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The Effectiveness of Canada's Navy on Escort Duty

Karl Skogstad[1]

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Abstract

This paper examines the potential costs a country faces when it fails to develop domestic arms manufacturing. I examine these costs using the historical example of Canada's decision to not develop domestic naval shipbuilding capacity prior to World War II. Canada's primary naval responsibility during the war was to escort convoys between the United Kingdom and North America. However its lack of advanced domestic shipbuilding capacity and congestion at Allied shipyards, meant that Canada could not obtain the relatively advanced destroyer class vessels necessary for convoy duty. Instead it had to rely on less advanced corvette class vessels, which were simple enough to be manufactured domestically. Using a unique data set, created for this project, I match convoy movements to German U-boat locations in order to examine the escort composition and the number of merchant ships lost when an engagement occurred. Using this data I find that destroyers were 2.14 more effective than corvettes at preventing the loss of a merchant ship. Then, by constructing a counterfactual scenario, I find that developing a domestic ship building industry in Canada would have netted the Allies a benefit of 28.7 million 1940 Canadian dollars.

JEL classification: N42, F51, F52, H56, H57

Keywords: Canadian Navy, World War II, Convoys, Domestic Arms industries.

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1 Introduction

Many OECD countries pursue industrial policies designed to establish and maintain domestic arms manufacturing facilities.[2] These governments believe that the benefits from having domestic arms industries outweigh the necessary cost of maintaining them. This paper examines the costs and benefits of establishing and maintaining arms industries using the historical example of Canada's World War II naval experience.

There are several potential benefits of maintaining domestic arms industries. First, it is believed that many positive externalities in the form of advanced technologies result from arms industries. Second, there is prestige associated with having a domestic arms industry. Third, it may not be politically feasible to expend large sums of money to procure weapons from foreign firms. Fourth, and the focus of this paper, is the notion that it acts as a form of insurance in case the ability to procure weapons internationally is lost during times of high demand.

International trade models, such as the Ricardian model or the Heckscher-Ohlin model, demonstrate the welfare advantage of countries specializing in the production of goods in which they hold a comparative advantage and then trading with other countries. What these models miss, and what some policy makers fear, is the case where trade is unilaterally stopped. Examples of this include the case of China cutting off the export of rare earth elements to Japan during their dispute over the Senkaku Islands in 2012, and the surge of demand for ammunition during the wars in Afghanistan and Iraq, which led to shortages in some NATO countries. It is possible that the cost of developing and maintaining domestic industries is lower than the potential cost of being unable to procure the necessary weapons when needed.

This argument is difficult to evaluate as it is hard to estimate these potential costs. Without observing the counterfactual, it is difficult to make welfare comparisons between the two cases. This paper uses a historical example in an attempt to measure these costs. The specific example in this case can be thought of as a worst case scenario: a country that was almost completely unprepared for a large conflict.

During World War II, the primary role of Canada's navy was to escort convoys between North America and the United Kingdom.[3] Unfortunately, Canada's pre-war navy was unable to perform this role adequately as it had only 10 ships capable of

[2] For instance, Canada's Industrial Regional Benefit Policy requires that foreign firms that receive military procurement contracts from the Government of Canada must in turn spend 100% of the value of that contract with Canadian firms.

[3] See Schull (1950) for the official history of Canada's navy in World War II

acting as escorts. Thus, the Canadian government requested that domestic shipyards begin construction of destroyers, a type of ship that excelled at escorting convoys. Regrettably, Canadian industries were not up to the challenge of building ships to naval standards.[4] Exacerbating the situation was that Canada could not procure the ships from other countries. In desperate need of escorts, the Government of Canada procured the plans for the Flower-class Corvette from the UK. This ship was of much simpler design and could be produced in Canada.

Corvettes were easier to build than destroyers, but were also much less capable ships. Here I am interested in quantifying this difference in order to determine the cost borne by Canada and its allies from Canada being unable procure the proper ships.

To determine this cost, I develop a unique data set which combines information from the German Navy, the Allied navies, and the Allied Merchant Marine. Information concerning convoys traveling from North America to the United Kingdom is combined with information on the composition of the escort ships on each day of their passage. This in turn is combined with the location of German U-boats. By examining the sinking of merchant vessels on each day of each convoy, and analyzing the type and number of escorts used versus the number of U-boats attacking the convoy, I can quantify how much better destroyers were than corvettes at protecting merchant ships from sinking.

Under my preferred regression specification, I find that destroyers were 2.14 times more effective than corvettes at preventing merchant ship losses. Under a counterfactual scenario I develop, wherein Canada could produce destroyers during the war, I find that it would have been possible for 33 merchant ships to be saved from the U-boats with a net benefit to the program of \$28.7 million 1940 Canadian dollars. Given that the 1939 Canadian defence budget stood at \$36.3 million, the potential savings were quite substantial.

This is not the first paper that attempts to quantify the difference in ability of weapon platforms. The examination of the use of helicopters versus fixed wing aircraft during the Vietnam War by Hildebrandt (1999) estimates a similar value. In that scenario, the weapons were complements whereas in this case, the ships used were substitutes for one another. Rohlfs (2011) examines the use of armoured and infantry divisions during World War II to examine the value placed on different human lives and how the US military used different weapons to accomplish different tasks.

This paper is organized as follows. The next section provides additional historic background information on the conflict. Section 3 outlines the data sources for this

[4]Macpherson and Milner (1993)

project. Section 4 provides an analysis of the data and quantifies the difference in the capacity of destroyers over corvettes. Section 5 examines a counterfactual scenario in which Canada does invest in production facilities in peace time. I use this to estimate the cost incurred by Canada and its allies due to the lack of domestic production. Section 6 concludes.

2 Historical Setting

At the outbreak of the war, the Allies immediately took control over the routing of all ships heading towards the British Isles. Most ships were organized into convoys, a group of merchant ships traveling together under the escort of naval vessels. The experience of the Allies in the First World War had shown that the use of convoys greatly reduced the sinking of ships by U-boats.[5] These convoys carried the necessary supplies to ensure the survival of the UK and facilitate the buildup of the military forces necessary to retake continental Europe.

There were many convoy routes used by the Allies during the war, however this paper focuses on the three major routes between North American and the UK. These routes, labelled by the Allies as HX, SC, and ON, were arguably the most vital convoy routes and were the ones on which the Royal Canadian Navy (RCN) played the largest role. Ships in HX and SC convoys carried a variety of cargo including lumber, fuel, minerals, machines and foodstuffs from North America to the UK.[6] Ships in the ON convoys were empty of cargo as they made the return trip to North America. Between these three routes, a total of 848 convoys sailed. Of these, 119 suffered a successful German attack, with 448 merchant ships being sunk or damage. This resulted in a loss of nearly two and a half million tons of shipping.

Protecting the merchant ships were a wide variety of naval vessels, though the four most common types were destroyers, corvettes, minesweepers, and frigates. At the outbreak of the war, destroyers were the ships deemed most preferable for escort duty based on the experience of World War I. However, a lack of available destroyers led to corvettes being used extensively as they could be constructed quickly and were rudimentary enough to be built in shipyards that had no prior naval construction experience. The lack of available escorts also meant that minesweepers, which were not originally intended for use as convoy escort, were often used in that role. Finally, frigates, introduced much later in the war, were similar to destroyers yet they could be constructed

[5] Hague (2000)

[6] Note that they did not carry soldiers.

in less experienced shipyards. It is important to note that the choice of escort ships for a particular convoy was not based on the cargo carried by that convoy, as this was relatively homogeneous across convoys, but instead on which ships were currently available.

