# Impact of vehicles on recruitment of toheroa on Oreti Beach, Southland, New Zealand

A report to Te Ao Mārama, Environment Southland, Invercargill City Council and Department of Conservation

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## Executive Summary

The Oreti Beach population of toheroa are of national conservation importance because of their outlying and limited distribution, long-term declines of both northern and southern populations, general degradation of marine ecosystem health, and the importance of toheroa as a customary food of Māori. Crushing of juveniles by vehicle traffic has been mooted as a potential threat to toheroa recruitment, but reliable scientific measures of its putative importance are lacking.

The three main objectives of this study were to (I) improve accuracy of existing measures of risk posed to juvenile toheroa each time they are run over by a vehicle; (ii) combine these measures with year round estimates of the vehicle traffic streams and the distribution of toheroa down and along Oreti Beach to construct a model that predicts the proportion of toheroa recruitment blocked by vehicles; and (iii) use the model and companion study of recreational use of Oreti Beach to assess the current and future impact of vehicles on toheroa population and provide information to support future management decisions to rebuild the populations resilience and sustainability.

Around 4% of juvenile (<40 mm) toheroa were damaged (and presumed killed) each time they are driven over by the car or motorbike, whereas utilities and 4WD vehicles killed 2% per pass. We found no evidence that multiple passes in quick succession over the same sand increased juvenile mortality rates.

Traffic volumes entering the beach via Main Entrance (Dunns Road) were recorded between 7 April 2010 and 11 April 2012 using an automatic traffic counter. In total 96,088 and 90,859 vehicles visited in each of the two years of this study, an average of 256 vehicles per day. The number of vehicles per day varied between 42 and 1587. Around 7% additional vehicles visited via North Entrance.

The locations of cars, utilities/4WDs and motorbikes were recorded during 34-km-long ‘circuits’ of Oreti Beach between 18 January 2011 and 14 January 2012. Altogether 196 circuits were distributed over 73 sampling days, with seasonal sampling effort closely matching visitor numbers as recorded by the traffic counter. Altogether 36% of vehicles encountered were utilities/4WDs, 57% were cars (including vans) and 2% were motorbikes. The remaining (5%) vehicles included buses, pushbikes, four-wheeled motorcycles, horses, sulkies, blow carts, caravans and trailers. The impact of these miscellaneous vehicle types have not been estimated in this study.

The spatial distribution of vehicles and toheroa, and juvenile toheroa mortality rates, were used to construct a simple deterministic spreadsheet model that predicts vehicle-added mortality in all 20 m x 5 m sections on Oreti Beach. Over the course of a whole year, the model predicts that vehicles add at least 23% to the natural mortality experienced by juvenile toheroa. Cars cause the greatest overall mortality (15% cumulative mortality over 12 months) though impact is largely confined to 2 Km either side of Main Entrance. Utilities/4WDs range more widely along the beach than cars (around five times longer trip distance on average) but are less frequent users). Utilities/4WDs are estimated to add 12% mortality to natural mortality of juveniles. Motorbikes contribute only 1% added mortality to juvenile toheroa.

Vehicle-added mortality is greatest near Main Entrance (up to 72% annually), and reduces rapidly to both the north and south. A secondary peak in vehicle-added mortality occurs to the north of North Entrance, largely due to an influx of utilities/4WDs entering the beach here and travelling to the Waimatuku Stream. Vehicles entering the beach at Main Entrance add 18% mortality, compared to 4.8% by all vehicles entering at North Entrance. Closure of the North Entrance would therefore make only a minor contribution to any vehicle impact mitigation.

Most impact of vehicles occurs high on the beach, within 80 m of the sand dunes. Reduction of traffic in this zone would be the main priority for mitigation of vehicle impacts.

Seasonal variation in vehicle-added mortality reflects changes in the number of vehicles using the beach. Considered on a monthly basis, vehicle-added mortality to toheroa is greatest in December (5%) and lowest in May (2%). To understand the true impact of vehicles on the toheroa population, however, we need to gain a better understanding of i) the time of year that juvenile toheroa settle on the beach, and ii) how long they take to grow to a size where they are no longer killed by vehicles (≥ 40 mm). The longer the time spent at a vulnerable size, the greater the mortality, especially if peak settling precedes or coincides with the summer peak in vehicle numbers on the beach. If toheroa take three months to grow to an invulnerable size, for example, then overall vehicle-added mortality is about half of that if it takes them 12 months to outgrow the vulnerable stage.

An adjunct study of the Burt Munro Challenge motorbike beach race event on 28 November 2008 estimated that around 53,000 juvenile toheroa were killed on the 850 m long race track, but statistical uncertainty means that the number of fatalities could have been as low as 31,000 or as

high as 70,000. This indicates a minimum mortality rate of 72% (41 – 90%) amongst the toheroa living on the race track. Although this impact is severe, it is also localised and juveniles repopulate the race-track area by drifting along the shoreline and resettling in the upper beach zone where the race takes place. Complete colony surveys by NIWA estimated that there were around 7 and 6 million juveniles living on Oreti Beach in February 2005 and February 2009 respectively. If similar densities were present during our studies, the 2008 beach races killed less than 1% of the juvenile population, whereas this study estimates that year-round traffic killed around 23%. Clearly management of risks to toheroa recruitment from every-day traffic is much more important than further reduction of the Burt Munro Challenge beach race impacts, which have already been minimised since 2008 by relocation of the racetrack and better management of spectators' vehicles.

To test whether the predicted vehicle-added juvenile mortality is affecting the Oreti Beach toheroa population, we constructed statistical models that compared mortality predicted with observed abundance of toheroa in NIWA survey transects. These models show that adult abundance declines sharply in areas of Oreti Beach where the model predicts vehicles to have imposed higher juvenile mortality. Similarly, juvenile abundance also declined steadily with increasing predicted vehicle mortality in 2002 and 2009 surveys, but not in 2005. The lack of decline in 2005 probably arises because juvenile toheroa had settled shortly prior to the survey and hence there had been insufficient time for vehicle impact to significantly alter the distribution of juvenile abundance.

The abundance of juvenile toheroa was severely reduced in the 30 - 70 m zone below the dune line in the 1 km section either side of Main Entrance compared to further along the beach. This reduction coincides with (a) the extreme high impact zone from vehicles near Main Entrance, and (b) predictions that risk from vehicles peaks at 50% at 40 m from the dunes and then steadily declines to reach 17% by 100m, and 3% by 200 m from the dune line.

Our model predicts that adult toheroa are eliminated altogether from around 11% of the 18 km long colony, and reduced by 70-90% over a further 10% of its length because juveniles are killed by vehicles. If the average added annual mortality from vehicles (23%) is applied across the full colony, the model predicts that vehicles have reduced the size of the adult population by between 63% and 79%.

There is broad scale agreement between the traditional knowledge of the kaitiaki, field measurement of mortality and traffic streams, our vehicle impact model, and correlations of reduced toheroa abundance with where the model predicts highest impacts from vehicles: Vehicles driving on Oreti Beach are reducing the population of adult toheroa along a considerable portion of the beach. The best overall working model for guiding traffic management decisions is that sporadic recruitment of toheroa follows unexplained population knockdowns that are beyond the control of the kaitiaki and other environmental managers. Recruitment to rebuild the population after these knock-downs is being partially blocked by vehicles in the central and extreme northwest zones of Oreti Beach in particular.

Although the abundance of toheroa has been fluctuating, it remains at a sufficient density to allow most harvesters to gather a feed, so currently there is no sign of the need for restricting authorisations of customary harvests. Rather, vehicles pose a longer term threat to the speed and degree of recovery after knock-downs by other, as yet poorly understood, impacts on the colony (probably related to broad scale climate or oceanic perturbations). However, the number of cars registered in New Zealand has been steadily increasing and this trend is likely to continue, so the threat to toheroa will gradually get worse if traffic is not managed in some way.

Seasonal or zone closures, inserting partial barriers to prevent vehicles moving along the crucial upper intertidal zone, and/or forming roads along the inland or seaward margins of the dunes are all potential mitigation options to explore. Nationally co-ordinated and replicated adaptive management experiments are recommended to minimise costs and hasten learning about how best to build the resilience of toheroa populations. Maintaining and extending standardised toheroa surveys is paramount to test the effectiveness of recovery strategies and scale the urgency of interventions against scientifically robust measures in population abundance. Studies of population growth and recruitment and population connectivity along Oreti Beach are needed to better understand why observed changes are happening and what to do about them.

Our study of recreational use of Oreti Beach emphasised the importance of access to Oreti Beach for maintaining a wide range of lifestyle and economic benefits for Southlanders and tourists. It is recommended that key stakeholders form a working group and collaborate to develop effective management strategies which balance the threat to toheroa and the significant recreational value of Oreti Beach.

# Contents

## Recreational use of Oreti Beach, Southland, New Zealand, 2010-2012

# Acknowledgements

This research was jointly funded by Environment Southland (through a grant to Te Ao Mārama), the Department of Conservation and Invercargill City Council. Invercargill City Council provided an automatic traffic counter by the main entrance to Oreti Beach, and the services of Gama Rajapaksa to gather those data. Dr Mike Beentjes and the Ministry of primary Industries (formerly Ministry of Fisheries) has made the NIWA historical toheroa survey data available for re-use for this study – the original study was funded by the Ministry of Fisheries. Ms Julie Futter, then an MSc student at the University of Otago, helped with field work work for the first phase of studies on vehicle impacts on Toheroa. Additional field work was performed by Kiersten-Anna Fletcher-Zirke, Greg Larkin, James Harvey and Helen White. Greg Larkin (from Environment Southland) provided logistical support and analysis, and together with Dallas Bradley have peer reviewed and guided the methods throughout. David Taylor, Department of Conservation, Southland Conservancy, advised the study. Michael Skerrett (Te Ao Mārama) championed the need for the research - he initiated and then provided overall guidance of the project.

# 1. Introduction: the need for this research

Toheroa (*Paphies ventricosa* Gray) is a large endemic bivalve found on sandy beaches that are fully exposed to surf[1]. Toheroa are burrowing filter feeders that live in greatest numbers midway between high and low tide levels. The main toheroa populations are found in the upper North Island, with smaller populations along the Kāpiti coast and in Southland at Oreti Beach, Bluecliffs Beach and Orepuki. Toheroa were intensively fished in the past, both in commercial operations and by recreational fishers until nationwide declines in the population sparked a closure to the fishery in 1980. Since then, harvesting of toheroa has been completely prohibited with the exception of Māori customary take and one-day recreational 'seasons' at Bluecliffs Beach in 1980 and Oreti Beach in 1993.

The Southland populations of toheroa are of national conservation importance because of their outlying and limited distribution, long-term declines of both northern and southern populations, general degradation of marine ecosystem health and the importance of toheroa as a customary food of Māori. Ongoing conservation concern for toheroa in Southland stems mainly from severe decline in the population at Bluecliffs Beach since the 1960s due to beach erosion. These declines force greater emphasis on securing the Oreti Beach and newly discovered[2] Orepuki Beach populations for customary use and ecological conservation. Numbers are lower now at Oreti Beach than in the 1970s, but the habitat appears relatively stable and toheroa numbers have been approximately steady or even increasing slightly in the past decade[3]. The establishment of a mātaitai[4] on Oreti Beach in 2010 in part reflects the importance placed on maintaining the health of toheroa, a taonga (treasured species) of the local kaitiaki (Māori environmental guardians).

Superbly thorough and standardised population monitoring at Oreti Beach has been conducted at 3-4 year intervals since 1998 by NIWA researchers and funded by the Ministry of Fisheries[5]. These surveys provide excellent baselines from which the success of future restoration actions can be assessed. Now that robust monitoring techniques are in place and have quantified historical

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[1] Good overviews of the biology and ecology of toheroa are provided by Rapson (1952), Cassie (1955), Redfearn (1974), Beentjes et al. (2006) and Williams et al. (2013).

[2] The population there has been well known to locals and apparently originated from translocation by the kaitiaki in the 1950s (Futter & Moller 2009). It was recently surveyed and found to have a dense though not extensive breeding bed, the overall population size being about a third of that remaining at Bluecliffs Beach.

[3] Beentjes & Gilbert (2006b).

[4] Mātaitai are Māori community led customary fishing reserves that were created under the Treaty of Waitangi (Fisheries Claims) Settlement Act 1992 (better known as the 'Sealord's Deal'). However, reserves could not be established until the South Island Customary Fishing Regulations were gazetted in 1998.

[5] Carbines & Breen (1999); Beentjes et al. (2003); Beentjes & Gilbert (2006b), Beentjes (2010a).

declines, the kaitiaki wish to identify the main threats to toheroa and consider options for intervention and restoration. In common with many shellfish populations, toheroa recruitment of the spat are sporadic and sometimes do not result in recruitment to the breeding population[6]. The reasons for these cohorts' failed recruitment are poorly understood, but it has been suggested that poor growth and survival resulting from insufficient phytoplankton and other organic food particles[7] may contribute.

Crushing by vehicle traffic has been mooted as a potential threat to toheroa, but reliable scientific measures of its putative importance are lacking. An extremely brief study of a small toheroa bed on Ninety Mile Beach (Northland/Taitokerau) in 1998 estimated that 14% of the juveniles[8] were crushed by vehicles[9]. However, only three 1 $m^2$ quadrats were sampled during that study, and the traffic at the time was unusually heavy because of a fishing competition. Interviews with the kaitiaki and knowledgeable locals in Southland recently also identified vehicle traffic, especially on Oreti Beach, as potentially posing a threat to population recruitment[10].

Oreti Beach is enjoyed by many thousands of residents and visitors to Southland[11]. Many people drive their cars, utilities and motorbikes a considerable distance along the beach because it is readily accessible and the sand is reasonably firm and gently sloping. Whether they be swimming, picnicing, fishing or just sight-seeing, driving along the beach and sheltering in or near their vehicle is clearly an important part of peoples' recreation and enjoyment of Oreti Beach. Recreational tourism at Oreti Beach is also economically important for Southland. For example, hundreds of motorbike enthusiasts from around New Zealand congregate in Southland for the New Zealand Beach Racing Championship motorbike races as part of the *Burt Munro Challenge* week[12].

The importance of Oreti Beach for local recreation, tourism and the maintenance of a strong toheroa population raise the prospect of potential conflict concerning the use of the beach. It is therefore paramount that reliable scientific estimates of the impact of vehicle traffic on toheroa recruitment are made as a first step to considering mitigation options should significant risk to toheroa recruitment be demonstrated.

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[6] Williams et al., (2013).

[7] Marine ecologists call these particles the 'seston' (Gardner 2008).

[8] Juvenile toheroa are defined as less than 40 mm in shell length. Sub-adults are 40-99 mm and adults are greater than 100 mm.

[9] Hooker & Redfearn (1998).

[10] Futter & Moller (2009).

[11] See Scott et al. (2014) for a study of recreational use of Oreti Beach.

[12] www.burtmunrochallenge.com/

## 2. Aims of this research

The specific aims and research path of the research described in this report were to:

1. Improve accuracy of existing measures of risk posed to juvenile toheroa each time they are run over by a vehicle.
2. Combine these measures of risk with year round estimates of the vehicle traffic streams to construct a model that predicts the proportion of toheroa recruitment blocked by vehicles in different parts of Oreti Beach and for the entire toheroa colony.
3. Evaluate the evidence of vehicle impacts on the toheroa population and consider potential options to mitigate the impact.

## 3. Study area and Methods

Oreti Beach is 29 km long, running southeast to northwest. It has a main vehicle entrance, at Dunns Rd., is situated 10 km from central Invercargill city (Figure 1)[13]. The beach is a gently sloping fine-sand beach with scattered and small areas of gravels and cobbles. The width of the beach (from high to low in spring tides) averages 210 m and the tidal fall is 1.2 – 1.3 m below mean sea level[14]. Toheroa are found over about 18 km of the beach, spread from near the Oreti River outflow in the southeast to the Waimatuku Stream in the northwest (Figure 2). For this reason we concentrated our study of recreation on Oreti Beach on this same 18 km stretch.

Our research aims were realised from the following steps (which also provide a roadmap for the structure of this report):

1. Measurement of the proportion of juvenile (<40 mm long) toheroa damaged when run over by a single pass of a vehicle (Section 3.1).
2. Counting the number and type of vehicle encountered on Oreti Beach throughout the year. These observations are described in much more detail in a separate companion report by Scott et al. (2014), but salient findings are described in Section 3.2 of this report.
3. Plotting the positions of stationary vehicles, turning circle marks left on the beach, and interview data to estimate the relative strength of three traffic streams (Section 3.3.2) and the distance 'along' the beach they travelled before turning back to leave via the way they entered the beach (Section 3.3.3).

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[13] Throughout this report we refer to this as 'Main Entrance'.

[14] Beentjes & Gilbert (2006b).

