Vessel Noise and Orca Vocalization: Implications for Policy

Alexandra Kougentakis
October 27, 2007
Beam Reach Marine Science and Sustainability School
http://beamreach.org/071

Introduction

The Southern Resident killer whales (SKRWs) of the Pacific Northwest have long shared their habitat with humans and marine vessels. The anthropogenic impacts of commercial and private boatcraft are several, including oil spills from petroleum tankers, depletion of salmon prey by fishing ships, and noise disturbance, leading to the designation of SKRWs as an endangered population by the National Marine Fisheries Service (NMFS) in 2005. Anthropogenic noise is one of the least-studied threats and is often underemphasized, in spite of having been identified by the International Whaling Commission Scientific Committee (IWC/SC) Standing Working Group as a "potential population level threat to marine mammals." (IWC/SC 2004). It is this understudied area that is the focus of interest in this paper.

A number of different vessel types traffic through the Juan de Fuca and Haro Straits of northwestern Washington, and the impacts of the noise generated by each are as yet largely not understood. Recent studies have examined the role of whale-watching boats, which have increased in number with the growth in popularity of such ecotourism industries. Vessels have the potential to affect whale communications and behavior, whether through short-term disturbances such as the masking of calls, or through graver effects such as hearing loss. In 2002, a scientific model was proposed to measure noise created by whale-watching boats and effects on orcas. (Erbe, 2002) Software that factored in the propagation of broadband noise, specific physical oceanography properties, and the currently accepted orca audiogram model (Szymanski,

1999) was used to analyze the data collected on SKRW vocalization. Estimates were made for ranges over which boat noise could be audible to orcas, mask their calls, cause behavioral change and cause hearing damage. Each of these zones was distinguished by a successively higher received level (RL) of vessel noise by the orcas.

An NMFS study regarding the effects of vessel noise on orca behavior used techniques that had been applied to northern resident orcas to investigate their southern counterparts. (Bain et al, 2006) Horizontal avoidance of vessels and increased surface active behavior among orcas was noted across different boat types, including those not focused on whale-watching. The boater practice of leap-frogging, in which whale-watching boats enter the path of the whale in order to come within closest possible range while technically following guidelines, was similarly correlated with avoidance behavior in the northern resident population. (Williams et al, 2002)

The different vocalization types used by orcas for communicating are echolocation clicks, whistles and pulsed calls. Each signal type serves specific functions, with echolocation figuring most prominently in the gathering of information about objects in the surrounding environment, whistles being associated with social behavior, and pulsed or variable calls appearing to be important in the coordination of such group activities as hunting and traveling (Richardson et al, 1995; Miller, 2002). The frequency ranges for the different signals vary, with an interval of 8-80 kHz for clicks, 0.5-10.2 kHz for whistles, and 1-10 kHz for calls (Au et al, 2004; Thomsen et al, 2001; Miller, 2002). Average center frequency for echolocation is 50 kHz, and harmonics in calls can be as high as 30 kHz, values which correspond to the accepted most sensitive hearing frequency range of 18-42 kHz (Au et al, 2004; Miller 2002; Szymanski, 1999). The orca audiogram indicates that the animal’s range of hearing extends far beyond its own communication parameters, however, with behavioral and electrophysicological response estimated to reach up to 100 kHz (Szymanski et al, 1999).

Currently there is little understanding of the connection between orca vocalization and behavior, but it is unquestionable that communication is a crucial part of life for orcas and the behavioral impact of anthropogenic noise is likely linked to the disruption of their communication. It is difficult to determine with certainty that vessel noise is the actual cause of changes that may be observed in whales' vocalization patterns. The only direct effect on communication that was considered by Erbe was that of masking, an effect that is inferred rather than directly observed. Other possible ramifications of vessel noise for vocalization include differences in call duration between periods when vessels are present and periods when they are absent. (Foote et al, 2004) Call frequency is another possible area of impact; a student research study was only able to find a significant difference in the frequency of certain calls, depending on whether or not boats were present, for a single pod (Ayres and Danforth, 2002). No significant correlation was found for data recorded from mixed pods, which led the students to conclude that boat noise was generally not a reliable indicator of changes in call frequency.