It is necessary to understand why destroyers were preferred over corvettes, however simply comparing corvettes to destroyers is difficult, as there are many variety of each type of ships.[7] In Section 5, I present a counterfactual scenario wherein Canada produced destroyers during the 1930s. For this reason, I will compare the capability of the Royal Navy (RN) A-class destroyer to that of the Flower-class corvette.[8] The A-class was the earliest UK destroyer constructed during the 1930s, so it is likely that any Canadian built destroyer would have shared similar characteristics. Table 1 compares the Flower-class corvette to the A-class destroyer and the River-class frigate.[9]

The table makes it clear that corvettes were smaller, slower, and could not travel as far as destroyers. They could barely keep up with the convoys they needed to protect, especially if they had to detach to hunt U-boats. Their limited range meant that they would often have to depart from the convoy before the passage was complete, with predictable consequences for the merchant ships in the convoy. Their smaller size meant that they carried fewer weapons, and less equipment. Perhaps most importantly though, their small size made for an uncomfortable passage. The North Atlantic can be very hazardous, and high waves meant that water would often crash over the low corvette decks. Passage aboard a corvette was wet, cramped, and overall very uncomfortable.[10] It is reasonable to believe that the quality of the ship adversely affected the quality of the sailors aboard.

At the beginning of the war, the RCN found it difficult to fulfill its escort duties as it lacked the necessary ships. Canada had not developed a large navy during the First World War, nor had it develop a large navy in the inter-war years. At the beginning of the Second World War, Canada's navy consisted of six British-built destroyers and 4 Canadian-built minesweepers.[11]

To make up for this shortcoming, the Canadian government began investigating how they could acquire more ships. Attempts to acquire destroyers from the UK proved difficult due to congestion at their shipyards from their high domestic demand. US shipyards were unable to supply ships due to their neutral stance. When it was clear that

[7]Three types of corvettes and over fifty types of destroyers were used by the Allies.
[8]By far the most common class of corvette.
[9]The class of frigate that was constructed in Canada during the war.
[10]Milner (1985) and Macpherson and Milner (1993)
[11]Schull (1950)

destroyers could not be acquired from foreign shipyards, Canada explored procuring them domestically. However, Canadian shipyards lacked the necessary human and physical capital to construct destroyers. As such, the Canadian government procured plans for the Flower-class corvette from the UK. Since these ships were technologically simpler, they could be constructed in Canada.

Table 2 gives the size of the RCN on various dates during the war. Clearly, corvettes made up the bulk of the RCN. The table also makes clear that the number of destroyers in Canadian service remained low throughout the war, rising only when they could be acquired from the US and the UK under special circumstances.[12]

During the war, naval construction in Canada was widely dispersed amongst a number of yards. At the outset of the war, the cumulative naval construction experience of all Canadian yards was 5 minesweepers produced at 5 different shipyards across Canada. By the end of the war, over 25 shipyards had produced escort-capable ships.

Canada was not the only country providing escorts for the North Atlantic convoys. The US, France, the Netherlands, Norway, and Greece all provided escort ships as well. However, along with Canada, it was the UK which provided the largest share of total Allied escorts. It is difficult to quantify who provided more resources on the HX, SC, and ON convoy routes, however, factoring in the convoy routes towards Africa and the Mediterranean, it is clear that the UK provided the lion's share of Atlantic escort services for the Allies. The RN had a higher ratio of destroyers to corvettes when compared to the RCN. Additionally, their ships were typically more technologically advanced.[13] Quantifying the ability of the sailors between the two navies is difficult, however anecdotal evidence suggests that the institutions of the RN provided better trained sailors than their Canadian counterparts, as one would expect from an institution with centuries of experience.

The main threat to the convoys in the North Atlantic was from German submarines, known as U-boats. The German navy operated 1153 U-boats during the war.[14] Though Germany did possess a small surface fleet, it was rarely used against convoys. Occasionally aircraft launched from occupied France would attack convoys, but this was uncommon after 1941. Also note that the other Axis nations did not commit naval forces to the North Atlantic. These facts allow me to consider U-boats as the sole threat to convoys in my analysis.

[12]For instance, Canada acquired six destroyers in the "Destroyers for Bases Agreement" with the US.

[13]Milner (1985)

[14]Helgason, Corijn, and Viglietti (2014)

The standard U-boat strategy was to work in groups known as "Wolfpacks." They would string themselves in a line across probable convoy routes and wait for a convoy to pass within range of a U-boat. This U-boat would then relay the position of the convoy to the other U-boats in the pack. They would then converge upon the convoy and attack as a group, hoping to overwhelm the defenders. The Germans would sometimes receive intelligence regarding when a convoy had left port, but in the vastness of the ocean, it was difficult to locate the convoys.[15] Because of this, it is important to note that German U-boat commanders would attack a convoy regardless of its escort. Finding a convoy was such a difficult feat that it was difficult for the Germans to pass up the opportunity to attack, despite the risks. Additionally, the German submariners considered themselves the elite warriors of the German military. Their pride and zeal demanded that an attack be made.[16] Perhaps most importantly, failing to attempt an attack could be considered a dereliction of duty, which came with high costs for the U-boat commander.

3 Data

The data for this project comes from a variety of different sources. Information regarding the Merchant Marine is combined with data on the navies of the Allied countries, which in turn is combined with German naval data.

The first step is to determine what the level of observation will be. Since a convoy's escorts was not constant throughout the crossing, it is necessary to analyze the data on a convoy-day level; that is a convoy's location on a particular date. A convoy's location on a particular date is matched to the number of U-boats that are engaging the convoy on that day. This in turn is matched against the composition of the Allied escort.

The Naval Museum of Calgary holds the John Burgess collection of convoy records for the North Atlantic convoys. For each convoy, the following data are provided: Date and port of sailing, date and port of arrival, ships lost in convoy on each date, names of escorts and the dates they were with the convoy, planned convoy route, distance traveled, average speed, list of ships in convoy and their cargoes, remarks on adverse weather, and a report on the convoy's crossing including any re-routing to avoid U-boats.[17]

[15] Bekker and Ziegler (1974) and Busch (1955)

[16] Busch (1955)

[17] Lawson (2013) and Holdoway (2014) are additional sources of information regarding convoy size, names of escorts, and merchant ship losses.

From these data, I extract the location of the convoy at 8:00am on each day of its voyage. This time was chosen as it matches the time of known U-boat locations. A convoy report often only provides ten location points and times, so there exists some ambiguity regarding the location of the convoy between these points. Also, convoys would periodically alter course to prevent interception by U-boats. However, the data are rich enough and the speeds of convoys are reliable enough to ensure that interpolating between known points provides reliable location data. Additional data sources for certain convoy routes are also available, and match well with my projections.

Next, it was necessary to compile information on the escorts. The Burgess papers only include the name of the ship and the dates on which it accompanied the convoy. The class of ship and its nationality was found using Helgason, Corijn, and Viglietti (2014).

Finally, this information is matched to the location of U-boats on each day. The War Diaries of the Commander in Chief - Submarines of Germany[18] have all been digitized and made available online.[19] On each day, every U-boat would report its location at 8:00am. The location is given using a coordinate on the German Naval Grid. Each grid section is 54 nautical miles in length, with varying width (typically 50 to 60 Nautical miles). Given the coordinate provided by the U-boat, I place it at the center of the grid section.[20] Obviously, given the size of the grid section, this does lead to some measurement error that is simply unavoidable. The grid sections are small enough to provide a sufficient level of precision for this task.

Unfortunately, the data series are not all complete. Of the 364 HX convoys, data are only available for the first 299. Thus, this data series only runs from September 39, 1939 through to June 19, 1944. There are also missing data for some ON convoys. The missing convoys are scattered throughout the series, leaving 281 of the 307 ON convoys available for use. The location of U-boats is an additional limiting factor. Complete U-boat location is only available between November 1st, 1941 and January 15th, 1945. This cuts off the first two years of the war and the final 4 months. The loss of data on the final four months is not too worrisome as Allied losses in convoys were rather small by this point.[21] On the other hand, the missing data on the first two years is quite unfortunate. Convoy losses were rather high in this period due to the technological limitations of the Allies at the time. On the other hand, there were very few corvettes in operation at the time, so it would not improve the estimates on the relative effectiveness of that class of ship.

[18] Admiral (later President) Karl Dönitz

[19] Mason (2014)

[20] As calculated by Kockrow (2012)

[21] A total of 3 between the three convoy routes.

