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SHIP OPERATING CHARACTERISTICS AND THEIR IMPLICATIONS FOR SHIPTRACK FORMATION

by

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March 1998

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Shiptrack occurrence is restricted to a narrow range of environmental conditions and ship operating characteristics. Under environmental conditions favorable for shiptrack formation, not all vessels produce a track. Shiptrack producing diesel vessels are distinguished from non-shiptrack producing diesel vessels by a 17.7 percent higher rate of fuel use, 8.8 percent larger power plant size, and one knot higher transit speed. T-tests comparing these two populations indicate that power/transit speed, power*fuel/speed, power*fuel, tonnage/fuel use, power/hull cross-section, transit speed, power plant size and rate of fuel use are tactically distinct (greater than 60% confidence level). These parameters and ratios of parameters may be useful in predicting the occurrence and non-occurrence of shiptracks.

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SHIP OPERATING CHARACTERISTICS AND THEIR IMPLICATIONS FOR SHIPTRACK FORMATION

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ABSTRACT

Shiptrack occurrence is restricted to a narrow range of environmental conditions and ship operating characteristics. Under environmental conditions favorable for shiptrack formation, not all vessels produce a track. Shiptrack producing diesel vessels are distinguished from non-shiptrack producing diesel vessels by a 17.7 percent higher rate of fuel use, 8.8 percent larger power plant size, and one knot higher transit speed. T-tests comparing these two populations indicate that power/transit speed, power*fuel/speed, power*fuel, tonnage/fuel use, power/hull cross-section, transit speed, power plant size and rate of fuel use are tactically distinct (greater than 60% confidence level). These parameters and ratios of parameters may be useful in predicting the occurrence and non-occurrence of shiptracks.

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I. INTRODUCTION

Shiptracks are anomalous curvilinear cloud lines first observed by the Television and Infrared Operational Satellites (TIROS) visual imagery (wavelengths between 0.3μm-0.7μm) in 1965. Today shiptracks are most easily observed using the Advanced Very High Resolution Radiometer (AVHRR) imagery (channel 3, 3.7μm) component of the NOAA Polar Orbiting Operational Environmental Satellite (POES) series (Figure 1). These cloud phenomena are manifested by an increase in albedo within existing stratus and stratocumulus clouds. The area of enhanced albedo forms curvilinear cloud lines, which may extend laterally for hundreds of kilometers and persist for days. Understanding the mechanisms of formation, necessary environmental conditions and ship operating parameters remains an active area of investigation due to shiptrack military applications and potential broader implications for global climate changes.

Conover (1966) first described the shiptrack phenomenon using TIROS visual imagery. He proposed that ship exhaust, carried upward by buoyant forces, introduces additional hygroscopic nuclei into the stratus cloud layer. The modified stratus has an increased droplet density, which raises albedo by 25 percent over background stratus. Conover inferred the impact of the ambient environment from the occasional occurrence of large concentrations of shiptracks. He suggested that shiptracks are not the result of a rare effluent from a particular ship, but rather the existence of an atmospheric condition which makes it possible for a variety of ships to produce shiptracks. Figure 1 shows a high shiptrack concentration (in the visual

Figure 1. Comparison Of Shiptrack Depiction Using Visual imagery (AVHRR Ch. 1 (left) and near infrared imagery (AVHRR Ch. 3 (right). From Chartier (1995).

and near IR wavelengths) over a broad geographic region. Examination of shiptrack occurrence/non-occurrence, under conducive environmental conditions, affords the best opportunity to assess vessel operating characteristics and shiptrack formation. To this end, data collection on non-shiptrack producing vessels is restricted to geographic regions containing a high concentration of shiptracks. By examining these regions, questions regarding environmental conditions and mechanism of shiptrack formation are mitigated to a large degree. Non-occurrence of a shiptrack in a region of high shiptrack concentrations is attributed to ship operating characteristics and not environmental conditions or mechanisms of formation. Figure 2 is an example of a vessel traveling in a conducive environment producing a shiptrack. Figure 3 is a example of a vessel traveling in a conducive environment, but not producing a shiptrack.

The objectives of this thesis are threefold:

1. Quantify operating characteristics of vessels producing shiptracks in a conducive environment.

2. Quantify operating characteristics of vessels not producing shiptracks in a conducive environment.

3. Quantify the difference between the two ship populations using appropriate statistical techniques.

Chapter II includes background information on the shiptrack/albedo relationship, mechanisms of shiptrack formation, environmental considerations and ship operating parameters. Chapter III includes presentation of the data and techniques used to compile it. Chapter IV includes an

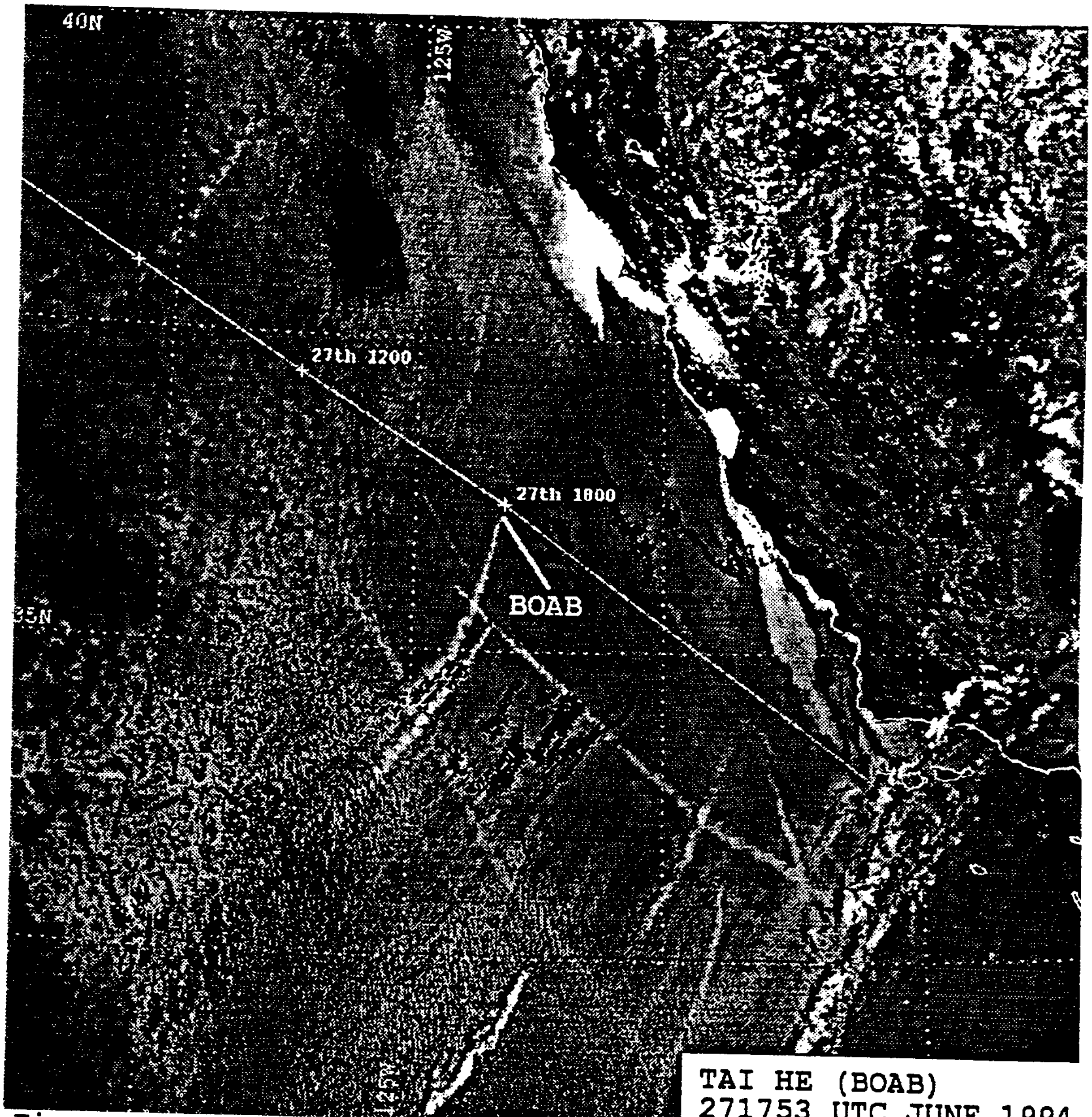

Figure 2. NOAA 09 1753 UTC 27 June 1994 Ch. 3 satellite imagery depicting shiptrack production in a conducive environment. Solid lines denotes merchant vessel Tai He position history based on synoptic weather reports. Ship location indicated by callsign BOAB. From Brown (1995).

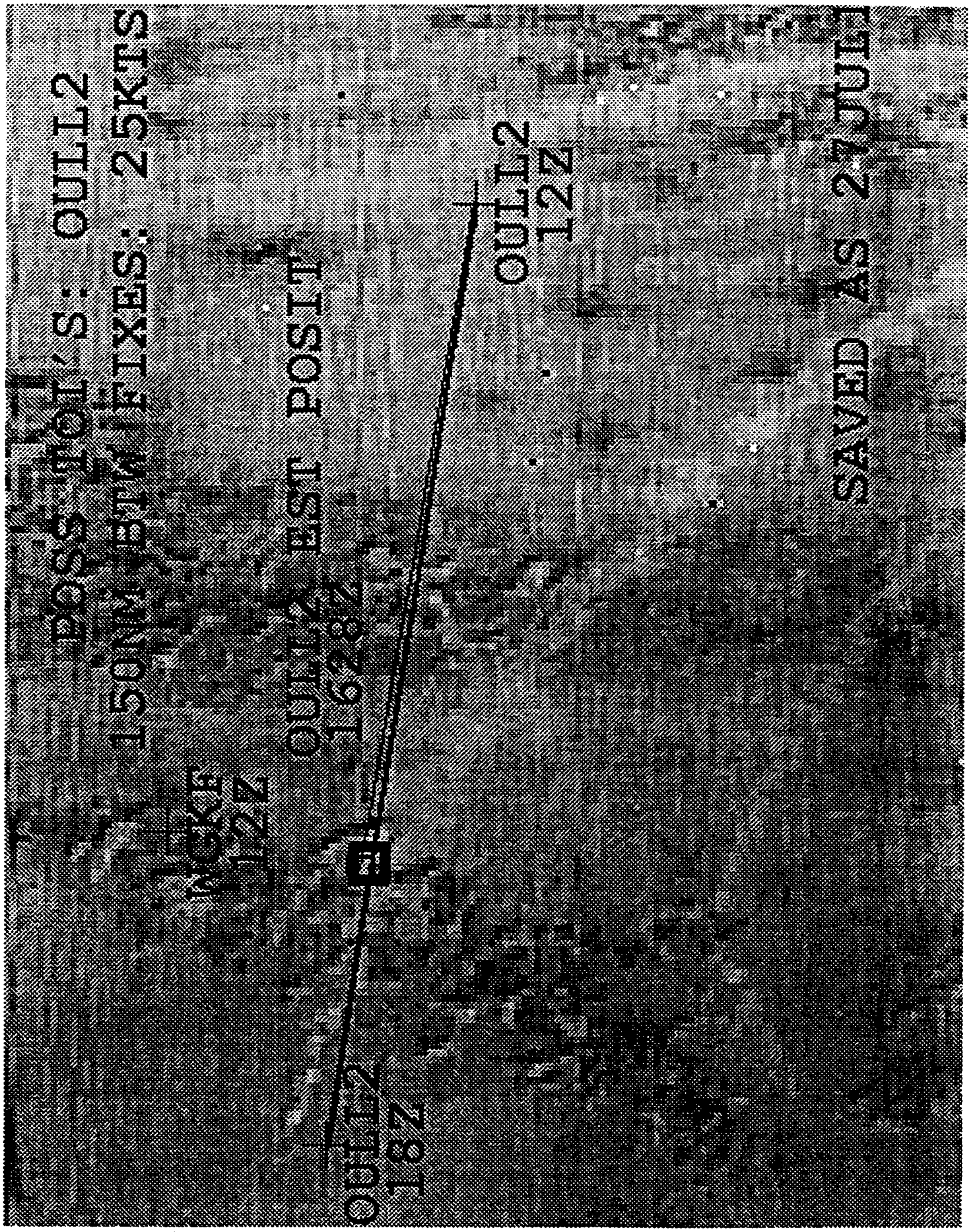

Figure 3. NOAA 12 1628 UTC 27 July 1997 Ch. 3 Satellite imagery depicting a vessel (M/V Marie Maersk) transiting a conducive shiptrack formation environment, but not producing a shiptrack.

overview of the study and results. Chapter V includes the conclusions and recommendations.

II. SHIPTRACK BACKGROUND

A. SHIPTRACK/ALBEDO RELATIONSHIP

Shiptracks are curvilinear cloud lines with higher albedo than the background clouds. Cloud albedo changes, in response to modification of the physical characteristics of a cloud, are of particular concern for shiptrack formation. Change in droplet total cross-sectional area per unit volume, known as the extinction coefficient, accounts for interaction of the droplets with radiation. The extinction coefficient, Q_{ext}, is described by equation 2.1:

$$\sigma_{ext} = \int_0^\infty \pi r^2 Q_{ext}(m, r) n(r) dr \quad (2.1)$$

where r is particle radius, πr^2 is particle cross-sectional area, $Q_{ext}(m,r)$ is the extinction efficiency factor, m is the complex index of refraction, and n(r) is the number of particles for a given radius. $Q_{ext}(m,r)$ is a function of both composition and size of a particle and describes the effects of both scattering and absorption due to the interaction of a particle with radiative energy of a specified wavelength. Changes in the size, composition or distribution of constituents or suspended particles in the atmosphere directly affect the amount of extinction observed.

Given a fixed liquid water content and unit volume (e.g. portion of a cloud), an increase in cloud condensation nuclei (CCN) increases the total number of droplets per unit volume and decreases the mean radius of the droplets. The total cross-sectional area per unit volume is approximated by equation 2.2:

$$\sigma = (KN)^{1/3} W^{2/3} \quad (2.2)$$

were σ is the extinction coefficient, K is a constant of proportionality, N is the number of droplets per unit volume, and W is the liquid water content. For shiptrack formation, it is assumed that introduction of vessel effluent into a cloud layer increases N, decreases the radius and therefore increases the extinction coefficient. Figure 4 illustrates channel 3 reflectance vs. droplet size (after Mineart, 1988).

Cloud reflectivity can be approximated by equation 2.3:

$$R = (\chi sl)/(1+ \chi sl) \quad (2.3)$$

where χ (~0.1) is a weak function of droplet size, s is the extinction coefficient and l is cloud thickness. Therefore, cloud reflectivity caused by an increase in droplet number is given by equation 2.4:

$$\Delta R/R = (1/(1+ \chi sl))(\Delta s/s) \quad (2.4)$$

where ΔR is the change in reflectivity, R is reflectivity, χ (~0.1) is a weak function of droplet size, Δs is the change in extinction coefficient, and s is the extinction coefficient. A localized increase in albedo of a stratus or stratocumulus broken or overcast layer is the primary daytime evidence of a ship passing beneath the cloud layer.

B. FORMATION MECHANISM

Conover's (1966) initial work on shiptrack observations provided the first insight into a formation mechanism and favorable environmental conditions for shiptracks. Figure 5 (after Brown, 1995) illustrates how ship effluent moves vertically through the planetary boundary layer and is

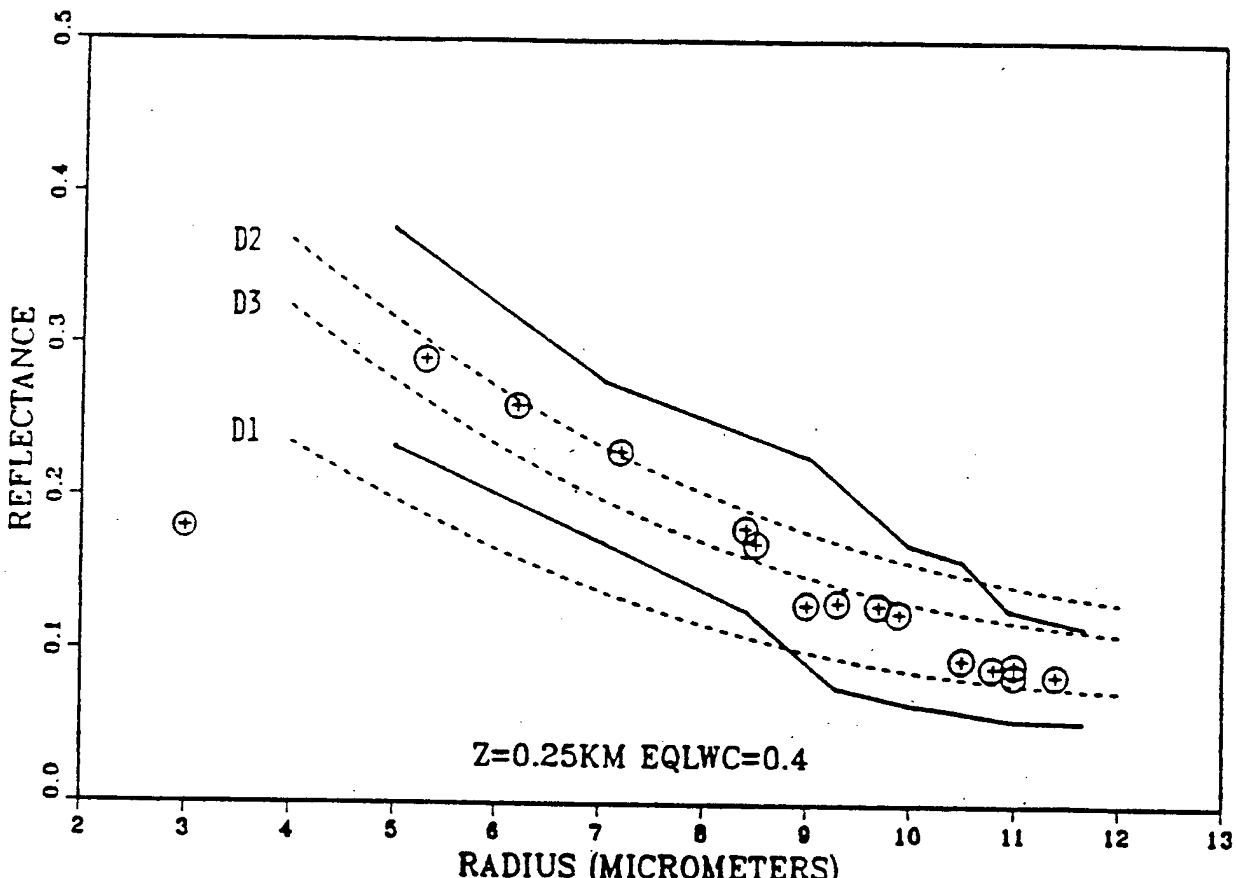

Figure 4. Channel 3 Reflectance Verses Droplet Radius. Dashed lines indicate model cloud reflectance from droplet distributions D1, D2, and D3; solid lines indicate 95 percent confidence interval for data points. EQLWC refers to equivalent liquid water content. After Mineart (1988). favorable environmental conditions for shiptracks.

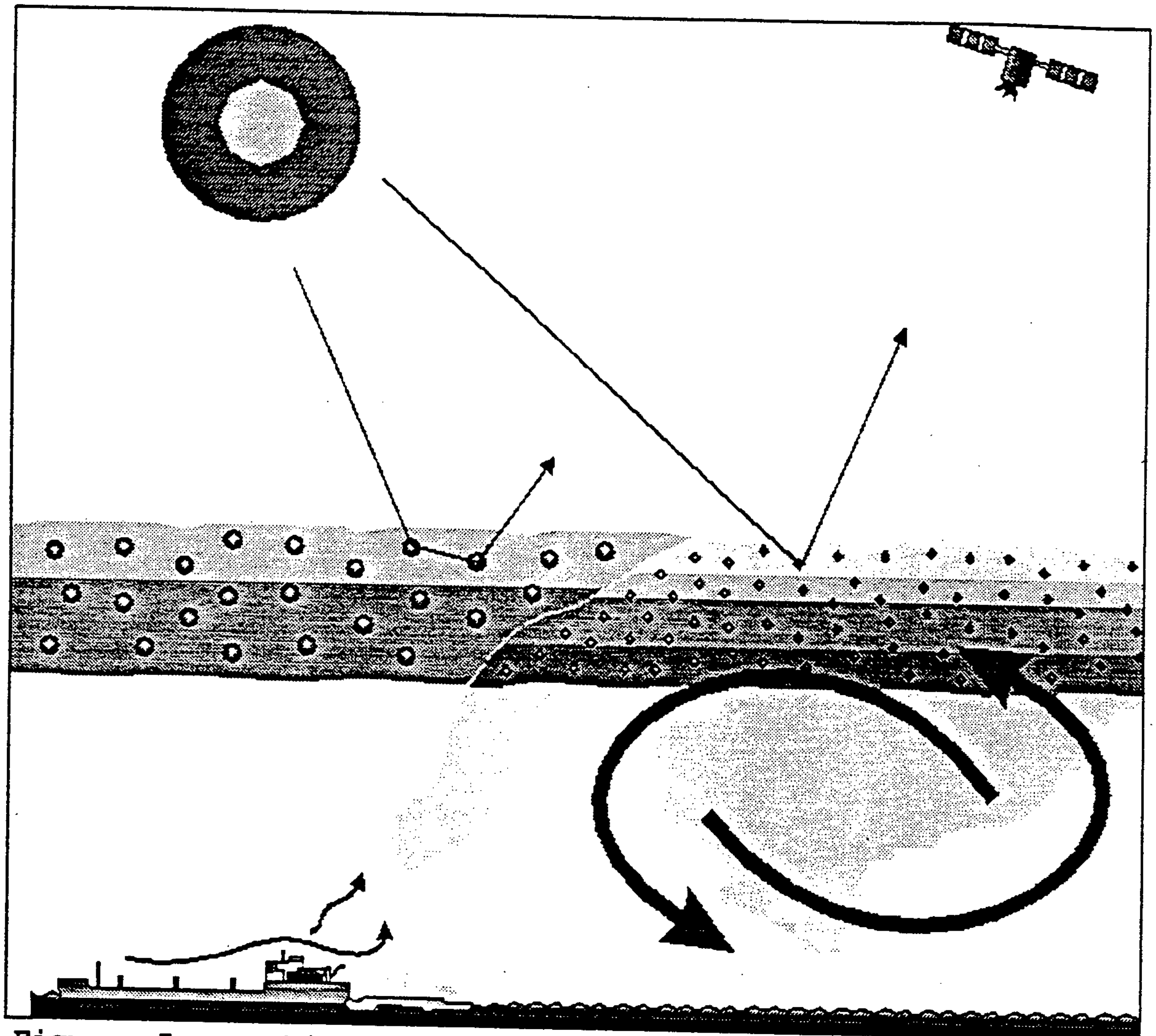

Figure 5. Shiptrack Formation Mechanism. Ship Exhaust introduces hygroscopic nuclei into the marine atmospheric boundary layer (MABL). Increased Cloud Condensation Nuclei (CCN) reduces the cloud water droplet size and increases its 3.7μm signature relative to uncontaminated clouds. Uncontaminated clouds have larger water droplets and thus greater absorption and lower 3.7μm signature. Large arrows represent turbulent mixing in the MABL. Thin, straight arrows represent solar radiation at 3.7μm. After Brown (1995).

entrained in the stratus cloud layer. In this conceptual model, introduction of CCN in the stratus layer increases the available nuclei for the water droplets and locally reduces the average droplet size. The relative difference between the background cloud albedo and the increased albedo associated with the shiptrack cloud is the signature of a vessel transiting beneath the cloud layer.

Porch et al. (1990) addressed the buoyancy effect of the ship's plume on marine cloud instability. They suggested that heat from the ship's power plant introduced into the Maritime Atmospheric Boundary Layer (MABL), with the associated buoyant effects, may be as important in shiptrack cloud formation as the energy release from the nucleation process.