The increase in whale-watching on the San Juan Islands in recent decades has been paralleled by protection efforts for SKRWs. The Whale Museum on the island of San Juan has focused on monitoring and advising vessels since the 1980s, using an adaptive management model to determine a set of principles, which has been periodically updated, to guide the behavior of all vessels trafficking through the area. The current edition is "Be Whale Wise," and includes a graphic illustration to indicate the range of distance from orcas at which boats must travel more slowly or stop completely ("Be Whale Wise," Internet). Research and the participation of stakeholders such as the Whale Watch Operators Association Northwest

(WWOANW) have contributed to the efforts of the Whale Museum to establish a list of best-practices guidelines for commercial operators. Both private and commercial vessels are monitored by the Soundwatch Program, an educational division of the Museum.

The adaptive management model is an outgrowth of early efforts, most notably initiated by CS Holling in the 1970s, to develop environmental impact assessment and resource management methods. The process involves bringing together scientists, resource managers, decision-makers and policy advisors. A foundational principle which was emphasized by Holling was the uncertainty involved in the prediction of future behavior of natural systems, given the inherent limitations of models. This should not discourage the pursuit of management altogether, but rather points out that shortcomings must be dealt with through monitoring and continued research. Effective communications between scientists and policy-makers is crucial and is often one of the elements that is most lacking (Morgan, 1998). Policy change is therefore a very gradual process, and although a recovery plan was proposed by NMFS in 2006, legislative protection for SKRWs did not appear immediately.

On September 11, 2007, ordinance NO. 35 – 2007 (Ordinance NO. 35-2007, Internet) was approved by the Council of San Juan County, officially codifying much of what the "Be Whale Wise" guidelines had dictated for voluntary compliance. The decree, which designates a $750 fine for the harassment of killer whales, was submitted for review in June 2007, but the push for binding legislation can be considered to date back to the early monitoring efforts of the Whale Museum. A continuing quandary will be the matter of enforcement; resources for the prosecution of environmental legislation are ever paltry and insufficient. The whale-watching industry had a strong record of positive compliance with the guidelines while they were only voluntary, according to Kari Koski of Soundwatch (Koski, 2007), but private boats are less predictable. The first citation under the new act was given on September 27, 2007, to a private boater who had come within the prohibited range of two orcas. (Le, 2007) The legal proceedings to follow will be the first test of the law's power.

The impact caused by vessel noise in the Puget Sound needs to be more closely investigated. Data that can authoritatively inform policy needs to consider vessel factors, e.g. size and speed, and also the biological effects for marine life. Some vessel types are inherently louder than others, leading to higher received levels (RLs) of noise by orcas that can have greater impacts on behavior and communication abilities. The distance of the vessel from an area occupied by orcas is also crucial in affecting how much of the source level (SL) of the noise will be transmitted. Applying the same standards to all boats may undermine the effectiveness of the regulations. Short-term noise effects such as masking and behavioral change can have significant long-term impacts on a small population, in the case of SKRWs currently 87; group survival is contingent upon the welfare of each individual. Further research on the effects of vessel noise can contribute to more effective standards, which could perhaps lead to the amendment of the current legislation.

My paper will seek to build upon previous research as well as to contribute new insights to facilitate the creation of reasoned policy that will allow continued use of the Puget Sound by humans, while providing protection for orcas. In particular, I am interested in surveying and characterizing the sound propagation of the vessels that will be encountered during the period of study. The vocalization of orcas will be noted and characterized to assess the apparent interference that different noise levels may have. Source power density spectra for both orca calls and boat noise will be calculated to allow for a direct comparison; as of the time of this study, source power density spectra for orca calls have not been previously studied. Finally, the adequacy of the previously voluntary guidelines that have been designated as law will be assessed with regard to the distances from orcas and the speeds that are recommended for whale-watching boats.

METHODS

The methods used in this study were developed with the aid of similar work conducted in previous studies (Veirs and Veirs, 2006) as well as through the counseling and support of Val Veirs. The research area was predominantly in the Haro Strait, and was conducted aboard the *Gato Verde*, a catamaran chartered for 8 weeks of use by the Beam Reach program to enable data collection as well as to teach program participants sailing skills and the philosophy of sustainability.

Sound transmission loss (TL) was measured in the Spieden channel. Recorded orca calls were played on an underwater speaker that was moved using a dinghy to different distances from the *Gato Verde*. A hydrophone array consisting of four hydrophones spaced 10 m apart was deployed off the port bow of the catamaran to measure the sound level received at the boat from each distance. The array was connected to a custom pre-amp power source, on which the gain settings were changed between a few of the distances. The power source was connected to an Acer model computer that recorded the underwater sound in one-minute files.