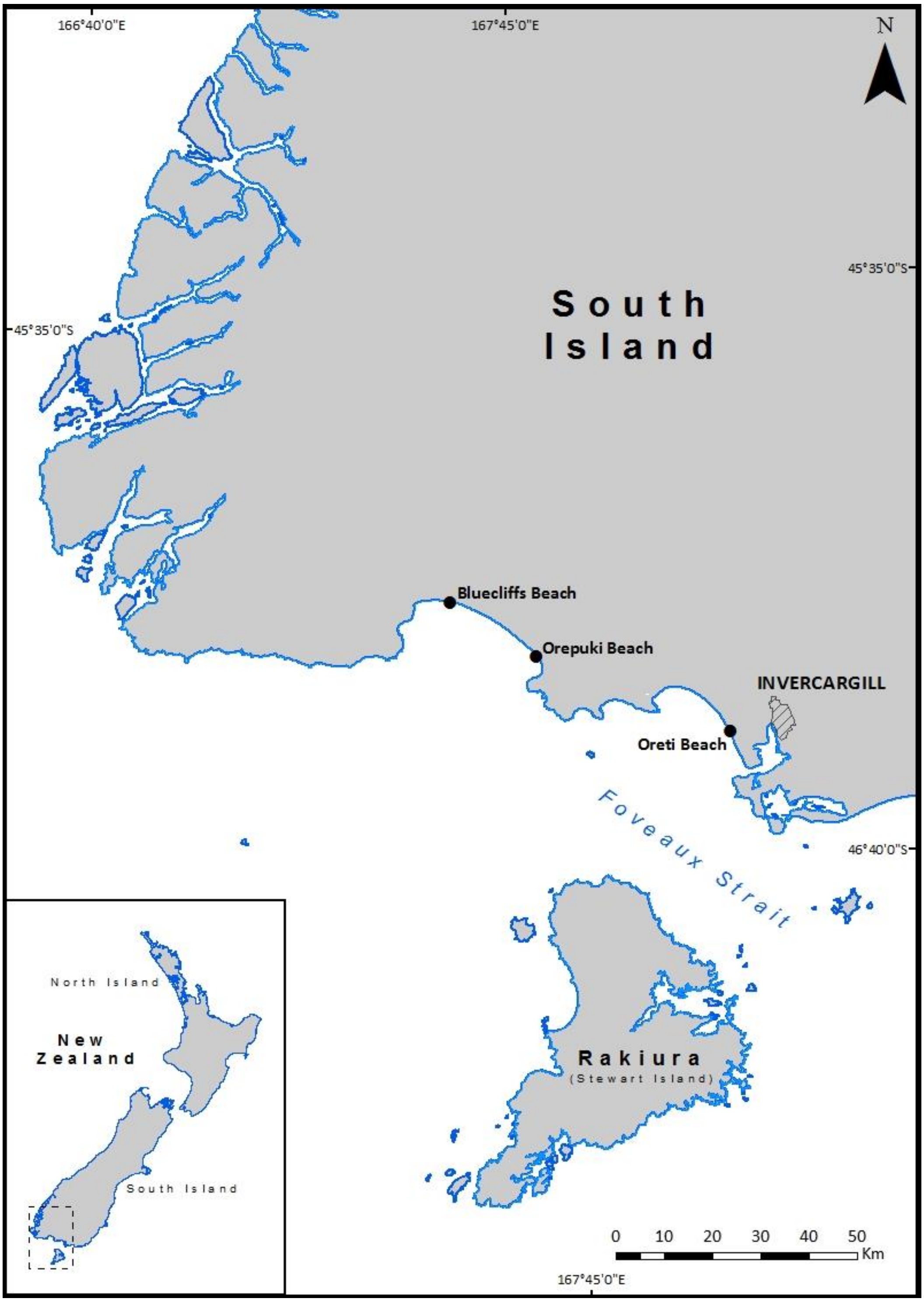

*Figure 1: Location of the Toheroa study area and two other nearby colonies of Toheroa at Bluecliffs Beach and Orepuki Beach.*

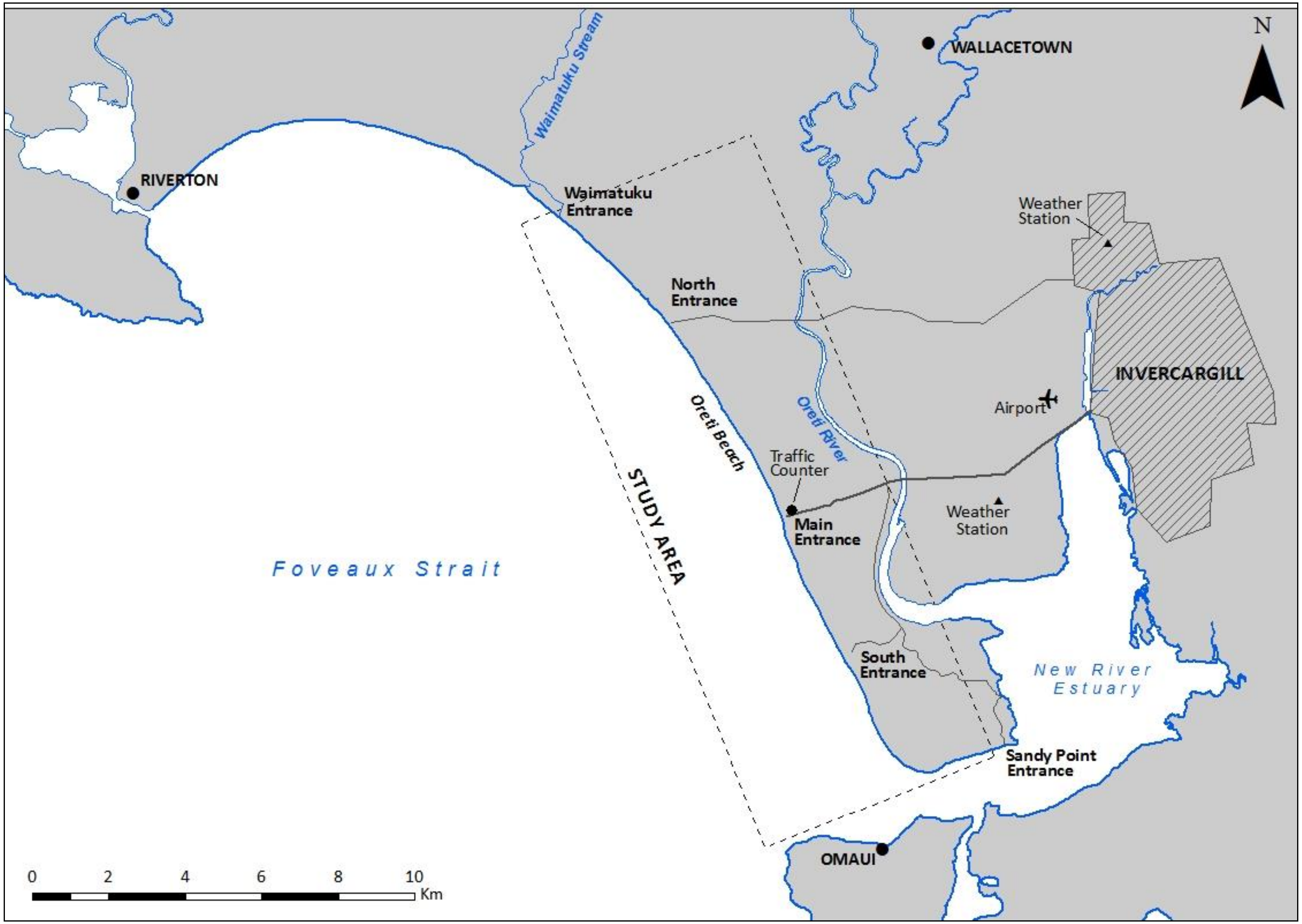

*Figure 2: A map of the Oreti Beach study area.*

4. Plotting the position of all encountered moving vehicles ‘down’ (between the dunes and low tide) and dividing traffic flow along the beach into 5m swathes down from the dune line (section 3.3.4).
5. Multiplying the proportion of the vehicles in each type and traffic stream by the total number of vehicles passing an automatic traffic counter at Main Entrance every 10 minutes for two years to estimate the average number of vehicles visiting each 20 m section along Oreti Beach (Section 3.3.5). The passes along the beach were then further divided into the proportion occurring at each level down the beach (#4) to estimate the average number of vehicles passing over every 20 x 5 m pixel of the study area.
6. Multiplying the risk per pass (#1 above) by the predicted total number of passes (from #5) to provide an estimate the proportion of juveniles killed in each pixel by each type of vehicle in each month and for the whole year (Section 4).
7. Testing the model by seeing if it predicted variation in the abundance of adults and juveniles along Oreti Beach as measured in three surveys by NIWA in 2002, 2005 and 2009 (Section 4.2).
8. Testing the model by seeing if it predicted the change in abundance of juveniles down the beach in areas of heavy traffic flow (near Main Entrance) compared to low traffic flow (Section 4.3).
9. Predicting future impacts on toheroa recruitment by scaling the number of vehicle visits observed in this study by the percentage increase expected in vehicle registrations in New Zealand (Section 4.6).
10. Assessing the impact of vehicles on toheroa recruitment (Section 5) by combining all the available data from (i) interviews with kaitiaki[15], (ii) historical surveys of abundance performed by NIWA, (iii) estimates of the impact of the 2008 Burt Munro Challenge motorbike races[16], and (iv) the field observations and model of traffic on Oreti Beach (this study).
11. Proposing some management options for consideration by all stakeholders for reducing the threat of motor vehicles to recruitment and resilience of the Oreti Beach toheroa population (Section 5.6).

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[15] Described by Futter & Moller (2009).

[16] Estimated by Moller et al. (2009).

## 3.1 Measurement of risk to juvenile toheroa when run over by a vehicle

A preliminary study in April 2009 measured the proportion of experimentally translocated juvenile toheroa that were damaged when run over by a test car, two utilities/4WDs[17] and a motorbike[18]. We collected juvenile toheroa as they drifted in the high tide zone or as they tried to rebury themselves in the sand. They were then placed in lines on wet sand just above the ebbing tide line and allowed to rebury themselves before being run over by research vehicles moving at 30 km per hour. These translocated animals were then dug up and closely examined for cracks and measured. We refer to the proportion of toheroa damaged in these trials as a '*translocation* risk measure' in this report.

Experimental translocation of juveniles to test areas saved a lot of research time by avoiding the need to dig large quantities of sand and also controlled for some of the variables that could affect damage frequencies[19]. However translocation may also have introduced potential biases:

- Translocated individuals may not have burrowed into the sand to the same degree when experimentally placed in lines or quadrats just above the falling tide
- Animals found drifting in the tide may have been qualitatively different from ones remaining buried in ways that made them less or more vulnerable to being damaged in the experimental sites.
- Features of the microhabitats chosen for transplanting experiments may not have been fully representative of the types of micro-habitats where toheroa become naturally concentrated on the beach.

Accordingly, our follow-up study in 2012 measured injuries to naturally buried rather than translocated juveniles to cross-check that the above potential biases had not confounded the preliminary results. We also sought larger sample sizes to improve the statistical accuracy of the estimated risk of damage per vehicle pass. The proportion damaged amongst juveniles recovered from digging stretches of sand where they had naturally buried is referred to as an '*in situ* risk measure' in this report.

For the 2012 *in situ* risk measures, 15 to 30 m sections of Oreti Beach were run over by a car and ute/4WD travelling in a straight line at 30 km per hour[20]. We did the trials in a remote part of the

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[17] Utilities and four-wheel drive vehicles (Off-road vehicles) were combined in our analysis and hereafter are refered to as "utes/4WDs".
[18] See Moller et al. (2009) for a detailed description of methods and results.
[19] Transplantation of intact juveniles ensured that prior damage from being run over by previous vehicle passes could be eliminated and enabled tighter statistical control of replication and stratification of impact trials in different parts of the beach and by different vehicles.

southern end of the beach in order to reduce the chance that another vehicle had driven over the same stretch of sand in the last month. The test vehicles were driven over sand 20 – 90 minutes after it was last covered by the receding tide. The sand was only run over once in most treatments. However, Northland studies have highlighted that repeated traffic over the same spot may pose additional risk to the toheroa[21]. It is hypothesised that vibration and/or the semi-liquification of the sand profile stimulates the toheroa to move closer to the surface[22]. As in the preliminary trials, we tested for the increased mortality from multiple passes by running down the same tyre tracks five times in a 20-30 minute period before digging up any juveniles under the transect.

After each treatment, the top 100 mm of sand along the tyre marks was dug up and sieved. We took care to insert the spade horizontally starting at > 100 mm below the surface[23] and then lift each section of the sand carefully on a spade so that damage by the spade itself did not occur. Also, we used our hands to separate and gently discard the sand outside the tyre mark itself so that toheroa that had lain just outside the tyre line were not included in the inspections for damage. Each juvenile toheroa recovered was measured and instances of cracks, chips along the edge or displaced valves were recorded[24].

We also repeated some translocation experiments in this 2012 follow-up study to test whether methodological biases distort the earlier data[25]. As before, we collected samples drifting in high sections of the beach in the two hours before high tide and placed them in experimental marked quadrats just above the next receding tide. Any individuals that had not re-buried themselves within 10 minutes were discarded. Each quadrat was then run over 20-30 minutes later by one of the test vehicles, either once or five times according to treatment.

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[20] The same car and model of ute/4WD as used in the preliminary trials were used in this follow-up study (they were referred to as 'A' and 'B' by Moller et al. 2009).

[21] Redfern (1974); Brunton (1978); Morrison & Parkinson (2001).

[22] It is also possible that pooling of water following the pass of the vehicle causes toheroa to become oriented side-on rather than their natural vertical position. Any following vehicle is therefore more likely to run over it (the side on profile is bigger), the animal is closer to the surface, and the animal is not firmly supported by surrounding sand.

[23] A deeper hole was dig at the start of the tyre track to allow horizontal insertion of the spade in successive 'bites' along the track.

[24] See Figure 13 of Moller et al. (2009) for examples of the type of damage found.

[25] The only substantive difference in methods between the preliminary (April 2009) and this study was that translocated toheroa were allowed to rebury within the 0.5 x 1 m metal quadrats used for toheroa population surveys (see Figure 6a of Moller et al. 2009). The high metal sides of the quadrat were used to chorale the individuals placed on top of the sand so that they buried themselves within a demarked area which we then drove over with the test vehicles.

Altogether we recovered 2,566 juvenile toheroa from 87 trials that had been run over by test vehicles in both surveys combined (Table 1). Just under half of these were recovered from under test vehicle tracks over undisturbed sand for the *in situ* risk measurement method in 2012.

First we tested whether the proportion of toheroa damaged varied significantly with vehicle type, number of vehicle passes (single vs. 5-passes), level on the beach (top 10 m below high tide marks cf. mid and lower areas[26]) and measurement method (*in situ* cf. *translocation*)[27]. There was no evidence that level on the beach affected damage rates, but statistically significant differences were detected for all other factors. Therefore we rebuilt the statistical model without level on the beach as a factor.

*Table 1: Number of juvenile toheroa recovered to measure proportion damaged when run over by test vehicles in 2009 and 2012. The number of separate trials (transects, quadrats or tracks) is given in brackets.*

| **Treatment** | | **2009** | **2012** | | **Both Surveys** |
|---|---|---|---|---|---|
| ***Vehicle Type*** | ***Vehicle Passes*** | *Translocation risk measures* | *In situ risk measures* | *Translocation risk measures* | *All risk measures* |
| **Car** | 1 | 65 (10) | 466 (15) | 216 (4) | 747 (29) |
| | 5 | | | 86 (2) | 86 (2) |
| **Ute/4WD** | 1 | 118 (12) | 513 (8) | 272 (4) | 903 (24) |
| | 5 | 48 (5) | | 119 (3) | 167 (8) |
| **Motorbike** | 1 | 59 (6) | 344 (11) | 260 (7) | 663 (24) |
| **All vehicle types** | All | 290 (13) | 1323 (34) | 953 (20) | 2566 (87) |

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[26] A small number of the 2009 transects in the top 10 m of the beach showed significantly higher damage rates than further down the beach. The sand in the top strip was conspicuously softer and the test vehicles left a deeper wheel rut than when driven on firmer sand.

[27] We used a Generalised Linear Mixed Model with an underlying logistic probability function to account for the binomial nature of the test (damaged vs intact). The survey year was added as a random effect because we used a different ute/4WD and a different motorbike for the 2012 trials than in 2009.

Altogether 32 (15%) of the pooled sample of 253 juveniles that had been run over 5 times were damaged, compared to 60 (5%) of 990 juveniles run over just once. If the probability of being damaged was independent of the previous pass of the vehicle, we would expect the survival rate from a single pass (0.95) raised to the power of 5 (=0.78) to be damaged after 5 passes, and therefore 22% to be damaged in the trials with 5 passes. In fact only 15% were found to be damaged after 5 passes, so there is no evidence that multiple passes triggered a higher damage rate from vehicles following close behind. Individual toheroa may vary in their vulnerability (perhaps relating to the depth they are buried or undulations in the sand) so that successive passes actually kill fewer toheroa than on the first pass over a given stretch of sand? However there were too few trials with 5 passes in our study, and treatments were not formally balanced, so reliable testing of any effect of number of vehicle passes on risk to toheroa requires further research. We conclude in the meantime that number of passes does not affect cumulative damage rates and our model of vehicle impacts ignores the number of times the same piece of beach has been run over by a vehicle in quick succession.