Radke et al. (1989) made airborne measurements of shiptrack and non-shiptrack cloud parameters (Figure 6). Within shiptrack clouds they documented an increase in droplet (and particle) concentration, an unexpected increase in liquid water content, and a decrease in droplet size compared to non-shiptrack clouds. Changes in total water concentration, liquid-water content and total concentration of cloud interstitial particles of air samples with in shiptracks are result in corresponding radiative changes in the shiptrack cloud. Figure 6 depicts increase in upwelling flux density within a shiptrack cloud and an increase in the radiance ratio of visible radiation/near infrared ratio.

Chartier (1995) examined the time required for shiptrack formation. He determined that a vessel transiting a conducive environment averaged 25 minutes for shiptrack formation. The average shiptrack width was 9km and length was 296km.

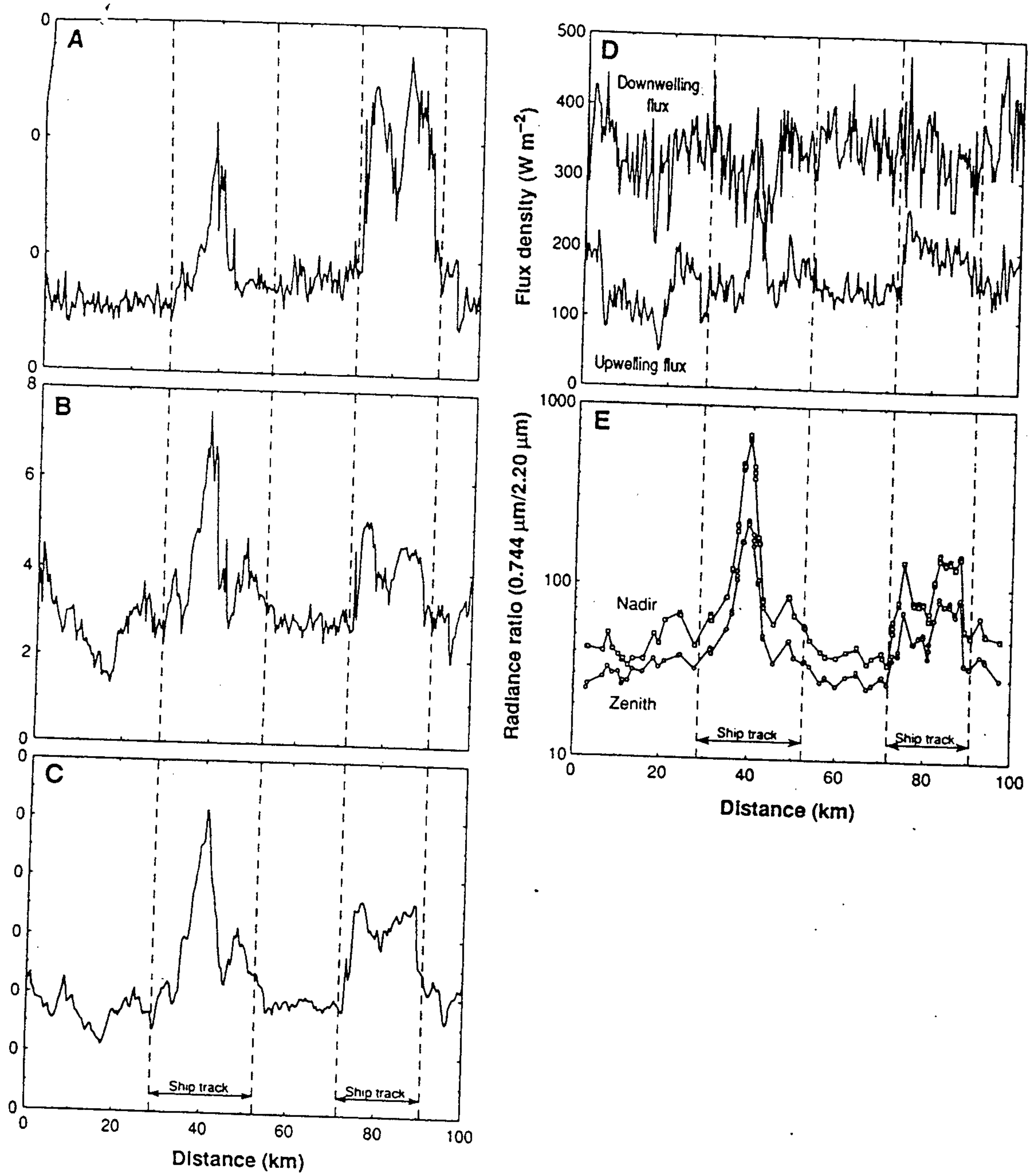

Figure 6. Cloud Characteristics Associated With Shiptrack clouds and uncontaminated clouds. After Radke et al. (1989).

C. ENVIRONMENT

Conover (1966) attributed shiptrack formation to a critical atmospheric condition rather than a special characteristic of a vessel's power plant. Conducive environmental conditions for shiptrack formation are a low, convectively unstable MABL, slight supersaturation near the top of the MABL, and a MABL '...deficient in cloud forming nuclei.' Trehubenko (1994) documented a decrease in shiptrack occurrence as the MABL depth increased to 750m, above which shiptracks were not observed. Chartier (1995) attributed 85% of the variation in shiptrack characteristics to the environment required for shiptrack formation.

D. SHIP PARAMETERS

The operating characteristics of a vessel passing through a conducive environment influence, to a large degree, the formation of shiptracks. The ship parameters considered in this study are:

1. Propulsion system type, e.g. oil, steam reciprocating, gas turbine, nuclear.

2. Propulsion system power measured by the total maximum designed break horse power or shaft horsepower.

3. Fuel consumption measured by the quantity of fuel used per day.

4. Fuel type, e.g. coal, diesel oil, high viscosity fuel, intermediate fuel oil, oil fuel.

5. Age of vessel.

6. Size of vessel.

7. Classification of vessel, e.g. tanker, cargo carrier, bulk carrier, vehicle carrier, etc.

8. Transit speed.

III. DATA

Previous shiptrack studies focused on mechanisms of shiptrack formation, physical characteristics of the cloud phenomena and environmental considerations. Chartier (1995) briefly addressed ship tonnage as a factor affecting shiptrack formation, however, this area of research is largely unexamined. This study examines vessels operating characteristics in conjunction with the occurrence and non-occurrence of shiptracks. Three diesel vessel populations were used for this study:

1. Shiptrack producing diesel vessels.

2. Non-shiptrack producing diesel vessels.

3. A random diesel vessel population.

Operating characteristics for each diesel vessel in each population were obtained from Lloyd's Register of Ships (1992). Data sets, AVHRR and statistical methods used to analyze data in this study are discussed in this chapter.

A. SHIPTRACK OCCURRENCE DATA SET

This study examines 50 shiptrack producing diesel vessels compiled by Rogerson (1995) from the 1994 Monterey Area Shiptrack (MAST) experiment. Rogerson correlated a shiptrack to a specific vessel by visual (vice automated) comparison of an observed shiptrack on AVHRR imagery (channel 3) with ship positional data obtained from periodic weather observations (Figure 7). Ship characteristic data were obtained from Lloyd's Register of Ships (1992) (Appendix A).

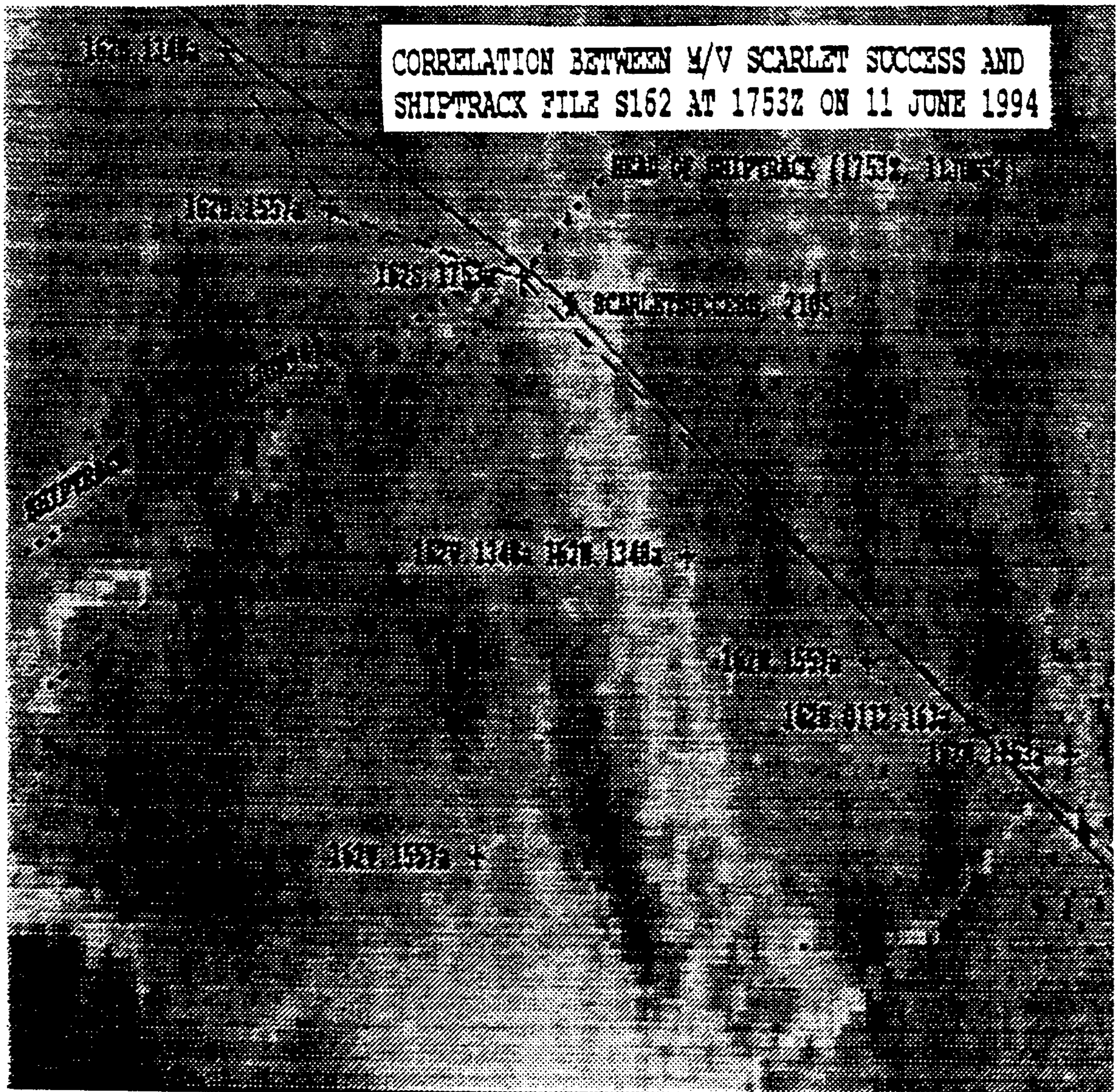

Figure 7. Zoomed Image with A Typical Ship-Shiptrack correlation. After Rogerson (1995).

B. NON-SHIPTRACK OCCURRENCE DATA SET

Non-shiptrack occurrence data were collected using vessel weather reports and AVHRR (channel 3) imagery collected primarily from June-September 1997 in the eastern Pacific. Within this data set, only regions with a high concentration of shiptracks distributed over a broad geographic area were considered. This restriction was placed on the data set to mitigate the affect of environmental variations, such as a significant perturbation in boundary layer height, frontal passage, etc. Within an environmentally homogeneous region, a more meaningful assessment of a vessel's operating characteristics on the occurrence/non-occurrence of shiptracks can be made.

A non-shiptrack producing vessel was identified by verifying its position (based on weather observations) and its proximity to observed shiptracks (Figure 3). Ship operating characteristics were obtained from Lloyd's Register of Ships (1992) (Appendix B).

C. RANDOM DIESEL DATA SET

A random population of diesel vessels was generated for statistical comparison with the shiptrack and non-shiptrack producing populations. Statistical comparison was used to identify vessels operating parameters, which distinguished one population from the other. The random population was generated from a subset of all vessels submitting weather observations from the eastern Pacific in June-September 1997. For a vessel to be included in the random population, its call sign must be recorded in Lloyd's Register of Ships (1992), it must be of similar classification to the other 2 populations (e.g. bulk carriers, cargo, tankers, etc.), and it must not be included in the other populations (Appendix C).

D. NOAA ADVANCED VERY HIGH RESOLUTION RADIOMETER (AVHRR)

The AVHRR instrument is a component of the NOAA Polar Orbiting Operational Environmental Satellite (POES) series satellites. Current operational POES include the NOAA 12 and NOAA 14. The AVHRR instrument measures radiant and solar-reflected energy from sampled areas of the Earth in five spectral bands (visible through infrared) with a sub-satellite resolution of 1.1 km. For this study channel 3, with a band width of 3.55μm-3.93μm, is used exclusively for shiptrack evaluation. Although the visible imagery (channel 1, 0.58μm-0.68μm) and infrared imagery (channels 4 and 5, 10.3μm-11.33μm and 11.5μm-12.5μm, respectively) show shiptracks, channel 3 shows the highest contrast in albedo (Figure 1).

E. STATISTICAL TECHNIQUES FOR DATA ANALYSIS

From the three population data sets basic statistical calculations were performed, e.g. average, standard deviation, mode, median, maximum and minimum. To obtain statistical relationships among the three populations, the following techniques were use to analyze the data:

1. Graphical comparison of percent occurrence vs. various vessel parameters is presented in the results.

2. The T-test comparison of population pairs is used to compare how distinct the mean values of two populations are from each other. The usefulness of the T-test statistic is measured by a level of significance, e.g. a 0.05 level of significance implies a 95 percent confidence level (statistically significant). In this study, a level of significance between 0.0 and 0.4 (100-60 percent confidence level) is considered tactically significant, i.e. may have

operational value vice purely statistical value. That is, if a T-test result for a given ship operating characteristic or ratio of characteristics falls within this range, the two populations are considered to be distinct from each other and may be used to predict the occurrence and non-occurrence of shiptracks. Conversely, a level of significance between 0.6 and 1.0 (40-0 percent confidence level) is considered tactically insignificant. If a T-test result for a given ship operating characteristic or ratio of characteristics falls within this range, the two populations are considered to be indistinct from each other and may not be used to predict the occurrence and non-occurrence of shiptracks.

In this study 12 parameters or ratios of parameters are evaluated. Parameter values are obtained from Lloyd's Register of Ships (1992) and do not represent *in situ* measurements. Parameters evaluated are:

-Transit speed: Transit speed refers to the speed, in knots, which the ship is capable of maintaining at sea in normal weather and at normal service draught.

-Fuel use: Fuel use refers to the tonnage of fuel used in one day, as stated by the vessel owner or as obtained from other reliable sources.

-Power rating: Power rating is the total maximum designed shaft power approved (break horsepower).

-Tonnage: Tonnage refers to gross tonnage, which is the capacity in cubic feet of the spaces within the hull, and of the enclosed spaces above the deck available for cargo, stores, fuel, passengers and crew.

-Power/hull cross-section ratio. The product of a vessel's maximum beam and draft yields the cross-section.

-Tonnage/fuel use ratio.

-Power/fuel use ratio.

-Speed/fuel use ratio.

-Power/speed ratio.

-Tonnage/power ratio.

-Power*fuel/speed ratio.

-Power*speed product.

3. Bivariate plots of T-test ratios listed above with regressions, associated correlation coefficients and levels of significance are analyzed.

IV. RESULTS AND DISCUSSION

A. OVERVIEW OF STUDY

This study compares vessel's operating characteristics of three diesel populations: vessels which produce shiptracks (shiptrack producers), vessels which do not produce shiptracks (non-shiptrack producers), and a random diesel vessel population. Operating parameters for each vessel from each population were compared to determine their association with the occurrence/non-occurrence of shiptracks. Ship weather reports constituted positional fixes for each vessel. AVHRR imagery (channel 3) was used to identify the occurrence and non-occurrence of shiptracks in conducive environments. The vessel's operating characteristics were obtained from Lloyd's Register of Ships (1992). From these data various statistical analysis techniques were used to determine which vessel parameters are the most useful in predicting shiptrack occurrence and non-occurrence.

B. STATISTICAL RESULTS

Table 1 summarizes ship-operating parameters for the three diesel vessel populations examined. Figures 8-19 plot vessels operating parameters vs. percent occurrence. Table 2 summarizes T-test results for 36 different population pairs. Figures 20-31 are bivariate plots with linear regressions and associated correlation coefficients.

1. Shiptrack Producing Population vs. Non-Shiptrack Producing Population

a. Ship Parameter Statistical Summary

Appendices A and B summarize specific operating parameters for both populations being considered. Table 1 summarizes the general statistical data for each operating parameter examined. Overall, shiptrack producing diesel vessels have a 17.7 percent higher fuel use rate, an 8.8 percent larger power plant, are 1.0 knot faster and are comparable in tonnage to non-shiptrack producing diesel vessels.

b. Ship Operating Parameter Plots

Plots of shiptrack and non-shiptrack operating parameters vs. percent occurrence are distinctive in the following categories: fuel use (tons/day), power (BHP), transit speed (kts), the ratios of tonnage/fuel use, power/speed, power/hull cross-sectional area, power*fuel use, and power*fuel use/speed.

Figure 8 is a plot of fuel use vs. percent occurrence. The shiptrack population plot has a symmetrical distribution with no category containing more than 20 percent of the population. The non-shiptrack population has a dominant mode at the second lowest bin, between 30-45 tons/day, which contains 45 percent of the population. The shiptrack average is 73.0 tons/day and the non-shiptrack average is 59.3 tons/day. The T-test is used to compare fuel use for the two populations. A 0.30 level of significance is obtained indicating a 70 percent confidence level that the two populations are distinct in their rate of fuel use.

Burning fuel in a ship's propulsion plant produces effluent. Introduction of effluent into the MABL provides new CCN for cloud water droplets to form on. For fixed liquid water content within a cloud, additional CCN will cause an increase in the number of cloud water droplets and a decrease in size due to their redistribution within the cloud. This manifests itself radiometrically as a localized increase in reflectance and possible shiptrack clouds. The non-shiptrack diesel population has an average fuel use 13.7

tons/day less than the shiptrack diesel population. From this it can be inferred that the non-shiptrack population introduces less effluent, produces less CCN, and, therefore, modifies the MABL less than the shiptrack population, and is less likely to leave a shiptrack cloud signature.

Figure 9 is a plot of vessel power vs. percent occurrence. The distribution of both populations is bimodal at bins 10-15,000 BHP and 25-30,000 BHP. The lower mode accounts for 53 percent of the non-shiptrack population vice 24.5 percent for the shiptrack population. The shiptrack average is 24,906 BHP and the non-shiptrack average is 21,104 BHP. A 0.29 level of significance is obtained from the T-test.

Vessel power is positively correlated with fuel use; i.e. larger power plants use more fuel (see regression results in sub-section d. of this section). The non-shiptrack population has a smaller power plant compared to the shiptrack producers. It can be inferred that the smaller power plant uses less fuel, produces less effluent, fewer CCN and is thus less likely to leave a shiptrack.

Figure 10 is a plot of vessel transit speed vs. percent occurrence. The non-shiptrack population is distinguished by narrower range of speeds and no observations in the lowest bin (13-14.5kts) or the highest two bins (22-23.5kts and 23.6-25.0kts). The shiptrack population distribution is broader, with representation in every bin. The shiptrack average is 19.5kts and the non-shiptrack average is 18.6kts. A 0.27 level of significance is obtained from the T-test.

Vessel speed affects the concentration of effluent in a MABL. Ignoring all other factors, and given a fixed amount of effluent, a faster moving vessel introduces a lower concentration of effluent per volume of MABL than a slow moving vessel. When speed is evaluated by itself, the results are inconsistent with shiptrack/non-shiptrack formation. The larger power plants of the shiptrack population correlate with faster transit speeds, which decreases the likelihood of shiptrack formation. Conversely, the smaller power plants of the non-shiptrack population correlate with slower transit speeds, which favors shiptrack formation. Although speed is a useful discriminator of ship/non-shiptrack diesel populations, other factors, such as power and fuel use act to mitigate the affect of vessel speed.

Figure 11 is a plot of the ratio of tonnage/fuel use vs. percent occurrence. The plots are similar for the two populations except the non-shiptrack population mode is one bin higher (450-600) and has significantly more weighting in the highest two bins. The shiptrack average is 470 and the non-shiptrack average is 665. A 0.20 level of significance is obtained from the T-test. A 0.04 level of significance is obtained by omitting outliers (see Figure 22 and discussion in sub-section d. of this section).

Although the shiptrack/non-shiptrack vessels are similar in size, the rate of fuel use is not similar. The shiptrack population correlates with greater fuel use, therefore, has a smaller ratio. The non-shiptrack population's ratio of tonnage/fuel is larger, reflecting a lower rate of fuel use.

Figure 12 is a plot of the ratio of power/transit speed vs. percent occurrence. The shiptrack population distribution is positively skewed with three modes at 501-750, 751-1000 and 1251-1500, which contain 67 percent of the population. The non-shiptrack population is also positively skewed with identical modes containing 86 percent of the population. The shiptrack average is 1,183 and the non-shiptrack average is 979. A 0.10 level of significance is obtained from the T-test.

This ratio compares power, which is positively correlated with shiptracks, and vessel speed. The shiptrack population's higher ratio average value suggests that the rate of power increase offset the effect of higher transit speeds for shiptrack formation. The non-shiptrack ratio average is lower due to a lower power value in the ratio. Vessel speed only modestly decreases. A ship with a smaller power plant produces less effluent and is less likely to form shiptracks.

Figure 13 is a plot of the ratio of power/hull cross-section vs. percent occurrence. The shiptrack population distribution is positively skewed with a mode between 46-60, which contains 29 percent of the population. The non-shiptrack population is also positively skewed with a conspicuous mode between 31-45, which contains 33 percent of the population. A 0.25 level of significance is obtained from the T-test.

Figure 14 is a plot of the product of power*fuel use vs. percent occurrence. The shiptrack population distribution has a dominant mode between 0.5-1.0, which contains 28 percent of the population. Otherwise, each bin below 4.0 contains 4-12 percent of the population. There is no additional representation except in the last bin (greater than 6.0). The non-shiptrack population has a conspicuous mode between 0-0.5, which contains 34 percent of the population. Overall, the population is heavily weighted in the lower bins and has no representation above 3.0. The shiptrack average is 2.2 and the non-shiptrack average is 1.3. A 0.12 level of significance is obtained from the T-test.

Vessel power and fuel use is positively correlated with shiptrack formation. More power requires more fuel, which introduces more effluent, increasing the likelihood of shiptrack formation. The shiptrack population reflects a significantly higher average ratio of 2.2 compared to the non-shiptrack population's average of 1.3.

Figure 15 is a plot of the product of power*fuel use/speed vs. percent occurrence. The shiptrack population distribution has three dominant bins between 0.02-0.08, which contain 48 percent of the population. Otherwise, all other bins each contain 4-12 percent of the population. The non-shiptrack population has a bimodal distribution with 55 percent of the population in the first two bins. The shiptrack average is 0.1 and the non-shiptrack average is 0.06. A 0.11 level of significance is obtained from the T-test.

This ratio compares the product of power and fuel use to vessel speed. Power and fuel are both positively correlated with shiptrack occurrence. The shiptrack population has a higher ratio than the non-shiptrack population despite having a higher vessel speed. This implies that the larger product of the numerator more than offsets the higher average vessel speed compared to the non-shiptrack population.

c. T-Test Results

Table 2 summarizes the T-test results in descending order from the highest level of significance to the lowest. Using the tactically significant criteria previously defined, the shiptrack producing diesel vessel population and non-shiptrack producing diesel population are distinguishable in eight categories: power/speed, power*fuel/speed, power*fuel, tonnage/fuel use, power/cross-section, speed, power, and fuel use. This suggests that each population mean is tactically distinct from the other. Therefore, these eight categories may be useful in predicting the occurrence and non-occurrence of shiptracks. A common thread among these categories is the influence of fuel use, either directly (e.g. tonnage/fuel use) or indirectly (e.g. power/speed). Higher fuel usage is associated, to some degree, with occurrence of shiptracks.

