^3 ds}{\int_0^{\bar{L}} A(s)s^3 ds} \tag{25}$$

Note that the constants θ and N_0 cancel. Inasmuch as smaller vessels have larger overhead in term of weight to cargo carrying capacity than larger vessels, this relationship is biased in favor of smaller vessels.

The other important consideration is the load factor. Define b_i as the load factor. The actual amount of cargo, Y, carried through the Straits will be given as

$$Y = \theta N_o\left(\int_{75}^{100} a_1b_1s^3ds + \int_{100}^{150} a_2b_2s^3ds + \int_{150}^{200} a_3b_3s^3ds + \int_{200}^{250} a_4b_4s^3ds + \int_{250}^{300} a_5b_5s^3ds\right) \tag{26}$$

Assume that all vessels less than 100 meters have a load factor of 100 percent, vessels between 100 meters and 150 meters have a load factor of 75 percent, and vessels over 150 meters have a load factor of 50 percent. Vessels under 150 meters in length comprise over 75 percent of the traffic. Tankers and bulk carriers will be in ballast approximately 50 percent of the time. These assumptions are intended to bias the case in favor of small vessels. Table 3 below gives the values of the parameters.

distribution of traffic and load factors		
length	a_i	b_i
75-100	0.0152	1
100-150	0.0078	0.75
150-200	0.0034	0.5
200-250	0.0008	0.5
250-300	0.0004	0.5

Table 3:

The distribution of carrying capacity and cargo are plotted in Figure 7 below.

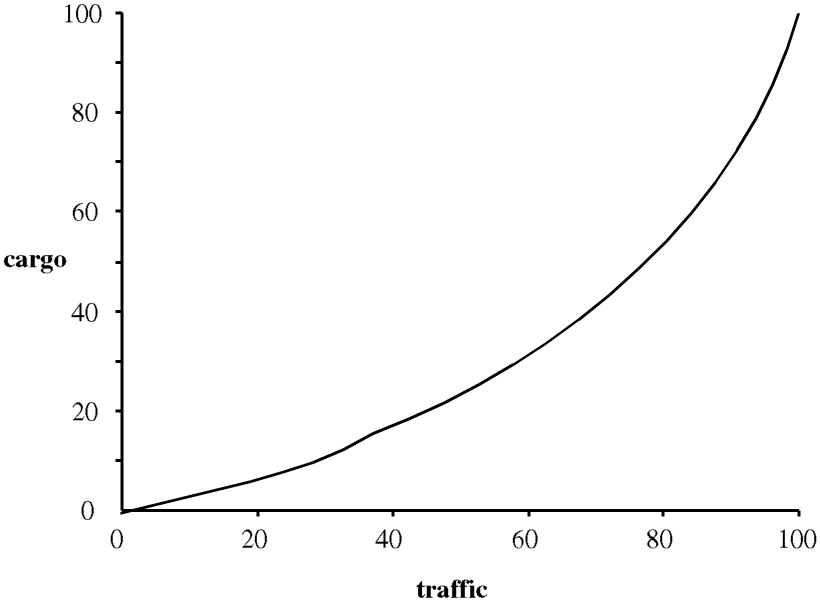

Figure 7

The question that follows is how much can traffic be reduced and still handle cargo. Assume that the minimum length of the vessels, L_{MIN}, is greater that 100 meters and that all the cargo carried by excluded vessels is reallocated uniformly to vessels under 150 meters in length. Let q be the increase in the cargo carried by these vessels, then

$$Y = \theta N_o \left(q \int_{L_{MIN}}^{150} a_2 b_2 s^3 ds + \int_{150}^{200} a_3 b_3 s^3 ds + \int_{200}^{250} a_4 b_4 s^3 ds + \int_{250}^{300} a_5 b_5 s^3 ds \right) . \tag{27}$$

Equations (26) and (27) can be used to solve for q ,

$$q = \frac{\int_{75}^{100} a_1 \frac{b_1}{b_2} s^3 ds + \int_{100}^{150} a_2 s^3 ds}{\int_{L_{MIN}}^{150} a_2 s^3 ds} \tag{28}$$

Note that most of the parameters have been eliminated and the only assumption needed is the ratio of the load factors of vessels less that 100 meters in length and vessels greater than 100 meters in length. Let R be the reduction in traffic that results from imposing a restriction on the length of vessels that transit the Straits, then reduction in traffic necessary to carry the cargo is given by equation (29)

$$\Upsilon = 1 - \frac{N}{N_o} = 1 - \left(q \int_{L_{MIN}}^{150} a_2 ds + \int_{150}^{200} a_3 ds + \int_{200}^{250} a_4 ds + \int_{250}^{300} a_5 ds \right) \tag{29}$$

Figure 8, below, gives the value of Υ for values of L_{MIN} between 100 and 150 meters.