We cross-checked whether any change in size of juvenile toheroa between the 2009 and 2012 damage trials could explain the observed difference between the study methods. The average size of damaged and undamaged specimens was almost exactly the same, so there was no evidence that size within the juvenile stage affects risk from vehicles.

Accordingly, we then simplified and rebuilt the statistical model a third time without the data for 5 passes included and retaining the experimental method as an explanatory variable. This reconfirmed that the *translocation* method measured higher rates of damage than *in situ* experiments (p=0.019) and that utes/4WDs had lower risk than cars and motorbikes (p<0.001)[28]. About 4% of juvenile toheroa that are run over *in situ* by a motorbike or a car are damaged, whereas the risk per pass of a utility/4WD was about 2% (Table 2). *In situ* risk measurements will be more representative of the actual rates of damage to juvenile toheroa on Oreti Beach, so we have used them in the model to predict added mortality over the entire beach.

In view of the bias introduced by *translocation*, we recommend that all future studies use the *in situ* method for estimating risk even though it is enormously more time consuming and therefore delivers lower statistical power.

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[28] The GLMM also found that the interaction between experimental method and vehicle type effects was not statistically significant (p=0.461).

*Table 2: Proportion of juvenile toheroa that were damaged during one pass by different vehicle types. The 95% confidence intervals given in brackets are estimated by the GLMM.*

| Vehicle Type | In situ | Translocation |
|---|---|---|
| **Car** | 0.043<br>(0.025-0.061) | 0.065<br>(0.035-0.103) |
| **Ute/4WD** | 0.0195<br>(0.010-0.036) | 0.031<br>(0.017-0.051) |
| **Motorbike** | 0.041<br>(0.023-0.067) | 0.098<br>(0.067-0.14) |

## 3.2 Vehicle use of Oreti Beach

### 3.2.1 Vehicle visits measured by a traffic counter

An automatic traffic counter[29] was placed on the last stretch of the road near "Main Entrance" (Dunns Road) before it reaches Oreti Beach (Figure 2) between 7th April 2010 and 11th April 2012[30]. An electrical loop buried in the tar-sealed road counted the number of vehicles travelling west (towards the beach) or east (towards Invercargill) every 5 minutes. There is also a very rough (impassable for vehicles but used by pedestrians and horses) "South Entrance", 4 km south of Dunns Road) and a slightly more used "North Entrance", 6 km north of Main Entrance. Infrequent traffic enters the study area from the northwest by crossing the Waimatuku Stream[31] or the extreme south via the "Sandy Point Entrance" (Figure 2).

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[29] The counter was a MetroCount™ MC5805 Loop Counter (MC5800 Series RSUs, August 2008). It was programmed with a 'debounce time' so that the second axil of passing vehicle was discounted. Gama Rajapaksa checked the number of passing vehicles against the number of passes registered each time he tended the traffic counter to download data and change batteries (every one to two months). There was a perfect correspondence between the count and the number of observed periods. The sensitivity of the device was set to record passes by all motor vehicles, including motorbikes, but not trailers.

[30] Vehicle counts were missing from one lane during most of the first week in December 2010 when a roading contractor disrupted the loop; and for a day in September 2010 and a week in May 2011 when batteries failed. We did not need the eastbound data missing from December 2010 as we only used westbound counts. Estimates for the day in September 2010 and week in May 2011 when the battery failed were obtained by substituting the average number of vehicles entering at the same time of the day in the three days before and after each gap.

[31] These are mainly four-wheeled drive utilities or motorbikes that have travelled all the way along Oreti Beach from Riverton.

Most drivers that we interviewed within the study area entered via Main Entrance and stated that they intended to leave the same way[32]. Comparisons of vehicle numbers encountered near the two entrances suggest that approximately 4% of the vehicles visiting Oreti Beach came on via North Entrance and therefore were missed entirely by the automatic traffic counter[33].

We estimate that the total number of vehicles visiting Oreti Beach via the Main Entrance between 10 April 2010 and 9 April 2011 was 96,088; and that 90,859 vehicles visited between 10 April 2011 and 9 April 2012. This gives an average of 256 vehicles per day visiting Oreti Beach via Main Entrance over the two years of the study. The number of vehicles per day varied between 42 and 1587[34].

The average number of vehicles visiting Oreti Beach per day varied seasonally, being lowest in the colder months (May to September) and highest in late spring and summer (Figure 3). Our models of seasonal variation in vehicle impacts used the average monthly number of visits in our two year study (bars in Figure 3).

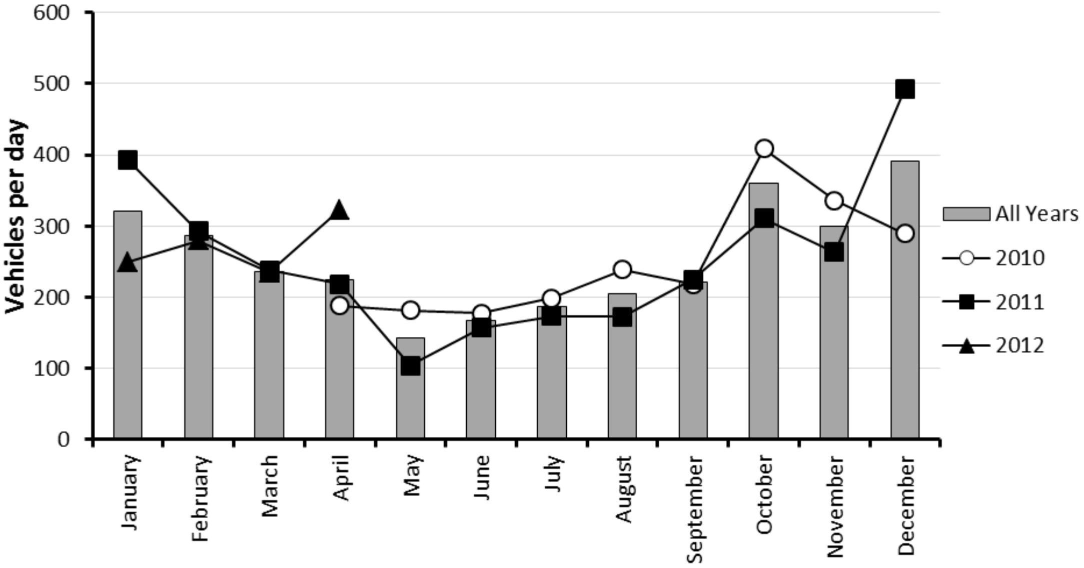

*Figure 3: Average number of vehicles per day, as recorded by traffic counter, entering Oreti Beach via Main Entrance in each month of the study.*

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[32] See Figure 17 of Scott et al. (2014).

[33] Scott et al. (2014).

[34] See Scott et al. (2014) for a more detailed analysis of vehicle variation according to day of week, time of day, tide and climatic factors.

### 3.2.2 Observations of vehicle movements on Oreti Beach

We counted and recorded the locations and activity of all vehicles and people encountered while travelling by motorbike in 36-km-long ‘circuits’ of the complete study area. We rode onto the beach at Main Entrance, then along to one end[35], back and past Main Entrance to the other end, and then back again and out Main Entrance.

The first circuit was on 18 January 2011, the last on 14 January 2012. The circuits were concentrated in times of the year when we expected most activity and vehicles on the beach, while retaining some sampling at all seasons and times of the week to understand year round variation in use of the beach. We performed three circuits during daylight on most ‘sampling days’: one starting near the high tide time; one about mid tide; and one close to low tide time. Sampling days were performed on a Saturday, Sunday and a randomly selected weekday in each ‘sampling week’ because most visits occurred in weekend days. We aimed for three sampling weeks per month in the warmer and ‘peak’ visiting season; two sampling weeks per month in the ‘shoulder’ months; and one sampling week per month in the ‘low’ visitor season[36]. Altogether 196 circuits were distributed over 73 sampling days[37].

The following were recorded during each circuit:

- Locations (using a hand-held GPS)[38] of stationary vehicles in a single pass “along the beach” (i.e. distance from Main Entrance running south or north) to provide random encounter positions. We plotted the location of these stationary vehicles only on the way out from Main Entrance (never on the return) to avoid double-counting.
- Locations (using a hand-held GPS) of moving vehicles “down the beach” (i.e. between the dune line and water level) at the first encounter of each vehicle. We gathered these locations of moving vehicles on both the outward (from Main Entrance) and return loop (travelling back towards Main Entrance).

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[35] We alternated whether we first turned south or north in successive circuits.

[36] Peak season: Dec, Jan, Feb, Mar; Shoulder season: Apr, May, Oct, Nov; Low season: Jun, Jul, Aug, Sept.

[37] See Table 1 of Scott et al. (2014) for more detail on the seasonal distribution of field observations.

[38] Garmin GPSmap76CSx, accurate to 3-5m.

- Interviews of beach users at their stationary vehicle. Most questions related to beach use[39], but they were also asked about the beach entrance that they used and where they intended to exit the beach.
- Locations of all turning circles left on the sand, or observed as the vehicle turned to return back the way they had come.
- Other measures relating to recreational use of Oreti Beach, including locations and activities of people, interviews with flounder and toheroa fishers, locations of "doughnuts"[40].

Vehicles have been classified into three main groups for the purposes of this study:

- Cars (including vans)
- Utilities and four-wheel-drives (utes/4WDs)
- Motorbikes

A number of other types of vehicles were encountered (buses, pushbikes, horses, sulkies, blow carts, caravans and a mobility scooter). These represented only 5% of 'vehicles' using Oreti Beach and have been excluded from consideration. Similarly the impacts of trailers being towed by cars, Utes/4WDs and vans have not been considered.

### 3.2.3 GIS and Distance Calculations

Spatial analyses and map production were carried out in ArcGIS 10.1 using the New Zealand Transverse Mercator projection.

To calculate the distance of each GPS data point down the beach (seaward from the sand dunes), the dune margin was first digitised at a scale of 1:10,000 from Bing Satellite Imagery of the study area captured in March 2008. Using the 'Near' tool in ArcGIS, the down the beach distance from each data point to this dune line was calculated.

The along the beach (dune-parallel) distance between each data point and the Main Entrance (Dunns Road) was approximated by first dividing the dune margin into a series of straight segments to account for the curvature of the beach. All segments were 1000 m in length with the exception of the three southern-most segments which were shortened to 500 m, 250 m and 250 m segments to

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[39] See Scott et al. (2014).

[40] See Scott et al. (2014).

allow for the increased curvature of the beach as it turns towards in Sandy Point[41]. At each vertex, lines were constructed perpendicular to the dune line orientation, and shore-level points placed at 20 m intervals along these lines. The along the beach distance within each segment was measured as the distance between each corresponding point (e.g. 20 m, 40 m, 60 m). The distance between each GPS data point and the nearest shore-level point (towards Main Entrance) along the section-dividing lines was first calculated using the 'Near' tool within ArcGIS, and this measurement was then added to the cumulative distances along the beach at the appropriate shore level[42].

We checked for error from this method of approximating the along the beach distance by comparing it with the distance to the Main Entrance of ten randomly chosen points in the study area for which we determined the exact distance by tracing a shore-level line exactly parallel to the dune line at its distance down the beach. The differences between the accurate and approximate estimates for the along the beach distances of the ten points were trivial when scaled against an 18 km long study area (the average difference was just 5.2 m, equivalent to a 0.12% error[43]).

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[41] These smaller segments were used for calculating the along the beach travel distances, but they were combined into a combined segment S8 for all further analyses.

[42] For example, using the 'Near' tool, a data point in segment S4 may have been found to be 376 m from the nearest shore-level point (e.g. 120 m "contour") on the segment-dividing line between segments S3 and S4. The distances across the S3, S2 and S1 segments at the 120 m shore level are 1009, 1013 and 995 m respectively. Adding these to the distance within the S4 segment gives a dune-parallel distance of 3393 m for this point.

[43] The error in the 10 randomly chosen points ranged from 0 m (0%) to 15.3 m (0.34%). We also tested the errors for the most northern and most southern seaward points recorded in the entire study: they were 41 m (0.43 %) and 55 m (0.68%) respectively.

## 3.3 Modelling mortality of toheroa caused by vehicles

### 3.3.1 Predicting injuries to toheroa 'down' and 'along' Oreti Beach

Our model is constructed by interpretting the position and direction of movement of vehicles encountered on Oreti Beach during the circuits and extrapolation from the count of all vehicles detected by the automatic traffic counter at Main Entrance (Figure 2). The model used these estimates of traffic to estimate the number of vehicle passes and their cumulative addition of juvenile mortality for each 20 m (along) x 5 m (down) contiguous sections of the study area throughout a yearly cycle. Although technically the model deploys an array of contiguous sections of the entire beach, readers might prefer to think of the sections as 20 x 5 m 'pixels' in a picture that was 18 km long and 200 m wide (36,000 pixels in total).

During the course of the study, 3307 vehicles (stationary and moving) were observed on Oreti Beach. The majority (64%) of these vehicles were sighted within one kilometre north or south of Main Entrance and 77% occurred within two kilometres either side of Main Entrance (Figure 4). The distribution of vehicles was slightly skewed to the north, with only 4.7% of vehicles occurring beyond two kilometres south of Main Entrance compared to 18% in the area further than two kilometres north of Main Entrance. Small peaks in vehicle abundance are associated with the North Entrance and the Waimatuku Stream.

The distribution of stationary cars along Oreti Beach (Figure 5a) closely mirrors the distribution for all vehicles (Figure 4). However stationary cars were even more concentrated around Main Entrance, with 78% and 88% within one and two kilometres of the entrance respectively. Although utes/4WDs are also concentrated around Main Entrance (47% within 1 km, 65% within 2 km), they were more commonly sighted further along the beach than cars (Figure 5b). The distribution of motorbikes (Figure 5c) varies considerably from other vehicles, with observations being largely uniform throughout the beach north of Main Entrance. Very few motorbikes (7%) were observed south of Main Entrance. For some motorcyclists, the riding of motorbikes back and forth was the main recreational activity istself, rather than riders simply using the bike as a means of transport to and the beach for other activities. Altogether 87% of motorbikes were intercepted as moving vehicles, compared to 31% of all types of four-wheeled vehicles.

Utes/4WDs generally travelled considerably further away from Main Entrance, both to the north and south, with around twice the proportion travelling more than one kilometre compared to cars (Table 3). Utes/4WDs ranged more widely to the north of Main Entrance, with a small proportion even driving as far as the Waimatuku Stream to the north of North Entrance.

Cars entering Oreti Beach from North Entrance most commonly turned southward (57% of the time), whereas utes/4WDs predominantly turned northward (73% of the time). Almost all vehicles turning south from North Entrance travelled less than 1 km, whereas many of those turning north travelled a greater distance (Table 4).