Important information is also contained in low levels of significance. Using the tactically insignificant criteria previously defined, only one category is indistinguishable for the two populations - tonnage. Its 0.73 level of significance suggests that the two population means are virtually identical. Tonnage is the only vessel parameter examined that is completely independent of fuel use.

d. Regression Results

Bivariate plots of ship parameters with linear regressions and correlation coefficients are used to compare the shiptrack and non-shiptrack populations. Parameters compared are: power vs. speed, tonnage vs. fuel, power vs. hull cross-section, tonnage vs. power, power vs. fuel use, and speed vs. fuel use. Bivariate plots of the same parameters are used to show how ship type is distributed for both populations.

Figure 20 is a comparison of power vs. speed for shiptrack and non-shiptrack populations. The data distribution has a positive correlation and is represented well by a linear regression. The non-shiptrack regression line is slightly above the shiptrack population regression line. This indicates the non-shiptrack population is overall slightly faster per ton than the shiptrack population. The non-shiptrack population is also not well represented above 30,000 BHP.

Figure 21 is a comparison of power vs. speed for each ship type in both populations. The distribution of ship types is similar for both populations with container carriers distributed in the higher 2/3 of the plot. All other ship types are observed in the lower 1/3 of the plot.

Figure 22 is a comparison of tonnage vs. fuel for shiptrack and non-shiptrack populations. The data distribution has a positive correlation for the shiptrack population and is represented by a linear regression. The non-shiptrack population is positively correlated; however, it can not be represented meaningfully with a linear regression. Using the non-shiptrack distribution vice regression for comparison, the majority of the individual plots are below the shiptrack population regression line. This indicates the non-shiptrack population uses less fuel per ton than the shiptrack population. Outliers in lower right quadrant of plot are ships from the same manufacturer. Omission of these data points increases the correlation to 0.89 and 0.88 for the shiptrack and non-shiptrack populations, respectively.

Figure 23 is a comparison of tonnage vs. fuel use for each ship type in both populations. Both populations have similar distributions except for vehicle carriers. The shiptrack vehicle carriers have two distinct groups. One group's tonnage is between 10,000 and 20,000 tons and fuel use rate between 40-60 tons/day, the second group's tonnage is between 40,000 and 50,000 tons and fuel use rate of approximately 40 tons/day. The non-shiptrack observations are associated with the latter group.

Figure 24 is a comparison of power vs. hull cross-section for shiptrack and non-shiptrack populations. The data distribution has a positive correlation and is represented well by a linear regression. Although the non-shiptrack regression line is slightly above the shiptrack population regression line, their slopes are similar and there are no obvious distinctions between them.

Figure 25 is a comparison of power vs. hull cross-section for each ship type in both populations. The distribution is similar for both populations. Container carriers dominate the higher end with representation from both populations.

Figure 26 is a comparison of power vs. tonnage for shiptrack and non-shiptrack populations. The data distribution has a positive correlation and is adequately represented by a linear regression. Although the non-shiptrack regression line is slightly above the shiptrack population regression line, their slopes are similar and there are no obvious distinctions between them.

Figure 27 is a comparison of power vs. tonnage for each ship type in both populations. Both populations have similar distributions. Of note is the tight packing of shiptrack and non-shiptrack vehicle carriers near 45,000 tons and 15,000 BHP. The only occurrence of a non-shiptrack bulk carrier coincides with the lowest power vs. tonnage shiptrack occurrence.

Figure 28 is a comparison of fuel vs. power for shiptrack and non-shiptrack populations. The data distribution has a positive correlation and is exceptionally well represented by a linear regression. Although the non-shiptrack regression line is slightly below the shiptrack regression line, their slopes are similar and there are no obvious distinctions between them, however, the shiptrack population has two data points with exceptionally high values.

Figure 29 is a comparison of fuel use vs. power for each ship type in both populations. Both populations have similar distributions with container carriers dominating the upper 2/3 of the plot.

Figure 30 is a comparison of speed vs. fuel use for shiptrack and non-shiptrack populations. The data distribution has a positive correlation and is well represented by a linear regression. Although the regression lines cross each other at the higher end, the non-shiptrack population appears to use a higher rate of fuel per knot.

Figure 31 is a comparison of speed vs. fuel use for each ship type in both populations. Both populations have similar distributions with container carriers dominating the upper 2/3 of the plot.

2. Shiptrack Producing Population vs. Random Diesel Population

a. Ship Parameter Statistical Summary

Appendices A and C summarize specific operating parameters for each of these populations. Table 1 summarizes the statistical data. Overall, shiptrack producing diesel vessels have a slightly higher fuel use rate, a larger power plant, are 0.4 knots faster and are smaller than the random diesel population. This discrepancy in size between the random diesel population and the shiptrack and non-shiptrack populations may reflect a lack of larger Trans-Pacific vessels in the area examined. Another possibility is smaller shiptrack vessels are less efficient, requiring larger power plants and fuel usage rates to achieve comparable levels of performance.

b. Ship Operating Parameter Plots

Plots of shiptrack and random diesel population operating parameters vs. percent occurrence are distinctive in the following categories: tonnage and the ratio of power/fuel use and power/tonnage.

Figure 16 is a plot of vessel tonnage vs. percent occurrence. The shiptrack population plot has a dominant mode between 40-45 tons, which contains 23 percent of the population. The distribution is skewed negatively with 0 to 16 percent of the population in each bin. The random population has a dominant mode between 40-45 tons and more weighting in the lower to middle bins. The shiptrack average is 31,133 and the random average is 34,351. A 0.31 level of significance is obtained from the T-test.

The shiptrack population vessel tonnage is lower than the random population. This factor affects various ratios and has implications for fuel and power efficiency.

Figure 17 is a plot of the power/tonnage ratio vs. percent occurrence. The distribution between the two populations is similar with modes between 1-1.5. However, 79 percent of the shiptrack population is accounted for in bins 0.5-1.0 and 1.0-1.5 compared to only 60 percent of the random population. The random population has slightly more representation in the higher ratio bins. The shiptrack average is 1.5 and random average is 1.7. A 0.14 level of significance is obtained from the T-test.

The shiptrack population has a lower average tonnage/power ratio than the random population. This reflects the shiptrack population's smaller size and larger power plant. This combination suggests shiptrack producers have less efficient power plants and require more BHP per ton. As discussed earlier, a larger power plant introduces more effluent to the MABL, which enhances shiptrack cloud formation.

Figure 18 is a plot of the power/fuel use ratio vs. percent occurrence. The shiptrack population distribution is dominated by a mode at adjacent bins at 300-315 and 315-330, which accounts for 46 percent of the population. The random diesel population has a mode between 285-300 and is well represented in the lower value bins. The shiptrack average is 332.4 and the random average is 315.1. A 0.14 level of significance is obtained from the T-test.

Both variables are positively correlated with shiptrack formation. The higher average value of the shiptrack population reflects the larger power plant compared to only a slight increase in fuel use.

c. T-Test Results

Table 2 summarizes T-test results in descending order from the highest level of significance to the lowest. Using the tactically significant criteria defined above, the shiptrack producing diesel vessel population and random diesel population are distinguishable in three categories: power/fuel use, tonnage/power, and tonnage. The power/fuel ratio is particularly enigmatic since the level of significance associated with fuel is 0.87, and the level of significance associated with power is 0.92, both tactically insignificant. This implies that power is indistinguishable between shiptrack producers and the random population. Similarly, fuel use is indistinguishable between the two populations. The ratio of these two indistinguishable characteristics yields a very high level of significance, which is unexpected and problematic. Tonnage results provide some insight to the high level of significance associated with the tonnage/power ratio. Table 1 shows that the random diesel population's mean tonnage is higher than the shiptrack producing diesel population. The level of significance of the tonnage term probably dominates the ratio since the power term is virtually indistinguishable in these two populations.

Eight categories are tactically indistinguishable: speed/fuel, power*fuel, power*fuel/speed, speed, power/speed, fuel use, power and power/cross-sectional area. Fuel use is a common thread for each of these categories and suggests that the similarity in fuel use rates for the two populations render most categories examined of limited use.

3. Non-Shiptrack Producing vs. Random Diesel Population

a. Ship Parameter Statistical Summary

Appendices B and C summarize specific operating parameters for each of these two populations. Table 1 summarizes the general statistical data. Overall, non-shiptrack producing diesel vessels use less fuel, have a smaller power plant, are 0.9 knots slower and are smaller than the random diesel population.

b. Ship Operating Parameter Plots

Plots of non-shiptrack and random diesel population operating parameters vs. percent occurrence are distinctive in the following categories: fuel use, power, tonnage/fuel, power/speed, power/hull cross-sectional area, power*fuel, power*fuel/speed, tonnage and speed/fuel.

Figure 8 is a plot of fuel use vs. percent occurrence. Both populations are bimodal in the same bins; however, the population percentages in each mode are distinctive. The non-shiptrack population mode between 30-45 tons/day accounts for 44 percent of the population vice 27 percent for the random diesel population. Conversely, the non-shiptrack population mode between 75-90 tons/day accounts for only 22 percent of the population vice 33 percent for the random diesel population. The non-shiptrack average is 59.3 tons/day and the random population average is 69.8 tons/day. A 0.38 level of significance is obtained from the T-test.

The non-shiptrack average fuel use rate is 10.5 tons/day less than the random population. The non-shiptrack population introduces less effluent, produces less CCN, and, therefore, modifies the MABL less than the random population, thus is less likely to produce a shiptrack cloud signature.

Figure 9 is a plot of vessel power vs. percent occurrence. The distribution of both populations is similar with common modes between 10-15,000 BHP and 25-30,000 BHP. However, the non-shiptrack population has a significantly higher percent occurrence in the lower mode. The non-shiptrack average is 21,109 and the random average is 22,940. A 0.36 level of significance is obtained from the T-test.

Vessel power is positively correlated with fuel use; i.e. larger power plants use more fuel. The non-shiptrack population has a slightly smaller power plant compared to the random population. The smaller power plant uses less fuel, produces less effluent, fewer CCN and is thus less likely to leave a shiptrack.

Figure 11 is a plot of the ratio of tonnage/fuel use vs. percent occurrence. The non-shiptrack distribution has a dominant mode between 450-600. The random population distribution mode is shifted one bin lower, between 300-450. The non-shiptrack average is 665 and the random average is 524. A 0.39 level of significance is obtained from the T-test.

The larger tonnage/fuel ratio for the non-shiptrack vessels reflects the lower rate of fuel use compared to the random population. The non-shiptrack tonnage/fuel ratio has smaller inputs for the numerator and denominator compared to the random population. However, an even lower rate of fuel use in the denominator offsets the small numerator input resulting in a higher ratio. This suggests that fuel use is the dominant variable in this ratio.

Figure 12 is a plot of the ratio of power/speed vs. percent occurrence. The non-shiptrack distribution is relatively narrow and positively skewed. The random diesel distribution is much wider and has representation in every bin. The non-shiptrack average is 979 and the random average is 1,215. A 0.08 level of significance is obtained from the T-test.

The lower power/speed ratio of the non-shiptrack population reflects the smaller power plant compared to the random population. The non-shiptrack power/speed ratio has smaller inputs for the numerator and denominator. However, the decrease in power in the numerator offsets the smaller denominator input resulting in a lower ratio. This suggests that power is the dominant variable in this ratio.

Figure 13 is a plot of the ratio of power/hull cross-sectional area. The distributions of the two populations are similar, although the random distribution is more uniform over the entire range. A 0.38 level of significance is obtained from the T-test.

Figure 14 is a plot of the product of power*fuel use vs. percent occurrence. The non-shiptrack population has a conspicuous mode between 0-0.5, which contains 33 percent of the population. Overall, the population is heavily weighted in the lower bins, and has no representation above 3.0. The random population is similarly weighted in the lower bins, but and it is also represented in the highest bin (greater than 6.0). The non-shiptrack average is 1.3 and the random average is 1.9. A 0.25 level of significance is obtained from the T-test.

Vessel power and fuel use is positively correlated with shiptrack formation. More power requires more fuel, which introduces more effluent increasing the likelihood of shiptrack formation. The non-shiptrack population's lower average ratio of 1.3, compared to the random population's average of 1.9 suggests it is less likely to produce shiptracks.

Figure 15 is a plot of the product of power*fuel use/speed vs. percent occurrence. The non-shiptrack population has a bimodal distribution with 55 percent of the population in the first two bins, 0-0.02 and 0.02-0.04. The random population's distribution is also bimodal, with 26 percent of the population in the 0.06-0.08 bin. The non-shiptrack average is 0.06 and the random average is 0.1. A 0.20 level of significance is obtained from the T-test.

This ratio compares the product of power and fuel use to vessel speed. Fuel use and power are both positively correlated with shiptrack occurrence. The non-shiptrack population has a lower ratio than the random population, despite having a lower vessel speed. This implies the product of the numerator is smaller and dominates the non-shiptrack ratio compared to the random population.

Figure 16 is a plot of vessel tonnage vs. percent occurrence. The non-shiptrack distribution has a dominant mode between 40-45 tons, which accounts for 20 percent of the population. Three secondary modes occur between 10-15 tons, 20-25 tons and 45-50 tons; otherwise the distribution is fairly uniform. The random population distribution has a dominant mode between 40-45 tons, which contains 23 percent of the population. Each of the other bins has 0 to 13 percent of the population. The non-shiptrack average is 31,037 and the random average is 34,351. A 0.32 level of significance is obtained from the T-test.

The non-shiptrack vessel size is smaller than the random population's vessel size. This factor will affect various ratios and has implications for fuel and power efficiency.

Figure 19 is a plot of the ratio of fuel use/speed vs. percent occurrence. The non-shiptrack distribution is narrower than the random distribution and is bimodal. The dominant mode, between 2.0-2.5, accounts for 33 percent of the non-shiptrack population. A secondary mode, between 4.0-4.5, accounts for 22 percent of the population. The random diesel population distribution is more symmetric with a mode between 3-3.5. The non-shiptrack average is 3.1 and the random average is 3.6. A 0.38 level of significance is obtained from the T-test.

The lower fuel/speed ratio average for non-shiptrack diesels is attributed primarily to their lower fuel use rates.

c. T-Test Results

Table 2 summarizes the T-test results in descending order from the highest level of significance to the lowest. Using the tactically significant criteria defined above, the non-shiptrack producing diesel population and the random diesel population are distinguishable in nine categories: power/speed, power*fuel/speed, power*fuel, tonnage, power, power/cross-section, speed/fuel, fuel use and tonnage/fuel. These two populations are distinguishable in all categories examined except speed, power/fuel and power/tonnage.

WEATHER	REPORTING			DIESEL		VESSELS			59 SHIPS
	POWER RATING BHP	FUEL USE TONS/DAY	RATIO POWER/ FUEL USE	RATIO SPEED/ FUEL USE	SHIP TONNAGE	RATIO TONNAGE/ POWER	POWER* UEL USE 1E-06	RATIO TONNAGE/ FUEL USE	SHIP SPEED KNOTS
AVG	22940.0	69.8	315.1	3.6	34351.0	1.7	1.9	523.8	19.1
STD	11622.0	33.6	48.4	1.3	16106.0	1.1	2.1	313.4	3.6
MODE	30150	76	396.7		32629	1.1	2.3	429.3	22
MEDIAN	22645	72.5	205.4	3.5	32629	1.4	1.5	447.2	20
MIN	4080	17	205.4		5087	0.5	0.1	299.2	13
MAX	56960	173.5	396.7		77454	6.9	8.8	1960.9	25.5
DIESEL	SHIPTRACK				PRODUCERS				50 SHIPS
	POWER RATING BHP	FUEL USE TONS/DAY	RATIO POWER/ FUEL USE	RATIO SPEED/ FUEL USE	SHIP TONNAGE	RATIO TONNAGE/ POWER	POWER* UEL USE 1E-06	RATIO TONNAGE/ FUEL USE	SHIP SPEED KNOTS
AVG	25193.0	71.3	334.4	3.4	31869.0	1.5	2.1	469.8	19.5
STD	13336.0	34.7	34.9	1.3	14053.0	0.8	2.2	295.3	3.0
MODE	16800				37209	1.4	NA	NA	24.25
MEDIAN	22770	67	329.5	3.3	34500	1.3	1.5	389.3	19.25
MIN	6200	25.5	243		1454	0.5	0.15	146	14
MAX	56956	163.5	396.7		61926	3.9	9	1512.1	24.25
DIESEL	NON-SHIPTRACK				PRODUCERS				15 SHIPS
	POWER RATING (BHP)	FUEL USE TONS/DAY	POWER/ FUEL USE RATIO	SPEED/ FUEL USE RATIO	SHIP TONNAGE	TONNAGE/ POWER RATIO	POWER* UEL USE 1E-06	TONNAGE/ FUEL USE RATIO	SHIP SPEED KNOTS
AVG	21108.9	59.3	325.0	3.1	31037.0	1.7	1.3	664.7	18.6
STD	12738.3	26.8	33.1	1.0	14249.1	0.9	1.0	393.5	2.7
MODE		35.5				1.5		NA	18.5
MEDIAN	14890	48.5	321.1		33405	1.4		490.5	18.4
MIN	10330	31	284		7701	0.7		332.7	15
MAX	51920	98.5	383.9		52181	3.9		1512.1	23.3

Table 1. Summary of Ship Operating Parameters.

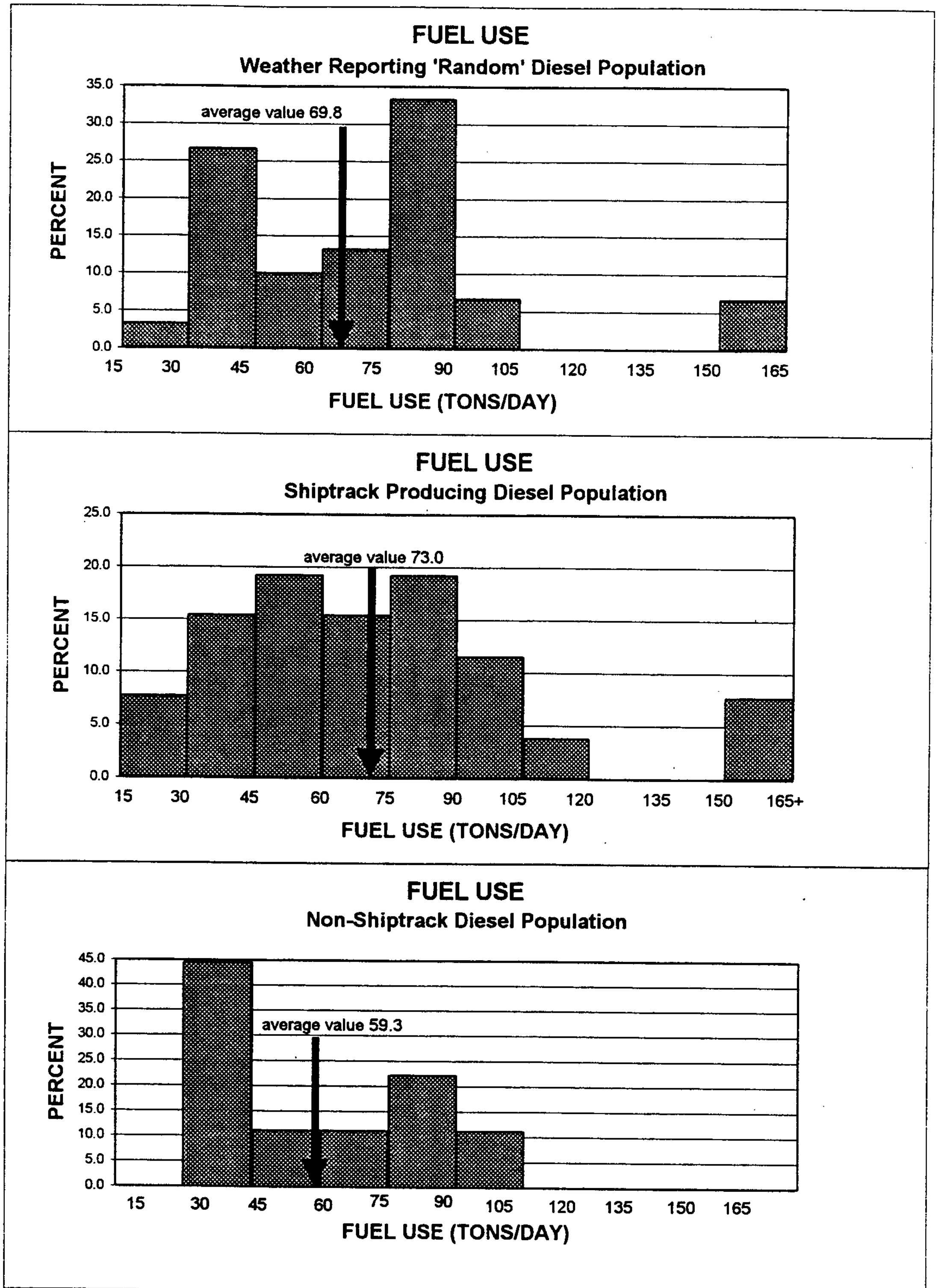

Figure 8. Fuel Use for Each Diesel Population. Data is not available for every vessel in each population.

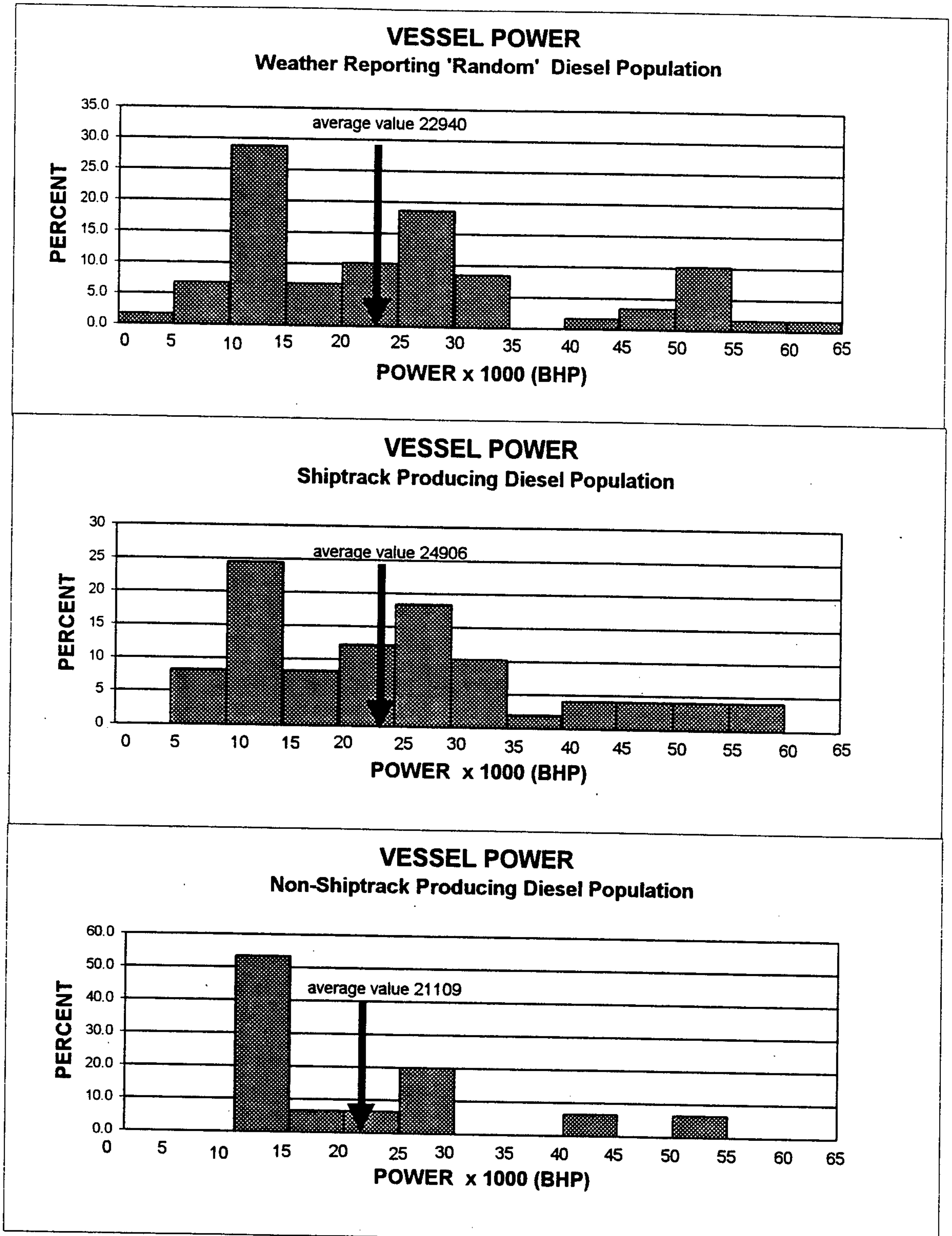

Figure 9. Vessel Power for Each Diesel Population.