Ultimately, taking into account the data limitations, the analysis will focus on 479 convoys, with 7,395 convoy-days.

In my analysis, the dependent variable of interest is a function of the number of merchant ships sunk or damaged while in convoy. I consider a damaged ship to be equal to a sunk ship for a few reasons. First, there were few damaged ships relative to sinkings. A hit by a torpedo would usually spell the end of a merchant ship. Second, a damaged ship was removed from operations for a lengthy period of time. Third, it represents a failure by the escorts to prevent an attack. Usually, the merchant was damaged rather than sunk not because the escorts were somehow able to lessen the blow, but rather because of where the torpedo impacted.

As already mentioned, since escort composition varied greatly day by day during the crossing, it is not possible to look at the success or failure of the convoy as a whole, rather one must look on a day by day basis. The first instinct may be to simply look at the composition of escorts on days that merchant ships were lost. This is not appropriate, for this only contains information on when the escorts failed. One must look at all cases when U-boats engaged the convoys, and evaluate the results of the escorts in these cases.

With the convoy positions matched to the U-boat positions, I am in a position to do just that. Since there is some measurement error present in the data, I make the assumption that a U-boat is engaged with a convoy if it is within 200 nautical miles (nm) of the convoy. 200nm is a large distance, and it is quite possible that by including such a large distance I am examining convoy-U-boat engagements that may have not occurred. However, this cost comes at the benefit of including engagements that occurred, but wouldn't be included with a shorter measure, due to the existence of measurement error.[22]

Table 3 provides data concerning the number of merchant ships lost on each convoy route. Analyzing Table 3 reveals that most convoys made it across the Atlantic with no losses. However 57 convoys lost at least one merchant ship. Table 4 reveals that most convoys had at least one day where a U-boat was within the 200nm radius. Most convoys had to deal with between 3 to 6 days of U-boat engagements. On the high end, some convoys had to deal with over 10 days of having to fight off the U-boats. With average crossing times being just over two weeks, those transits were particularly harrowing.

Beyond simply examining how many days during passage a U-boat was within range

[22]The results are robust to reasonable changes in this distance.

of the convoy, I also examine how many U-boats were within range on a particular day. Table 5 indicates the number of convoy-days within the sample with a given number of U-boats within range of the convoy. Most days had very few U-boats nearby, but it was not uncommon for the Germans to be able to concentrate more than 10 U-boats to engage a convoy. Restricting the sample to days where a merchant ship was lost or damaged, reveals that it was mostly when the Germans were able to concentrate their forces against the convoys that success was achieved.

Next, turning to the escort composition of the convoys, Table 6 shows that the average daily number of escorts for a convoy was around 7. This number fluctuated throughout the war, but had an upward trend as the war progressed and more ships were commissioned.

At this point I will be introducing a change to the nomenclature. I wish to group ships into one of two groups based on the desire to use them as escorts. The first group is escort-capable ships that were used as escorts because it was felt that they could perform the task, not because they would necessarily excel in the role. I call this group Corvettes and is primarily composed of corvettes and minesweepers. The other group of ships, called Non-Corvettes, are ships that were perceived to be well suited for escort duty. This group includes destroyers and frigates. Across all three convoys, there was a clear dominance of the use of Corvettes over Non-Corvettes.

Focusing on the nationality of the escorts reveals that Canadian escorts made up just over two fifths of the escort force on average. However, since the Allies tended to favour having ships from the same nation working together, many days had only Canadian ships escorting the convoy, or only non-Canadian ships. This can be seen in the final two rows of the table, where the percent of convoy-days where the escort was predominantly from Canada or the UK is recorded.[23] On average 30% of the convoy days involved a predominantly Canadian escort, and around 25% of the convoy days involved a predominately British escort.

This table also reveals just how much more Canada relied on Corvettes than other nations. The average number of Canadian Corvettes in a convoy is around 2.53, whereas the average number of Canadian Non-Corvettes is just over 0.5. Comparing these values to those for non-Canadian countries reveals that they tend to use fewer Corvettes, around 2.09 per convoy, and many more Non-Corvettes, around 2.03.

[23]Defined as 75% or more of the escorts being from the given nation.

4 Analysis

The goal is to quantify how much better Non-Corvettes were than Corvettes at preventing merchant ship losses. This is a difficult measure to quantify, as it is not clear what aspects should be included. For instance, during an attack, Non-Corvettes may be better able to intercept enemy U-boats forcing them to turn back, which lowers the number of merchant ships sunk. Additionally, Non-Corvettes may be better at sinking U-boats, as their speed affords them more time to try and sink a U-boat before being forced to return to the convoy. These additional U-boat sinkings could potentially lead to fewer future merchant ship losses. Although this second statement is likely true, I focus solely on the first.

I run a number of different regressions to quantify this difference in ability. My preferred approach is the use of probit regressions, however negative binomial regression results are included as a robustness check. The results indicate that Non-Corvettes were anywhere from 1.26 to 6.98 more effective than Corvettes at preventing merchant ship losses, with most estimates closer to 2, and with my preferred specification measuring the difference as 2.14.

As mentioned, my preferred approach is to use a probit regression to quantify the different abilities of the two types of ships. Although it does not make full use of the information available, this approach is reasonable as it may be the case that what is important is not *how* many ships were sunk, but rather *whether* or not a ship was sunk. Luck played an important role in how many merchant ships were actually sunk, given a U-boat was able to elude the escorts. So, instead of running a regression on how many ships were sunk, a regression is run where the dependent variable is a binary variable that takes on a value of one if a positive number of ships were sunk or damaged for a given convoy-day observation and zero otherwise.

The log-likelihood function to be estimated in this case is given by:

$$ln\ \mathcal{L}(\beta) = \sum_{i=1}^{n} \Big((y_i)\, ln\left(F\left(X_i\beta\right)\right) + (1-y_i)\, ln\left(1 - F\left(X_i\beta\right)\right) \Big) \tag{1}$$

where y_i is a binary variable that takes a value of 1 when a ship was either sunk or damaged in a given convoy on a given date. X_i is the set of independent variables. In the baseline case this includes the number of Corvettes escorting the convoy, the number of Non-Corvettes escorting the convoy, and the number of U-boats within 200nm. $F\left(X_i\beta\right)$

is equal to the CDF of the standard normal distribution. β is a vector of coefficients to be estimated.

The results of the probit regressions are given in Tables 7 and 8. Recall, that the unit of observation is a convoy-day given that a U-boat was within 200nm. Regression 1 indicates that the probability of at least one merchant ship been sunk is decreasing in both the number of Corvettes and number of Non-Corvettes present with the convoy. Non-Corvettes are found to be 1.6 times as effective as Corvettes at preventing successful attacks.[24] Additionally, the probability of a merchant ship sinking is increasing in the number of U-boat attacking the convoy.

Regression 2 examines whether or not there were returns to having ships from a single nation working together. Ships from the same nation would have similar doctrines and training experience. Additionally the esprit de corps of the sailors may be higher when working with ones own countrymen. As such two dummy variables are introduced that examine the impact of having at least 75% of the escorting ships being either Canadian or British. The results indicate again that additional Corvettes and additional Non-Corvettes both contributed to fewer merchant ship sinkings. However, in this case Non-Corvettes are measured as being 2.14 times as effective as Corvettes. The results also indicate that there were indeed large returns to having escorts comprised mostly of a single nation. All else equal, having the escort ships comprised of a single nation's navy could cut the probability of suffering a loss by upwards of 75%. Larger returns to having British ships working together is not surprising due to that nation's greater maritime experience.

Regression 2 is my preferred specification, but other variables of interest were examined and other approaches were taken to ensure the robustness of these results.

Regression 3 examines the effect that being within range of land-based aircraft has on the convoy. A dummy variable is used that takes a value of one if prior to May 1st, 1943 the convoy was within 550nm[25] of airfields in Canada, Newfoundland, Iceland, the UK, and the US prior and for all dates after May 1st 1943. After May 1st, 1943, a sufficient number of long-range B-24 Liberators were made available to provide continuous air cover. At the same time, a larger number of aircraft carriers were available to provide additional air cover. Unfortunately, it is not possible to know whether the convoys actually had aircraft providing support on a given day, only that there was the potential for aircraft to be present. The results indicate that convoys were less likely to suffer a loss when air cover could potentially be present. The estimate of the relative effectiveness of Corvettes and Non-Corvettes is not affected much by this

[24] Found using the average marginal effects.