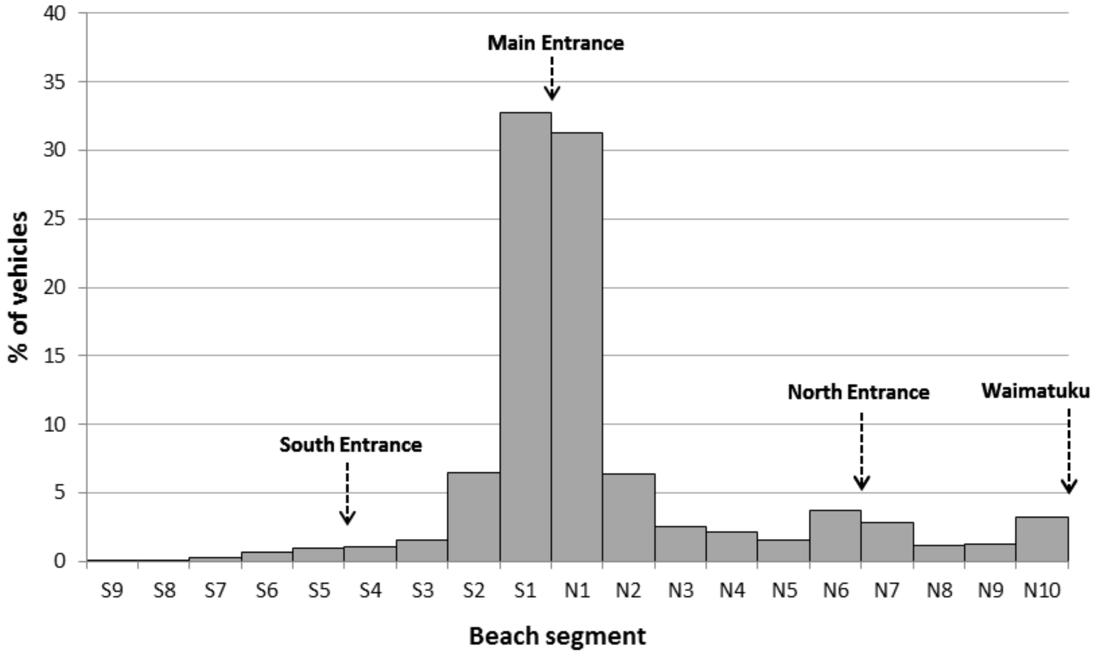

*Figure 4: Distribution of all observed vehicles on Oreti Beach during the course of the study. 'Beach segment' refers to kilometre divisions south (S) and north (N) of Main Entrance.*

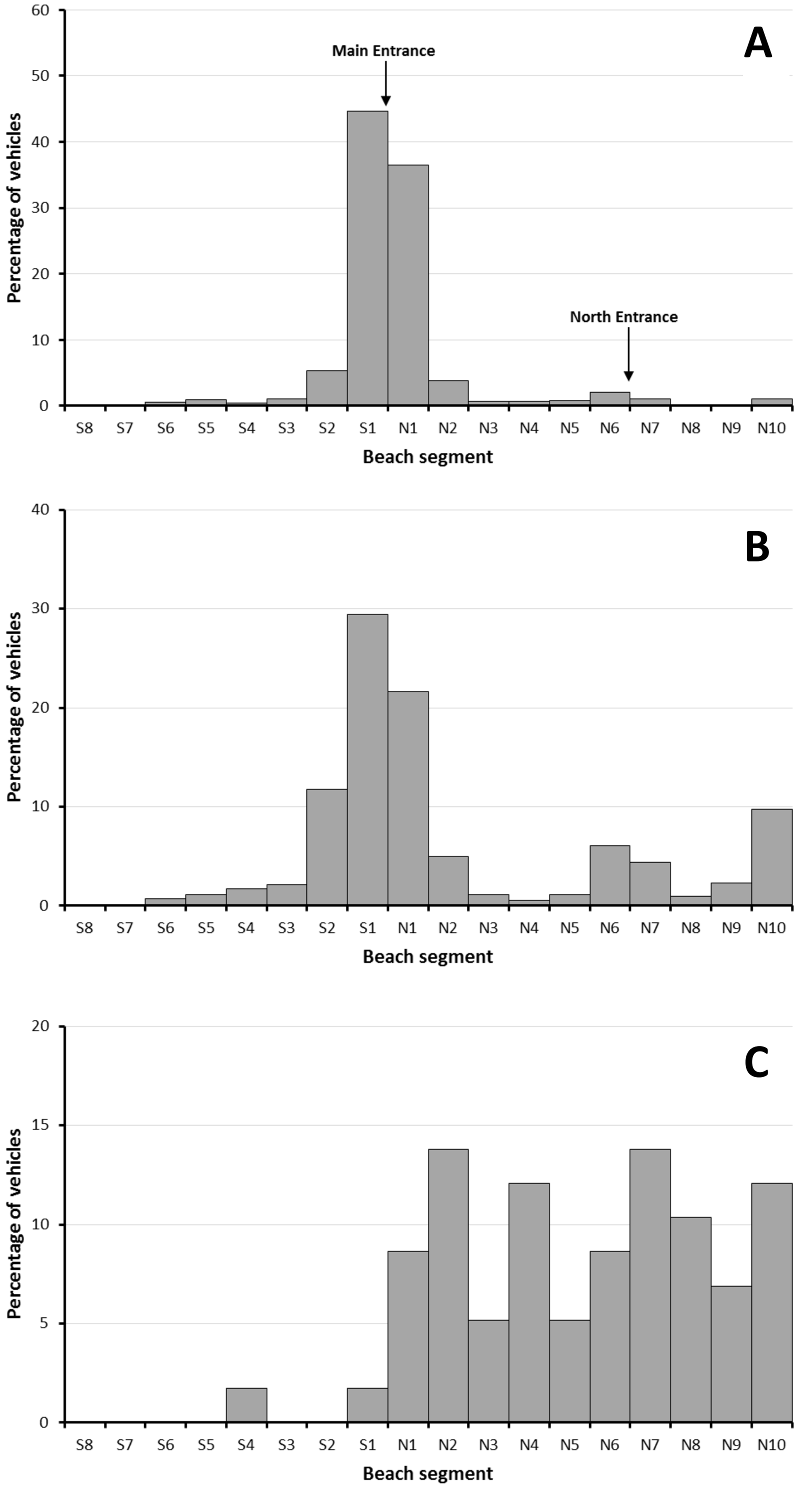

*Figure 5: Distribution of all observed a) stationary cars, b) stationary utes/4WDs and c) all motorbikes on Oreti Beach during the course of the study. 'Beach segment' refers to kilometre divisions south (S) and north (N) of Main Entrance.*

*Table 3: Summary of vehicle distribution north and south of Main Entrance.*

| | **Cars** | **Utes/4WDs** |
|---|---|---|
| ***Turning southward*** | | |
| Median distance (m) | 143 | 597 |
| Maximum distance (m) | 6321 | 6720 |
| Percentage travelling more than 1 km | 16 | 38 |
| Percentage travelling more than 2 km | 6 | 13 |
| ***Turning northward*** | | |
| Median distance (m) | 245 | 565 |
| Maximum distance (m) | 9756 | 9763 |
| Percentage travelling more than 1 km | 15 | 33 |
| Percentage travelling more than 2 km | 6 | 18 |

*Table 4: Summary of vehicle traffic north and south of North Entrance.*

| | **Cars** | **Utes/4WDs** |
|---|---|---|
| ***Turning southward*** | | |
| Median distance (m) | 177 | 141 |
| Maximum distance (m) | 2950 | 2890 |
| Percentage travelling more than 1 km | 2.9 | 3.6 |
| Percentage travelling more than 2 km | 1.1 | 0.2 |
| ***Turning northward*** | | |
| Median distance (m) | 1762 | 3175 |
| Maximum distance (m) | 3750 | 3790 |
| Percentage travelling more than 1 km | 57.6 | 74.0 |
| Percentage travelling more than 2 km | 48.5 | 69.1 |

### 3.3.2 Modelling traffic flow as three separate streams

Prediction of the percentage of juvenile toheroa killed by each type of vehicle in each pixel required division of the traffic into three streams and estimation of distances travelled by each stream which we then overlaid on each other:

- "*Main Entrance stream*": cars or utes/4WDs coming and going via Main Entrance. They are assumed to either park just by the entrance or make a single outward journey along the beach before turning once and returning to leave via Main Entrance.
- "*North Entrance stream*": cars or utes/4WDs coming and going via North Entrance. They are assumed to park by the North Entrance, or venture outwards in a single return journey before leaving via North Entrance.
- "*Motorbike stream*": Many bikes turn multiple times and stop only occasionally, so a single return trip model of the type used for four-wheeled vehicles cannot be applied for motorcycles[44]. Instead we estimated the overall distance travelled by motorbikes as they continuously cruised north and south along the beach.

A very small number of vehicles[45] enter the study area over the Waimatuku Stream and have henceforth been omitted in the simulations. Based on interviews of beach users, we found that a small proportion of the vehicles entering via Main Entrance leave via North Entrance, and vice versa[46]. We have assumed that these single passes along the beach in opposite directions about cancel each other out and consider that our simplified conceptualisation of the stream models as all being return trips has introduced a very slight underestimation of distances travelled along the beach and subsequent damage to juvenile toheroa.

We have estimated (i) the proportion of traffic in each stream, (ii) the proportion of each turning north cf. south at each entrance, and (iii) the average distance travelled along the beach by vehicles in each of these flows by analysing the positions of stationary cars and utes/4WDs only (Figure 5). Had we included the distribution of moving vehicles we would certainly have greatly underestimated average trip distance on the beach. Some of the stationary vehicles may have continued further along the beach from where we saw them stopped, so the model will still underestimate trip distance and present a minimal impact scenario.

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[44] Riding itself is the main pleasure in the activity rather than the destination itself. Also sometimes motorbikes are carted onto the beach on a trailer or utility rather than driving there like all other vehicle types.

[45] Especially motorbikes and utilities/4WDs.

[46] See Figure 16 of Scott et al. (2014).

Vehicles parked above the tide line or just outside the entrance on Dunns Road[47] were counted as having “entered” Oreti Beach, even though they are subsequently excluded as posing zero risk to juvenile toheroa that occur from the high spring tide mark down to the low tide mark[48]. Many parked vehicles very close to Main Entrance, but we nevertheless used the GPS locations of each vehicle and our GIS to assign them to just the left or the right of a centre line running directly from the gap in the main dunes at the entrance perpendicular to the shoreline. Cars entering the beach actually sweep left or right in an arc, but we have simplified the model of their trajectory as a single path starting at the entrance’s centre line and running parallel to the shore along the beach.

All the vehicles observed stopped south of Main Entrance were assumed to have come from and to leave by Main Entrance. This is a safe simplification because only 2 of 42 interviewees that came on to the Beach via North entrance ventured south of Main Entrance and the number entering via North Entrance and turning south is overall about 3% of the two traffic streams combined. Estimating the number of vehicles turning right (northwards) at Main Entrances is more complicated because we first need to disentangle the encounters of vehicles entering the northern half of Oreti Beach via North Entrance (at the border of N6 and N7). For simplicity we have assumed that all the vehicles we encountered in N1-N2 (0 – 2 km north) were all part of the Main Entrance stream[49]. We then calculated the proportion of stationary vehicles found in N3, N4 and N5 (2 – 5 km north) from the proportion of four-wheeled turning circles found in the sand that turned back towards the Main entrance cf. back towards the North Entrance[50] (Table 5). The proportion of stationary vehicles from each stream in the remaining segments (N6 to N10) was estimated from the overall proportion of interviewees intercepted in this zone that said they came in via Main *cf.* North Entrance i.e. of 40 interviews conducted in segments N6-N10, 35 (87.5%) entered via North Entrance (Table 5).

On this basis we estimated that 95.9% of cars and 79.6% of utes/4WDs come onto Oreti Beach as part of the Main Entrance stream, compared to 4.1% and 20.4% respectively in the North Entrance stream (Table 6). A higher proportion of those vehicles going onto the beach via North Entrance are ute/4WDs (72.0%) than at Main Entrance (32.3%), probably because the North Entrance is often difficult to negotiate and sometimes totally blocked by wind-blown and loose sand.

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[47] Vehicles outside the beach were arbitrarily assigned a position on the dune baseline (0 m down the beach) in all quantification.

[48] This ensures that all vehicles counted by the automatic counter are accounted for in the model.

[49] This is a safe assumption because the Northern Entrance stream is only 7 % of that flowing from Main Entrance, and less than 5% of vehicles turning south go more than 2 km along the beach.

[50] We do not use the proportion of turning circle marks for N6 in the same way because they become overlain and confused close to each entrance.

*Table 5: Percentage of stationary vehicles assigned to Main Entrance stream and North Entrance stream according to one kilometre segments north of Main Entrance.*

| | **N1** | **N2** | **N3** | **N4** | **N5** | **N6 - N10** |
|---|---|---|---|---|---|---|
| **% Main Stream** | 100% | 100% | 100% | 97.6% | 94.7% | 12.5% |
| **% North Stream** | 0% | 0% | 0% | 2.4% | 5.3% | 87.5% |
| **Calculation method** | Assume all main | Assume all main | Turning circles | Turning circles | Turning circles | Interview data |

The same assignations of stationary vehicles to each traffic stream were used to divide the flow of each into southbound (turning left as they enter) and northbound (turning right) journeys. For example, we estimate the 55.2% of the cars turn south at Main Entrance and 44.8% turn northwards (Table 7); and 72.7% of the utes/4WDs turn northward at North Entrance, many of which are targeting travel as far as the Waimatuku Stream.

These counts of stationary vehicles estimate that automatic counts of vehicles entering via Main Entrance must be multiplied by 1.0756 to include the extra North Entrance traffic (Table 6)[51]. This leads to an estimate that 7.03% of the cars and utes/4WDs (pooled sample) on the beach come on via North Entrance.

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[51] Calculated by summing the multipliers for cars and utes/4WDs in the 2nd and 3rd to last columns.

Table 6: Traffic streams for each vehicle type and the multiplier used to estimate the number entering via North entrance from the automatic counter placed at Main Entrance.

| Vehicle Type | All interceptions and all activities | Number of stationary vehicles assigned to each stream | | Predicted percent of different vehicle types in each stream | | Multipliers used to estimate number of each type from automatic traffic counter at Main Entrance | | |
|---|---|---|---|---|---|---|---|---|
| | | Main Entrance Stream | North Entrance Stream | Main Entrance Stream | North Entrance Stream | Main Entrance Stream | North Entrance Stream | Motorbikes in both streams combined |
| Car | 1866<br>(58%) | 1326<br>(95.9%) | 56<br>(4.1%) | 1790<br>(62.1%) | 76<br>(22.8%) | 0.660 | 0.0267 | |
| Ute/4WD | 1170<br>(36%) | 559<br>(79.6%) | 143<br>(20.4%) | 932<br>(32.3%) | 238<br>(72.0%) | 0.323 | 0.0659 | |
| Motorbike (two-wheeled) | 61<br>(2%) | | | 49[†]<br>(1.7%) | 12[†]<br>(3.8%) | | | 0.0203[¥] |
| Other[‡] | 115<br>(4%) | | | 110<br>(3.8%) | 5<br>(1.4%) | | | |
| Total | 3212<br>(100%) | | | 2881<br>(100%) | 331<br>(100%) | | | |

[†] The percentage of motorbikes entering via North Entrance has been assumed to be the same as for utes/4WDs to estimate this figure.

[¥] One multiplier is used for motorbikes because they are not assigned to separate traffic streams.

[‡] 'Other vehicles' have been eliminated from the model altogether because they are too diverse to estimate risk to toheroa and overall make up a small proportion of visits.

Table 7. Splits of Main Entrance and North Entrance traffic streams into southbound and north bound journeys and the average distance travelled in return journeys along Oreti Beach.

| Vehicle Type | Parameter | Main Entrance Stream | | North Entrance Stream | | Combined Main & North Streams |
|---|---|---|---|---|---|---|
| | | Turning south | Turning north | Turning south | Turning north | |
| Cars | Proportions | 0.552 | 0.448 | 0.571 | 0.429 | |
| | Mean distance travelled along (m) | 516 | 615 | 322 | 2380 | 1173 |
| | Lower 95% ci distance travelled along (m) | 448 | 524 | 225 | 1724 | 995 |
| | Upper 95% ci distance travelled along (m) | 584 | 707 | 419 | 3036 | 1351 |
| Utilities / 4WDs | Proportions | 0.596 | 0.404 | 0.273 | 0.727 | |
| | Mean Distance travelled along (m) | 1016 | 1473 | 270 | 2462 | 2672 |
| | Lower 95% ci distance travelled along (m) | 882 | 1165 | 185 | 2199 | 2259 |
| | Upper 95% ci distance travelled (m) | 1149 | 1781 | 355 | 2725 | 3084 |

### 3.3.3 Estimating the distance travelled along the beach by cars and utes/4WDs

The proportion of vehicles that travel successively increasing 20 m distances south along the beach from Main Entrance was also estimated from the observed frequency distribution of the distance of parked cars from Main Entrance. A cumulative frequency distribution, expressed as a percentage, was calculated for all observed stopping points of four-wheeled vehicles heading either south or north from each entrance. We converted these data into a “reverse cumulative frequency distribution”. For example, for south bound traffic entering via Main Entrance, the cumulative frequency distribution was scaled from the extreme southeast end of the study area for each 20 m section along the beach back to Main Entrance. This reverse cumulative frequency distribution gives the proportion of the south turning Main Entrance traffic that passes over each 20 m length of the beach ranging out south of from Main Entrance (Figure 6). For example, 100% of the stream passes the first 20 m section south of Main Entrance; 50% of cars travel over every 20 m section as far as 140m m south from Main Entrance; just 10% venture along the first 1340m; and just one car (0.14%) of this stream passed over all the sections out to 6320 m south of Main Entrance before returning over the same length of sand (Figure 6).

The same approach was taken for northbound traffic from Main entrance except that the reverse cumulative frequency was scaled for every 20m section all the way from the Waimatuku Stream at the extreme northern end of the study area (Figure 6). For example, 25% of the utes/4WDs that turned right at Main Entrance and continued to 1520 m or beyond.

The North Entrance stream trip distances were calculated from the reverse cumulative frequencies of stationary vehicles for each 20 m segment of the beach in the same way as for the Main Entrance stream. The strong northward skew of the North Entrance stream is clearly evident, with 30% of the north turning traffic going all the way to the Waimatuku Stream (Figure 7). Although both cars and utes/4WDs travelled throughout the northern extent of the beach, utes/4WDs generally travelled further.