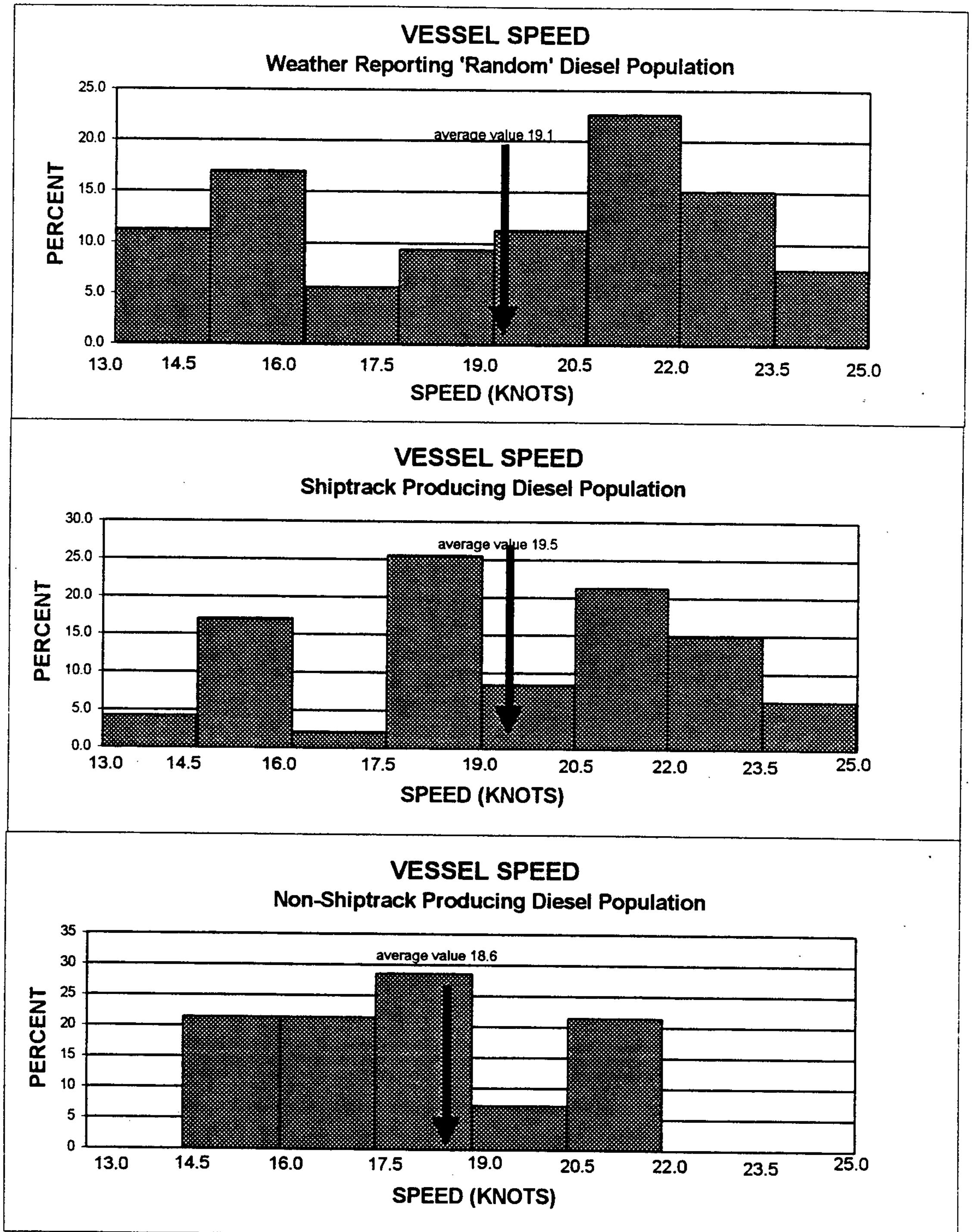

Figure 10. Vessel Transit Speed for Each Diesel Population. Data is not available for every vessel in each population.

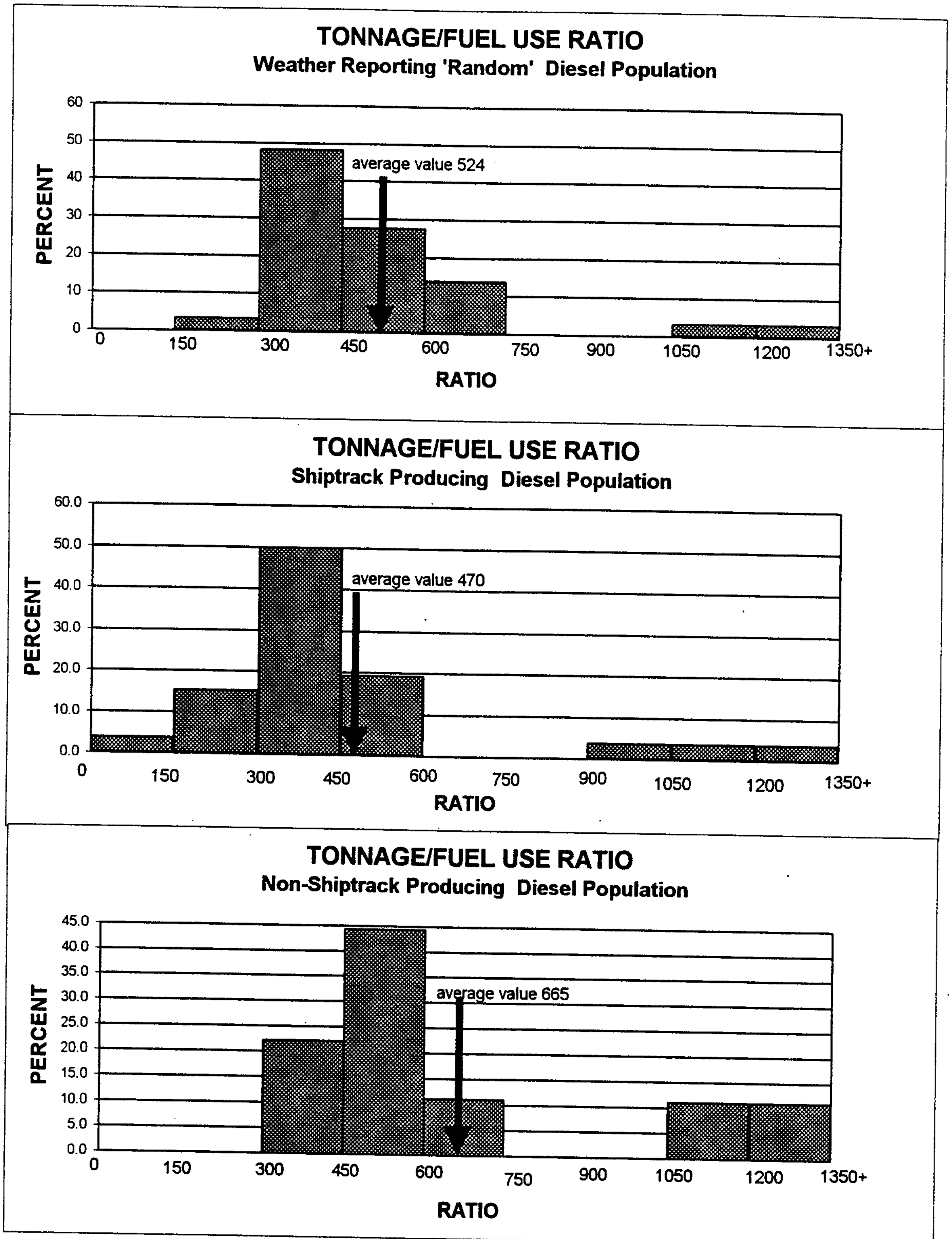

Figure 11. Ratio of Vessel Tonnage to Fuel Use for Each diesel population. Data is not available for all vessels.

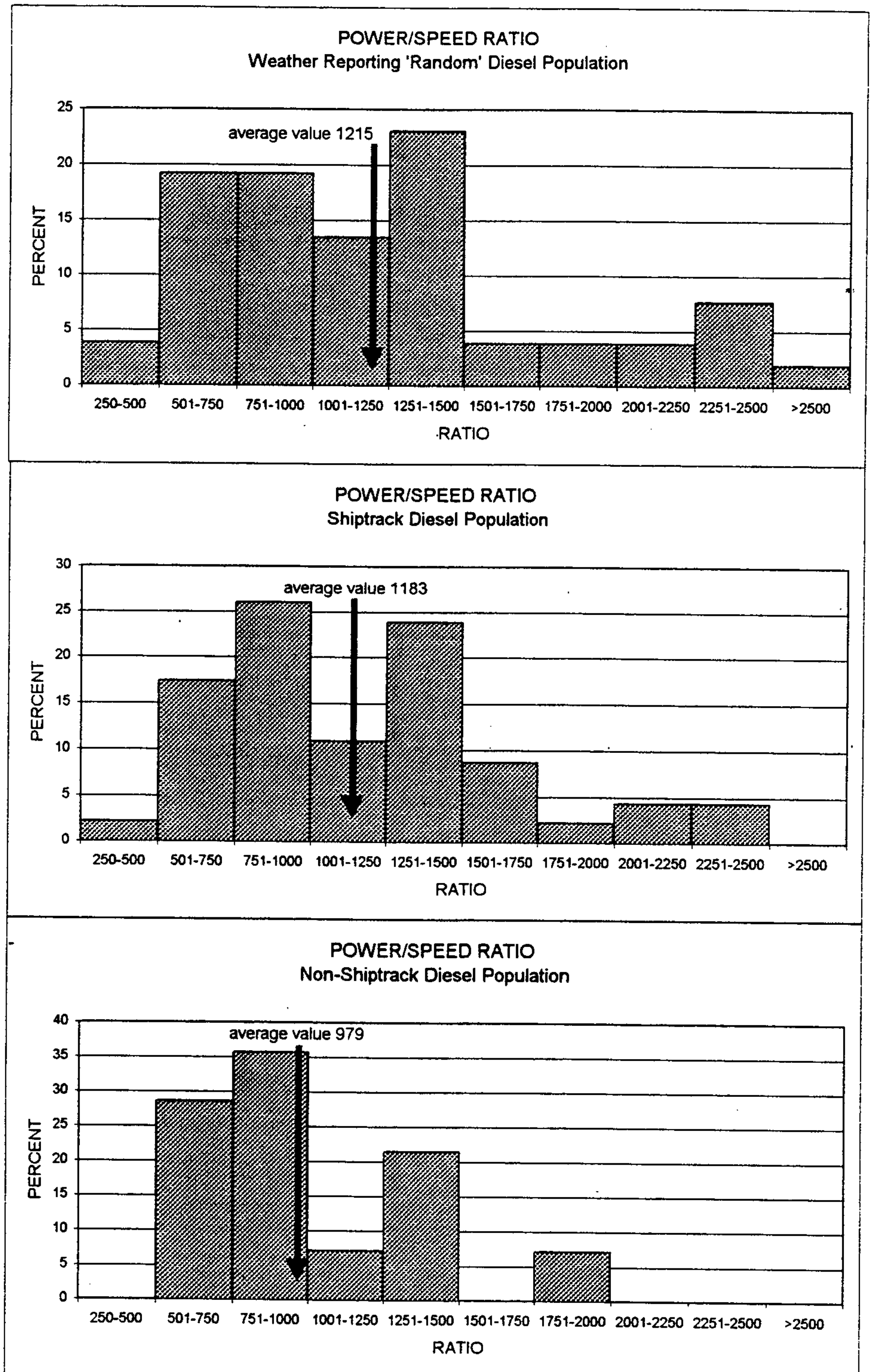

Figure 12. Ratio of Power to Vessel Speed for each diesel population. Data is not available for all vessels.

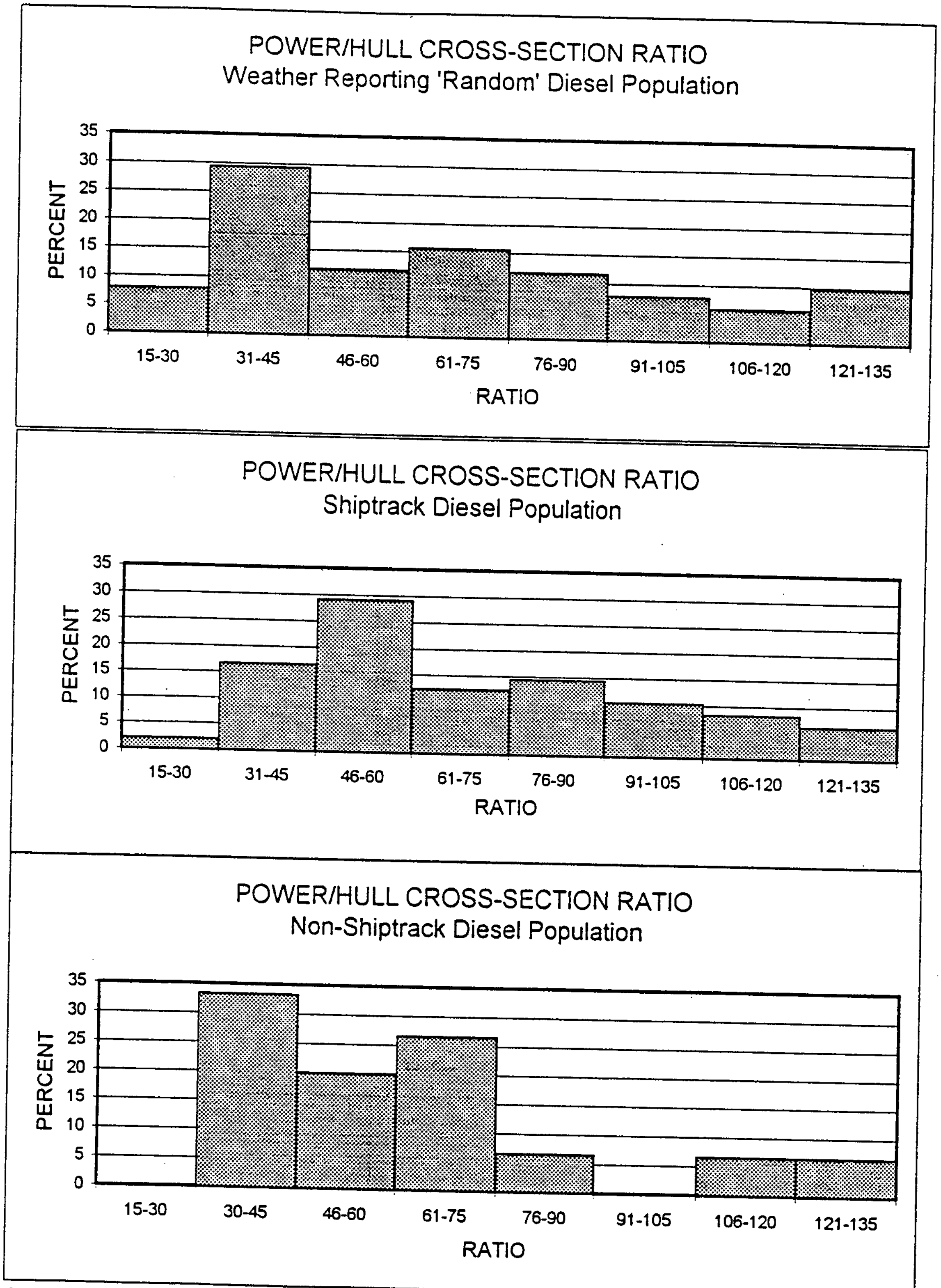

Figure 13. Ratio of Power to Hull Cross-Section for Each diesel population. Data is not available for all vessels.

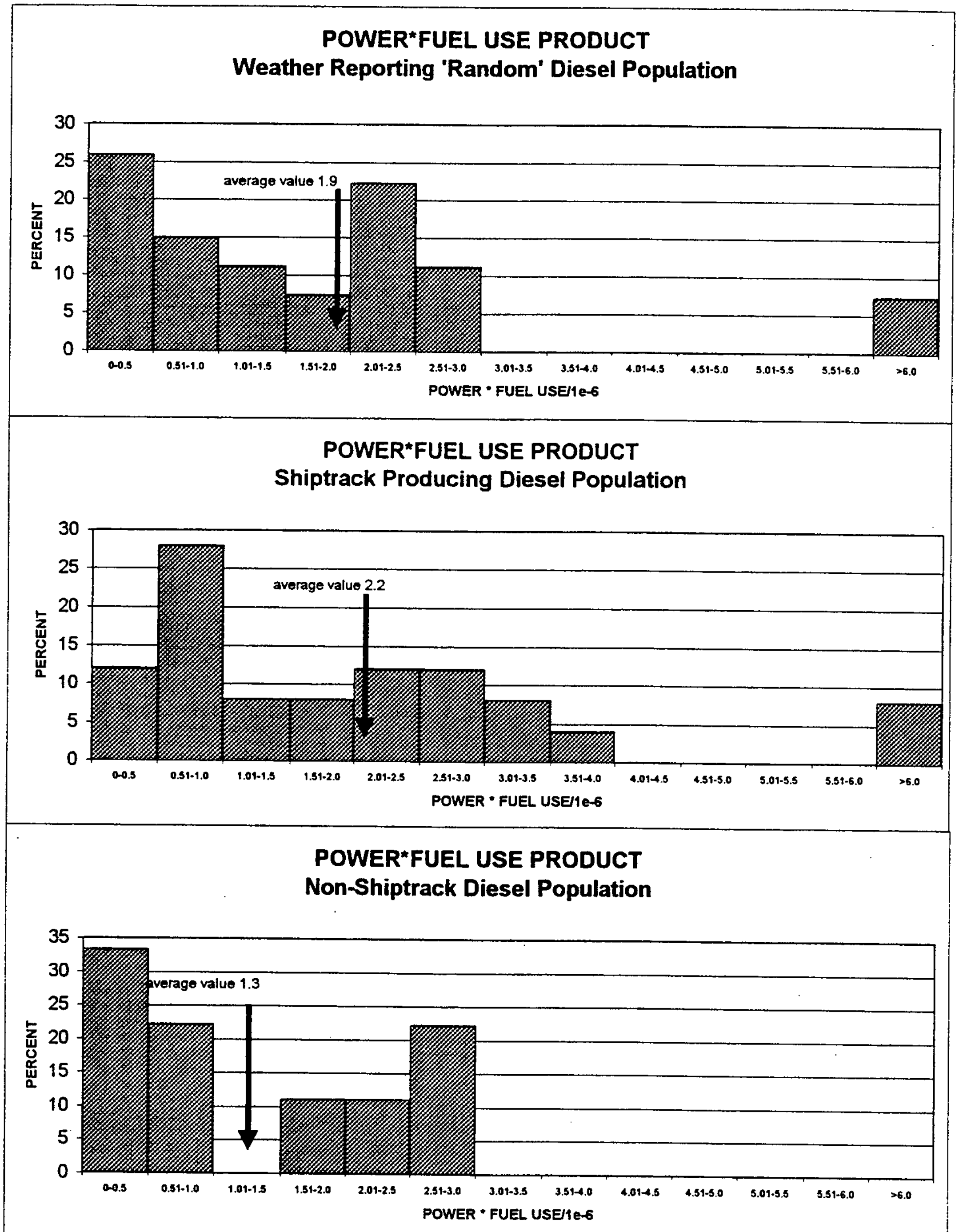

Figure 14. Product of Power and Fuel Use for Each Diesel population. Data is not available for all vessels.

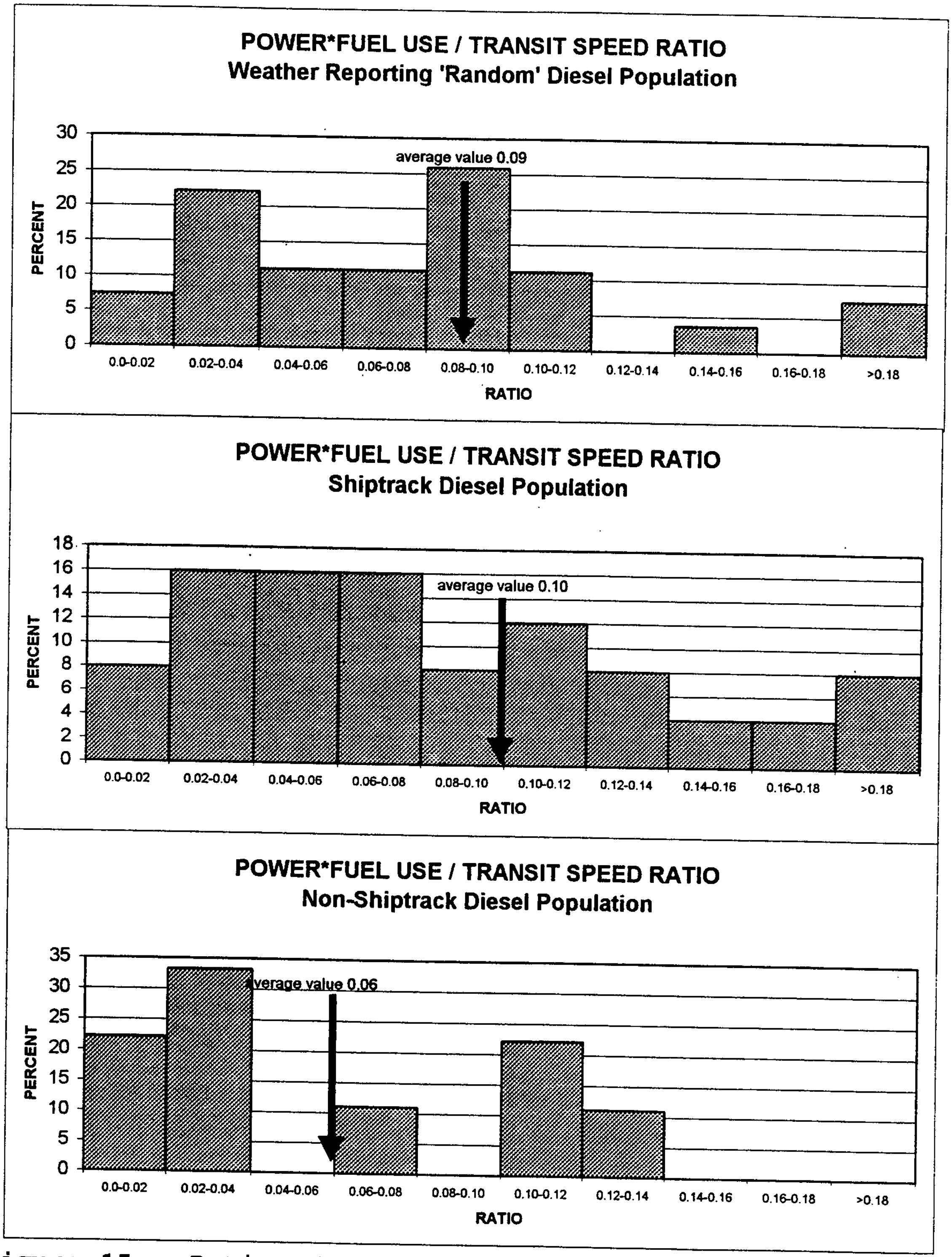

Figure 15. Ratio of Power and Fuel Use to Speed for Each diesel population. Data is not available for all vessels.