[25] The maximum operational range of patrol aircraft.

addition.

Regression 4 examines the possibilities for non-linearities in terms of the effectiveness of escorts. A dummy variable is added that takes the value of 1 whenever the number of U-boats within 200nm of the convoy exceeds the number of escorts. One could imagine that if the U-boats outnumber the escorts, the escorts would be forced to a "zone" defence, as opposed to a "ship-to-ship" defence. The dummy does indeed indicate that when the escorts were outnumbered, the probability of a successful attack increased. Additional regressions were run to examine the nature of the non-linearity including quadratic forms of escort types and number of U-boats.[26] The results indicated that the effectiveness of escorts was a linear function, and that the marginal effectiveness of U-boats was decreasing in their number. This is difficult to believe. I hypothesize that the limited number of successful attacks and the limited number of observations with large number of U-boats prevents an accurate estimate from being obtained.

Regression 5 and 6 examine the impact of time on the estimates. Regression 5 adds a time trend variable that takes a value of 1 on November 3rd, 1941 and increases daily. The results indicate that the probability of a sinking occurring is decreasing as time passes. This could indicate the human and physical capital of the Allies was increasing in quality at a faster rate than Germany's. This regression gives the result that Non-Corvettes were over 4 times as effective as Corvettes.

The use of a simple time trend may be misleading due to the different phases of the battle. Figure 1 reveals that between August 1942 and May 1943 merchant ships were lost at a faster than average rate. Even though the average number of engagements remained constant, the number of successful attacks was much higher during this period. The surge of U-boats into the North Atlantic during these months provides only a partial explanation. These months may reflect a period where Allied intelligence was relatively less effective at routing convoys away from U-boat wolfpacks. After May 1943 there is a significant change. The introduction of increased air cover and the removal of U-boats from the North Atlantic partially explain why the number of sinkings plateaued after May 1943. Although the Germans did try to re-enter the North Atlantic again en-mass in September 1943, they never again achieved the same success. For this reason, Regression 6, which uses a dummy variable for this time period, better explains the trends seen in the data. The result is an estimate of the relative effectiveness of Non-Corvettes of 1.83, closer to estimates achieved in the other specifications.

Preliminary data analysis indicated that Canadian ships may have performed worse than those from other nations. To examine this Regression 7 splits the escorts by na-

[26] Results available on request.

tionality. The results indicate that both non-Canadian Corvettes and non-Canadian Non-Corvettes outperformed their Canadian counterparts. Again, a similar effectiveness of Non-Corvettes over Corvettes is obtained (1.87).

Given a sinking occurred, it may not be the case the number of sinkings was a factor of luck, but rather a function of the escort composition. If this is the case, improved regression results can be obtained by using the full information available regarding the number of ships lost or damaged, and making use of statistical methods to analyze count data. One's first instinct may be to use a poisson regression model, however, testing the data immediately indicates an overdispersion in the dependent variable. Thus, I instead use a negative binomial regression model to analyze the data. This distribution better matches that of the overly dispersed data. The results of these regression are presented in Tables 9 and 10.

Regressions 8 through 12 are the negative binomial analogue of Regressions 2 through 6. The results indicate no major change in the estimated parameters between the two approaches. However, the estimates of the relative effectiveness of Non-Corvettes was lower in all these regressions than their probit analogues, ranging from 1.3 in regression 12 to 1.92 in regression 11.

One concern with using the negative binomial regression models is the large number of zeroes present in the data. I adjust for the large number of zeroes using a Zero-Inflated Negative Binomial Regression.[27] The idea behind this regression is that there is an underlying, unobserved process that is leading to the large number of zeroes present in the data. Thus, two separate regressions are run.

First the potential source of the zeroes must be identified. The observed zeroes can be the result of two possibilities. First, although U-boats were close to a convoy (less than 200 nautical miles), perhaps the convoy just simply was not attacked. Second, if the convoy was attacked, the zero could be the result of the action by the escorts. I am interested in the second case, and thus control for the first by running a logit regression on a binary variable of loss or no loss, using the number of U-boats as the regressor.

Regression 13 displays the results of the zero-adjusted regression. The upper half is a negative binomial regression of the number of ships sunk or damaged on the standard variables. The lower half is a logit regression of whether or not the dependent variable is zero regressed on the number of nearby U-boats. Analyzing the lower section first reveals that the log-odds of being an excessive zero (that is a zero that results from no battle having occurred), decreases by 0.307 for each additional U-boats. Thus, the

[27]See IDRE (2011) for an excellent overview of the procedure.

more U-boats around, the more likely the zero that results is caused by the work of the escorts, as expected. The more U-boats around, the more likely there was an engagement. The top half of the regressions reveals results similar to those previously obtained. In this case Non-Corvettes are measured to be 1.24 times more effective than Corvettes at preventing losses in convoys.

Despite making use of more information, the results of the negative binomial regressions are not preferred to those of the probit regressions. There is simply not enough variation in the number of ships sunk or damaged to provide the precision required for the analysis. Additionally, there is a lot of uncertainty involved once a U-boat breaches the escort screen, and the number of ships sunk is not necessarily indicative of the quality of the escorts. However, the results are still useful, as they support the results of the probit regressions.

All the regressions indicate the same result. Non-Corvettes were better than Corvettes at preventing successful attacks. My most preferred approach, Regression 2, measures this relative effectiveness at 2.14. The presence of more U-boats increased the probability of a successful attack. Finally, there were significant returns to having escorts comprised of ships from a single nation, particularly the UK. Finally, there is some evidence that Canadian Corvettes, in particular, performed very poorly.

With this measure in hand, I can now turn my attention to analyzing a counterfactual scenario, wherein Canada invested in Destroyer production facilities during the years leading up to the war.

5 Counterfactual

With a quantitative measure of the ability of Non-Corvettes over Corvettes in hand, I investigate a counterfactual scenario, wherein Canada developed domestic production capabilities of Non-Corvettes, specifically destroyers, in the years before the war. My results indicate that, using my preferred estimation measurements, 33 merchant vessels could have been saved for a net benefit of $28.7 million 1940 Canadian dollars.

The counterfactual scenario proceeds as follows. In the early 1930s the Canadian government approaches Canadian shipyards and asks them to construct a number of destroyers. Peacetime allows the shipyards to acquire the necessary human and physical capital to construct these ships. Later, when war does occur, these shipyards would possess the ability to construct destroyers.

I make three assumptions at this point. First, the ability to produce destroyers will not migrate to other Canadian shipyards. Certainly it is possible that other shipyards could acquire this ability if other Canadian shipyards already possessed it. However, this migration of ability from British to Canadian shipyards during the war was not observed, despite strong incentives. The second assumption is that the ability to produce destroyers does not affect the construction schedules of the other yards. Third, I assume that the German and Allied navies also do not react to the changes in Canada's navy. This is not unreasonable due to the relative small size of Canada's navy vis-a-vis that of the UK and other Allied nations.

The first question to answer is how Canada would have developed and maintained destroyer production facilities during the 1930s. The best way to do so would be simply through a destroyer production program. Based on the 1930s destroyer output of the RN, I assume that Canada places a pre-war order for 9 destroyers, in line with the standard for the time. In some ways this is a conservative estimate, as just prior to the start of the war the Canadian government had decided to procure 18 Tribal-class destroyers.[28]

The next challenge is to identify where these would be constructed. Up until the war only 5 naval ships had been built in Canadian shipyards. The yards that received the contracts to build these minesweepers provides some evidence as to which yards might receive contracts for destroyers. It is also useful to examine which yards ultimately produced frigates during the war. These yards might have a comparative advantage at producing larger more complex ships, so they may be the more likely candidates to win pre-war destroyer contracts. The procurement of the pre-war minesweepers indicates the desire to spread the work amongst as many shipyards and across as many geographic regions as possible. Based on these factors, the counterfactual scenario presented here will be one in which 9 destroyers are constructed at the following three yards: Yarrows Ltd., Davie Shipbuilding and Repairing Co. Ltd., and Canadian Vickers.