The files were analyzed using Beam Reach (BR) Analyzer (September 2007) software. The sensitivity settings were adjusted as was appropriate for each of the changes in gain setting, and the intervals between calls were used to set the background level of noise for each file. A segment of the whale call was chosen, and the RL for the 0-25 kHz frequency was recorded. These values were graphed on a set of axes along with the log of the corresponding distance to determine the linear relationship. The TL, signified by the slope of the calculated trendline, was used as a locally measured parameter to determine SLs of orca calls and vessels' noise. (See Figure 1)

The measurement of vessel noise was broken into two components: the analysis of the sound generated by individual vessels and the cumulative sound generated in the marine environment by all vessels in the vicinity. To determine the noise levels of individual boats, a single moving boat needed to be within a 400-meter distance from the *Gato Verde*, as determined by a Newcon Optik Laser Rangefinder, 7x25 LRM2500CI. This radial distance was chosen as it reflects the outermost extreme at which boat behavior is advised by the SoundWatch guidelines. The hydrophone array was deployed off the port stern of the boat and noise was recorded continuously by computer in one-minute files. Background noise files were taken for each half hour interval at points during which there were no vessels within 400 m of the *Gato Verde*. Boats were identified using binoculars and the Soundwatch "Boat ID Guide" of the Soundwatch Program. Boat speed will be approximated with the help of Todd Shuster, the captain of the *Gato Verde*.

The RL of each vessel recording for the 0-25 kHz range was determined using BR Analyzer. RL data points were used with the boat's distance and the TL from the sound propagation model to determine SL for each vessel event. BR Analyzer was also used to generate a source power density spectrum in conjunction with Microsoft Excel software for the vessel with the mean SL.

Cumulative vessel noise sound files were taken at points during which there was no more than one individual boat within 400 m of the *Gato Verde* and numerous moving boats were present further off. A comprehensive boat count was taken and boat types were noted according to the scheme established by SoundWatch. The distances of all boats within 800 m were noted within the ranges 100-400 m and 400-800m; all other boats were recorded as being further than 800m. BR Analyzer was used to determine RLs over the 0-25 kHz frequency range for each of the cumulative vessel files, and 1-3 sequential files were used to determine mean RLs for individual events.

The hydrophone array was also deployed during orca events to record vocalizations. Information regarding approximate boat numbers and distances were noted during each event. Calls were localized using Ishmael 1.0 software (NOAA). All files containing clear calls were analyzed, and in files with calls that could be successfully localized, only the first call was considered for the determination of distance. SL was calculated using the RL data calculated by BR Analyzer software and the estimated distance from Ishmael. In addition to assessing the sample of call SLs in and of itself, mean SLs were taken within specific time intervals for comparison with the corresponding background noise level. Power density spectra, which demonstrate the distribution of total average power over a given frequency range, were compared between the average orca SL, the average vessel SL and average ambient noise.

The assessment of the "Be Whale Wise" guidelines utilized the SLs that had been calculated for individual vessels to calculate what the approximate RLs would be at the specific distances from the orcas cited to regulate boater behavior. Two different units of measurement are used because yards are more common in the US, while meters are standard in Canada. Therefore the "slow zone" in which boats are advised to travel at less than 7 knots is somewhat ambiguous, and yields four points to be considered: 100 m, 91.44 m (100 yards), 400 m, and 365.76 m (400 yards).

RESULTS

FIGURE 1

Sound level in dB as determined by propagation loss:

$$RL = m(LOG(R)) + SL$$

$$RL = 23.263*LOG(R) + SL$$

Model used for calculation of SLs

Sound Spreading Model

The fundamental principle of the sound propagation model used here (Figure 1) relied upon two variables to determine TL: the SL and the distance (R) between the source and the recipient. This assumes a roughly linear sound loss rate. The calculation within this study of a TL that is slightly different from the commonly accepted spherical spreading model is likely due to the effects of other key variables such as temperature, depth and bathymetry.

Individual Vessel

The sample size of recordings for individual vessels was 19. Descriptive data and calculated SLs for each boat are listed in Table 1. Mean boat SL within the sample was 173.428 dB, and 95% of all SLs were within the range 161.692-185.164 dB. A single data point is outside this interval, the Prince of Whales at 187.058 dB. The accuracy of the estimate is questionable because the other two SLs calculated for Prince of Whales zodiacs were both more than 10 dB less. Even though each sampling was at a different speed, the difference is sufficient cause for doubt. Two possible explanations for the discrepancy are that there was either a problem with the sampling of this data point, or perhaps the vessel was having engine trouble that was increasing its noise output at the time of recording. The removal of the outlier point strongly reduces the skewness of the distribution, from 0.522 to 0.073.