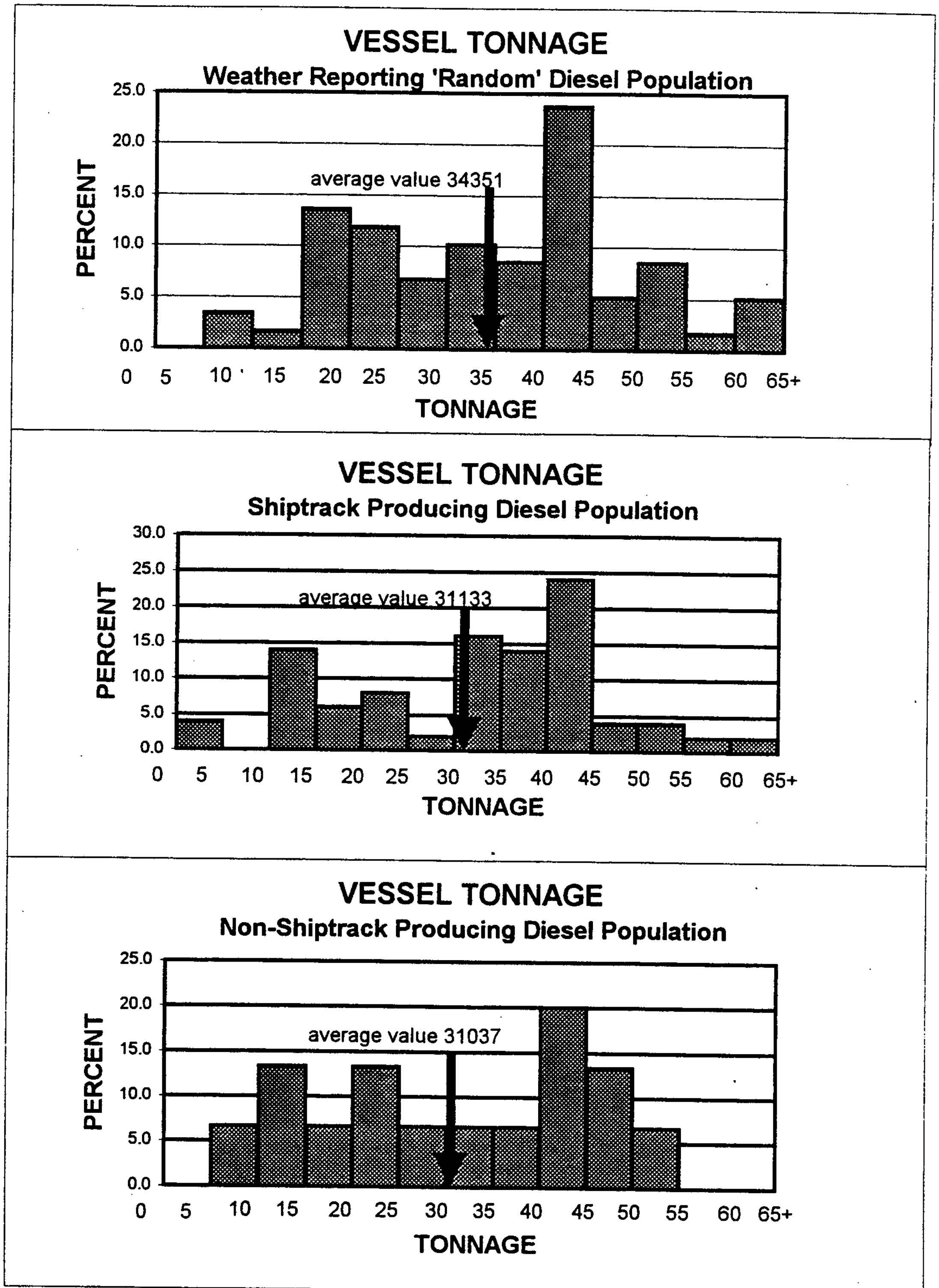

Figure 16. Vessel Tonnage for Each Diesel Population.

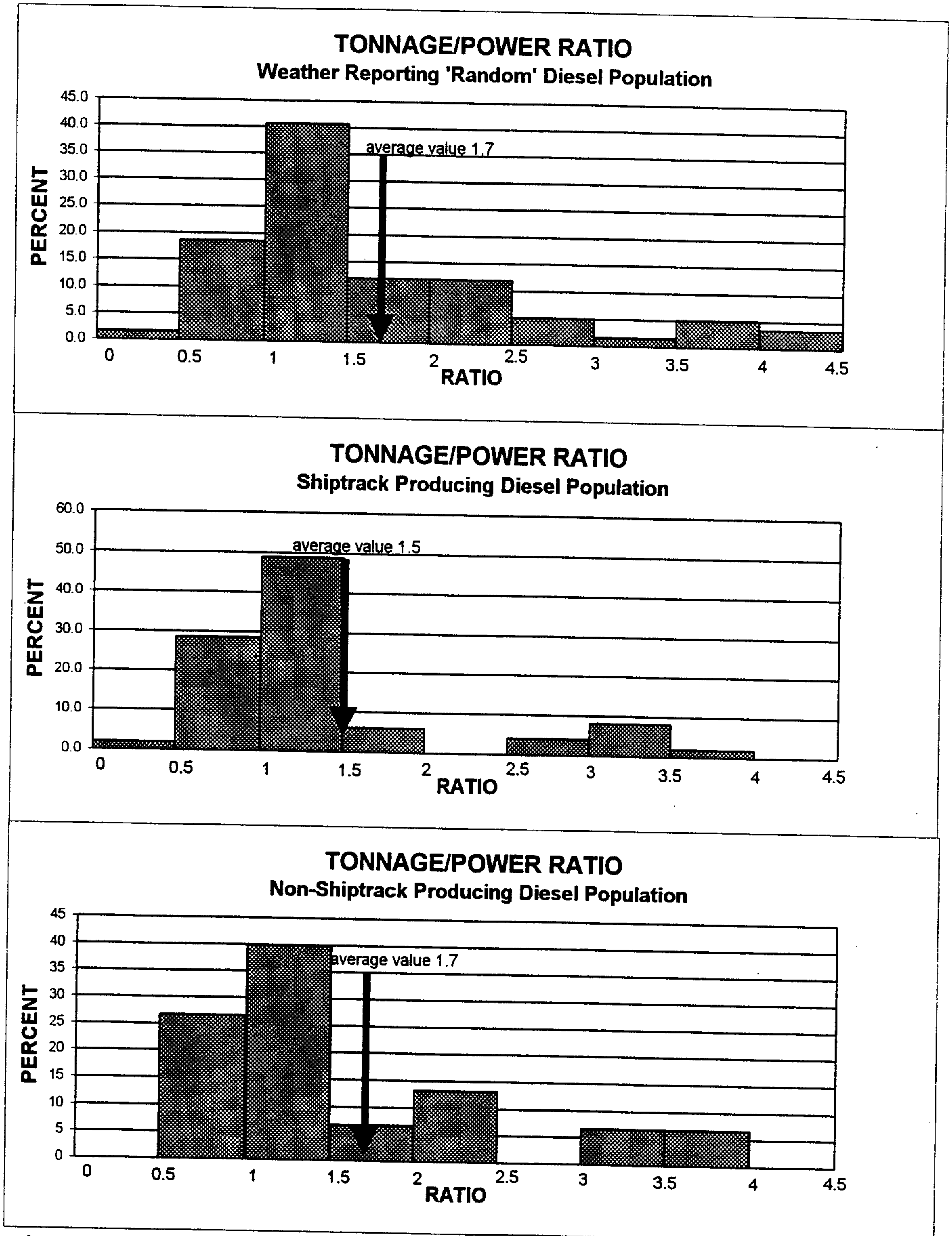

Figure 17. Ratio of Tonnage to Power for Each Diesel population. Data is not available for all vessels.

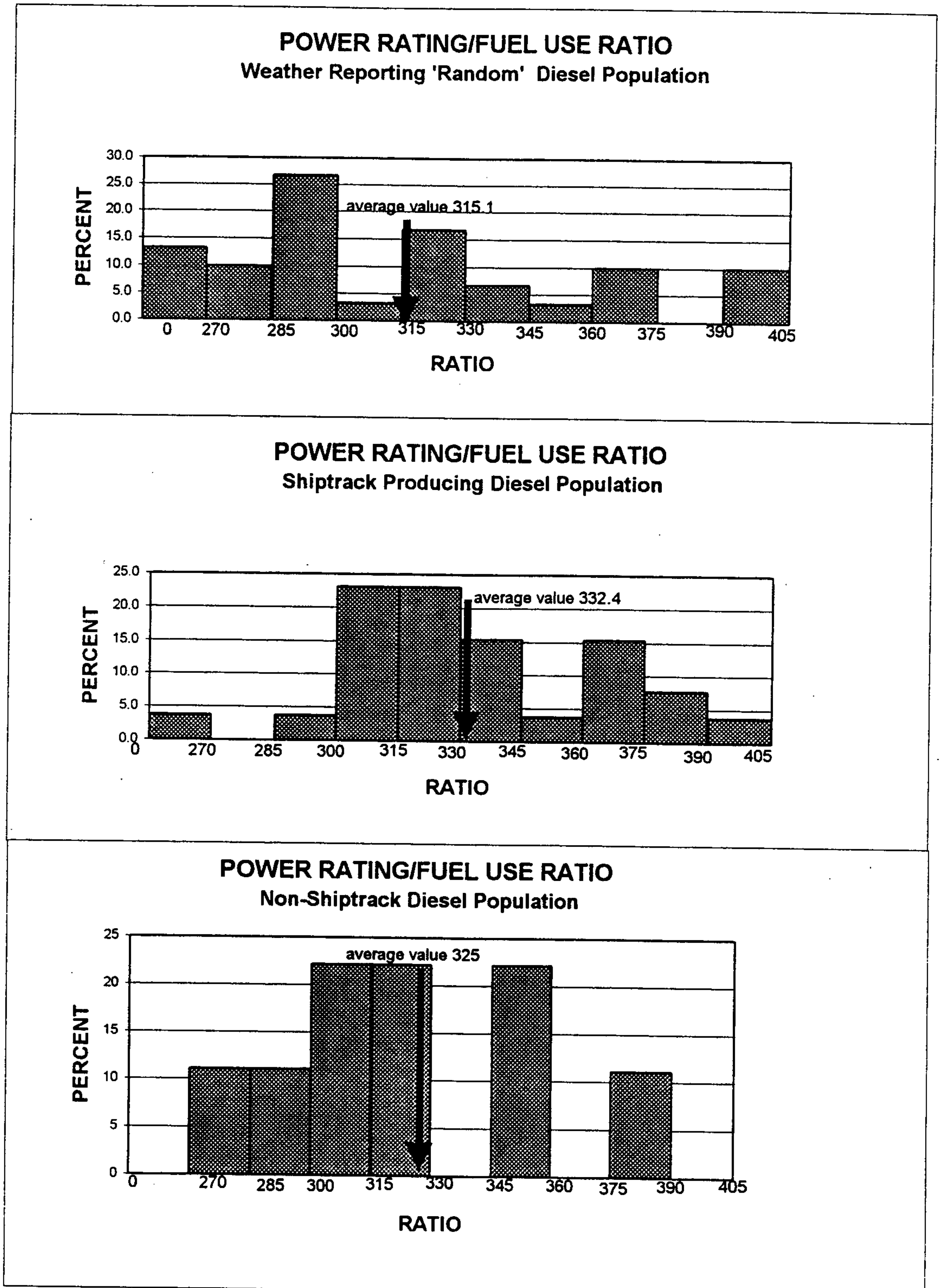

Figure 18. Ratio of Power to Fuel Use for Each Diesel population. Data is not available for all vessels.

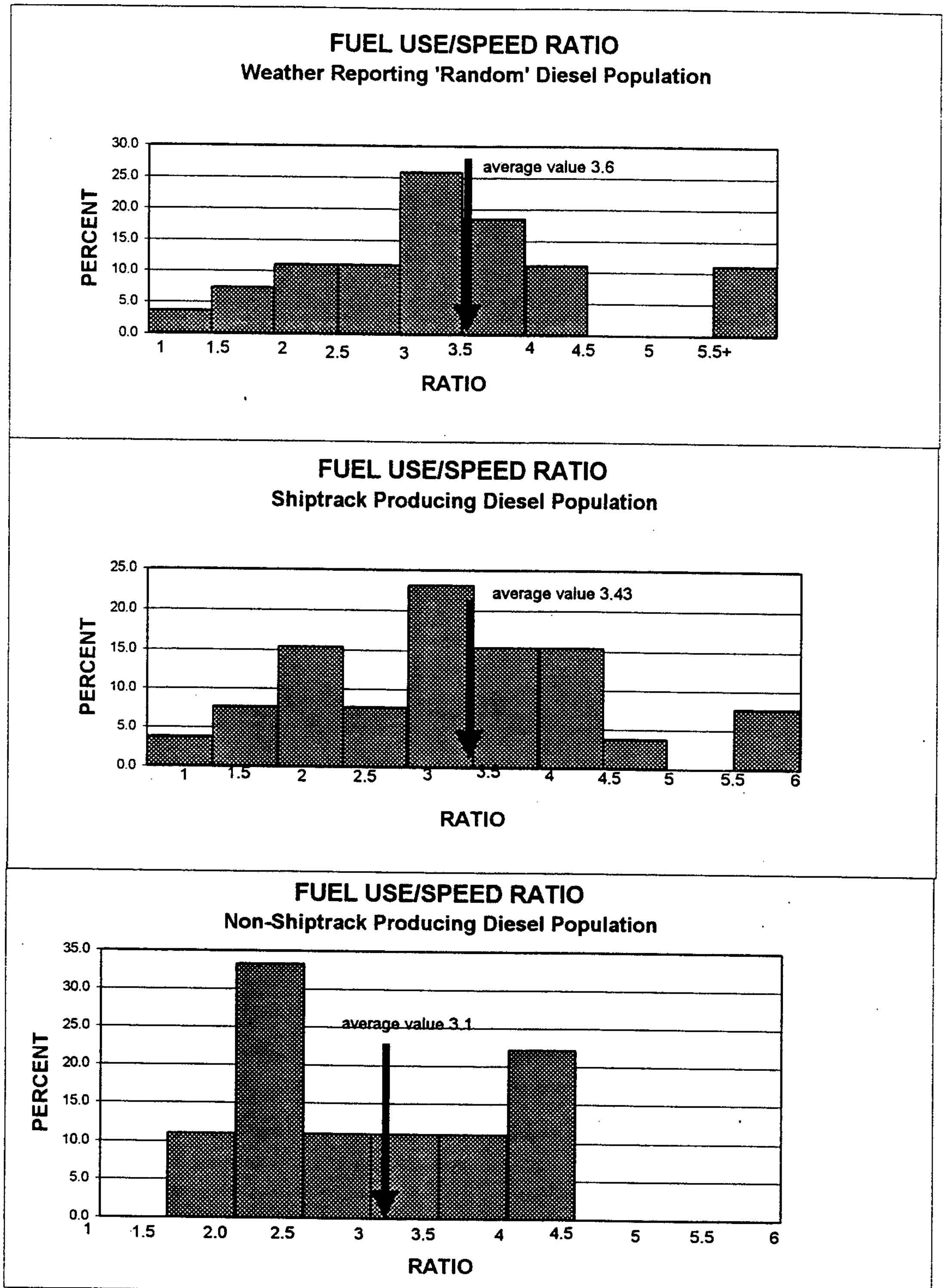

Figure 19. Ratio of Fuel Use to Speed for Each Diesel population. Data is not available for all vessels.

LEVEL OF SIGNIFICANCE IN DESCENDING ORDER					
T/NT		T/P		NT/P	
0.1	POWER/SPEED	0.14	POWER/FUEL	0.08	POWER/SPEED
0.11	POW*FUEL/SPD	0.14	POWER/TONNAGE	0.2	POW*FUEL/SPD
0.12	POWER * FUEL	0.31	TONNAGE	0.25	POWER * FUEL
0.2	TONNAGE/FUEL	0.45	TONNNAGE/FUEL	0.32	TONNAGE
0.25	POWER/X-SEC	0.63	SPEED/FUEL	0.36	POWER
0.27	SPEED	0.65	POWER * FUEL	0.38	POWER/X-SEC
0.29	POWER	0.7	POW*FUEL/SPD	0.38	SPEED/FUEL
0.3	FUEL USE	0.7	SPEED	0.38	FUEL USE
0.47	POWER/TONNAGE	0.77	POWER/SPEED	0.39	TONNAGE/FUEL
0.54	POWER/FUEL	0.84	FUEL USE	0.42	SPEED
0.6	SPEED/FUEL	0.86	POWER	0.54	POWER/FUEL
0.73	TONNAGE	0.9	POWER/X-SEC	0.56	POWER/TONNAGE

T=SHIPTRACK NT=NO SHIPTRACK P=RANDOM DIESEL POPULATION

Table 2. Diesel Vessel T-Test Level of significance for each category examined.

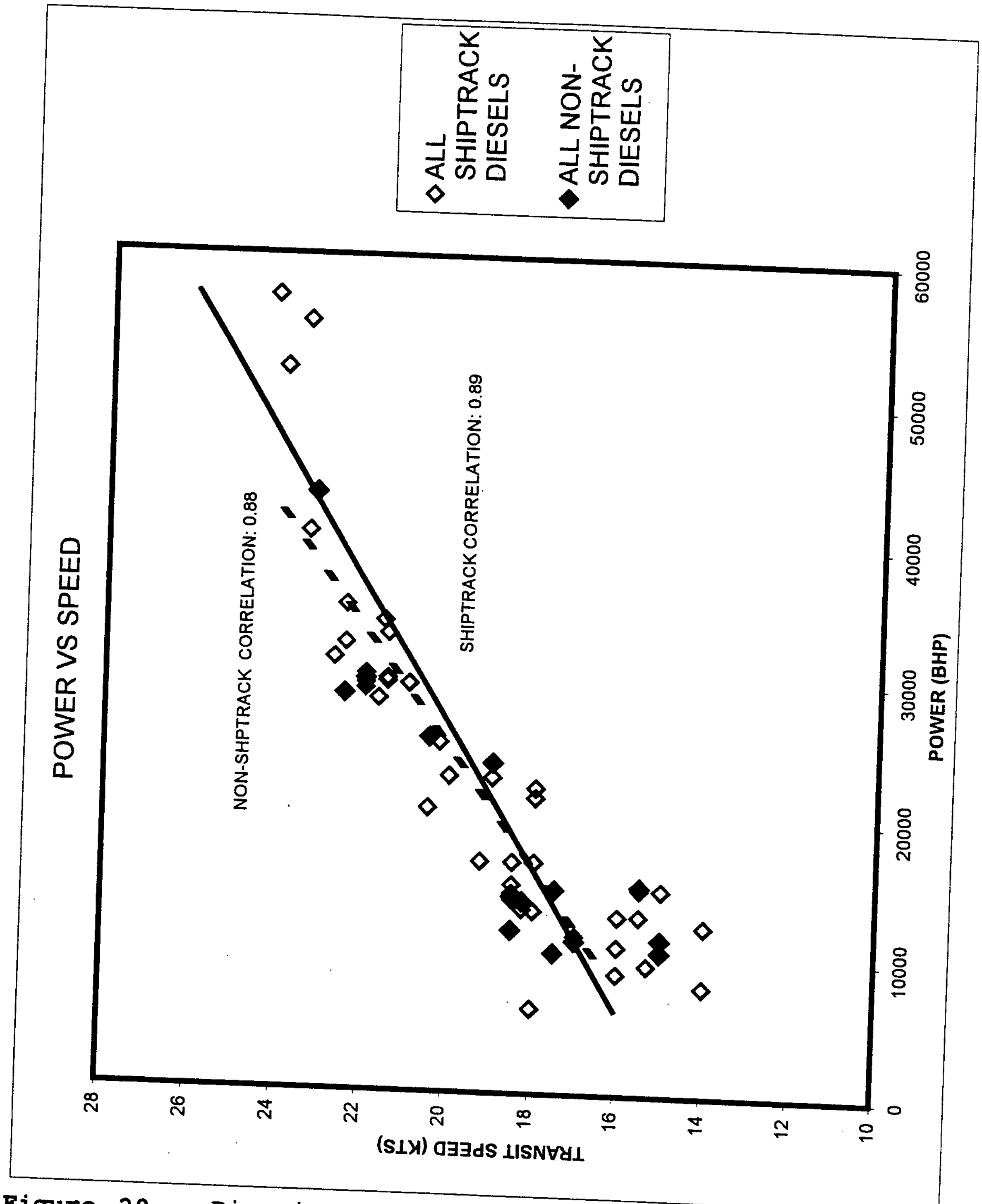

Figure 20. Bivariate Plot of Power vs. Speed for Diesel vessels. Shiptrack and non-shiptrack best fit linear regressions using least squares and associated correlation coefficients are included.

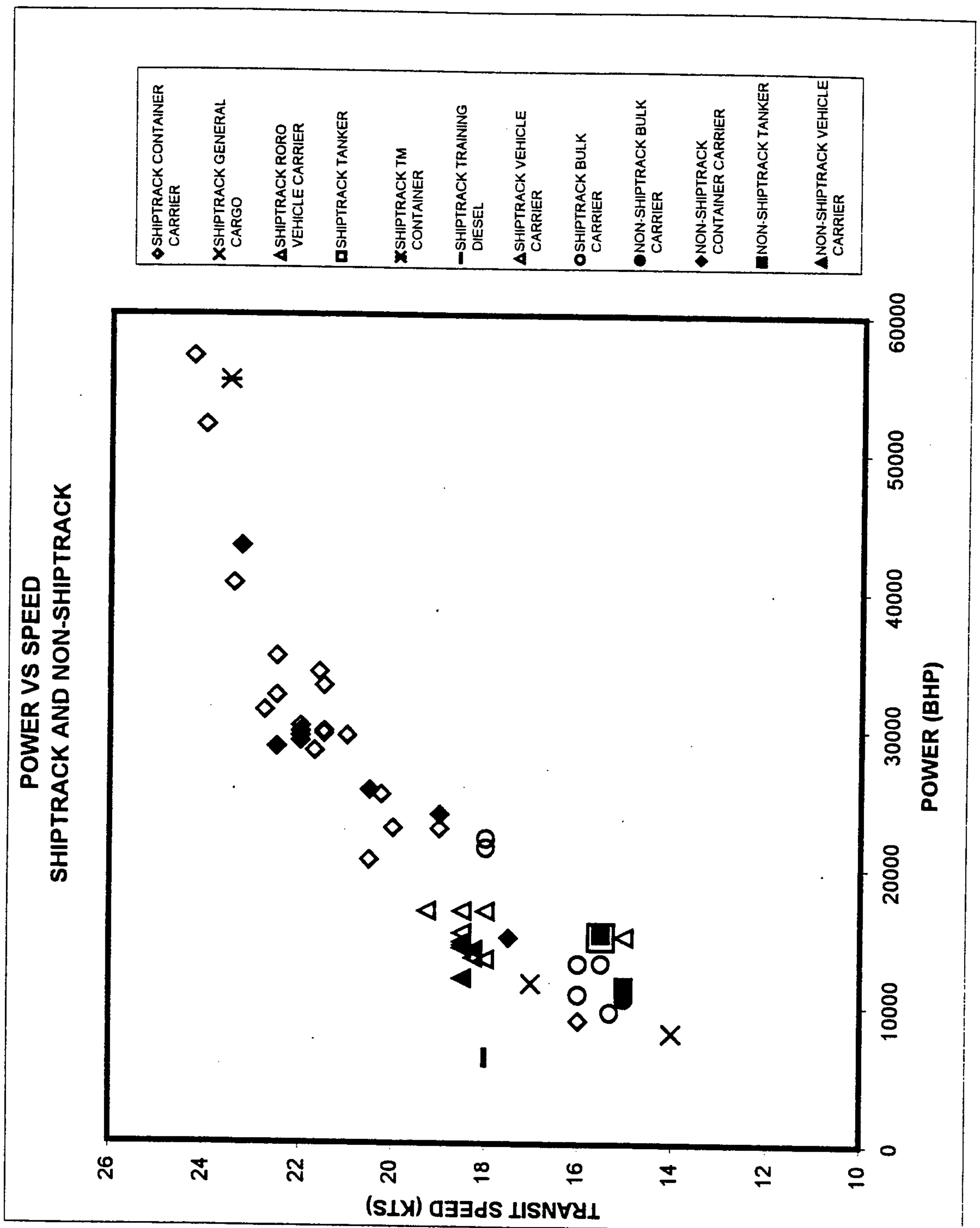

Figure 21. Bivariate Plot of Power vs. Speed for Each Type of diesel vessel in the shiptrack and non-shiptrack populations.