Figure 8

The distribution of cargo by size of vessels is such that 60 percent of the vessels are only carrying 30 percent of the cargo. Thus, any policy that increases the amount of cargo carried by larger vessels could result in a decrease in traffic without reducing the amount of cargo that transits the Straits. A policy that could change the distribution of the size of vessels transiting the Straits is a two-part tariff. A two-part tariff consists of a fixed charge that is independent of the size of the vessel and a fee contingent upon the size of the vessel.

Shipping is of course governed by the laws of supply and demand. But it is a more complicated market than many. On the demand side, cargo is a commodity with multiple attributes. At a very simple level, moving cargo involves the minimization of at least three separate costs: First, there is the cost of consolidating the cargo, loading it on the vessel, unloading and distributing it; second, there are the capital costs associated with the cargo; and third, there is the cost of shipping (freight rates). Shippers choose vessels so as to minimize the cost of moving the cargo. A shipper of a small cargo from a small port may choose to use a small vessel even though the cost of transportation per ton is less on a large vessel.

The supply of shipping is also very complicated. Ships are an irreversible form of investment. Once a ship is built, it is available to the market until it is scrapped. The actual supply depends on the time frame. In the long run, ships can be built or scrapped. In the medium run, ships can be laid up or brought back into service. In the short run, ships can be redeployed between markets. And in the very short run, the only variable that can be adjusted is freight rates. Thus, at any time the owner of the vessels must solve a very complicated dynamic optimization that involves not only the revenues from the cargo it is about to load, but also future revenues that depend on the location of the vessel and future cargos. The complexity of the market makes it very difficult to use standard supply and demand analysis to study this market. However, if we restrict our analysis to a time interval large enough so that the distribution of vessels among markets is in equilibrium, we can assume that for most cargos the shipping market is competitive. This implies that the rate of return on a particular type of vessel must be the same in all markets in which that type of vessel can compete.

Consider a shipper moving a cargo of type *i*, from port *j* to destination *k* using a vessel of length *s*. We can write the cost of shipping this cargo as

$$C_{ijk} \; = \; C^1_{ijk}(s) + C^2_{ijk}(s) \tag{30}$$

where $C^1_{ijk}(s)$ is the sum of the cost of handling the cargo and the capital cost and $C^2_{ijk}(s)$ is the freight rate. We will assume that in *most* cases the cost of handling the cargo and the interest cost increase as the size of the vessel increases and the freight rate declines. The justification for these assumptions is that smaller vessels provide more frequent service to smaller ports, but there are increasing returns to scale in the ship size. This curve may be strictly increasing, for example, cargo going in to very small ports or into the Danube where there are serious draft limitations. On the other hand, the cost of moving oil and other bulk cargos may be strictly decreasing for vessels under 20 to 40 thousand tons.

Some cargos will have an interior minimum. The cost curve is depicted in Figure 9 below.

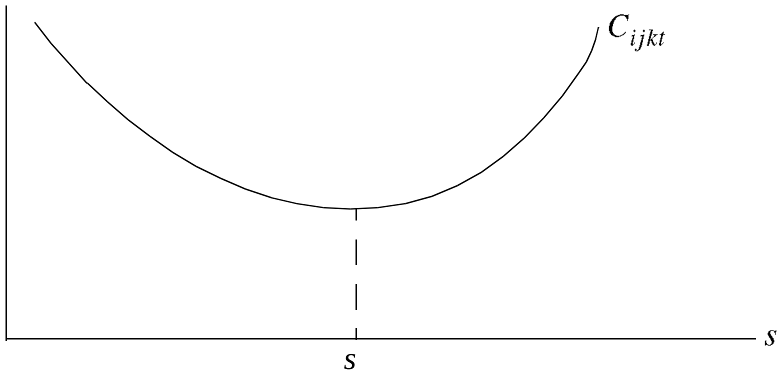

Figure 9

The lowest cost is given by s , so if the ships are available, the shipper would use a vessel of size s . In the medium run, this curve is likely to be quite flat. Vessels of various sizes will be competing for the same general cargo and any competitive advantages or disadvantages will be capitalized into the value of the vessel. In the long run, construction of new vessels will result in vessels that are more efficient given the distribution of cargo.

Let us suppose that a two-part tariff of the form

$$T = y + z \tag{31}$$

is imposed on vessels. If the market for ships is competitive, the cost of shipping is given by

$$\hat{C}_{ijk} = C^1_{ijk}(s) + C^2_{ijk}(s) + \frac{y}{s} + z\,. \tag{32}$$

The curve would shift as shown in Figure 10 below.