TABLE 1: Individual Vessel Data

NAME	TYPE	DISTANCE (m)	SPEED (knots)	dB (re 1μPa)
Prince of Wales	Small inflatable	329	5	187.058
Straitwatch	Small inflatable	30	1	166.422
San Juan Excursions	Medium hard bottom	50	5	171.873
Ocean Explorer	Small inflatable	169	5	175.057
Sea King Adventures	Small open hard bottom	40	5	166.049
Deer Harbor Charters: Pelagic	Medium hard bottom	82	<5	167.011
Prince of Wales	Small inflatable	250	15	175.183
Victoria Clipper III	Large hard bottom	300	25	182.075
Sea Fun Safaris	Small inflatable	140	10-15	174.455
San Juan Safaris: Sea Hawk	Medium hard bottom	154	10-15	179.668
Wild Whales Vancouver	Medium hard bottom	227	5	173.408
Springtide Charters: Marauder 4	Medium hard bottom	305	10	168.483
Orca Spirit	Medium hard bottom	157	5	170.173
Wild Cat Adventures	Large hard bottom	100	20	173.056
Research Boat	Small open hard bottom	385	5	175.556
Prince of Wales	Small inflatable	150	7	172.502
Eagle Wing Tours.com	Medium hard bottom	380	10	173.357
Victoria Express	Large hard bottom	284	10-15	179.651
SeaFun Safaris: Serengeti	Small inflatable	90	1	164.091

The noise levels of small inflatable and medium hard-bottomed boats both show a strong positive correlation to vessel speed ($p<.001$, $p<.001$) Linear analysis of the two variables, however, indicated insignificant levels of correlation, ($r^2=0.1371$, $r^2=0.3827$), (Figure 2). When the Prince of Whales 187.058 dB outlier is excluded, the correlation for small inflatable boats rises to 0.6521, and the factor of increase becomes 0.6785 from 0.519 (Figure 3). For the full data sets, between the two boat types, the differences in SL were insignificant ($p=0.6396$).

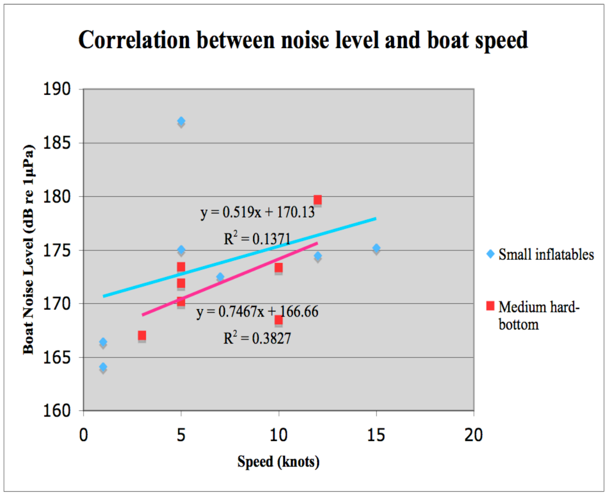

FIGURE 2: The relationship between the speed of a vessel and its noise level between two boat types. The closeness of the two data sets demonstrates the lack of significant difference between them.

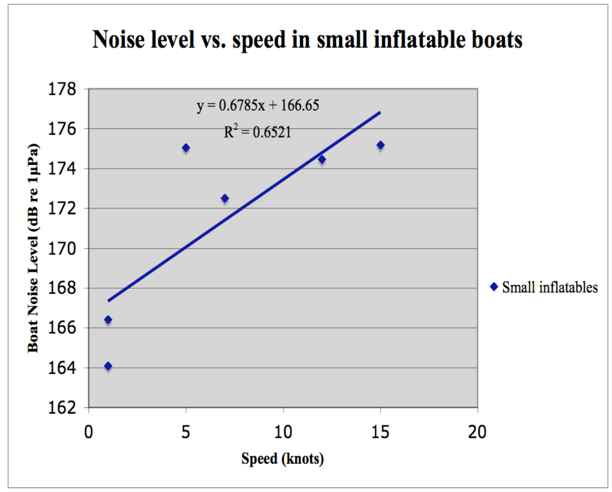

FIGURE 3: Noise to speed relationship of small inflatables without the 187.058 dB outlier

Cumulative Vessel Noise RLs

Using the *Gato Verde* as a proxy for an orca, 11 data points were taken to simulate the cumulative noise of an orca's environment when there are several boats present. (See Table 2) The mean RL was 119.045 dB, with a standard deviation of 3.718. All data points fit within two standard deviations of the mean except for one, (Event #1) an anomaly due to the presence of a tanker during the recording of that file that could be heard during playback.