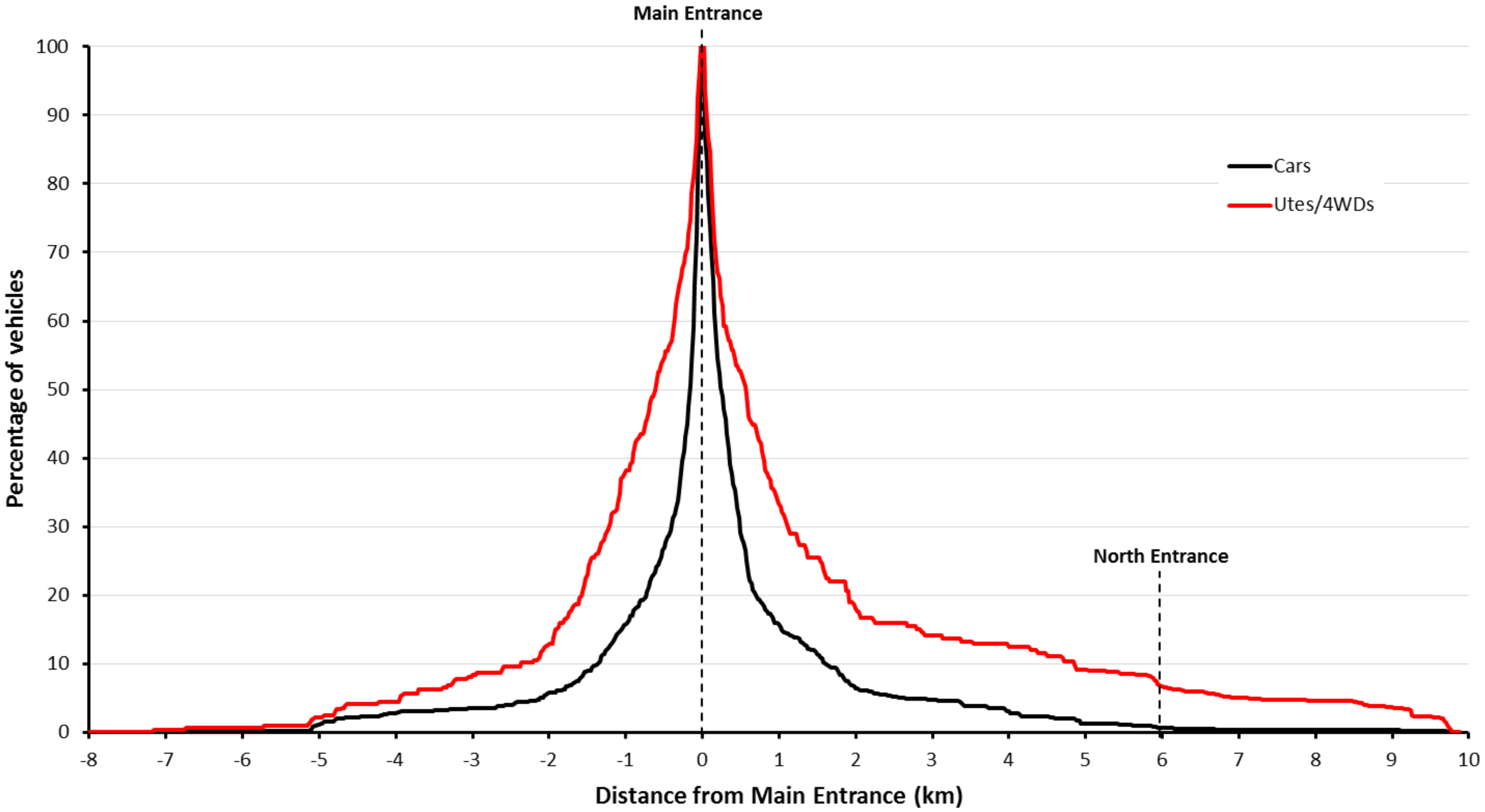

*Figure 6: Reverse cumulative frequency graphs for vehicles assigned to 'Main Entrance stream' south (-ve) and north (+ve) of Main Entrance ('0').*

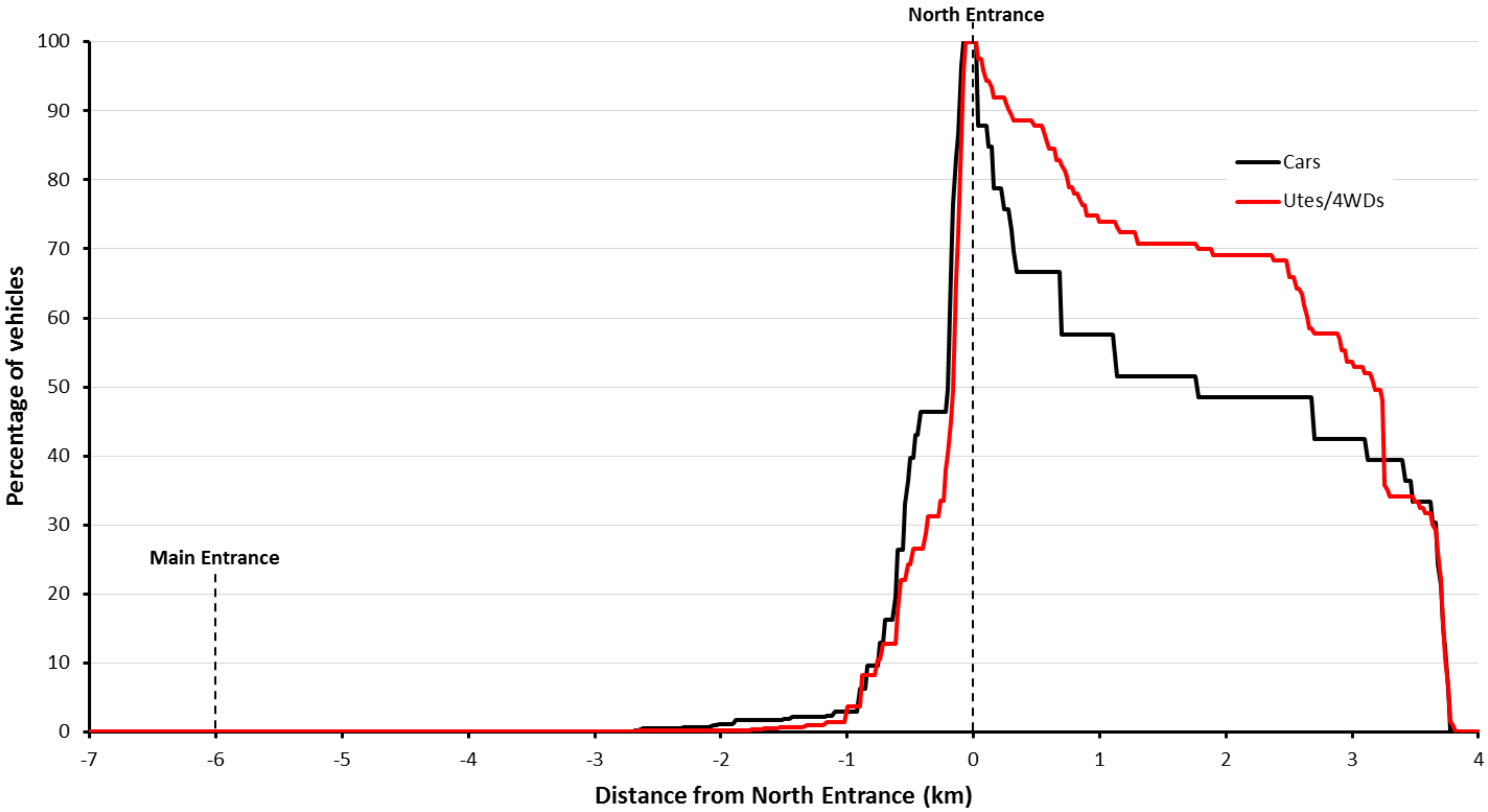

*Figure 7: Reverse cumulative frequency graphs for vehicles assigned to 'North Entrance stream' south (-ve) and north (+ve) of North Entrance ('0').*

### 3.3.3 Estimating the distance travelled along Oreti Beach by motorbikes

Motorbike impact was estimated by calculating the total distance run along the beach per visit. The latter was estimated by comparing the speed and continuity of movement of motorbikes with those of utes/4WDs and then multiplying the relative distance predicted for a motorbike by the estimated average distance travelled (return trips) per visit by a ute/4WD (Table 7). This method assumes that each visit by a motorbike and a ute/4WD lasted for about the same length of time on average.

Of 61 motorbikes observed during circuits, 93% were moving when first encounter by our observer. In sharp contrast, only 40% of encounters of utes/4WDs were of a moving vehicle. Accordingly we estimate that motorbikes spent 2.361 times more time moving than did utes/4WDs (Table 8). We had no formal estimates of the relative speed of utes/4WDs and motorbikes, but it was obvious that the latter usually drove much faster. Four field workers and two experienced managers from Environment Southland independently estimated the average ratio of the speed of motorbikes compared to utes/4WDs, as well as providing a lower and upper bound on their ratio estimates. There was reasonable agreement between the observers that motorbikes travel on average around 60% faster than the utes/4WDs, but uncertainty means this could have been as low as 30% faster, or as high as double the speed (Table 8). On this basis we estimate that motorbikes travel around 10 km on average per visit to Oreti Breach, but that it could have ranged from 7 to 15 Km.

Table 8: Estimation of Motorbike trip distances.

| Trip distance for Utilities/4WDs | | Relative Proportion time moving | Relative speed of Motorbikes compared to Utes/4WDs | Predicted average trip distance for Motorbikes |
|---|---|---|---|---|
| Mean Distance (M) | 2672 | 2.361 | 1.60 | 10,093 |
| Lower 95% ci Distance (M) | 2259 | 2.361 | 1.30 | 6,935 |
| Upper 95% ci Distance (M) | 3084 | 2.361 | 2.00 | 14,565 |

The distribution of motorbike encounters and their turning circles were pooled for each kilometre segment along the beach and a separate linear model fitted to the distributions south and north of Main Entrance (Figure 8). The distribution was variable, with little perceptible trend along the beach other than a step down in their occurrence south of Main Entrance. The estimated total distances moved by all motorbikes was then distributed across all 20m sections along the beach using the two regression lines depicted in Figure 8.

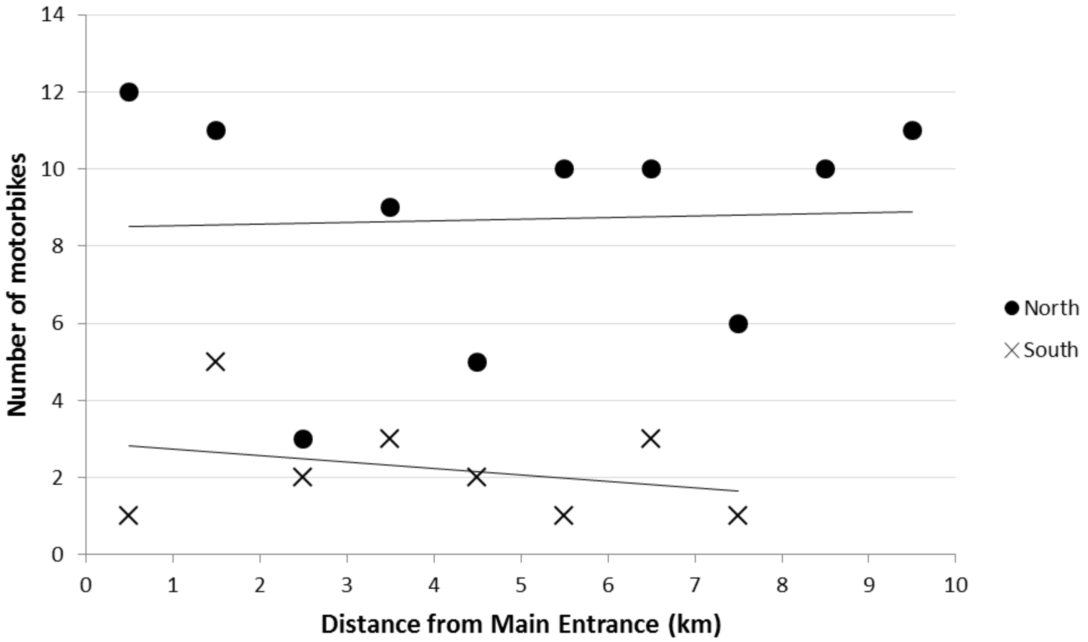

*Figure 8: Distribution of motorbikes (moving motorcycles and two-wheeled turning circles combined) along Oreti Beach, north and south of Main Entrance. The equations of the north and south model are $y = 0.0424x + 8.4879$ and $y = -0.1667x + 2.9167$ respectively.*

### 3.3.4 Distribution of traffic down the beach

The location “down” the beach (i.e. distance from the sand dunes) was estimated by GPS for each moving vehicle encountered randomly during the study period. Exploratory data analysis showed that the frequency distribution down the beach of cars (Figure 9a) and utes/4WDs (Figure 9b) was different in each one kilometre segment either side of Main Entrance (S1 cf. N1) and in the each outer flank (S2-S9 cf. N2-N10). Accordingly we have estimated separate functions for the proportion of these vehicles moving within each five metre slice down each of the four zones along Oreti Beach.

Most vehicles driving along Oreti Beach were concentrated in the upper part of the beach, within 50 m of the dunes (Figure 9a-c). Vehicles driving along the southern section of the beach (S2-S8) travelled lower down on the beach, presumably because the sand is harder and better for driving there.

Cars avoided the very soft sand around high tide mark, except in the vicinity of Main Entrance (Figure 9). A higher proportion of utes/4WDs and motorbikes tended to drive more in the soft upper reaches of the beach when further away from Main Entrance, presumably because they are less likely to get stuck than are cars.

Comparatively few motorbikes were encountered so we applied a single average distribution of motorbike passages across the full length of the study area (Figure 9C).

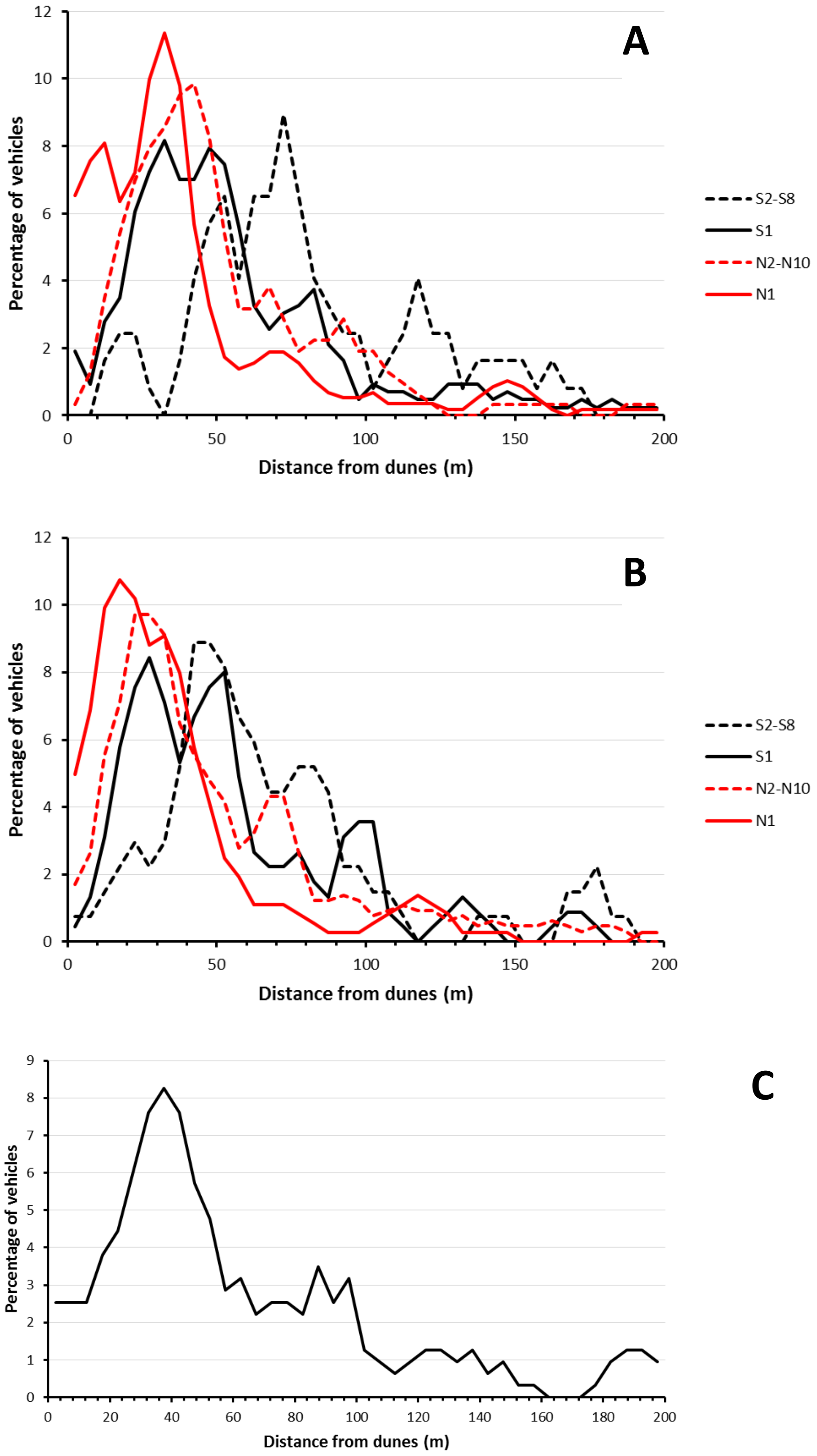

*Figure 9: Percentage of moving a) cars, b) utes/4WDs and c) motorbikes according to distance down beach.*

### 3.3.5 Model construction to predict added mortality from vehicles

A spreadsheet model can now be constructed to estimate the total proportion of juvenile toheroa killed in each pixel of the study area. Each pixel was allocated a cell within an Excel spreadsheet and the number of vehicles passing over it and the proportion of juveniles killed by them was estimated by the following steps:

i. Summing the observed number of vehicles passing the automatic counter to join the Main Entrance Stream in a given scenario period (we modelled 1, 3, 6, 9 and 12 month periods).
ii. Estimating the (uncounted) number joining the North Entrance Stream using a multiplier to extrapolate form the automatic vehicle count.
iii. Splitting each of the streams of cars and utes/4WDs into northbound and southbound journeys and calculating how far they travel along the beach before turning back.
iv. Further splitting the along beach distribution of cars and utes/4WDs into successive 5 m swathes down the beach.
v. Calculating the total distance travelled by motorbikes and distributing this across all the pixels according to the probability that we encountered motorbikes at a given section along and down the beach.
vi. Determining the number of passes of all vehicle types in each pixel for a given scenario.
vii. Estimating of the proportion of all the juvenile toheroa in a pixel that survive a single pass by each vehicle type. This calculation combined measurements of the average width of tyres[52] and the risk per pass of a front and back wheel line (Table 9).
viii. Raising the survival estimate in (vii) to the power of the number of visits to each pixel as estimated in (vi). The estimated added mortality is the converse of these survival estimates.
ix. Spatial distributions of risk along the beach were calculated as average mortality in each 20 m section along the beach (for all pixels 15-199 m down the beach); and risk down the beach was calculated as the average for each 5 m swath down the beach from the dune line.