By examining the output schedules of these four yards during the war I can ascertain their potential output schedule if they had had the ability to produce destroyers. To determine how long it takes to produce a destroyer, I examine wartime manufacturing records for British shipyards. First, to compare their efficiency to those of Canadian yards, I examine the average time it takes to construct corvettes, from laying down the first piece to its commissioning. This period is 333 days long for UK shipyards and 343 days long for Canadian shipyards, nearly identical. I conclude from this that the average time it takes to construct a destroyer in the UK is a good estimate for the length of time it would take to do so in Canada. This length of time is 600 days.

[28]Macpherson and Milner (1993)

In the counterfactual case 39 corvettes and minesweepers are no longer produced at the three shipyards, and instead 28 destroyers are produced in their place. I assume that once frigates can be built that they are built as they are a less expensive and assumed to be equally as effective way of guarding convoys compared to destroyers. Table 11 shows a comparison of the actual year by year commissioning of ships into the RCN to that of the counterfactual scenario. This table makes clear that the tradeoff between Corvettes and Non-Corvettes is not one-to-one.

Estimating the probable number of merchant ships that would be sunk with the new output schedule is not a straightforward task. Since Corvettes were not replaced with Non-Corvettes at a one-to-one ratio, it is not simply a matter of replacing a Corvette for a Non-Corvette in the independent variable that describes convoy escorts. Additionally, a few other factors concerning the use of destroyers must be accounted for. First, one of the advantages of destroyers is their ability to stay with a convoy longer before needing to depart to refuel and rearm. On average, a Corvette would remain with a convoy for 6.24 days during the sample period, whereas a Non-Corvette would remain on average for 7.01 days, or 12% more time. Additionally, destroyers were used more intensively than corvettes and minesweepers. This could be the result of needing fewer refits and repairs or simply a natural response to the incentive to get the high quality shipped turned around in port faster. On average, corvettes were starting new missions every 28 days. On the other hand, destroyers were beginning missions, on average, every 23 days.

Taking into account these differences, a new average escort profile was created. Table 12 presents the average number of escort ships by type in the actual and counterfactual scenarios. I then use this counterfactual average escort data to estimate the predicted number of sinkings under the counterfactual scenario. During the sample period, 245 ships were lost in convoy across the three convoy routes. Depending on the regression used, the predicted number of ships saved varies from 17 to 45. My preferred method, Regression 2, predicts a savings of 30 ships.

At this point, it is necessary to comment on the potential for saving ships in the time period September 1939 to October 1941 and January 1945 to May 1945. These time periods are not covered in the estimation. Let me first address the latter of the two time periods. During that time there were no losses in either the ON or SC convoys. The HX convoys suffered 7 losses in the period after the data set ends, that is from July 1944 onwards. No additional losses were likely to be prevented in this period.

The period before November 1941 is slightly more difficult to deal with. 203 ships were lost in the three convoys during this period. Since the first Canadian ships were not commissioned until late 1940 and early 1941, there is unlikely to be any change in the predicted sinkings for 1939 and 1940. The only difference was the additional 3 destroyers to have been acquired during the 1930s. Canada's pre-war destroyers were used extremely intensively during the early years of the war. Even an additional 3 would have made a major difference in the escort composition. On the other hand the counterfactual scenario for 1941 would not be in Canada's favour. The first counterfactual destroyers to be built during the war would have only been commissioned in October of 1941, whereas the corvettes they are replacing were commissioned in early 1941.

Additionally, it is difficult to apply the regression results to the pre-sample period as I do not have full information concerning U-boat movements during that time. However, it is known the U-boat fleet was a quarter of the size to that of the 1942/1943 time period. If I assume that U-boats were just as likely to encounter a convoy, then I can use the regression results to predict the losses during the pre-war period and the expected savings from the new production schedule. Under my preferred specification, an additional 3 ships are predicted to have been saved.

Overall, there is a predicted savings of 33 ships in the preferred specification of Regression 2. Next, the dollar value of the ships that would have been saved needs to be measured. Note that all the following dollar figures are in 1940 Canadian dollars, unless otherwise stated.

The size and cost of the merchant ships sunk during the war varied greatly. During the sample period, the largest ship sunk was nearly 17,000 tons, while the smallest was under 1,400 tons. On average, the size of ship lost in the convoy was 5,934 tons. In 1941, Canadian shipyards were able to build a 10,000 ton vessel for $1.785 million. Later in the war, the cost of these same ships fell to between $1.279 and $1.42 million. Additionally, Canadian shipyards built a 4,700 ton vessel for just over $1.2 million.[29] An estimate of $1.3 million for the replacement value of the merchant vessel is used.

On average, half of the ships sunk were carrying cargo, those in the HX and SC convoys. Typically the value of cargo is considered equal to that of the vessel.[30] Thus, the value of the ships that could have been saved was $42.9 million and the estimated value of the cargo was $21.45 million.

Next, it is necessary to measure the value of the lives lost onboard the merchant ships. On average 17.4 deaths occurred with the loss of each merchant vessel.[31] With a prediction of 33 ships sunk, this gives a loss of 574 men. Rohlfs (2011) examines

[29] Pritchard (2011)
[30] Poirier (1999)
[31] Hague (2000)

the value that the US government placed on the lives of infantry men and armoured troopers during the same war. He finds that the US government valued infantry men at between \$0 and \$40,000, and armoured troopers at between \$159,000 and \$476,000. Using the estimate of \$40,000, this gives a value of human life of \$22.96 million. If instead I use the private sector value of life used in the 1940s of \$120,000 this figure jumps to \$68.88 million.

There are additional benefits to the counterfactual program that are more difficult to measure. First, when a ship is sunk, not only are the ship, crew, and cargo lost, but so too are all additional trips made by that ship. Depending on when during the war it is sunk, this could translate into dozens of additional trips available to the Allied countries. Another variable that is difficult to measure is the increase in U-boat sinkings that destroyers might be able to achieve. The regression results show that destroyers outperform corvettes at preventing successful attacks, but they might also be more capable at sinking enemy submarines. Each additional U-boat that a destroyer sinks translates into lower threat for future convoys. These benefits are difficult to quantify and has not been done so at this time, though they both imply that a destroyer construction program would be more cost effective.

Turning now to the cost side of the equation, the first step is to calculate the additional cost of producing destroyers instead of corvettes and minesweepers. At the three yards of interest, the price of corvettes varied between \$570,000 and \$650,000 per vessel. The cost of minesweepers was similar, but slightly higher.[32] The cost savings of producing 23 fewer corvettes and 16 fewer minesweepers is equal to \$22.9 million.

This savings must be compared to the cost of producing the 31 destroyers that replaced these ships. Poirier (1999) estimates the cost of 1930 destroyers to be \$1.22 million. Given the immaturity of Canadian shipyards, I will use a value of \$2 million for the cost of a destroyer. This puts their total cost at \$62 million. For a net difference in warship construction of \$39.1 million.

The operating costs of destroyers varied from that of corvettes and minesweepers. First, to man all the ships an additional 1350 sailors would be required. At an average yearly cost of about \$825 per sailor, this additional wage bill is \$4.5 million for the years 1942 to 1945, when the ships would have been in operation. The additional operating cost in terms of fuel and supplies for these ships is also estimated to be approximately \$5 million.

A few additional costs and benefits can also be considered. First, the residual value

[32]Pritchard (2011)

of a destroyer is higher than that of a corvette. In theory, it would have been possible for the RCN to sell destroyers in the post war market for a higher return. Second, the ships would have been of greater use in the Korean War which was to follow shortly after. However, the post-war market was flooded with warships so the additional selling price is assumed to be very negligible. Additionally, the Korean War had very limited naval engagements so the benefit of better ships during that war would have been low. I assume a value of $0 for both of these values.