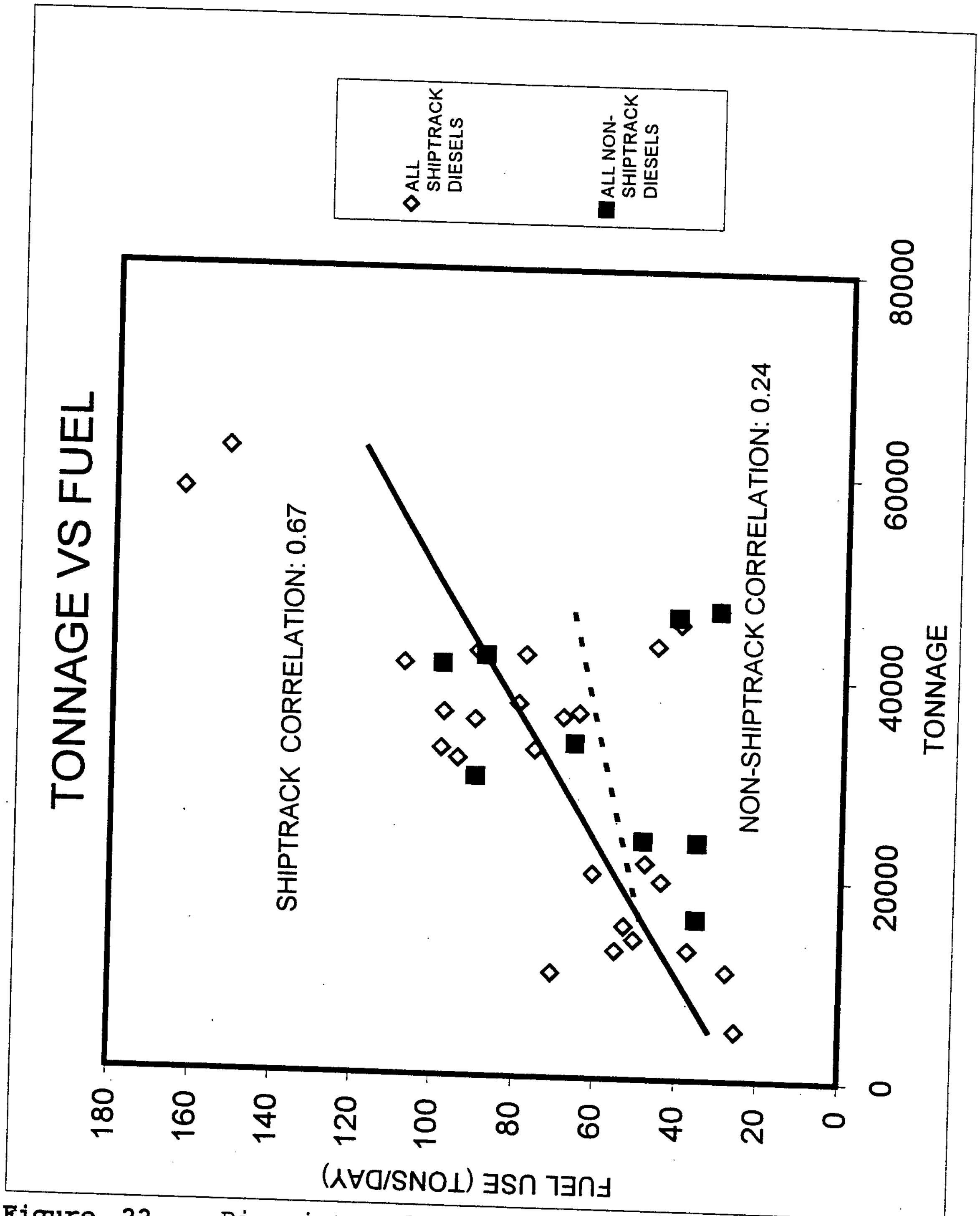

Figure 22. Bivariate Plot of Tonnage vs. Fuel Use for diesel vessels. Shiptrack and non-shiptrack best fit linear regressions using least squares and associated correlation coefficients are included.

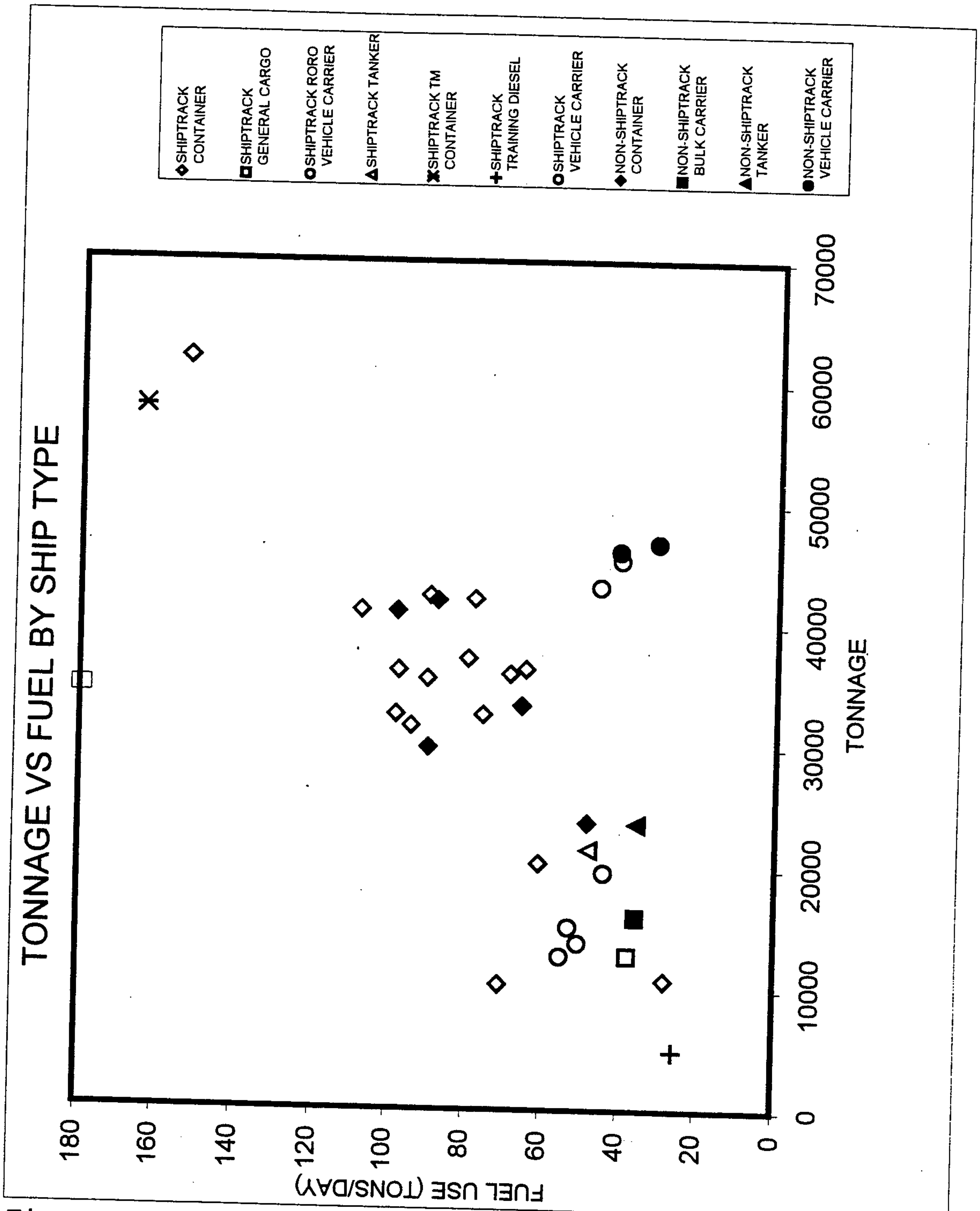

Figure 23. Bivariate Plot of Tonnage vs. Fuel Use for Each type of diesel vessel in the shiptrack and non-shiptrack populations.

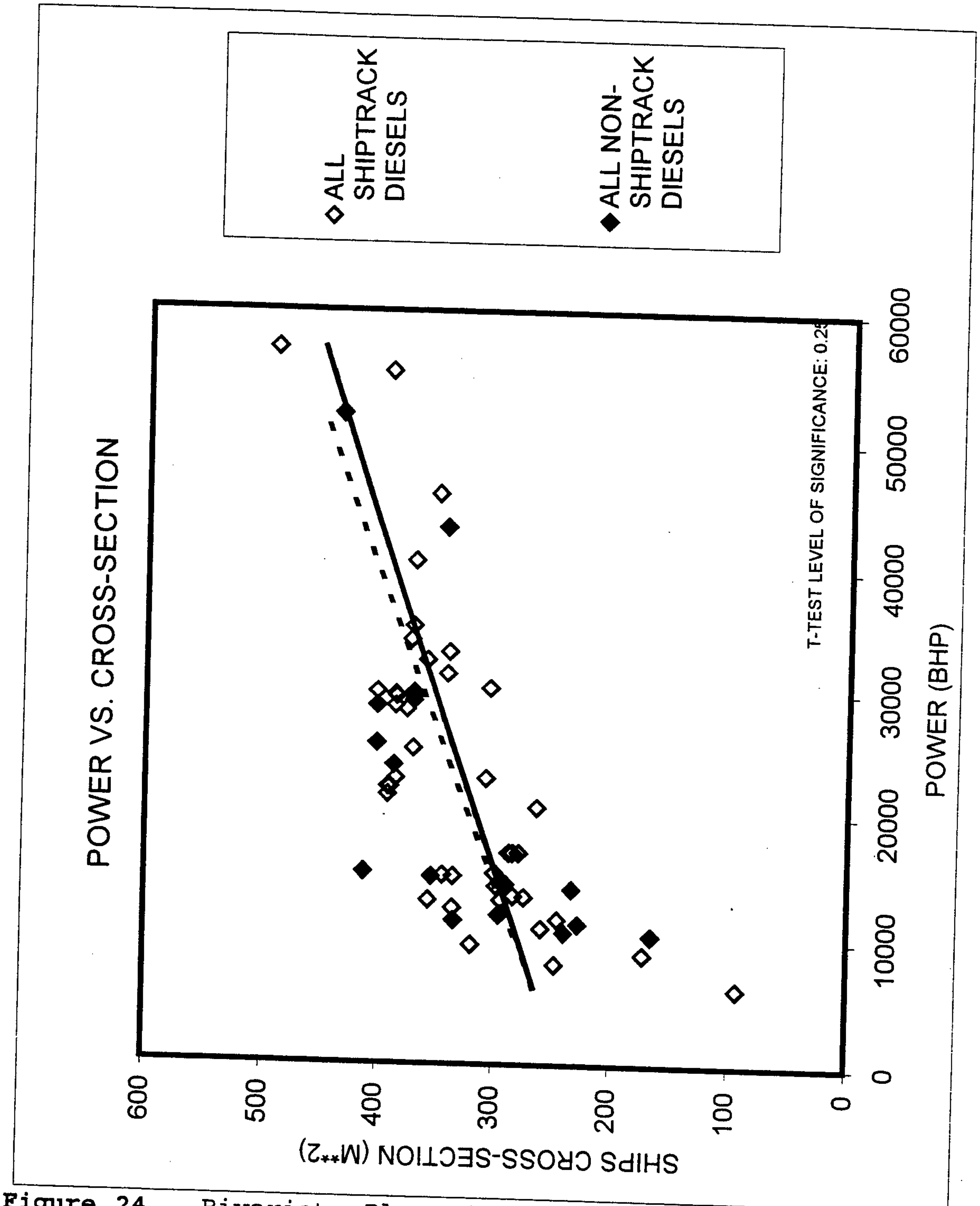

Figure 24. Bivariate Plot of Power vs. Hull Cross-Section for diesel vessels. Shiptrack and non-shiptrack best fit linear regressions using least squares and associated correlation coefficients are included.

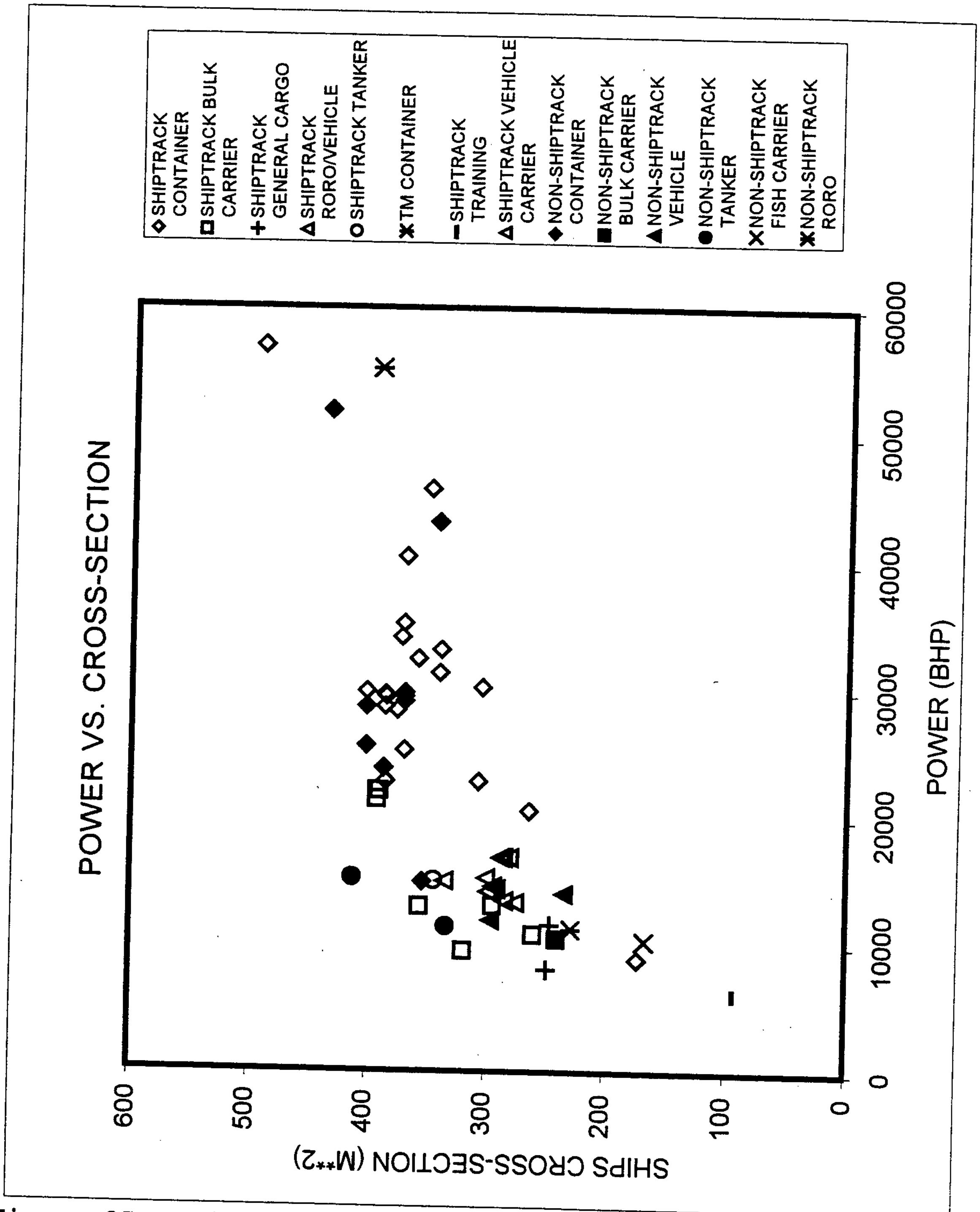

Figure 25. Bivariate Plot of Power vs. Hull Cross-Section for each type of diesel vessel in the shiptrack and non-shiptrack populations.

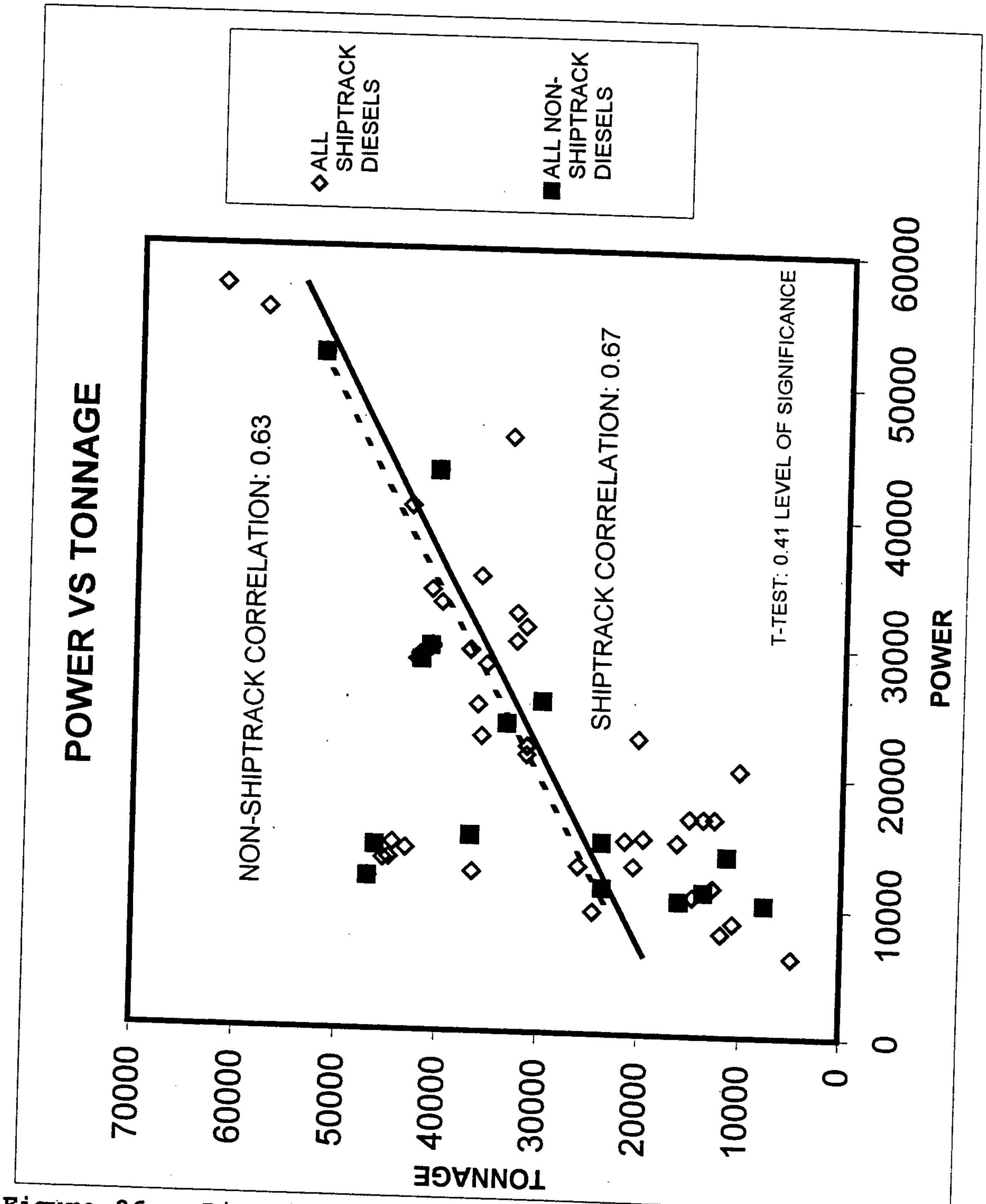

Figure 26. Bivariate Plot of Power vs. Tonnage for Diesel vessels. Shiptrack and non-shiptrack best fit linear regressions using least squares and associated correlation coefficients are included.

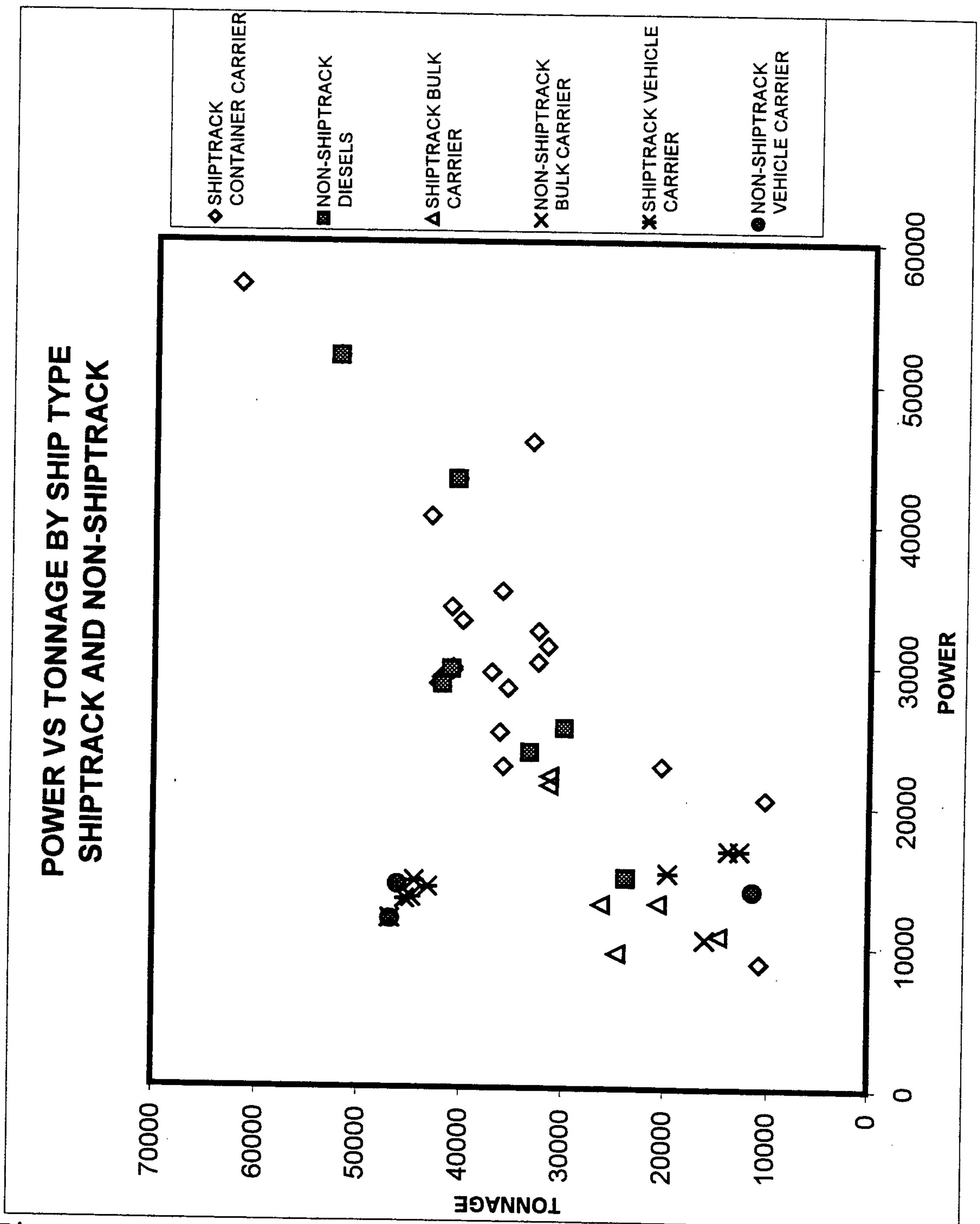

Figure 27. Bivariate Plot of Power vs. Tonnage for Each type of diesel vessel in the shiptrack and non-shiptrack populations.