A more formal description of these calculation methods is presented in Appendix A.

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[52] See Moller et al. (2009) for the methods and main analysis of these widths.

Table 9. Calculation of the proportion of all juveniles in a 20 x 5 m pixel that survive a single pass of a car, ute/4WD, or motorbike.

| Vehicle Type | Average tyre width (mm)[†] | Wheel lines | Proportion of 5m swath covered in pass | Risk to each toheroa run over by a wheel line[‡] | Survival of all juveniles in 20 x 5 m pixel per vehicle pass[¥] |
|---|---|---|---|---|---|
| Cars | 167 | 2 | 0.0668 | 0.043 | 0.9971 |
| Utes/4WDs | 170 | 2 | 0.0680 | 0.019 | 0.9987 |
| Motorbikes | 98.5 | 1 | 0.0197 | 0.041 | 0.9992 |

[†] Reported by Moller et al. (2009)
[‡] From Table 2 of this report
[¥] Calculated according to equation 3 in Appendix A.

Impact studies conducted overseas have emphasised the need to compute the overlap between the distributions of people, vehicles and vulnerable animals or plants on beaches[53]. If vehicle traffic is concentrated where toheroa are naturally sparse, overall impact will be reduced, and vice versa if vehicles and toheroa overlap more than expected by chance. We confronted this issue by building two models: a *Vehicle Distribution Model* that predicted average added mortality when all areas of the beach weighed equally, which we compared with an *Overlapping Distribution Model*. The latter aggregated estimates of the proportion of toheroa killed in each 20 m x 5 m pixel after first weighting each prediction by the relative number of juvenile toheroa expected to occur in that pixel. An extensive series of toheroa distribution and abundance surveys have been conducted at Oreti Beach over the past four decades by the Ministry of Fisheries and then the National Institute of Water and Atmospheric research (NIWA). We used NIWA's three February surveys since 2002 to predict the relative number of juveniles present in each pixel for this *Overlapping Distribution Model*.

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[53] James (2000), Priskin (2003), Schlacher & Morrison (2008), Schlacher et al. (2008a,b), Williams & Meecallef (2009).

## 3.4 Testing the model by linking predicted impacts to toheroa abundance

### 3.4.1 Historical surveys of toheroa at Oreti Beach

We also used the NIWA data to search for correlations between spatial variation in predicted mortality from vehicles and the abundance of juvenile toheroa measured in the standardised surveys conducted by NIWA in 2002, 2005 and 2009[54]. If our model has reliably estimated the size of the vehicle injury and it is quantitatively severe enough, we expected to find lower toheroa abundance in parts of the beach where more impact of vehicles is predicted by the model.

The toheroa surveys used a series of shore-perpendicular transects located at random within eight strata spanning the length of the Oreti Beach toheroa population (Figure 10). Each survey was timed to coincide with spring tides to allow for the greatest extent of beach to be surveyed at low tide. Along each transect, 0.5 m x 1.0 m quadrats were placed at five metre intervals and the sand excavated to a depth of at least 30 cm. For two transects per stratum, sand in each quadrat was sieved through a fine steel mesh to ensure that all juvenile toheroa were counted (‘sieved’ transects hereafter). For the remaining transects, the excavated sand was examined by hand and all encountered toheroa counted and measured. These ‘unsieved’ transects could not be used to estimate juvenile density, but all sub-adults and adults were detected by the method.

The density of juvenile toheroa in each transect was plotted against distance along the beach and a second-order polynomial function used to approximate the along the beach variability (Figure 11). The equation of this model was used to determine the proportion of juvenile toheroa occurring in each 20 m segment along the beach.

The distribution of juvenile toheroa down the beach was calculated for four along the beach zones as defined for vehicle distribution as each one kilometre segment either side of Main Entrance (S1 cf. N1) and each outer flank (S2-S9 cf. N2-N10). The percentage of juvenile toheroa in each quadrat down the beach at five metre intervals was averaged across all transects falling within each of these zones.

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[54] A historical synthesis of all the surveys is provided by Beentjes (2010a). The position of the NIWA transects was reconstructed from the GPS points marking the boundaries between eight sampling ‘strata’ recorded at Appendix 1 (p 40) of that report, and the southeast to northwest distance along the dune line from those strata boundaries to the start of each transect. The 1998 surveys, although using the same method, were conducted approximately seven weeks later in the year than the 2002, 2005 and 2009 surveys. We have therefore omitted these from the spatial analysis of toheroa distribution in this study. Additional transects were added in areas where adult toheroa were most abundant in order to increase the statistical power of the population estimates, so the distribution of measurements along the beach is uneven (Figure 10).

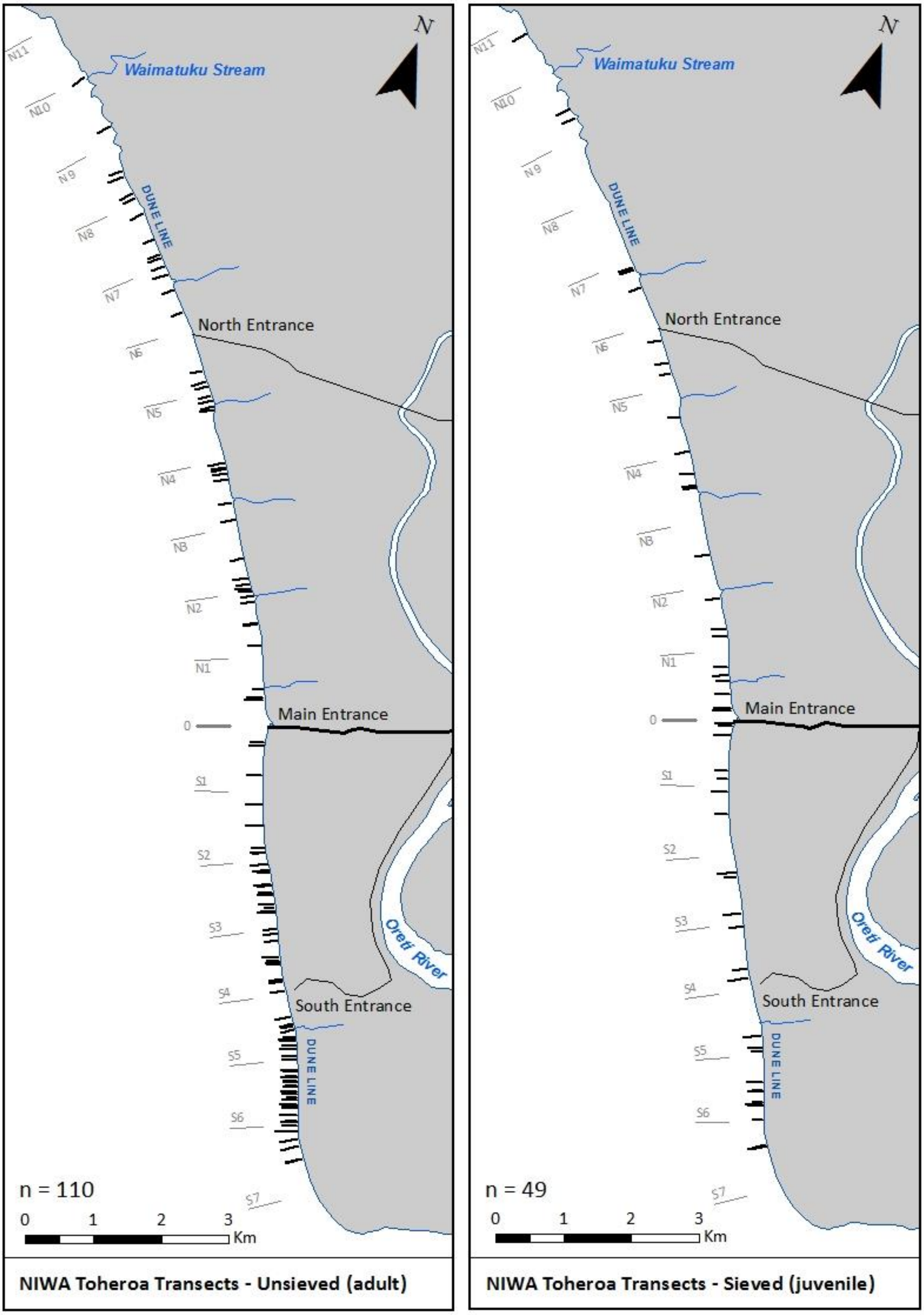

*Figure 10 Location of NIWA toheroa transects for 2002, 2005 and 2009 surveys.*

*Table 10: Summary of NIWA toheroa surveys used in this study to estimate the spatial distribution of toheroa on Oreti Beach.*

| **Year** | **Dates of survey** | **Number of transects** | | **Total estimated population** | | | **Report citation** |
|---|---|---|---|---|---|---|---|
| | | *Sieved* | *Unsieved* | *Juvenile (<40 mm)* | *Sub-adult (40-99 mm)* | *Adult (≥100 mm)* | |
| **2002** | 25 February – 1 March | 16 | 44 | 10,000,000 (± 2,728,266) | 298,000 (± 65,659) | 612,000 (± 143,146) | Beentjes *et al.* (2003) |
| **2005** | 7-11 February | 17 | 43 | 6,981,762 (±1,304,665) | 400,894 (±150,860) | 582,829 (±102,094) | Beentjes and Gilbert (2006) |
| **2009** | 9-13 February | 16 | 24 | 6,030,320 (±2,974,728) | 492,981 (±169,253) | 979,727 (±220,011) | Beentjes (2010a) |

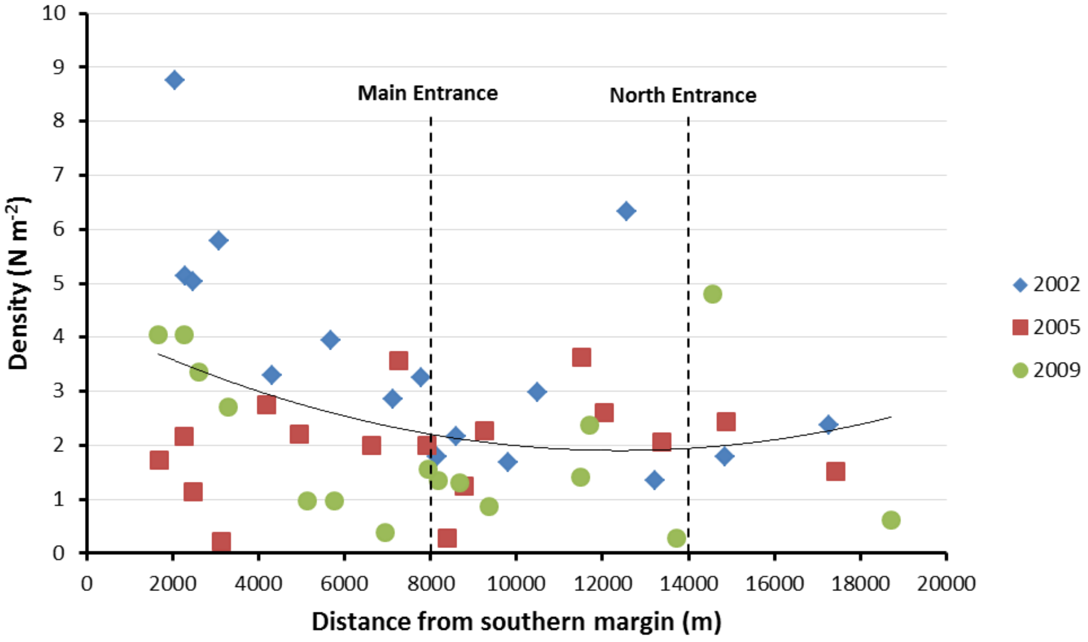

*Figure 11: Density of juvenile toheroa in each transect. A second-order polynomial curve fitted to all points with an equation of $y = 2E\text{-}08x^2 - 0.0004x + 4.2924$.*

### 3.4.2 Distribution of juvenile toheroa on Oreti Beach

The density of juvenile toheroa along Oreti Beach is highly variable (Figure 11), as indicated by the polynomial model only explaining 12% of the variation in juvenile density between sieved transects. The polynomial function suggests highest density towards the southern end of the beach, a low point between Main and North Entrances, and a slight rise north of North Entrance. However, the main feature of the juvenile distribution is extreme patchiness over short distances along the beach.

The broader spatial variation in juvenile density along the beach is probably related to adult density (more spat is released where the adults are more abundant), along shore dispersal of juveniles[55] and the timing of recruitment events and the impact of post-settlement mortality factors like vehicle injuries, desiccation or bird predation.

The distribution of juvenile toheroa down the beach near Main Entrance (S1 and N1) differed markedly to the rest of the beach (S2-S8 and N2-N10). Peak abundance occurred 80 – 90 m from the dunes, *c*. 25-30 m further seaward near Main Entrance; Figure 12). The peak in juvenile abundance for the rest of the beach was *c.* 50 m from the dunes. This shift probably results from increased vehicle pressure high on the beach around Main Entrance. We test this hypothesis later in this report.

### 3.4.3 Statistical Analyses

Exploratory data analysis and graphing were performed in Excel, followed by statistical hypothesis testing in Gen Stat 14th Edition[56]. The traffic count data were treated as a complete enumeration of visits to Oreti Beach over the two year study, so normal statistical hypothesis testing of differences in annual, seasonal, daily and hourly visitor patterns is not required. We mainly used the Generalised Linear Model (GLM) routines within GenStat for statistical models to test associations between mortality from vehicles with variation in toheroa density along Oreti Beach. Square root, $\text{Log}_e$ and $\text{Log}_{10}$ transformations of the response variables were all tried if inspection of residuals indicated uneven distribution of residuals around predicted response. The best fit was chosen where further addition of transformations or interaction terms led to only a marginal increase in the proportion of variance explained. We used a Generalised Linear Mixed Model (GLMM) for testing

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[55] Moller et al. (2009) noted considerable numbers of juveniles drifting in the tide and being redistributed along the beach. They hypothesise that some of these juveniles are actively increasing dispersal along the shore by extending siphons, though the high number drifting may simply reflect a high probability of being resuspended in the tide when flushed by waves (the smaller toheroa sist just below the surface and can easily be eroded).

[56] VSN International; www.vsni.co.uk/software/genstat

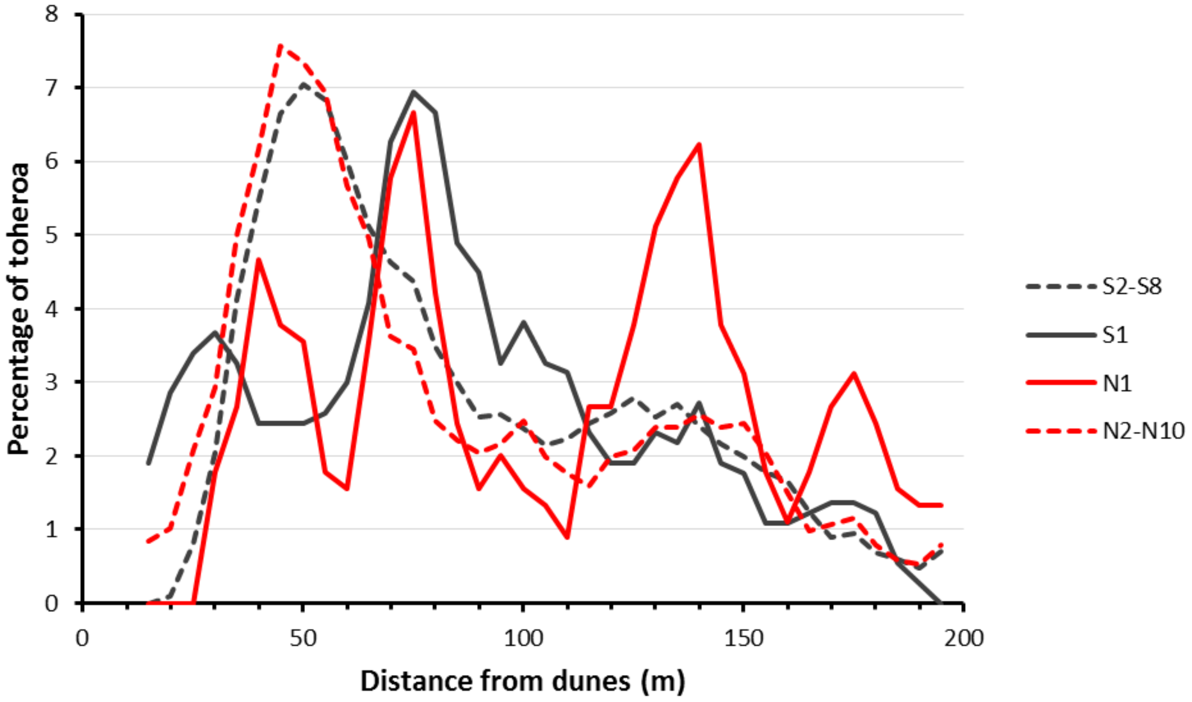

*Figure 12: Distribution of juvenile toheroa down Oreti Beach in four zones along beach. The sections along the beach are shown in Figure 10.*

changes in damage rates of different vehicles and experimental methods with year of survey as a random effect.