Setting up the shipbuilding industry during the 1930s might have cost more than simply the cost of the ships. Since the ships could not be built during World War II due to the lack of necessary human and physical capital, the cost of acquiring these must be accounted for. On some level, the acquisition of the human capital can be achieved through on-the-job learning. Simply by building high quality ships during the 1930s, the employees at that yard gain the knowledge of how to build high quality ships more efficiently. Thornton and Thompson (2001) provide strong evidence that on the job learning was a significant source of productivity growth in American shipyards during World War II.

The cost of the necessary capital is difficult to price. However, during the war the Canadian government spent over $40 million expanding shipbuilding capacity in the country.[33] It is not unreasonable to believe that these costs would not have been much different if they were incurred a decade earlier. In fact with less overall demand, it may have cost the government less to finance the necessary physical capital for these four shipyards during the 1930s.

Additionally, the cost of maintaining the skilled labour in the shipyards after the initial construction was complete, but before the war, must be calculated. Typically, policy makers hope that these firms can sustain themselves through selling to other countries or through selling to the private sector. Given the state of the economy during the 1930s this would not be very likely. I estimate the cost of maintaining the yards in a productive state and maintaining the skilled labour force at approximately $10 million. This is based on maintaining four yards for five years by providing them with contracts for government owned ships.

I can now sum up these costs and benefits to determine the value of the counterfactual policy. Table 13 summarizes these figures. The total benefit of the program is revealed to be $87.3 million compared to the cost of $58.5 million, for a net benefit of $28.7 million. This would indicate that were the Canadian government to have invested in the production capabilities to construct destroyers during the 1930s, they would have

[33] Pritchard (2011)

reaped significant benefits during the war.

This result is robust to a number of changes. Table 14 presents the possible ranges for the values in the analysis. First, the number of ships lost depends on the measure of effectiveness of Non-Corvettes versus Corvettes. My preferred regression results predict 33 ships lost, however, the other models predict a possible range of 17 to 45. Moving on to the value of ships saved, using the minimum and maximum value for each element here gives a range of \$1.8 million to \$11 million for the value of each merchant ship lost. This gives a range of total benefits between \$30.6 and \$493 million. Thus, it is clear that my preferred estimates are relatively conservative with a total benefit calculated at \$87 million. On the cost side, examining the minimum and maximum values for each element gives a potential range of between \$24 million to \$83 million for total cost.

Even with the worst case scenario of costs and the best estimates of the benefits the program would still have a net benefit. Additionally, the total benefit is conservative as it does not include those additional benefits mentioned above that are difficult to estimate. The results here are quite clear, the Canadian government could have benefited substantially from developing destroyer production capabilities prior to World War II.

6 Conclusion

In certain cases, such as the example studied here, there is the potential for positive returns to investing in domestic arms industry during peace time to insure that military equipment can be procured in a timely fashion in times of war.

Given there was such a high potential payoff from the construction of destroyers, why did Canada not invest in the ability to construct them during the 1930s? First, it may have been the case that for most of the 1930s, the Canadian government thought the likelihood of a future war was low. If all the data presented here at been known to the government in 1930, the investment would only pay off, in expectation, if the probability of war was greater than 0.37. Given this information was not available, and given that the perceived likelihood of war, especially a war on the same scale as World War II, was relatively low, it is not unexpected that the Canadian government did not invest. Additionally, some influential members of the government desired that Canada follow an isolationist policy, so that even if a future war was likely, Canada's involvement may have been limited.[34]

[34]In particular Oscar Skelton, Prime Minister King's closest advisor (Haglund (2002)).

Second, there was much uncertainty regarding the potential investment. It may have been the case that Canada would find it costly to develop destroyer production capabilities, and it was also quite possible that the quality of Canadian destroyers would have been low. If the Canadian government believed this to be the case, they would have optimally decided not to invest in destroyers during the 1930s. Finally, Canada could have been limited in what it was able to invest in. Simon S. Kuznet famously warned the American military during World War II that their ambitious production schedule threatened to create severe shortages in the civilian sector.[35] Perhaps Canada simply could not afford to invest in advanced military production during the 1930s. These three factors provide some explanation as to why the Canadian government ultimately did not invest in domestic naval construction prior to the war.

If the Canadian government had full information regarding the financial costs and technical benefits of constructing destroyers, was not constrained in its ability to devote resources towards the military, did not have strong isolationist members of government, and perceived the likelihood of a future war as high, then they would likely have found it worthwhile to invest in domestic shipyards in the 1930s.

The conclusion of this paper is not that all countries should immediately begin investing in the development domestic arms manufacturing facilities. In some sense, this study was of a worst case scenario, where the war was large and the cost of losing may have been very high. For limited conflicts, with a potentially low payoff from winning, it may not be necessary to invest in the facilities, instead one could simply purchase the equipment from foreign firms. Additionally, if the likelihood of future conflict is low, it is unlikely that the investment will yield dividends.

An additional problem would be to determine which weapon system to invest in. Had Canada invested heavily in technologies related to zeppelins or cavalry, the payoff would likely not have materialized. Even in the case of convoys, it was not the destroyer that ultimately won the Battle of the Atlantic, but it was instead the development of long-range aircraft that allowed for complete air coverage. It was the development of Radar that hindered the ability of U-boats to close in on convoys. Sonar too made the cost of a failed attack high for U-boats as escape was much more difficult. Finally, it was the the development of Ultra intelligence that allowed convoys to be routed around U-boats. When all these failed, having destroyers instead of corvettes did save ships and lives, but it was these other technologies which won the battle for the Allies.

Overall, there are situations that with luck and good foresight, the benefits of developing domestic production facilities could yield a net benefit, as clearly shown in the

[35] Fogel (2001)

example in this paper. One must be careful though to understand the costs, benefits, and risks associated with such a program.

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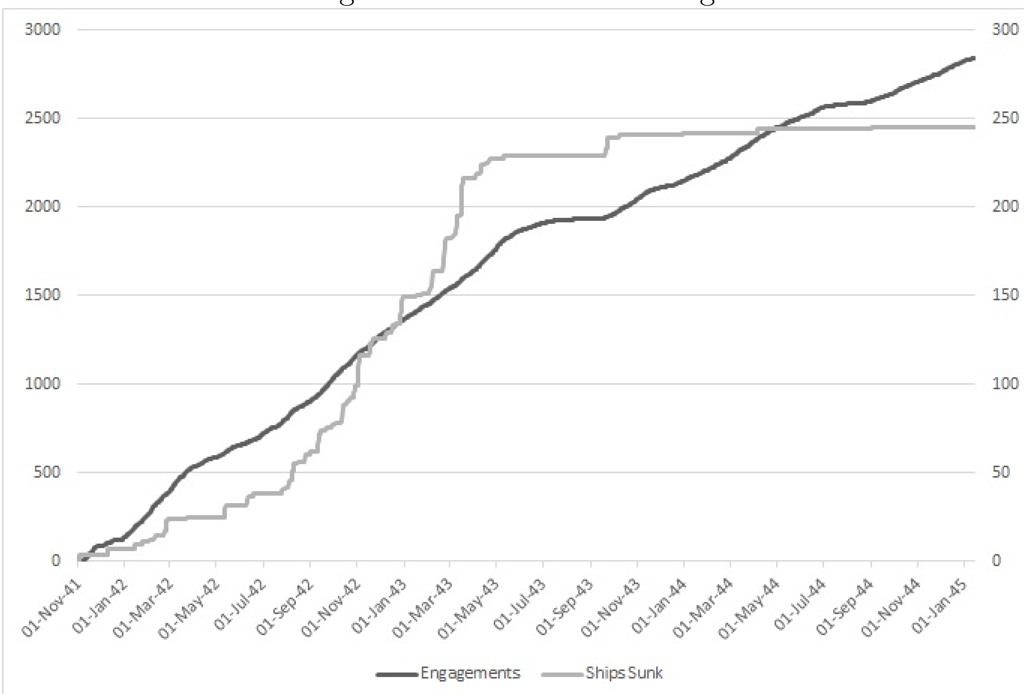
7 Figures

Figure 1: Cumulative Sinkings



Description: The darker line with the left axis is a cumulative measure of the number of Convoy-day engagements. For the most part it increases uniformly. The lighter line with the right axis is a cumulative measure of the number of merchant ships sunk. Between August 1942 and May 1943 the rate of sinkings grows at a much faster rate.