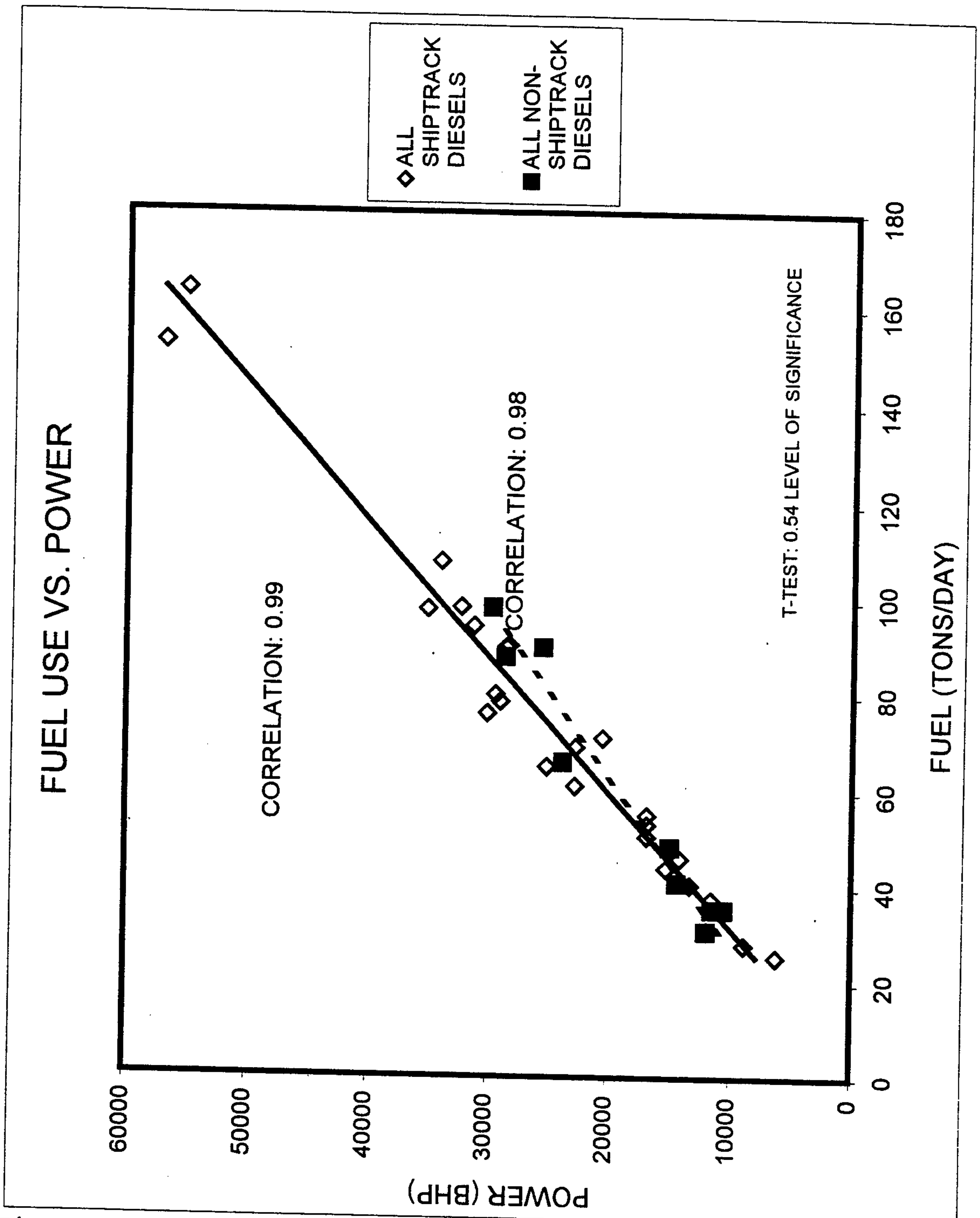

Figure 28. Bivariate Plot of Fuel Use vs. Power for Diesel vessels. Shiptrack and non-shiptrack best fit linear regressions using least squares and associated correlation coefficients are included.

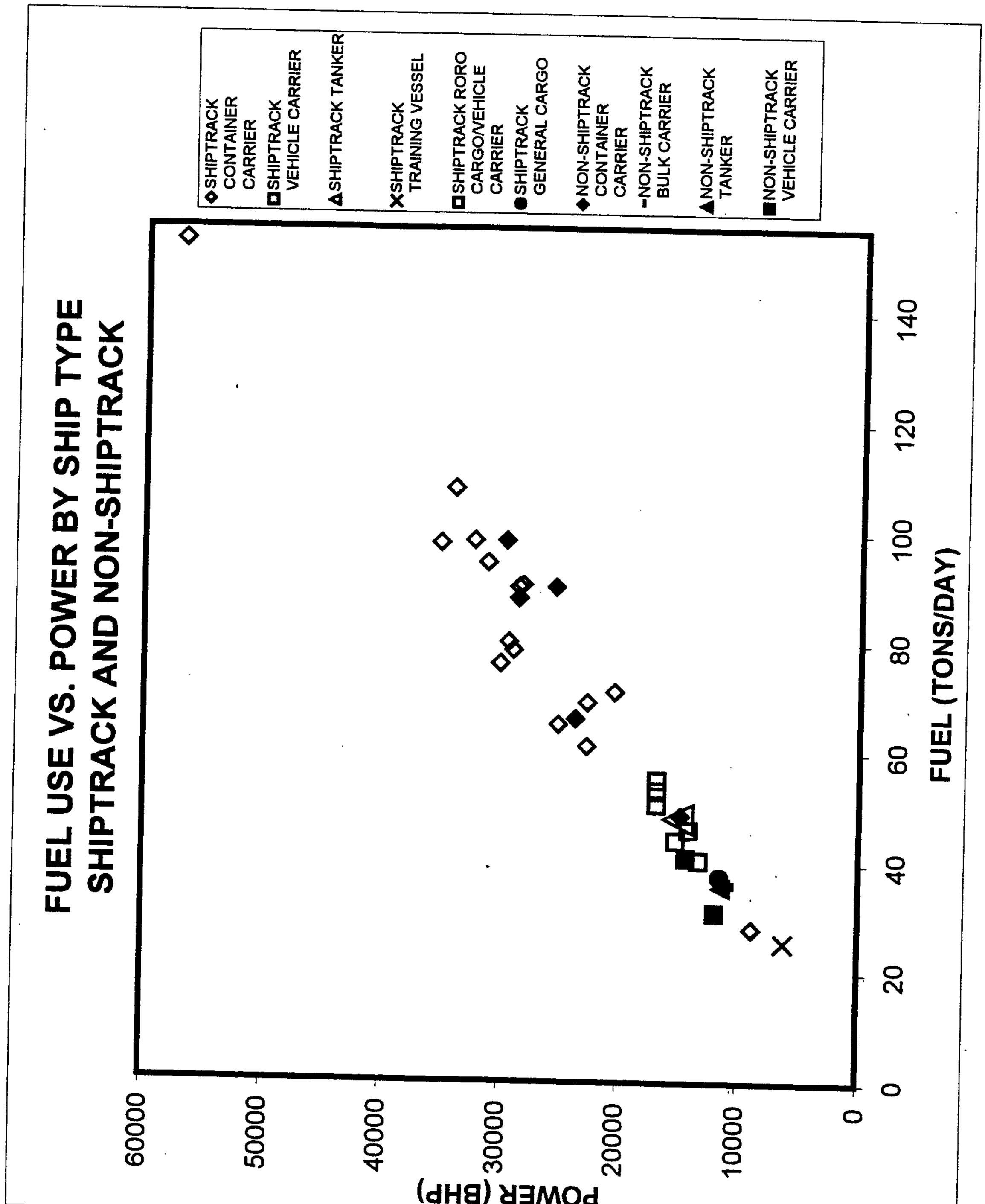

Figure 29. Bivariate Plot of Fuel Use vs. Power for Each type of diesel vessel in the shiptrack and non-shiptrack populations.

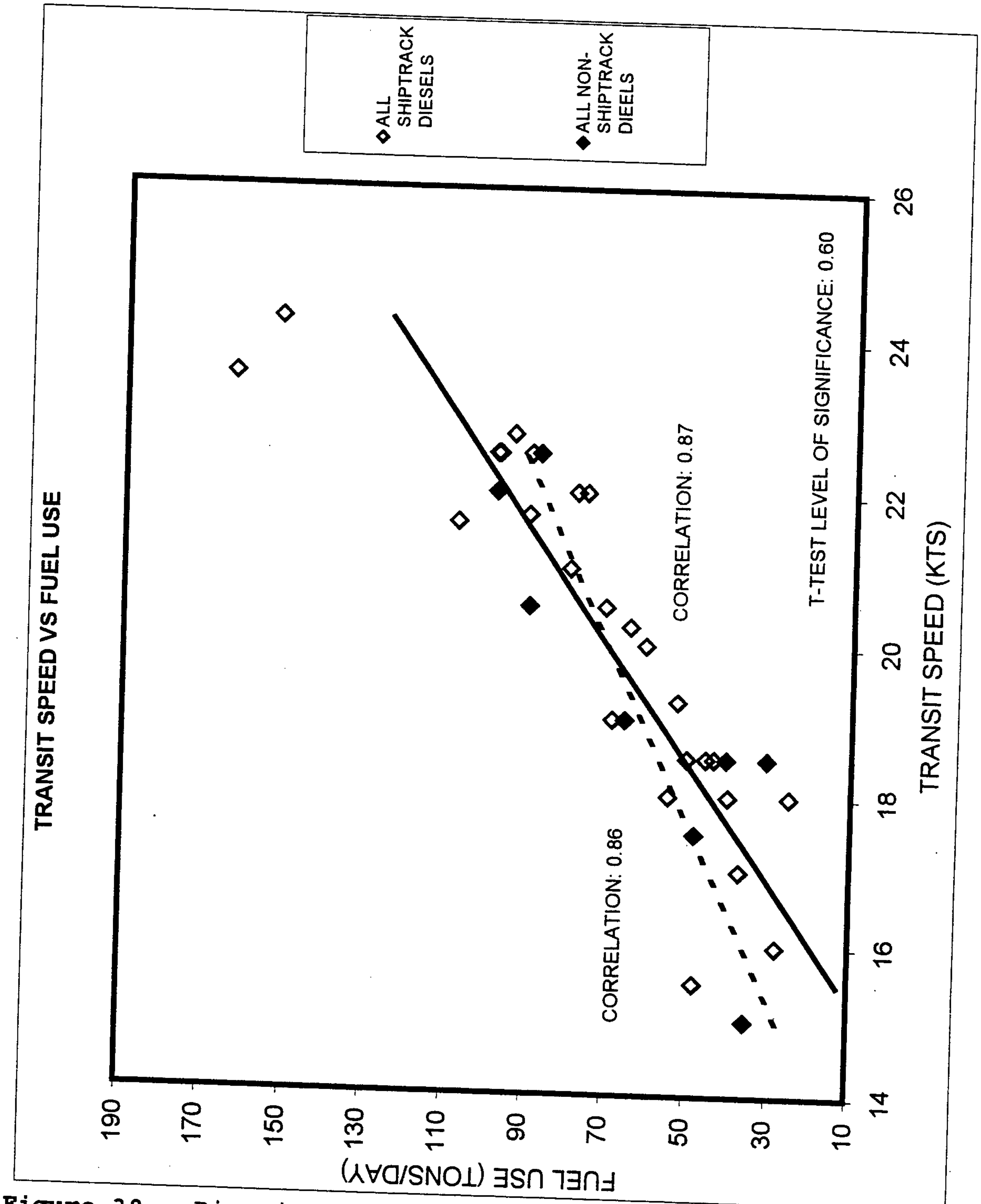

Figure 30. Bivariate Plot of Speed vs. Fuel Use for Diesel vessels. Shiptrack and non-shiptrack best fit linear regressions using least squares and associated correlation coefficients are included.

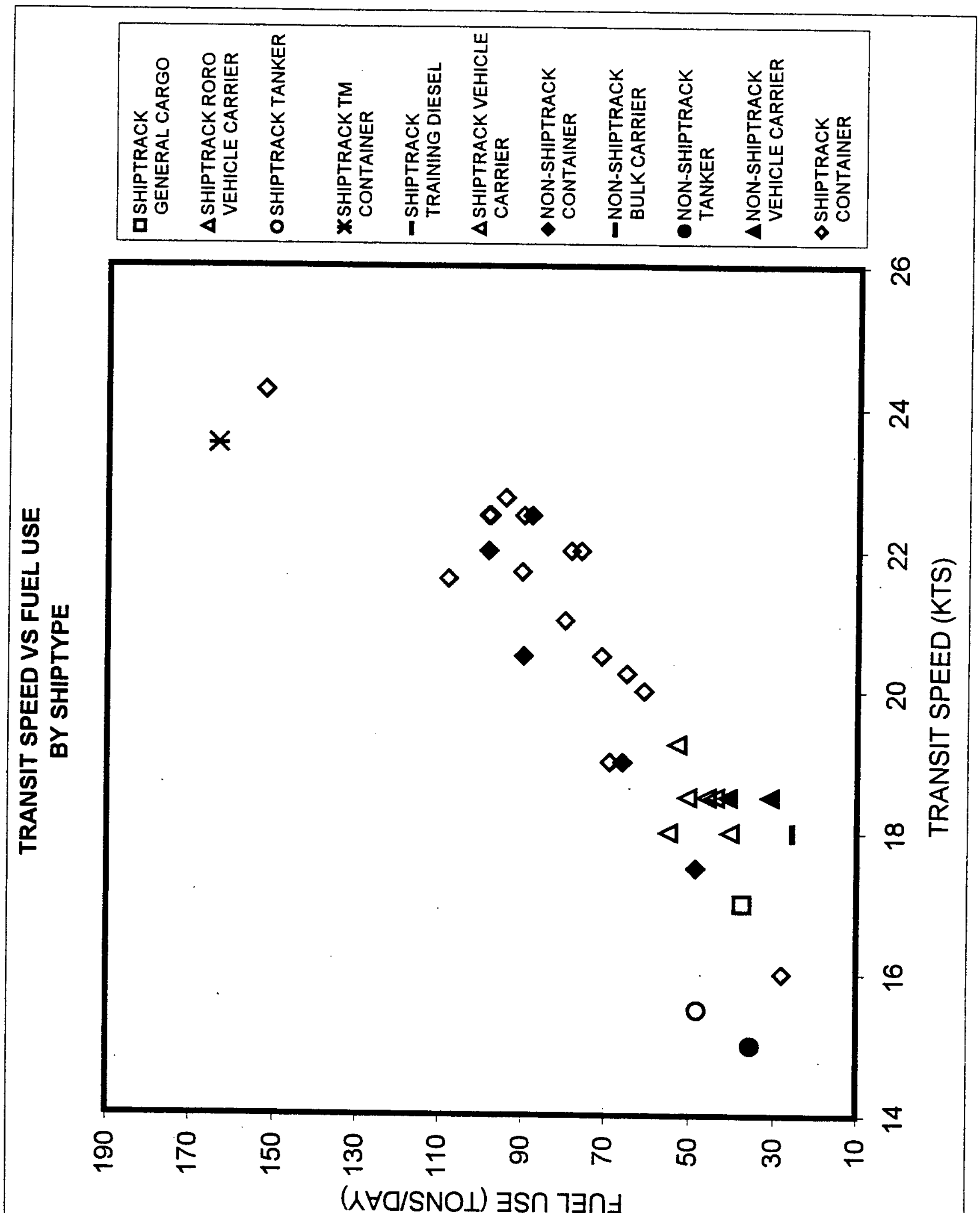

Figure 31. Bivariate Plot of Speed vs. Fuel Use for Each type of diesel vessel in the shiptrack and non-shiptrack populations.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

The objective of this thesis is to determine if a vessel's operating characteristics can be used to forecast the occurrence/non-occurrence of shiptracks under conducive environmental conditions. Using AVHRR (channel 3) imagery, ship's weather reports and Lloyd's Register of Ships (1992), three ship populations were examined to meet this objective. Shiptrack producing diesel vessels, non-shiptrack producing diesel vessels, and a random diesel vessel population were compared to determine differences and similarities in operating parameters.

Based on population averages, diesel shiptrack producers are one knot faster, nine percent more powerful and use 18 percent more fuel per day than the non-shiptrack producers. Compared to the random diesel population, shiptrack producers are nine percent more powerful, ten percent smaller, and use five percent more fuel. Finally, the non-shiptrack population compared to the random population is 0.5 kts slower, eight percent less powerful, uses 15 percent less fuel and is ten percent smaller.

These data are consistent with the shiptrack formation mechanism discussed in section 2.b., i.e. introduction of effluent by a ship's propulsion plant into the MABL provides additional CCN within a cloud layer, locally decreasing the water droplet size and increasing its reflectance.

Analyses of imagery also suggest that the number of shiptrack producing vessels is significantly higher than the number of non-shiptrack producers. A critical controlling factor in the formation of shiptracks is the state of the MABL; however, optimal shiptrack formation MABL conditions have not been quantified. Under conditions where shiptracks are observed, the following T-test comparisons identify parameters and ratios of parameters that may be tactically useful in estimating the occurrence/non-occurrence of shiptracks:

1. A comparison of vessel power and transit speed is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at a 0.10 level of significance. The non-shiptrack population has a lower power/speed ratio, which is obtained by increasing speed, decreasing power, or some combination of the two. As a ship's power plant size is reduced or its speed increased, the amount of effluent introduced into a volume of MABL is reduced and thus decreases the likelihood of shiptrack formation.

2. A comparison of power*fuel/speed is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at 0.11 level of significance. The non-shiptrack population has a lower power*fuel/speed ratio, which is obtained by decreasing power*fuel, increasing speed, or some combination of the two. Non-shiptrack vessels have smaller power plants and use less fuel than the shiptrack population, which yields a smaller value in the numerator of the ratio. Non-shiptrack vessels are also slightly slower than the shiptrack population, which yields a slightly smaller value in the denominator of the ratio. Because the power*fuel/speed ratio for the non-shiptrack population is lower than the shiptrack population, it can be inferred that the product of power and fuel use dominates the ratio. Because a smaller power plant requires less fuel, the amount of effluent

introduced into the MABL decreases diminishing the likelihood of shiptrack cloud formation.

3. A comparison of power*fuel is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at 0.12 level of significance. The non-shiptrack population has a lower power*fuel product, which is obtained by decreasing either power plant size, fuel use or some combination of the two. Non-shiptrack vessels have smaller power plants and use less fuel than the shiptrack population, which yields a smaller product. Because a smaller power plant requires less fuel, the amount of effluent introduced into the MABL decreases diminishing the likelihood of shiptrack cloud formation.

4. A comparison of vessel tonnage and rate of fuel use is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at 0.20 level of significance. The non-shiptrack population has a higher tonnage/fuel use ratio, which is obtained by increasing tonnage, decreasing fuel use, or some combination of the two. As the fuel required per vessel ton decreases so does the amount of effluent introduced to the MABL - resulting in no shiptrack cloud signature.

5. A comparison of vessel power and hull cross-sectional area is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at 0.25 level of significance. The non-shiptrack population has a lower ratio, which is obtained by increasing cross-section, decreasing power, or some combination of the two.

6. A comparison of vessel power rating is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at 0.29 level of significance. The non-shiptrack population has a lower power rating. A smaller power plant produces less effluent into the MABL and reduces the likelihood of shiptrack formation.

7. A comparison of fuel use rate is tactically useful for distinguishing shiptrack and non-shiptrack diesel vessels. T-test results show that the non-shiptrack/shiptrack populations are distinct at 0.30 level of significance. The non-shiptrack population has a lower fuel use rate. As the fuel use rate decreases, there is a corresponding decrease in the amount of effluent introduced into the MABL, decreasing the likelihood of shiptrack formation.

B. RECOMMENDATIONS

This study is the first dedicated examination of ship operating parameters and their affect on shiptrack formation. Data from this study suggest there are distinguishable operating parameters associated with shiptrack producers and non-shiptrack producers. Future studies will benefit from a larger database - more ships for each category and the co-location of shiptrack producers and non-producers.

APPENDIX A. OPERATING PARAMETERS FOR SHIPTRACK PRODUCING DIESEL VESSELS.

SHIPTRACK PRODUCING DIESELS VESSELS	LLYODS PAGE #	ENGINE DESIGN	NUBMER OF CYLINDERS	POWER RATING (BHP)	RATIO OF POWER/ FUEL USE	FUEL USE (TONS/DAY)	FUEL TYPE
ALLIGATOR PRIDE	158	OIL 2 SA	9	34101	315.8	108	DO/HVF
ANDERS MAERSK	226	OIL 2 SA	10	45800			DO/HVF
ANNA MAERSK	248	OIL 2 SA	10	45800			DO/HVF
CALIFORNIA CERES	678	OIL 2 SA	9	31300	331.2	94.5	DO/HVF
CALIFORNIA GALAXY	687	OIL 2 SA	7	25210	387.8	65	DO/HVF
CALIFORNIA MERCURY	679	OIL 2 SA	7	29431			DO/HVF
CALIFORNIA ORION	679	OIL 2 SA	9	32400	328.9	98.5	DO/HVF
CANADIAN HIGHWAY	693	OIL 2 SA	7	16800	305.5	55	DO/HVF
CAPE MAY	714	OIL 2 SA	9	29070	370.3	78.5	DO/HVF
CENTRUY LEADER NO 1	781	OIL 2 SA	7	13300	328.4	40.5	DO/HVF
CENTRUY LEADER NO 3	781	OIL 2 SA	8	13400			DO/HVF
CENTURY HIGHWAY NO 1	780	OIL 2 SA	8	14140	307.4	46	DO/HVF
DIRECT KIWI	1074	2VOIL4SA	10	22800	373.8	61	DO/HVF
GINGA MARU	1543	OIL 2 SA	6	6200	243.1	25.5	UNK
GLOBAL HIGHWAY	1555	OIL 2 SA	7	15200	345.5	44	DO/HVF
GLORIA PEAK	1559	OIL 2 SA	7	11550	308.0	37.5	DO/HVF
HANJIN SAVANNAH	63	OIL 2 SA	7	28350	313.6	90.4	DO/HVF
HENRY HUDSON BRIDGE	119	OIL 2 SA	9	28650	318.3	90	DO/HVF
HERCULES HIGHWAY	122	OIL 2 SA	8	11900	383.9	31	DO/HVF
HYUNDAI NO 11	231	OIL 2 SA	6	10800			DO/HVF
JO OAK	418	OIL 2 SA	7	15000	312.5	48	DO/HVF
KURAMA	756	OIL 2 SA	7X2	55199	337.6	163.5	DO/HVF
MAGLEBY MAERSK	985	OIL 2 SA	12	51920			UNK
MARIE MAERSK	1067	OIL 2 SA	12	51920			UNK
MERCURY	1177	OIL 2 SA	6	8000			UNK
MOKU PAHU	1268	2VOIL4SA	14				UNK
MONTERREY	1281	OIL 2 SA	6	21405			UNK
NED LLOYD SINGAPORE	1404	OIL 2 SA	6	20500	288.7	71	DO/HVF
NYK SUNRISE	1557	OIL 2 SA	9	40500			UNK
OAXACA	1566	OIL 2 SA	6	22080			UNK
OCCL FIDELITY	1640	OIL 2 SA	9	29610			UNK
OCEAN HIGHWAY	1578	OIL 2 SA	9	16800	332.7	50.5	DO/HVF
OOCL FAIR	1640	OIL 2 SA	9	33120			UNK
OOCL FREEDOM	1640	OIL 2SA	9	29810			UNK
ORION HIGHWAY	1658	OIL 2 SA	7	14560			UNK
PACKING	21	OIL 2 SA	6	13050			UNK
PACPRINCE	21	OIL 2 SA	5	9500			DO/HVF
POLYNESIA	190	OIL 2 SA	7	8855	316.3	28	DO/HVF
PRESIDENT ADAMS	214	V OIL 2SA	12	56956	373.5	152.5	DO/HVF
PRESIDENT MONROE	216	OIL 2 SA	12	43200			DO/HVF
PRINCE OF TOKYO	227	OIL 2 SA	8	12400			DO/HVF
SAN MARCOS	530	OIL 2 SA	7	16800	317.0	53	DO/HVF
SEA-LAND INDEPENDEN	638	OIL 2 SA	9	30150	396.7	76	DO/HVF
SKAUGRAN	851	OIL 2 SA	8	14945			UNK
STAR LIVORNO	961	OIL 2 SA	4	13000			UNK
TAI HE	1098	OIL 2 SA	6	22770	330.0	69	DO/HVF
TOLUCA	1269	OIL 2 SA	6	22080			UNK
ZIM AMERICA	1717	OIL 2 SA	8	29440			UNK
ZIM JAPAN	1718	OIL 2 SA	8	29474	368.4	80	DO/HVF
ZIM SAVANNAH	1718	OIL 2 SA	10	35200	359.2	98	DO/HVF

OIL=OIL ENGINES BHP=BREAK HORSEPOWER DO=BURNING DIESEL OIL

SA=SINGLE ACTING. THE NUMBER PREFIXED INDICATESE THE STROKE CYCLE

HVF=FITTED FOR BURNING HIGH VISCOSITY FUEL UNK=UNKNOWN

APPENDIX A. OPERATING PARAMETERS FOR SHIPTRACK PRODUCING DIESEL VESSELS.