Uncertainty in our models was estimated using (a) upper and lower 95% confidence intervals for the risk of injury from a single pass of a front and rear tyre over a juvenile toheroa; and (b) the upper and lower uncertainties in motorbike trip distances (Table 8). Complete enumeration of vehicles by the automated traffic counter greatly reduced other sources of sampling error, but the distributions of vehicles detected during beach circuits will have added additional uncertainty for divisions of traffic flows and the observed distributions along and down the beach. The 95% cis presented in the following figures are therefore best considered as approximate and probably underestimates of uncertainty.

# 4. Model Predictions

## 4.1 Mortality imposed by different types of vehicle

Our models predict an added 23% (Vehicle Distribution Risk model) to 27% (Overlapping Distribution Risk model) mortality of juvenile toheroa over the course of one year. The differences between the models are slight in all risk comparisons, so for simplicity reasons we mainly describe the predictions of the former in all that follows with a few stated exceptions.

According to the Vehicle Distribution Risk model, cars cause 15% added mortallity, utes/4WDs 12% and motorbikes 1% (Figure 13)[57]. The Vehicle Distribution Risk Model predicted slightly lower mortality compared to the Overlapping Distribution Risk Model.

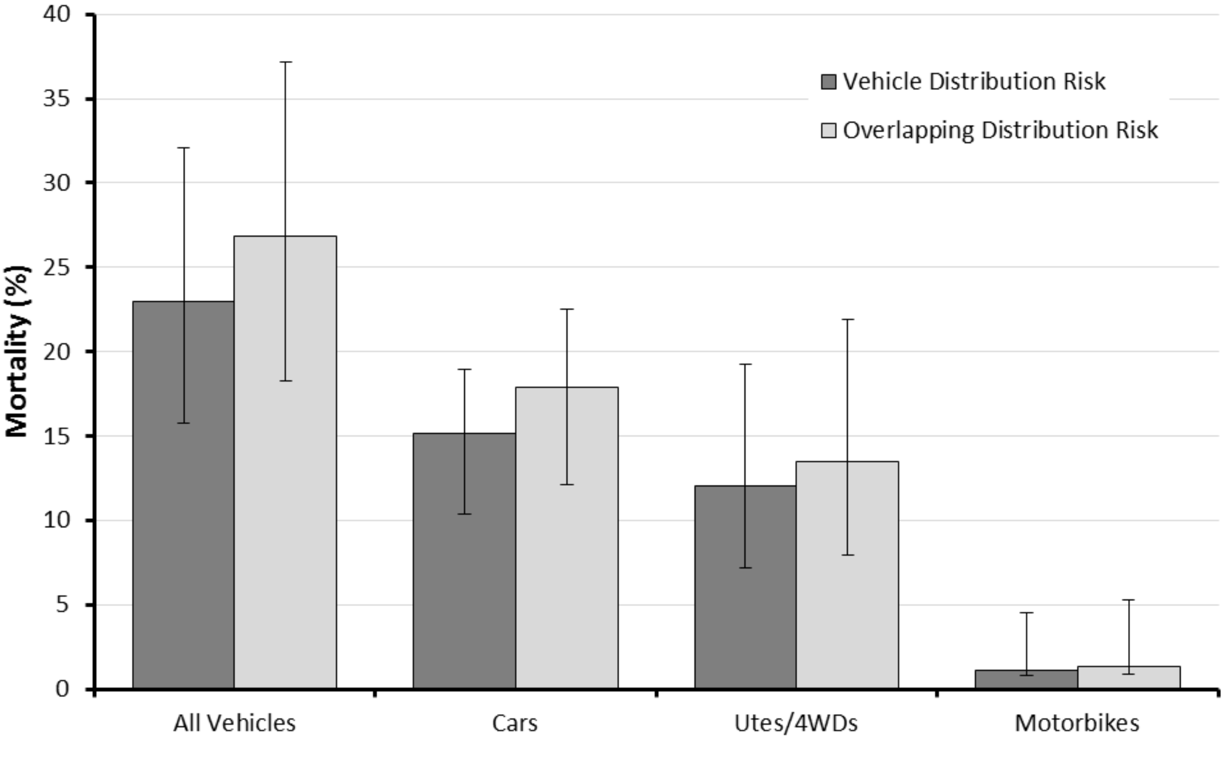

*Figure 13: Average added annual mortalitypredicted by each risk measure model for each vehicle type. The error bars predict 95% confidence intervals (here and in Figures 14 and 16-18).*

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[57] Year round averages are tabulated in the Appendix B for reference and subsequent scenario building if desired.

## 4.2 Variation in mortality along Oreti Beach

Not surprisingly, most vehicle-added mortality occurs around Main Entrance, with a peak of 72% added annual mortality predicted immediately south of the entrance (Figure 14). Mortality decreases steadily both to the north and south of Main Entrance, to reach 20% at around 3.5 km distant. Beyond 5 km south of Main Entrance, vehicle-added mortality is very low (<5%).

A secondary peak in mortality (*c.* 30%) occurs around North Entrance, with mortality remaining relatively high northward to near the Waimatuku Stream (Figure 14). This is due to an influx of vehicles, particularly utes/4WDs, from the North Entrance traffic stream. Mortality drops rapidly to a low of around 13% at 1 km south of the North Entrance (i.e. 5 km north of Main Entrance).

Cars account for the highest proportion of vehicle-added mortality along all of Oreti Beach, with the exception of the part of the beach north of North Entrance where utes/4WDs cause considerably higher added mortality (Figure 15). North Entrance is often impassable to non-4WD vehicles, leading to utes/4WDs dominating the stream of vehicles accessing the beach here.

Motorbikes cause greater mortality in the northern half of the beach, but their impact remains relatively low (*c.* 1% annual added mortality) throughout.

Vehicles entering the beach via Main Entrance impose 18% added annual mortality[58].

The North Entrance stream causes 4.8% annual added mortality[59].

Overall, vehicle-added mortality to juvenile toheroa is greater to the north of Main Entrance than to the south (Figure 16). The Vehicle Distribution Risk model (Figure 16a) predicts around 4% greater mortality north of Main Entrance[60]. Cars caused higher mortality in the south than the north, whereas utes/4WDs and motorbikes caused more mortality in the north than the south (Figure 16).

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[58] Using the Vehicle Distribution Risk model; It was 22% when using the Overlapping Distribution Risk model.
[59] Using the Vehicle Distribution Risk model; It was 5.4% when using the Overlapping Distribution Risk model.
[60] The Overlapping Distribution Risk model (Figure 16b) predicts around 9% greater north of Main Entrance.

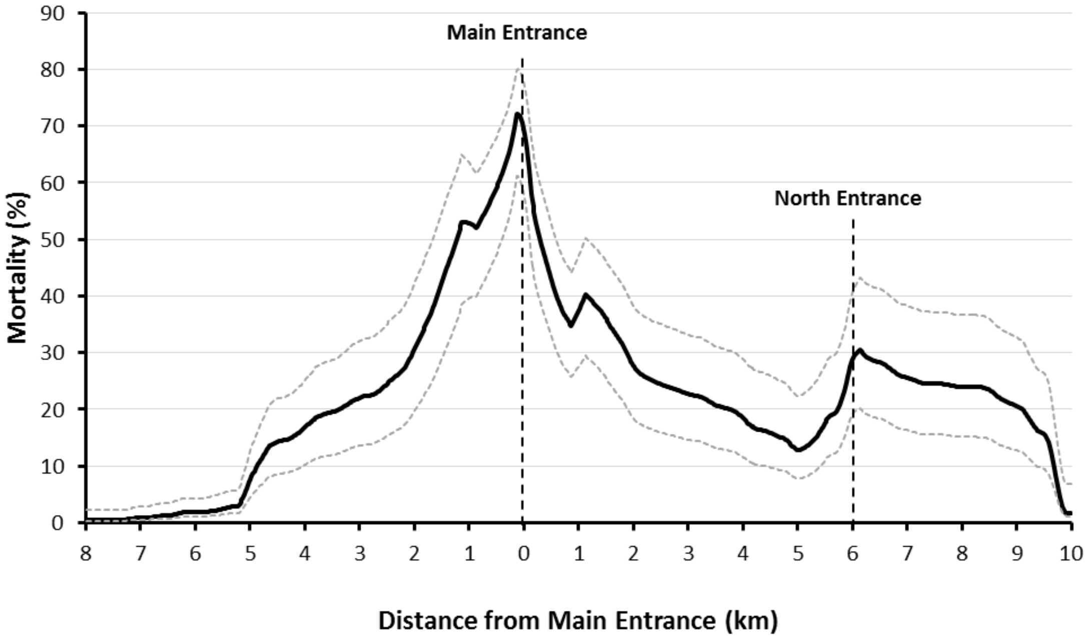

*Figure 14: Annual vehicle-added mortality along Oreti Beach (pooled for all vehicle types) using the Vehicle Distribution Risk model. Dotted lines indicate upper and lower 95% confidence intervals.*

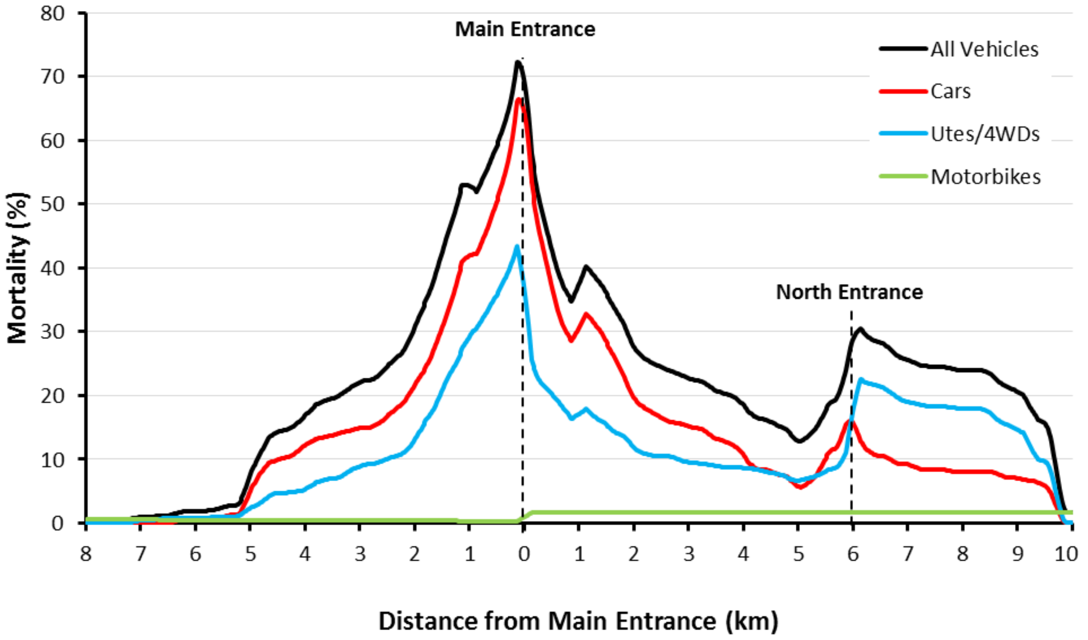

*Figure 15: Vehicle-added mortality along Oreti Beach for the three main types of vehicles considered in this study using the Vehicle Distribution Risk model.*

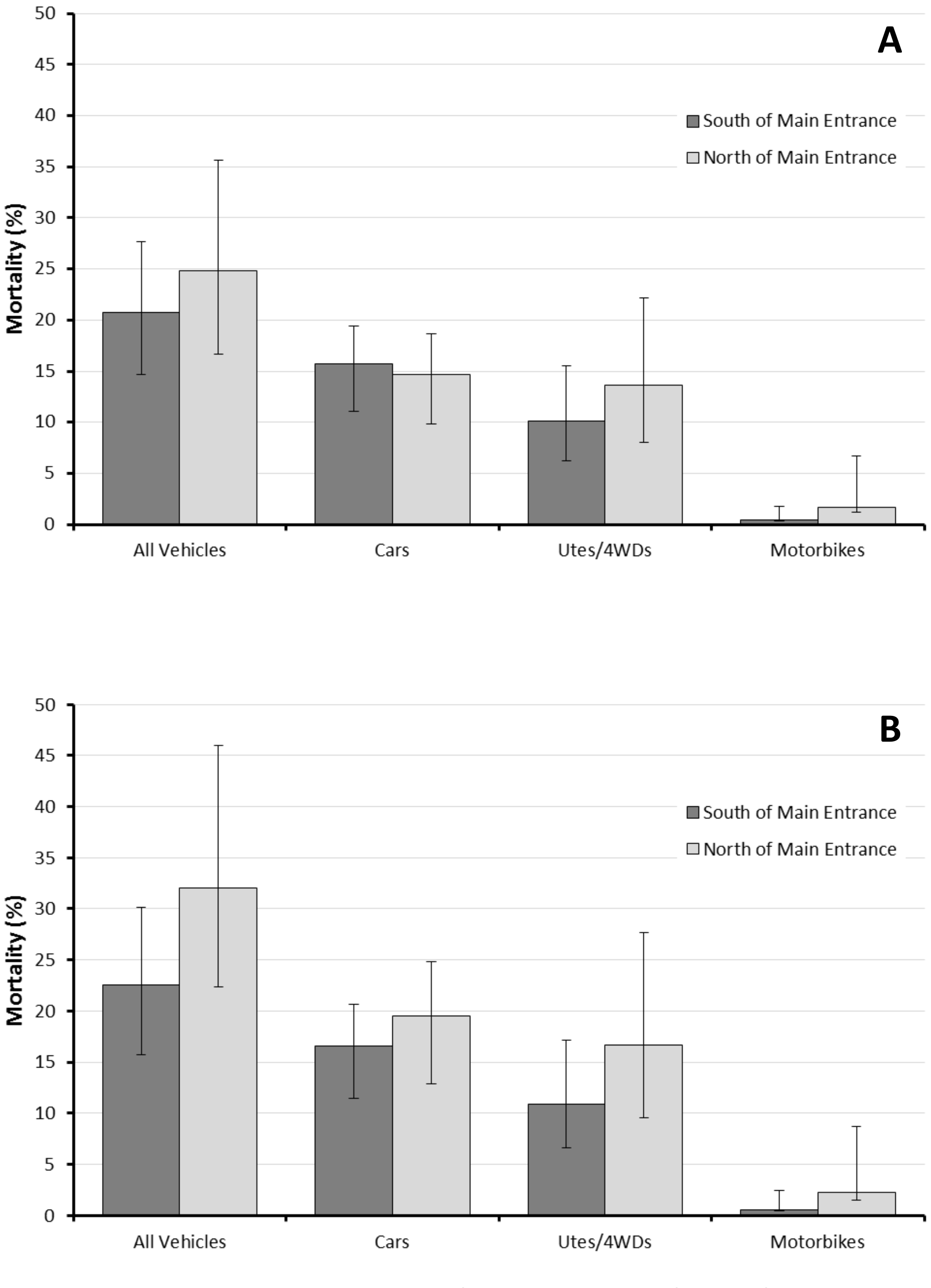

*Figure 16: Annual vehicle-added mortality for each main class of vehicle for the sections of Oreti Beach south and north of Main Entrance. a) Vehicle Distribution Risk model, b) Overlapping Distribution Risk model.*

## 4.3 Variation in mortality between high and low tide on Oreti Beach

Overall, vehicle-added mortality peaked at a distance of around 40 m from the sand dunes (c. 50%) before decreasing steadily seaward (Figure 17). Peak impact occurred approximately 20 m nearer the dunes for utes/4WDs than for cars (Figure 18). This probably reflects the need for cars to avoid the very soft sand high on the beach and relative lack of risk the utes/4WDs will become stuck, and that the later venture further from the entrances even during relatively high tides. The risk from motorbikes is much more dispersed down the beach than for cars and utes/4WDs.