After discounting the Event #1 data point, a slight linear correlation between total number of boats present and RL can be observed, (r^2=0.2259), however it is still too low to be considered significant. (Figure 4) Apart from Event #1, the cumulative RL event with the lowest measured intensity had only one boat less than the event with the highest intensity, demonstrating the relatively weak correlation between these two variables.

For four data points (Event #s 4-7), both the total number of vessels and the specific quantity within individual ranges were exactly equal, but cumulative RLs recorded differ within a range of 5 dB. For the two events with the highest RLs within this subset, the boats within the closest range (100-400m) had begun moving, thus explaining the RL difference.

TABLE 2: Ambient Noise Levels

Event #	RL (dB)	Total Boats	100m<R<400m	400m<R<800m	R>800m
1	127	4	0	0	4
2	115	8	1	0	7
3	117.5	13	1	2	10
4	120	13	1	1	11
5	121	13	1	1	11
6	119	13	1	1	11
7	116	13	1	1	11
8	114	14	1	2	11
9	121	14	0	3	11
10	122	15	Missing	Missing	Missing
11	117	8	0	5	3

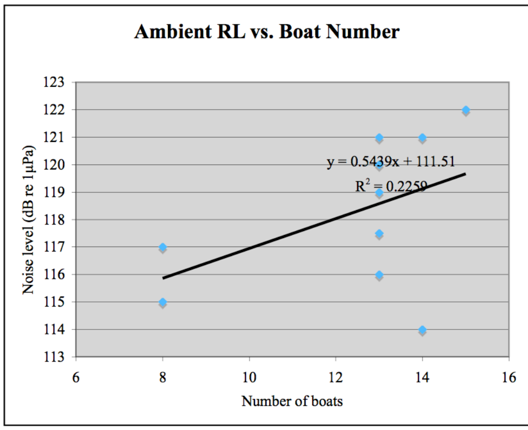

FIGURE 4: Description of boat numbers and ranges for ambient noise recordings.

Orca Call SL and Environmental Effects

The RLs for orca calls that were determined by BR Analyzer and the distances derived from Ishmael 1.0 were inserted into the sound propagation model (Figure 1) to determine SLs. The data set of 81 orca calls yielded a mean SL of 169.513 dB, and 95% of all calls were within 34 dB of the mean (see Figure 5).

SL is one of the key variables determining the range over which a signal can be detected, and background noise is another. The maximum ranges over which each signal level could be detected at the ambient noise levels calculated for cumulative vessel events are summarized in Table 3. The mean SL of orca calls within specific time intervals for each day of recording was taken to compare with the approximate ambient noise level that was simultaneously present (Figure 6). Though the linear relationship between the paired data points was not significant, (r^2=0.4814), there is a clear relationship between orca SL and ambient noise level ($p<.001$).

Power density spectrum comparison between the mean orca call and vessel noise source