8 Tables

Table 1: Corvettes, Destroyers, and Frigates Compared

Category	Corvette (Flower)	Destroyer (A)	Frigate (River)
Displacement (tons)	925	1337	1370
Length (feet)	205	320	283
Speed (knots)	16	35	20
Range (nautical miles)	3500	5000	7200
Crew (people)	85	138	107

Description: Various attributes of three escort vessels used extensively during the war.

Table 2: Composition of the RCN

Date	Destroyers	Corvettes	Frigates	Minesweepers	Other	Total
September 1st, 1939	6	0	0	4	0	10
January 1st, 1940	7	0	0	5	0	12
January 1st, 1941	12	4	0	4	8	28
January 1st, 1942	13	66	0	31	6	116
January 1st, 1943	13	76	0	66	6	161
January 1st, 1944	20	85	16	70	6	197
January 1st, 1945	19	114	68	84	6	291
May 1st, 1945	19	112	67	82	5	285

Description: Number of escort-capable commissioned ships in the RCN by type for selected dates.

Table 3: Merchant Marine Losses by Convoy

Series	0	1 to 2	3 to 5	6 to 9	10+
HX	126	8	4	1	1
SC	97	8	2	3	3
ON	199	12	8	3	4
Total	422	28	14	7	8

Description: A count of the number of convoys that had a given number of merchant ships sunk or damaged during their crossing.

Table 4: U-boat-Convoy Engagement Statistics

Convoy	HX	SC	ON	Total
Convoys with 1 to 2 days of engagement (# of Convoys)	22	15	20	57
Convoys with 3 to 6 days of engagement (# of Convoys)	63	38	83	184
Convoys with 7 to 9 days of engagement (# of Convoys)	44	37	69	150
Convoys with 10+ days of engagement (# of Convoys)	4	18	41	63
Convoys that had at least one engagement (# of Convoys)	133	108	213	454
Total convoy-days with engagement (Days)	698	701	1445	2844

Description: A count of the number of convoys in the sample that were engaged by U-boats for a given number of days during their crossing. For instance out of the 140 HX convoys used in the study, 4 of them were engaged by U-boats on at least 10 days during their crossing, while 22 were only engaged on 1 or 2 days.

Table 5: Convoy-days with given number of U-boats within range

	1 U-boat	2-3 U-boats	4-9 U-boats	10+ U-boats
HX	270	193	127	108
SC	269	207	135	90
ON	622	415	272	136
Total	1161	815	534	334
HX (Loss)	3	2	5	14
SC (Loss)	4	3	2	20
ON (Loss)	5	6	18	24
Total (Loss)	12	11	25	58

Description: A count of the number of convoy-day pairs in the sample that saw the convoy engaged by a given number of U-boats. This data is also presented for those convoys that suffered a loss. For instance, there were 90 convoy-day pairs in the SC convoy route that saw 10 or more U-boats engaged with the convoy. On 20 of these days, a loss was suffered by the convoy.

Table 6: Escort Statistics

	HX	SC	ON	Total
Average number of escorts by convoy-day	7.60	7.25	6.71	7.07
Average number of Corvettes by convoy-day	4.56	4.82	4.49	4.59
Average number of Non-Corvettes by convoy-day	3.04	2.46	2.22	2.48
Average number of Canadian escorts	3.07	3.05	3.09	3.07
Average number of non-Canadian escorts	4.53	4.22	3.62	3.99
Average number of Canadian Corvettes	2.48	2.55	2.57	2.54
Average number of Canadian Non-Corvettes	0.59	0.50	0.52	0.53
Average number of non-Canadian Corvettes	2.08	2.27	1.92	2.05
Average number of non-Canadian Non-Corvettes	2.45	1.95	1.69	1.94
Percent of convoys-days where greater than 75% of Escorts were Canadian	28.37	31.24	34.67	32.28
Percent of convoys-days where greater than 75% of Escorts were British	27.08	28.67	23.32	25.56

Description: A count of the average number of escorts on convoy-day, for a given convoy route. The data is broken up by ship class and nationality. Also, a percentage of the number of convoy-day pairs where the escort was predominantly from one a particular nation is included.

Table 7: Probit Regression Results

	1 Probit	2 Probit	3 Probit	4 Probit	5 Probit	6 Probit
Corvettes	-0.0356	-0.0387*	-0.0257	-0.0260	-0.0158	-0.0392
	(0.0240)	(0.0228)	(0.0251)	(0.0238)	(0.0230)	(0.0256)
Non-Corvettes	-0.0569**	-0.0828***	-0.0657**	-0.0646**	-0.0661**	-0.0717**
	(0.0260)	(0.0277)	(0.0280)	(0.0279)	(0.0285)	(0.0290)
U-boats	0.0808***	0.0838***	0.0756***	0.0657***	0.0856***	0.0741***
	(0.0069)	(0.0073)	(0.0074)	(0.0121)	(0.0076)	(0.0078)
Canadian Escort	.	-0.4103***	-0.3423**	-0.3782***	-0.3113**	-0.3649***
	.	(0.1302)	(0.1355)	(0.1288)	(0.1373)	(0.1334)
British Escort	.	-0.6117***	-0.6088***	-0.6123***	-0.5697***	-0.6504***
	.	(0.1383)	(0.1389)	(0.1370)	(0.1379)	(0.1405)
Air Cover	.	.	-0.4659***	.	.	.
	.	.	(0.1027)	.	.	.
Escorts Outnumbered	.	.	.	0.3360*	.	.
	.	.	.	(0.1753)	.	.
Date	.	.	.	.	-0.0007***	.
	.	.	.	.	(0.0002)	.
Aug. 1942 to May 1943	.	.	.	.	.	0.4017***
	.	.	.	.	.	(0.1123)
Constant	-1.9804***	-1.6870***	-1.4677***	-1.7940***	-1.5853***	-1.8706***
	(0.1367)	(0.1419)	(0.1611)	(0.1486)	(0.1443)	(0.1657)
Relative Effectiveness	1.60	2.14	2.56	2.48	4.17	1.83
Log Likelihood	-382.0331	-368.4271	-358.5667	-366.3813	-363.0394	-361.6657
R-Squared	0.1561	0.1861	0.2079	0.1907	0.1980	0.2011

Description: 2844 Observations. Robust Standard Errors in Brackets.
Two-tailed test: * 10% Significance. ** 5% Significance. *** 1% Significance.
The unit of observation is a convoy-date where a convoy was within 200nm of at least one U-boat. The dependent variable takes a value of 1 if any ship in the convoy was sunk or damaged by a U-boat. "Corvettes" and "Non-Corvettes" are a count of the number of escorting ships of that type that are currently with the convoy. "U-boats" is a count of the number of German U-boats within a 200nm radius of the convoy. "Canadian Escort" and "British Escort" are dummy variables with a value of 1 whenever at least 75% of the escort was comprised of ships from one of these nations. "Air Cover" takes on a value of 1 if the Convoy was within 550nm of an Allied airfield prior to May 1st, 1943 and a value of 1 for all subsequent dates. "Escorts Outnumbered" is a dummy variable that takes the value of 1 if the number of U-boats within 200nm of the convoy is greater than the number of escorts of any type. "Date" is a time trend variable where day 1 is November 3rd, 1941 and the variable increases by 1 each day. The August 1942 to May 1943 dummy takes a value of 1 for dates between August 1st, 1942 and May 31st, 1943. Relative Effectiveness is the average marginal effect of an additional Non-Corvette divided by the average marginal effect of an additional Corvette.