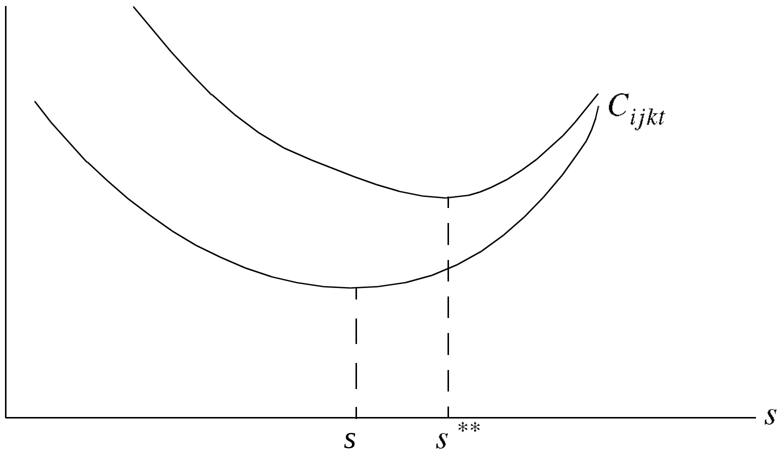

Figure 10

The cost will increase and the minimum point will shift to the right from s to s^{**}. To see this note that the minimum point is given by the solution to $\frac{d\hat{C}_{ijk}}{ds} \quad \frac{y}{s^2} = 0$. Thus, $\frac{dC_{ijk}}{ds} > 0$ at the point s^{**}, which implies that $s^{**} > s$.

Thus, a two-part tariff will increase the average size of a vessel that uses the Straits and the burden of the tax will be on the cargo. Analyzing whether the burden of the tax will be on the buyer or seller of the cargo is beyond the scope of this essay.

Oil is different from general cargo. There are two additional constraints to oil traffic. The first and most important is the rule that allows only one vessel carrying dangerous cargo to be in the Bosporus at a time. The second is the fact that very large tankers in excess of 150 meters in length need the entire channel to maneuver and thus require that traffic in the opposite direction be halted.

However, even under very restrictive regulations, there are on average over ten slots for tankers to transit the Straits a day. A 60-thousand ton tanker can carry approximately 400 thousand barrels of oil. Thus, ten such tankers can carry four million barrels a day. This number is far in excess of projected Caspian oil exports in the foreseeable future. The problem is how to allocate these slots in an efficient manner. One possible mechanism is an auction. Auctions are now used to allocate access to power grids. By comparison, an auction to allocate tanker slots would be very straight-forward. The economies of transporting of oil by tanker relative to pipelines are so large that it is likely to be cheaper to move oil out of the Black Sea by tanker under the strictest of safety standards than to use pipelines.[19]

Supporters of the Baku-Ceyhan pipeline face a dilemma. If access to the Straits is not restricted, then a pipeline that carries oil to the Mediterranean is not economically viable because of the large differential in the costs. The differential cost of moving oil by tanker from Novorossiysk to Augusta compared to Ceyhan to Augusta is under 20 cents per barrel. The capital costs alone of the Baku-Ceyhan pipeline are around $1.50 per barrel. Tariffs on pipelines reflect the cost of alternative means of transporting the product. SUMED tariffs, for example, are indexed to tanker rates. If traffic through the Straits is not regulated, a pipeline is not economically viable. However, if traffic through the Straits is regulated, the oil can be transported safely and economically and a pipeline is not necessary.

5. Conclusions

The step between the results of an economic study and policy recommendations is treacherous; there is the temptation to push the recommendations beyond what can be supported by the results of the study. I am going to yield to the temptation and indulge in some speculation.

The results of the paper suggest that in only a few years the Straits will simply not be able to carry the traffic without imposing substantial delays. Therefore, it will be necessary to ration access to the Straits. It is in the common interest of the countries that border the Black Sea that such a mechanism be implemented. One rationing mechanism is the market which can substantially reduce the amount of traffic without any reduction in the amount of cargo that transits the Straits. Economic rents can be created by a well defined system of property rights, however, changing rights of access to the Straits will have distributional consequences. The economic rents that result from privatization should be sufficient to compensate the losers. An international commission to do this can be established.

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[19] It must be emphasized that how safe is safe enough is a policy question that requires the judgment of experts in the field. However, a bench mark could be the standards imposed on shipping in American or Western European waters.

If the market rations access to the Straits, then safety regulations need not be used as a mechanism to regulate the volume of traffic. It may then be possible to have a more dispassionate technical discussion on safety. This is important as many people appear to view proposed regulations as a pretext in the argument for the Baku-Ceyhan pipeline. An accident that kills thousands of people or destroys historical treasures in Istanbul has not occurred. It is very difficult to get people to worry about an event that has very small probability occurring. Capacity of the Straits to carry traffic and safety are related and there are trade-offs; however, the economic surplus that could result from a rational allocation of the use of the Straits would permit an increase in safety without a reduction of the amount of cargo that transits the Straits.

An element that could play an important part in resolving the issue of the Bosporus is the market for natural gas. In 1994, when Turkey imposed unilateral navigation rules, Russia threatened to withhold natural gas from the Turkish market. In 1999, the roles are reversed. Central Asia now has an oversupply of natural gas and Turkey is one of the few markets for this gas. A stable market for Russian gas and for the use of the Russian gas pipeline system could be a factor in negotiations to revise the Montreux Convention.

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