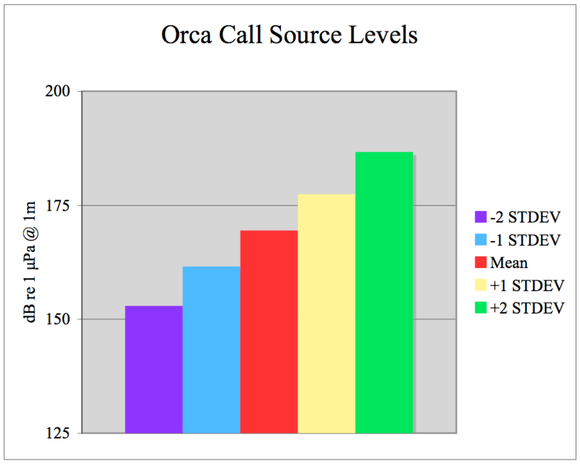

Figure 5: Orca call SLs within two standard deviations of the mean

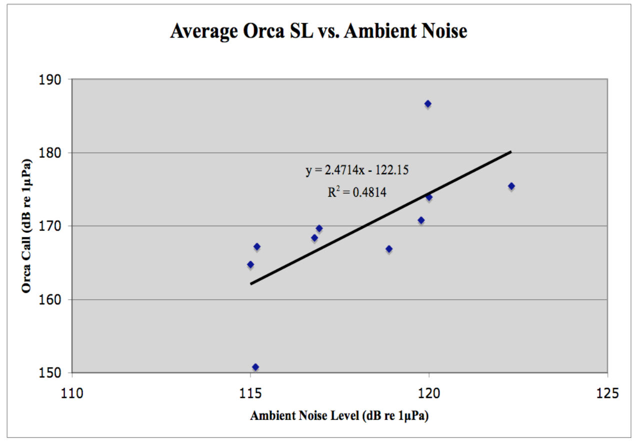

Figure 6: Mean orca call SLs plotted against corresponding ambient noise levels. The data on this graph is not related to table 3; instead these values reflect the approximate ambient levels occurring during vocalization events for which orca SLs were calculated.

levels, and mean ambient noise level, were compared (see Figure 7). The vessel has the highest power distribution, with a peak power level at 3760 Hz. The peak power level of the mean orca call is at 2540 Hz, the only frequency at which the power of the orca call exceeds that of the vessel (136.9 dB vs. 136.3 dB). Ambient noise power is below both that of the orca call and the vessel, with a peak of 83.3 dB at 4880 Hz.

Be Whale Wise

For the two lower distances from orcas that that is recommended by the Be Whale Wise Guidelines, at 91.44m (100 yards), the mean RL of individual vessel noise is 127.806 dB, and at 100m, the mean is 126.902 dB; 95% of vessels are within 116.807-139.542 dB and 115.166-138.638 dB, respectively. With less than a decibel difference between the means, the difference between the RLs at the two distances is insignificant ($p = 0.6377$) For the two maximum distances, at 365.76m (400 yards), the mean RL is 113.800, and at 400m the mean is 112.896 dB; 95% of vessels generate noise levels between 102.064-125.536dB and 101.16-124.632 dB,

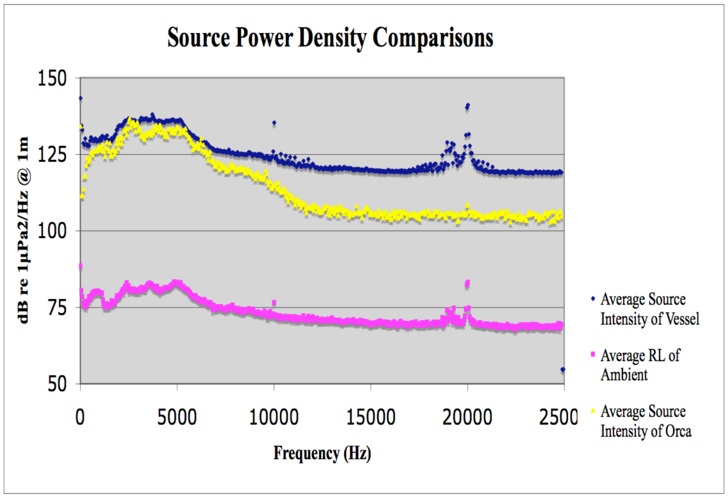

Figure 7: Comparison of power densities of mean vessel, mean orca call and mean ambient noise levels. Orca hearing is most sensitive at 20 kHz.

TABLE 3: Orca call range in ambient

Orca Call SL(dB)	Background Noise (dB)	Range (m)
169.513 (mean)	111.610 (2nd STDV)	308.37
	115.328 (1st STDV)	213.43
	119.046 (Mean)	147.72
	122.763 (1st STDV)	102.24
	126.481 (2nd STDV)	70.76
177.461 (1st STDV)	111.610 (2nd STDV)	677.24
	115.328 (1st STDV)	468.73
	119.046 (Mean)	324.42
	122.763 (1st STDV)	224.54
	126.481 (2nd STDV)	155.41
161.583 (1st STDV)	111.610 (2nd STDV)	140.66
	115.328 (1st STDV)	97.35
	119.046 (Mean)	67.38
	122.763 (1st STDV)	46.64
	126.481 (2nd STDV)	32.28
186.685 (2nd STDV)	111.610 (2nd STDV)	**1687.44**
	115.328 (1st STDV)	1167.90
	119.046 (Mean)	808.33
	122.763 (1st STDV)	559.46
	126.481 (2nd STDV)	387.21
152.978 (2nd STDV)	111.610 (2nd STDV)	60.02
	115.328 (1st STDV)	41.54
	119.046 (Mean)	28.75
	122.763 (1st STDV)	19.90
	126.481 (2nd STDV)	**13.77**

respectively. Here again the difference is less than one decibel and is determined to not be significant ($p=0.6378$).