Table 8: Probit Results Split by Nationality

	7 Probit
Canadian Corvettes	-0.0316
	(0.0325)
Canadian Non-Corvettes	-0.0591
	(0.0646)
Non-Canadian Corvettes	-0.0494*
	(0.0291)
Non-Canadian Non-Corvettes	-0.0888***
	(0.0322)
U-boats	0.0844***
	(0.0075)
Canadian Escort	-0.4748***
	(0.1693)
British Escort	-0.5713***
	(0.1598)
Constant	-1.6770***
	(0.1463)
Relative Effectiveness	1.88
Log Likelihood	-368.2412
R-Squared	0.1865

Description: 2844 Observations. Robust Standard Errors in Brackets.
Two-tailed test: * 10% Significance. ** 5% Significance. *** 1% Significance.
The unit of observation is a convoy-date where a convoy was within 200nm of at least one U-boat. The dependent variable takes a value of 1 if any ship in the convoy was sunk or damaged by a U-boat. "Canadian Corvettes" and "Canadian Non-Corvettes" are a count of the number of Canadian escorting ships of that type that are currently with the convoy. "Non-Canadian Corvettes" and "Non-Canadian Non-Corvettes" are a count of the number of escorting ships of that type from all other countries that are currently with the convoy. "U-boats" is a count of the number of German U-boats within a 200nm radius of the convoy. "Canadian Escort" and "British Escort" are dummy variables with a value of 1 whenever at least 75% of the escort was comprised of ships from one of these nations. Relative Effectiveness is the average marginal effect of an additional Non-Corvette divided by the average marginal effect of an additional Corvette.

Table 9: Negative Binomial Regression Results

	8	9	10	11	12
	Neg. Bin.	Neg. Bin.	Neg. Bin.	Neg. Bin.	Neg. Bin.
Corvettes	-0.1482***	-0.1032*	-0.1374**	-0.0887	-0.1376**
	(0.0519)	(0.0573)	(0.0602)	(0.0559)	(0.0575)
Non-Corvettes	-0.2168***	-0.1635***	-0.1952***	-0.1707***	-0.1796***
	(0.0612)	(0.0594)	(0.0663)	(0.0654)	(0.0624)
U-boats	0.2131***	0.1899***	0.1955***	0.2113***	0.1891***
	(0.0177)	(0.0197)	(0.0377)	(0.0170)	(0.0189)
Canadian Escort	-1.0772***	-0.9276***	-1.0476***	-0.8429**	-1.0229***
	(0.3505)	(0.3388)	(0.3488)	(0.3637)	(0.3350)
British Escort	-1.5970***	-1.5667***	-1.6043***	-1.4622***	-1.6958***
	(0.4067)	(0.4267)	(0.4040)	(0.4031)	(0.4372)
Air Cover	.	-1.0358***	.	.	.
	.	(0.2794)	.	.	.
Escorts outnumbered	.	.	0.2407	.	.
	.	.	(0.5044)	.	.
Date	.	.	.	-0.0018***	.
	.	.	.	(0.0005)	.
Aug. 1942 to May 1943	.	.	.	.	0.9097***
	.	.	.	.	(0.2912)
Relative Effectiveness	1.46	1.58	1.42	1.92	1.30
Constant	-2.2784***	-1.9031***	-2.3563***	-2.0194***	-2.7593***
	(0.3467)	(0.3535)	(0.4040)	(0.3533)	(0.3944)
Log Likelihood	-548.0483	-539.2251	-547.8941	-542.1790	-541.2306

Description: 2844 Observations. Robust Standard Errors in Brackets.
Two-tailed test: * 10% Significance. ** 5% Significance. *** 1% Significance.
The unit of observation is a convoy-date where a convoy was within 200nm of at least one U-boat. The dependent variable is the number of ships in the convoy that were sunk or damaged by a U-boat. “Corvettes” and “Non-Corvettes” are a count of the number of escorting ships of that type that are currently with the convoy. “U-boats” is a count of the number of German U-boats within a 200nm radius of the convoy. “Canadian Escort” and “British Escort” are dummy variables with a value of 1 whenever at least 75% of the escort was comprised of ships from one of these nations. “Air Cover” takes on a value of 1 if the Convoy was within 550nm of an Allied airfield prior to May 1st, 1943 and a value of 1 for all subsequent dates. “Escorts Outnumbered” is a dummy variable that takes the value of 1 if the number of U-boats within 200nm of the convoy is greater than the number of escorts of any type. “Date” is a time trend variable where day 1 is November 3rd, 1941 and the variable increases by 1 each day. The August 1942 to May 1943 dummy takes a value of 1 for dates between August 1st, 1942 and May 31st, 1943. Relative Effectiveness is the average marginal effect of an additional Non-Corvette divided by the average marginal effect of an additional Corvette.

Table 10: Zero-Inflated Negative Binomial Regression Results

	13 Zero-inflated Neg. Bin.
Corvettes	-0.1325**
	(0.0606)
Non-Corvettes	-0.1674***
	(0.0609)
U-boats	0.0782***
	(0.0181)
Dummy for a mostly Canadian Escort	-1.0643***
	(0.3299)
Dummy for a mostly British Escort	-1.6294***
	(0.3080)
Constant	-0.1891
	(0.4299)
Inflated Zeroes	.
U-boats	-0.3076***
	(0.0646)
Constant	2.6760***
	(0.3591)
Relative Effectiveness	1.26
Log Likelihood	-525.4379

Description: 2844 Observations. Robust Standard Errors in Brackets.
Two-tailed test: * 10% Significance. ** 5% Significance. *** 1% Significance.
The unit of observation is a convoy-date where a convoy was within 200nm of at least one U-boat. The dependent variable is the number of ships in the convoy that were sunk or damaged by a U-boat. "Corvettes" and "Non-Corvettes" are a count of the number of escorting ships of that type that are currently with the convoy. "U-boats" is a count of the number of German U-boats within a 200nm radius of the convoy. "Canadian Escort" and "British Escort" are dummy variables with a value of 1 whenever at least 75% of the escort was comprised of ships from one of these nations. Relative Effectiveness is the average marginal effect of an additional Non-Corvette divided by the average marginal effect of an additional Corvette.

Table 11: Counterfactual Commissioned Ship Schedule

	Reality		Counterfactual	
Year	Corvettes	Non-Corvettes	Corvettes	Non-Corvettes
1939	5	7	5	10
1940	19	14	19	17
1941	110	15	82	28
1942	157	16	118	39
1943	173	40	134	71
1944	220	97	181	128

Description: The actual and a counterfactual commissioning schedule for the RCN by the end of each year.

Table 12: Average Number of Escorts by Type

	Actual	Counterfactual
Total	7.06	7.33
Corvette	4.58	3.86
Non-Corvette	2.48	3.47
Canadian Corvette	2.55	1.82
Canadian Non-Corvette	0.54	1.53
Non-Canadian Corvette	2.04	2.04
Non-Canadian Non-Corvette	1.93	1.93

Description: The actual and counterfactual average number of escorts for convoys.

Table 13: Costs and Benefits of Counterfactual Building Program

Value of ships saved	$42,900,000
Value of cargo saved	$21,450,000
Value of lives saved	$22,960,000
Total benefit	$87,310,000
Net cost of new ships	$39,093,000
Operating cost of new ships	$9,500,000
Cost of maintaining shipbuilding industry	$10,000,000
Total cost	$58,593,000
Net benefit	$28,717,000

Description: A summary of the benefits and costs of the counterfactual production schedule.

Table 14: Costs and Benefits Range of Counterfactual Building Program

	Low	High
Ships saved	17	45
Value of ship	$1,200,000	$1,785,000
Value of cargo	$600,000	$900,000
Value of lives	$0	$8,265,000
Total expected value of a sunk merchant ship	$1,800,000	$10,950,000
Total benefit	$30,600,000	$492,750,000
Net cost of new ships	$14,820,000	$58,840,000
Additional operating costs	$9,500,000	$9,500,000
Cost of maintaining industry	$0	$15,000,000
Total Cost	$24,320,000	$83,340,000

Description: The possible ranges for the values used in the cost-benefit analysis.