SHIPTRACK PRODUCING DIESELS VESSELS	FUEL QUANTITY TONS	RATIO OF FUEL/ SPEED	TRANSIT SPEED KNOTS	TONNAGE TONS	RATIO OF POWER/ FUEL	YEAR BUILT	SHIP TYPE
ALLIGATOR PRIDE	150/4917	5	21.6	41126	3.682908	1988	CONTAINER
ANDERS MAERSK	924/6113			33401		1976	CONTAINER
ANNA MAERSK	924/6113			33401		1976	CONTAINER
CALIFORNIA CERES	272/3146	4.2	22.75	31694	2.95785	1981	CONTAINER
CALIFORNIA GALAXY	360/2485	3.2	20.25	36375	1.63865	1983	CONTAINER
CALIFORNIA MERCURY	113/4682		22	41442		1987	CONTAINER
CALIFORNIA ORION	435/2914	4.4	22.5	32654	3.1914	1980	CONTAINER
CANADIAN HIGHWAY	344/2834	3.1	18	12737	0.924	1978	VEHICLE CARRIER
CAPE MAY	268/4408	3.6	22	42145	2.281995	1986	CONTAINER
CENTRUY LEADER NO 1	146/1976	2.3	18	45422	0.53865	1984	VEHICLE CARRIER
CENTRUY LEADER NO 3	180/1993		18.25	44830		1986	VEHICLE CARRIER
CENTURY HIGHWAY NO 1	550/2177	2.5	18.5	43198	0.65044	1984	VEHICLE CARRIER
DIRECT KIWI	312/1208	3.1	20	20393	1.3908	1978	CONTAINER
GINGA MARU	1208	1.4	18	4888	0.1581	1972	TRAINING GOJ
GLOBAL HIGHWAY	219/2239	2.4	18.5	19700	0.6688	1982	VEHICLE CARRIER
GLORIA PEAK	181/1402	2.2	17	12816	0.433125	1976	GENERAL CARGO
HANJIN SAVANNAH	254/3801	4.2	21.7	35598	2.56284	1987	CONTAINER
HENRY HUDSON BRIDGE	229/4204	4.0	22.5	42407	2.5785	1987	CONTAINER
HERCULES HIGHWAY	124/1788	1.7	18.5	46875	0.3689	1987	VEHICLE CARRIER
HYUNDAI NO 11	288/1306		16	14779		1980	BULK CARRIER
JO OAK	609/2592	3.1	15.5	21541	0.72	1983	TANKER
KURAMA	671/10979	7.0	23.5	57870	9.0250365	1972	TM CONTAINER
MAGLEBY MAERSK	UNK		24	52181		1990	CONTAINER
MARIE MAERSK	UNK		24	52181		1990	CONTAINER
MERCURY	UNK		14	11961		1989	GENERAL CARGO
MOKU PAHU	UNK		15	1454		1982	TUG + 37K TON BARGE
MONTERREY	UNK		18	31430		1989	BULK CARRIER
NED LLOYD SINGAPORE	467/2601	3.5	20.5	10367	1.4555	1974	CONTAINER
NYK SUNRISE	UNK		23.4	43209		1991	CONTAINER
OAXACA	UNK		18	31430		1988	BULK CARRIER
OCCL FIDELITY	UNK		21.5	40980		1987	CONTAINER
OCEAN HIGHWAY	647/2708	2.7	18.5	13857	0.8484	1980	VEHICLE CARRIER
OOCL FAIR	UNK		21.5	40080		1987	CONTAINER
OOCL FREEDOM	UNK		21.5	40978		1985	CONTAINER
ORION HIGHWAY	UNK		18.5	44516		1984	VEHICLE CARRIER
PACKING	UNK		15.5	20627		1983	BULK CARRIER
PACPRINCE	194/1938		15.3	24632		1986	BULK CARRIER
POLYNESIA	166/1252	1.8	16	10774	0.24794	1979	CONTAINER
PRESIDENT ADAMS	332/?	6.3	24.25	61926	8.68579	1988	CONTAINER
PRESIDENT MONROE	295/5296		23.25	40627		1983	CONTAINER
PRINCE OF TOKYO	246/1569		14	36611		1974	WOOD-CHIP CARRIER
SAN MARCOS	447/2528	2.8	19.25	15192	0.8904	1980	RORO CARGO/VEHICLE
SEA-LAND INDEPENDEN	615/3478	3.5	22	32629	2.2914	1980	CONTAINER
SKAUGRAN	UNK		15	16366		1979	RORO CARGO/VEHICLE
STAR LIVORNO	UNK		16	26171		1982	BULK CARRIER
TAI HE	507/3087	3.6	19	35963	1.57113	1989	CONTAINER
TOLUCA	UNK			31340		1988	BULK CARRIER
ZIM AMERICA	UNK		21	37209		1990	CONTAINER
ZIM JAPAN	594/4406	3.8	21	37209	2.35792	1991	CONTAINER
ZIM SAVANNAH	670/5912	4.4	22.5	36263	3.4496	1981	CONTAINER

OIL=OIL ENGINES BHP=BREAK HORSEPOWER DO=BURNING DIESEL OIL
SA=SINGLE ACTING. THE NUMBER PREFIXED INDICATESE THE STROKE CYCLE
HVF=FITTED FOR BURNING HIGH VISCOSITY FUEL UNK=UNKNOWN

APPENDIX B. OPERATING PARAMETERS FOR NON-SHIPTRACK PRODUCING DIESEL VESSELS.

NON-SHIPTRACK DIESEL VESSELS	LLYODS PAGE #	ENGINE DESIGN	NUMBER OF CYLINDER	POWER RATING (BHP)	RATIO OF POWER/ FUEL USE	FUEL USE (TONS/DAY)	FUEL TYPE
CENTRUY HIGHWAY #3	780	OIL 2 SA	8	14342	349.8	41	DO/HVF
MOKU PAHU	1268	2 V OIL 4SA	14				UNK
SUNBELT DIXIE	1043	V OIL 4SA	14	14000			UNK
GEORGE WASHINGTON		OIL 2 SA	9	28645	325.5	88	DO/HVF
NATIONAL HONOR	1389	OIL 2 SA	6	11200			UNK
NED LLOYD VAN DIEMEN	1405	OIL 2SA	5	14890	307.0	48.5	DO/HVF
LONDON VICTORY	924	OIL 2 SA	7	15200			DO/HVF
IBN BAJJAH	237	OIL 2 SA	6	23800	360.6	66	DO/HVF
CHEVRON PACIFIC	818	OIL 2 SA	6	11400	321.1	35.5	DO/HVF
KOMOSOMELETS PRIMO	678	OIL 2 SA	7	10330			UNK
HEIDELBERG EXPRESS	100	OIL 2 SA	8	25560	284.0	90	DO/IFO
HERCULES HIGHWAY	122	OIL 2 SA	8	11900	383.9	31	DO/HVF
LOK PRAKASH	920	OIL 2 SA	6	10500	295.8	35.5	DO/HVF
PRESIDENT LINCOLN	215	OIL 2 SA	12	43200			DO/HVF
CALIFORNIA LUNA	679	OIL 2 SA	9	29746	302.0	98.5	DO/HVF
MARIE MAERSK	1067	OIL 2 SA	12	51920			UNK

OIL=OIL ENGINES BHP=BREAK HORSEPOWER DO=BURNING DIESEL OIL
SA=SINGLE ACTING. THE NUMBER PREFIXED INDICATESE THE STROKE CYCLE
HVF=FITTED FOR BURNING HIGH VISCOSITY FUEL UNK=UNKNOWN

APPENDIX B. OPERATING PARAMETERS FOR NON-SHIPTRACK PRODUCING DIESEL VESSELS.

NON-SHIPTRACK DIESEL VESSELS	FUEL QUANTITY (TONS)	RATIO OF FUEL/ SPEED	TRANSIT SPEED (KNOTS)	TONNAGE (TONS)	POWER x FUEL x 0.000001	YEAR BUILT	SHIP TYPE
CENTRUY HIGHWAY #3	166/2042	2.2	18.5	46186	0.6	1987	VEHICLE CARRIER
MOKU PAHU			15			1986	TUG + 37K T BARG
SUNBELT DIXIE	UNK		18.25	11447		1983	VEHICLE CARRIER
GEORGE WASHINGTON	457/3975	3.9	22.5	42000	2.5	1986	CONTAINER
NATIONAL HONOR	UNK		17	13680		1984	CARGO RORO
NED LLOYD VAN DIEMEN	366/2884	2.8	17.5	23790	0.7	1987	CONTAINER
LONDON VICTORY	225/3409		15.5	36865		1983	TANKER
IBN BAJJAH	413/3806	3.5	19	33405	1.6	1983	CONTAINER
CHEVRON PACIFIC	215/1907	2.4	15	23709	0.4	1984	TANKER
KOMOSOMELETS PRIMORYA	UNK		17.5	7701		1982	CARGO FISH CARRIER
HEIDELBERG EXPRESS	206/3948	4.4	20.5	29939	2.3	1990	CONTAINER
HERCULES HIGHWAY	123/1788	1.7	18.5	46875	0.4	1982	VEHICLE CARRIER
LOK PRAKASH	115/1448	2.4	15	16040	0.4	1980	BULK CARRIER
PRESIDENT LINCOLN	295/5296		23.25	40627		1984	CONTAINER
CALIFORNIA LUNA	233/4887	4.5	22	41110	2.9	1982	CONTAINER
MARIE MAERSK	UNK		24	52181		1978	CONTAINER

OIL=OIL ENGINES BHP=BREAK HORSEPOWER DO=BURNING DIESEL OIL
SA=SINGLE ACTING. THE NUMBER PREFIXED INDICATESE THE STROKE CYCLE
HVF=FITTED FOR BURNING HIGH VISCOSITY FUEL UNK=UNKNOWN

APPENDIX C. OPERATING PARAMETERS FOR WEATHER REPORTING 'RANDOM' DIESEL VESSELS.

WEATHER REPORTING DIESEL VESSELS	LLYODS PAGE #	ENGINE DESIGN	NUMBER OF CYLINDERS	POWER RATING (BHP)	RATIO OF POWER/ FUEL USE	FUEL USE (TONS/DAY)	FUEL TYPE	FUEL QUANTITY (TONS)
ALDEN W CLAUSEN	124	2 SA	6	11400	321.1	35.5	DO/HVF	215/1907
ALLIGATOR COLUMBUS	157	S2A	9	34101			UNK	
ALLIGATOR LIBERTY	158	2SA	7	29431			UNK	
AMBASSADOR BRIDGE	188	2SA	9	28620	319.8	89.5	DO/HVF	232/5540
ANADYR	215	4 V 4SA	16 EACH	65262			UNK	
AXEL MAERSK	406	2SA	10	45800			DO/HVF	924/6113
BT NESTOR	635	2SA	7	16800			DO/HVF	264/3250
CALIFORNIA JUPITER	678	2SA	8	29520			UNK	
CALIFORNIA LUNA	679	2SA	9	29746	302.0	98.5	DO/HVF	233/4887
CALIFORNIA ZUES	679	2SA	8	27700	348.4	79.5	DO/HVF	230/3364
CHESAPEAKE TRADER	816	2SA	5	11244			UNK	
CHEVRON COLORADO	817	1 GT 1 TR		12500	227.3	55	OF	1519
CONTSHIP AUSTRALIA	917	2SA	6	9245	205.4	45	DO/HVF	187/1900
COURIER	942	2 V 4SA	14 EACH	14000	345.7	40.5	DO/HVF	346/2794
DIRECT KEA	1074	2SA	6	15640	289.6	54	DO/HVF	
EVER GARDEN	1305	2SA	6	21600	291.9	74	DO/HVF	226/4726
EVER LEVEL	1307	2SA	7	22260			UNK	
GEORGIA RAINBOW II	1524	2SA	5	7703			UNK	
GREEN LAKE	1609	2SA	6	13199			UNK	
GUS W DARNELL	1651	2SA	5	15300			UNK	
HEIDELBERG EXPRESS	100	2SA	8	25560	284.0	90	DO/HVF	206/3948
KENNETH E HILL	579	2SA	7	20300	285.9	71	DO	4852
KENNETH T. DEER	579	2SA	6	11400	321.1	35.5	DO/HVF	216/1907
LOK PRAKASH	920	2SA	6	10300	323.9	31.8	DO/HVF	290/1364
MACKINAC BRIDGE	970	2SA	9	28650	318.3	90	DO/HVF	229/4204
MAGIC	985	4SA	6	8973			UNK	
MARCHEN MAERSK	1042	2SA	10	53565			DO/HVF	
MARIT MAERSK	1082	2SA	10	53565			DO/HVF	
MAYVIEW MAERSK	1138	2SA	12	51920			UNK	
MCKINNEY MAERSK	1141	2SA	12	51920			UNK	
METTE MAERSK	1189	2SA	10	53565			DO/HVF	
MING PLEASURE	1225	2SA	8	23690	287.2	82.5	DO/HVF	342/4519
NEDLLYOD DEJIMA	1402	2 2SA	8 EACH	50881	293.3	173.5	DO/HVF	2049/8947
NEPTUNE ACE	1420	2SA	6	10370			DO/HVF	223/1773
OMI COLOMBIA	1630	2SA	8	27300	292.0	93.5	HVF	7437
OOCL FAITH	1640	2SA	9	29810			UNK	
OOCL FORTUNE	1640	2SA	9	29610			UNK	
OVERSEAS JOYCE	1690	2SA	6	13150			UNK	
PACDUKE	5	2SA	7	11550	334.8	34.5	DO/HVF	168/290
PACIFIC PINTAIL	13	2 4SA	6 EACH	4080	240.0	17	DO/HVF	877/1203
PRESIDENT KENNEDY	215	V 2SA	12	56960	373.5	152.5	DO/HVF	332/332
PRESIDENT LINCOLN	215	2SA	12	46200			DO/HVF	295/5296
PRESIDENT WASHINGT	216	2SA	12	43200			DO/HVF	295/5296
PRINCE OF OCEAN	227	2SA	7	12600			UNK	
SEA LAND DEFENDER	637	2SA	9	30150	396.7	76	DO/HVF	615/3478
SEALAND ANCHORAGE	637	2SA	7	20286	294.0	69	DO/HVF	466/2012
SEALAND DEVELOPER	637	2SA	9	30150	396.7	76	DO/HVF	615/3478
SEALAND ENDURANCE	637	2 SA	9	30150	396.7	76	DO/HVF	615/3478
SEALAND EXPLORER	638	2 SA	9	30150	396.7	76	DO/HVF	615/3478
SEALAND TACOMA	639	2 SA	7	20286	294.0	69	DO/HVF	466/2012
SHIRAOI MARU	769	2SA	6	11219	284.0	39.5	DO/HVF	270/3790
SKAUBRYN	851	2SA	7	15200	298.0	51	DO/HVF	442/3503
SOLAR WING	885	2SA	8	12410	322.3	38.5	UNK	100
STAR GRIP	959	2SA	6	10120			UNK	
TAI SHING	1100	2SA	7	11200			DO	2291
TRITON HIGHWAY	1325	2SA	8	11900			UNK	
VERA ACORDE	1444	2SA	6	6900			UNK	
WESTWOOD ANETTE	1562	2SA	6	10980			UNK	
ZIM ITALIA	1718	2SA	8	29440	368.0	80	DO/HVF	594/4406

OIL=OIL ENGINES BHP=BREAK HORSEPOWER DO=BURNING DIESEL OIL
SA=SINGLE ACTING. THE NUMBER PREFIXED INDICATESE THE STROKE CYCLE
HVF=FITTED FOR BURNING HIGH VISCOSITY FUEL UNK=UNKNOWN

APPENDIX C. OPERATING PARAMETERS FOR WEATHER REPORTING 'RANDOM' DIESEL VESSELS.

WEATHER REPORTING DIESEL VESSELS	RATIO OF FUEL/ SPEED	TRANSIT SPEED (KNOTS)	TONNAGE (TONS)	RATIO OF POWER x FUEL USE	YEAR BUILT	SHIP TYPE
ALDEN W CLAUSEN	2.4	15	23709	0.4	1981	TANKER
ALLIGATOR COLUMBUS		21.9	41144		1991	CONTAINER
ALLIGATOR LIBERTY		22.05	42121		1986	CONTAINER
AMBASSADOR BRIDGE	4.0	22.5	42259	2.6	1986	CONTAINER
ANADYR		20.1	34151		1988	RORO
AXEL MAERSK			33400		1975	CONTAINER
BT NESTOR			36376		1979	TANKER
CALIFORNIA JUPITER		22	41668		1986	CONTAINER
CALIFORNIA LUNA	4.5	22	41110	2.9	1987	CONTAINER
CALIFORNIA ZUES	3.7	21.5	39678	2.2	1986	CONTAINER
CHESAPEAKE TRADER		14.5	24699		1982	TANKER
CHEVRON COLORADO	3.7	15	16941	0.7	1976	TANKER
CONTSHIP AUSTRALIA	2.5	17.7	16336	0.4	1991	CONTAINER
COURIER	2.6	15.75	21572	0.6	1977	TANKER
DIRECT KEA	3.0	18	27823	0.8	1969	CONTAINER
EVER GARDEN	3.6	20.5	37023	1.6	1984	CONTAINER
EVER LEVEL		21	24804		1980	CONTAINER
GEORGIA RAINBOW II		14	17590		1991	CARGO
GREEN LAKE		18.25	46950		1987	RORO
GUS W DARNELL		16.5	19037		1985	TANKER
HEIDELBERG EXPRESS	4.4	20.5	29939	2.3	1989	CONTAINER
KENNETH E HILL	4.2	16.75	43428	1.4	1979	TANKER
KENNETH T. DEER	2.4	15	21582	0.4	1982	TANKER
LOK PRAKASH	2.0	16	16835	0.3	1989	BULK
MACKINAC BRIDGE	4.0	22.4	42414	2.6	1986	CONTAINER
MAGIC		20	5103		1990	REFER C
MARCHEN MAERSK		23	52191		1988	CONTAINER
MARIT MAERSK		23	52191		1988	CONTAINER
MAYVIEW MAERSK		24	52181		1991	CONTAINER
MCKINNEY MAERSK		24	52181		1991	CONTAINER
METTE MAERSK		23	52191		1989	CONTAINER
MING PLEASURE	4.0	20.5	40464	2.0	1987	CONTAINER
NEDLLYOD DEJIMA	6.8	25.5	57327	8.8	1973	CONTAINER
NEPTUNE ACE		17.75	44979		1985	RORO
OMI COLOMBIA	5.8	16	67856	2.6	1974	TANKER
OOCL FAITH		21.5	40980		1985	CONTAINER
OOCL FORTUNE		21.5	40978		1985	CONTAINER
OVERSEAS JOYCE		18.5	48017		1987	RORO
PACDUKE	2.4	14.5	14648	0.4	1975	BULK
PACIFIC PINTAIL	1.3	13.5	5087	0.1	1987	NUC FUEL
PRESIDENT KENNEDY	6.3	24.3	61926	8.7	1988	CONTAINER
PRESIDENT LINCOLN		23.25	40627		1982	CONTAINER
PRESIDENT WASHINGT		23.25	40627		1983	CONTAINER
PRINCE OF OCEAN		15.5	36686		1991	WOOD CHIP
SEA LAND DEFENDER	3.5	22	32629	2.3	1980	CONTAINER
SEALAND ANCHORAGE	3.5	20	20965	1.4	1987	CONTAINER
SEALAND DEVELOPER	3.5	22	32629	2.3	1980	CONTAINER
SEALAND ENDURANCE	3.5	22	32629	2.3	1980	CONTAINER
SEALAND EXPLORER	3.5	22	32629	2.3	1980	CONTAINER
SEALAND TACOMA	3.5	20	20965	1.4	1987	CONTAINER
SHIRAOI MARU	3.0	13	77454	0.4	1986	BULK CONT
SKAUBRYN	3.5	14.5	19305	0.8	1982	RORO
SOLAR WING	2.0	19	41604	0.5	1988	VEHICLE
STAR GRIP		16.25	27192		1986	BULK
TAI SHING		15	17560		1975	BULK
TRITON HIGHWAY		20.8	45783		1987	RORO
VERA ACORDE			15788		1985	BULK
WESTWOOD ANETTE		15	28805		1987	BULK
ZIM ITALIA	3.8	21	37209	2.4	1991	CONTAINER

LIST OF REFERENCES

Brown, A., 1995: Temporal Effects of Shiptracks on Clouds. M.S. Thesis, Naval Postgraduate School, Monterey, CA, 122pp.

Chartier, R.E., 1995: Composite Shiptrack Characteristics. M.S. Thesis, Naval Postgraduate School, Monterey, CA, 75pp.

Coakley, J.A. Jr., R.L. Bernstein and P.A. Durkee, 1987: Effect of Ship-Stack Effluents On Cloud Reflectivity. *Science*, **237**, 1020-1022.

Conover, J.H., 1966: Anomalous Cloud Lines. *J. Atmos. Sci.*, **23**, 778-785.

Lloyd's Register, 1992: *Register of Ships*, 1992-93. Vol. A-G, Lloyd's Register of Shipping, London, 1654pp.

Lloyd's Register, 1992: *Register of Ships*, 1992-93. Vol. H-O, Lloyd's Register of Shipping, London, 1695pp.

Lloyd's Register, 1992: *Register of Ships*, 1992-93. Vol. P-Z, Lloyd's Register of Shipping, London, 1953pp.

Porch, W.M., C.J. Kao, and R.G. Kelley, 1990: Ship Trails and Ship Induced Cloud Dynamics. *Atmos. Enivron.*, **24A**, 1051-1059.

Radke, L.F., J.A. Coakley, Jr. and M.D. King, 1989: Direct and Remote Sensing Observations of the Effects of Ships on Clouds. *Science*, **246**, 1146-1149.

Rogerson, S.D., 1995: Implications of Shiptracks on Ship Surveillance. M.S. Thesis, Naval Postgraduate School, Monterey, CA, 57pp.

Trehubenko, E.J., 1994: Shiptracks in the California Stratus Region: Dependency on Marine Atmospheric Boundary Layer Depth. M.S. Thesis, Naval Postgraduate School, Monterey, CA, 57pp.

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