DISCUSSION

Individual Vessel Assessment

The sound propagation model applied here estimated vessel SLs to be between 164.091 and 187.058 dB. The TL rate of -23.263 dB is greater than the spherical spreading TL of -20 that is generally accepted for sound propagation in deep waters. Over short distances, however, the calculation of the TL rate as done here is fairly reliable, and may provide a more accurate assessment of the conditions that orcas experience in this setting over similar distances.

Vessel recording data was taken at points during which a single vessel was within 400 m of the *Gato Verde*. The wide range may have diminished the precision of RL estimation for boats that were further away, and therefore maximum vessel distance may need to be further limited in future research efforts.

It is important to note that these SL calculations only pertain to the noise generated at the specific speed of the boat during the time of the recording, and do not provide comprehensive assessments of the vessels' noise potential. Some of the larger boat companies employ technologies to reduce their noise levels, a factor not investigated here but which could be more closely examined in future research efforts.

Cumulative Noise

This study proposed a new model for the better understanding of the acoustic experience of orcas in their environment. Particularly in the presence of numerous wildlife touring vessels, it is important to understand the noise levels that marine life are exposed to, especially for species such as orcas for which communication plays a crucial role in survival. This part of the study did not involve additional processing as in the case of the source level calculations, which may mean that the information reflected here is more accurate.

The weak relationship between number of boats and cumulative noise level demonstrates that other factors, such as boat type and speed, may be more important. Between the maximum and minimum RLs of Events 4-7, where boat numbers and ranges were all equal, noise level more than doubles. The louder RLs were observed for Events during which previously stationary boats began moving, testament to the impact that a single moving boat can have.

The varying levels of impact of moving boats is predicated upon a number of factors that are often more complex than the most obvious qualities of speed or size. In addition to different engine technologies, some boat types, such as the small inflatable zodiacs, have the ability to "plane" when they reach certain speeds. During planning the hull rises and skims the surface of the water rather than pushing through it. Such movement can reduce the noise level generated by the vessel. Such variables can account for the lack of a strong linear relationship between noise level and boat speed, size, or the total number of boats present.

At the same time, these results should not be misinterpreted to means that an unlimited number of boats in the presence of orcas is benign. The sample size of 11 Events here is too small to be conclusive, and the conditions during each event varied widely, with some of the variables not manifest. Many of the boats during each Event were stationary, but it was not possible to say that they were silent because their engines may have been idling. Also, it was difficult to keep track of the exact time points at which boats went into motion, especially if a number of vessel started to move simultaneously. An improvement in data collection methods for this part of the study would be to establish communication with vessel operators in order to be able to obtain more accurate information about boat speed and timing of movement.

Possible Communication Difficulties for Orcas

The SL of orca calls was found to rise in relation to increasing ambient noise levels. The implication here is that high levels of vessel noise are in fact making it more difficult for orcas to communicate. They are thus forced to exert more energy in order to successfully perform crucial group activities such as foraging and traveling. Such a result was previously reported as well (Holt et al, 2007) This study only looked at the theoretical impact that ambient and vessel-generated noise levels could have, but other studies have called attention to other effects such as behavioral change and hearing loss (Erbe, 2002). While it may appear that orcas have the ability to overcome environmental difficulties by increasing the loudness of their vocalizations (the loudest call was estimated to be 190.655 dB, as opposed to the loudest vessel, 187.058 dB), physiological problems can still prove injurious. It is not known how much additional energy an orca needs to employ to increase its vocalization level, and with a precarious food supply and other environmental threats, the impact could be substantial. Hearing loss, whether short or long term, is the worst-case scenario because it completely eliminates communication.

Spectral density assessment showed the mean source power of a vessel to exceed that of the mean orca call at all frequencies but one. Ambient noise power was found to be consistently below both the orca call and the vessel across the 0-25 kHz interval. However, it is important to remember that the hearing ability of an orca is most sensitive between 18 and 42 kHz, with the single most sensitive frequency at 20 kHz. Vessel SL is substantially higher than orca SL at these frequencies, and the animals may also be more strongly affected by ambient noise within this frequency range.

The significance of the spectral density assessment is to stress the importance of distance limits for vessels in the vicinity of an orca pod. The extent of the ambient noise that orcas experience is largely determined by the range, in addition to speed and number, of the boats around them. The positive message to take from here is that on average, orcas should not have a great problem with communication; at the same time, even the mean orca call, when in the presence of a single vessel at the mean SL, can only be detected by another orca within a range of 147.72m. Setting appropriate minimum distances and limiting the number of vessels allowed to be around orcas at a time would therefore greatly aid their ability to communicate effectively.

Be Whale Wise

The mean RL of a single vessel at 91.44m, the minimum permissible distance, was 127.806 dB. On average, therefore, a single vessel exceeds the very highest data point noted for a cumulative RL event. It is however important to note that the Be Whale Wise Guidelines also recommend slowing vessel speed to no more than 7 knots within a 100-400 yard/meter radius of orcas, and the mean vessel SL incorporates vessels traveling at higher speeds as well. However, for a boat traveling at 5 knots at this distance, the mean RL for orcas would still be 125.5 dB (this calculation does not include the ambient noise outlier of 127 dB).

It is not usually the case that there is a single vessel in the surrounding environment of the orcas; ambient noise is generally comprised of numerous vessels around them, whether they are there by design or incidentally. It is thus important to consider what the sum of cumulative RLs can actually amount to. Sound levels cannot be added simply by adding dB-intensities, because the dB level is a logarithmic function. The formula for adding sound pressure levels is the following:

$$\mathbf{SPL = 10 \times LOG_{10}\Sigma 10^{(SPLi)/10}}$$

This formula means that two vessels at the average noise level of 173.428 dB have a combined source level of 176.428 dB (a doubling of sound amounts to adding 3 dB). Such a method can be used to calculate combined RLs at the distance limits specified by advisory guidelines or law. For the US law, at 100 yards, or 91.44 m, the mean RL that orcas are exposed to from a single vessel is 127.806 dB, meaning that two vessels, on average, would create an ambient noise level of nearly 131 dB. At such a volume an orca would need to be quite close to its fellow pod members in order to ensure that it can be heard by them. On the other hand, two boats at 116.807 dB, 2 standard deviations below the mean, would generate a noise level close to the average ambient level, providing a much-improved environment for communication.

CONSIDERATIONS FOR POLICY

The purpose of environmental policy is to place certain restrictions on human behavior so as to strike a balance between human activity and the principles of environmental preservation.

Adaptive management is an important aspect of environmental policy, but managing resources in a marine environment can be more difficult than for a terrestrial environment due to the higher levels of uncertainty. The problems facing the SKRW population are well-documented and have been cited by NOAA as threats to their survival. Anthropogenic noise levels have the potential to mask communication or even deafen the animals, thus interfering with important life activities. Vessels, particularly those whose purposes are wildlife touring, fishing or shipping, are the major sources of environmental noise for orcas, because the first two involve being within close range of the animals and the latter generates particularly high noise levels.

The research put forward here presents a model for the study of noise exposure of the orcas of the Puget Sound. The results denote a number of arguments for tougher restrictions than those created by the 2007 San Juan ordinance. The examination of the source noise levels of individual vessels and the assessment of ambient levels in relation to vessel presence are important because they provide a more comprehensive understanding of the acoustic environment that orcas experience. A system needs to be established to ensure that the orca population will not be exposed to unnecessary auditory stress; the "Be Whale Wise" guidelines seek to limit boat speed within a designated distance from the animals, a measure that was not incorporated into the current law. Future legislative efforts should not only employ this concept, but should further seek to limit the number of boats allowed to be around a group of orcas at once. The latter measure may be difficult to create because different whale-watching companies would be obliged to limit their excursions and coordinate with other companies to create an alternating schedule. An option that would give boat-operators greater control would be the installation of quieter engine technology, with associated incentives such as more excursions for quieter boats.

Boat operators already have a number of incentives, beyond any that might be granted to them via legislation, to reduce the noisiness of their vessels. Beyond their designation as an endangered population, SKRWs are also known for their unpredictable migration patterns. They may naturally choose to avoid areas with high ambient levels, a negative for vessels whose main trade is whale tourism, and the depletion of population numbers is obviously bad for business. Consciously seeking to limit environmental harm is well within the values of an industry whose purpose is after all, to promote an appreciation of the environment, and the use of low-impact technologies provides another selling point. Both policy and market dynamics can help to improve the habitat of the marine life in the Puget Sound.

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