As most vehicles access Oreti Beach via the Main Entrance, the impact of moving vehicles on juvenile toheroa is expected to be greatest in this area, as shown for the along the beach Vehicle Distribution Risk in Figure 14. The distribution of juvenile toheroa down the beach is markedly different in the area surrounding Main Entrance than for the rest of the beach, with the peak in juvenile abundance occurring approximately 25 m further seaward near Main Entrance and a comparative lack of juveniles between 30 and 70 m down the beach (Figure 12 & 19). Given that vehicle pressure is considerably greater in this zone, it appears that the high impact of traffic high on the beach has resulted in a reduction in juvenile abundance here and a seaward shift in the distribution. At more distant parts of the beach, where vehicle pressure is considerably lower, there appears to be little effect on the down the beach distribution of juvenile toheroa.

## 4.4 Patchiness of vehicle impacts

The extreme variation in vehicle traffic along the beach (Section 4.2) and its concentration in the upper 80m of the beach (Section 4.3) means that the risk to toheroa recruitment is extremely variable between pixels. The annual mortality models predict that over 95% of the juveniles are destroyed in around 2% of pixels; but less than 5% are killed in around 33% of pixels (Figure 20). The naturally protected pixels are far from Main Entrance and situated further down the inter-tidal zone. The skew in distribution of risk results in the mean being very much higher than the median mortality estimates. If the whole year is considered, the average added mortality is 23%, but if the median is only 12% mortality. If the January injury is considered, the average and median mortality are 4% and 1% respectively. This presents a dilemma in how best to depict the ‘central tendency’ of the distribution of injuries. We have mainly presented means and treat all parts of Oreti Beach as about equally important for toheroa populations, but large areas of the beach are protected from traffic impacts and these spatial refuges are likely to have been important for the resilience of the overall colony and use of the overlapping distributions model.

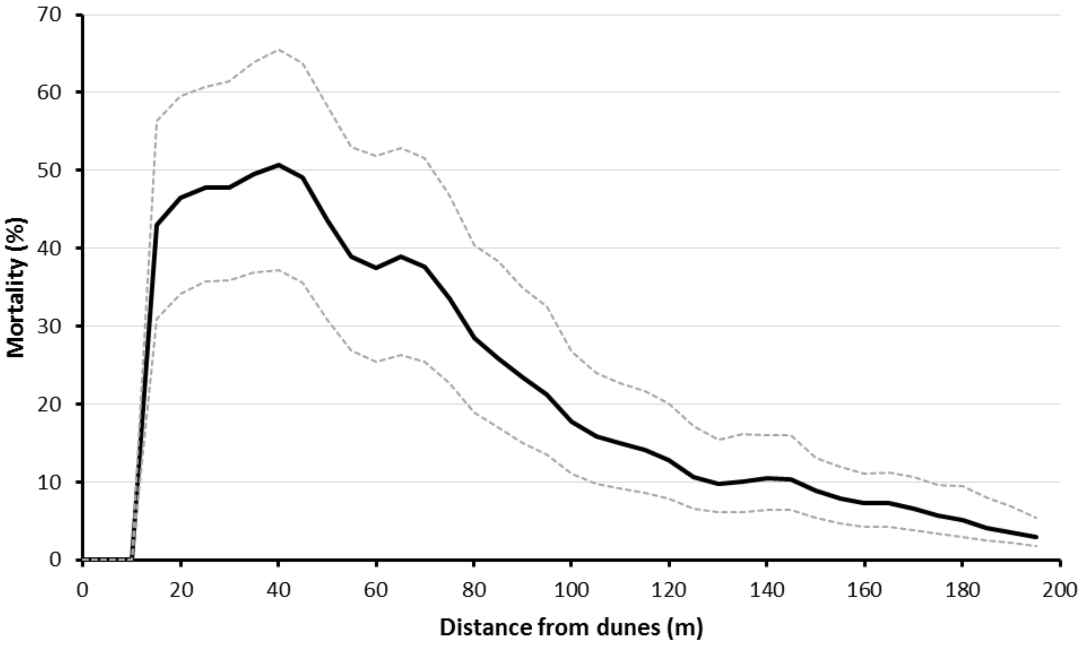

*Figure 17: Vehicle-added annual mortality down Oreti Beach (pooled for all vehicle classes) using the Vehicle Distribution Risk model.*

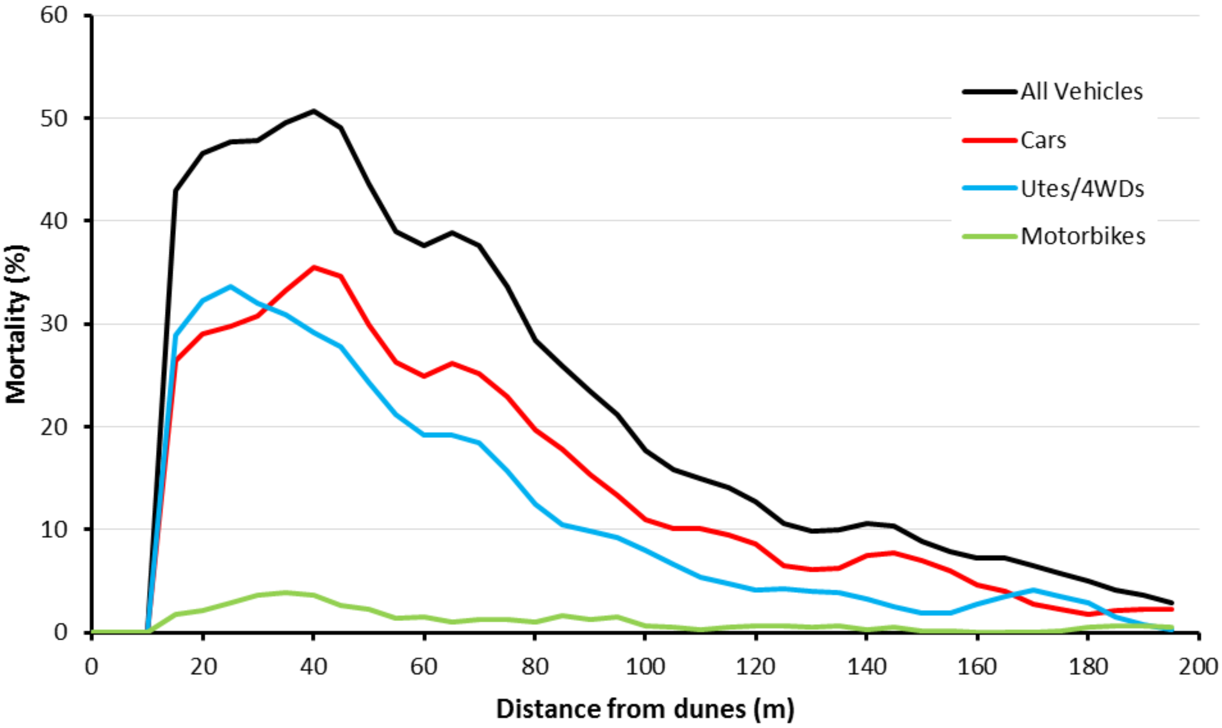

*Figure 18: Vehicle-added annual mortality down Oreti Beach for each vehicle type using the Vehicle Distribution Risk model.*

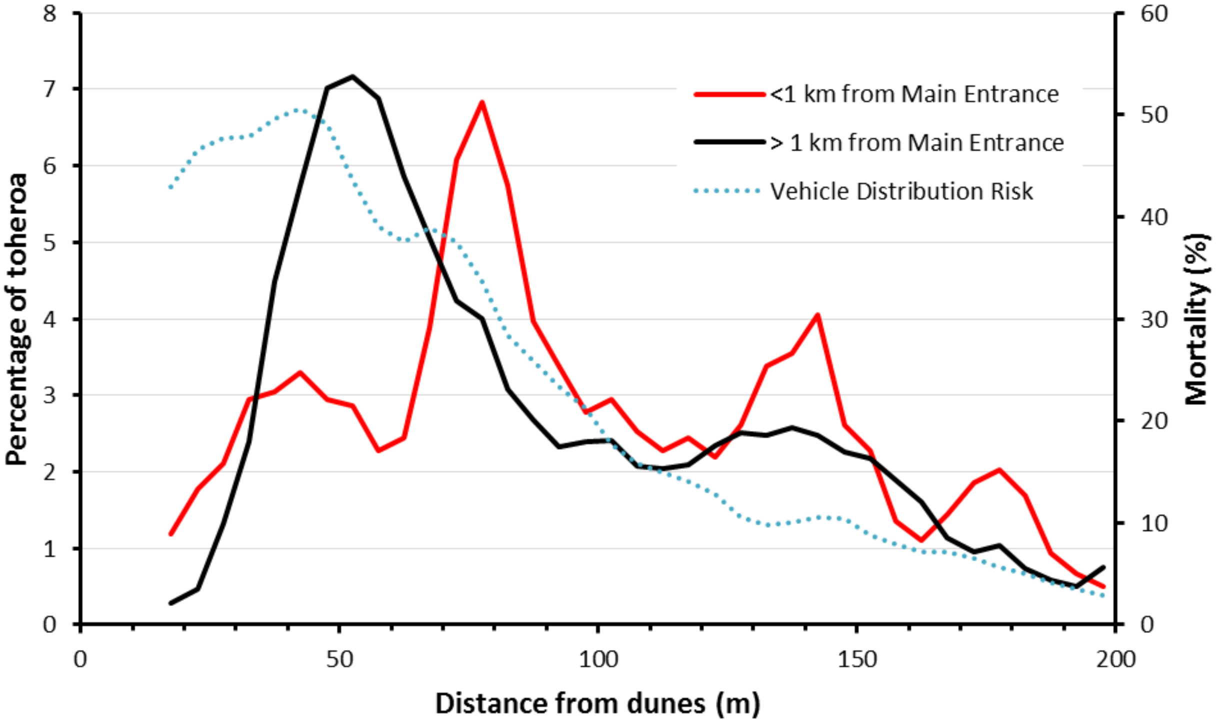

*Figure 19: Down the beach distribution of juvenile toheroa within and beyond one kilometre of Main Entrance. The annual Vehicle Distribution Risk is plotted on the secondary (right-hand) y-axis.*

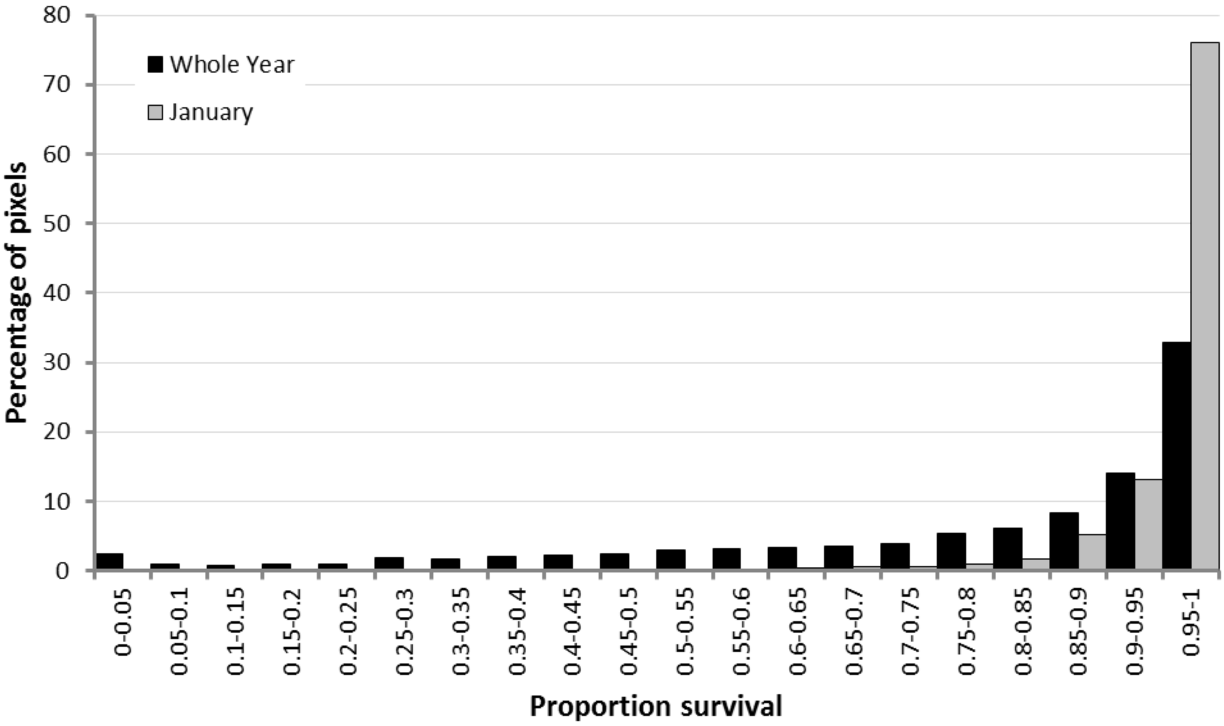

*Figure 20: Percentage of survival rates in 20 m x 5 m pixels on Oreti Beach.*

## 4.5 Seasonal variation in mortality and juvenile toheroa abundance

The above estimates of mortality have been for cumulative impacts for 12 successive months irrespective of when juvenile toheroa first settle on Oreti Beach. Overall impact of vehicles on recruitment to the sub-adult size class will vary if (i) juveniles grow fast enough to outgrow the vulnerable juvenile stage in much less than 12 months[61], and/or (ii) if cohorts are deposited on the beach in particular months. In this next section we illustrate the importance of growth rates and seasonal recruitment pulses on predicted vehicle impacts by simulating some hypothetical scenarios. However, relatively little is known about the growth rate of juevnile toheroa, spawning or seasonal recruitment patterns, so we can not advise on which of these scenarios is most likely to apply on Oreti Beach.

Considered on a monthly basis, vehicle-added mortality to toheroa is greatest in December (5%) and lowest in May (2%) (Figure 21). This is an exact mirror of the monthly vehicle variations measured by the traffic counter (Figure 3) because our rather simple model has applied constant risk estimates for everytime a juvenile is run over and has assumed equivalent vehicle distribution patterns along and down the beach in all seasons.

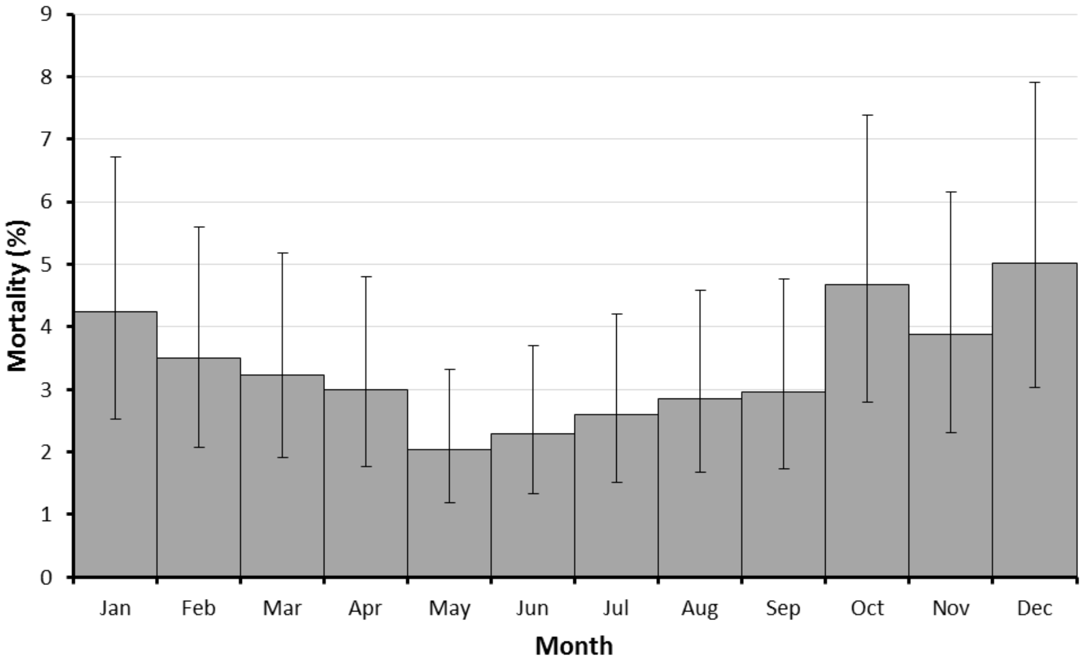

*Figure 21: Average vehicle-added mortality per month for all vehicles on Oreti Beach using the Vehicle Distribution Risk model.*

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[61] Subadults and adults are assumed to bury sufficiently into the sand to never be damaged by vehicles (Moller et al. 2009). Although this is logical, in fact there is only fragmentary evidence to confirm this.

Assuming a three month vulnerability period, vehicle-added mortality is greatest for spat arriving on the beach at the beginning of October (11.1%) and declines steadily to a low in mortality for spat arriving in May (6.1% mortality) (Figure 22a). This reduced impact on the April cohort comes about because the juveniles appear on the beach after the main seasonal peak (and so experience relatively little initial mortality) and then they are assumed to outgrow the vulnerable size clases before the next summer peak season arrives.

If juveniles remain at risk for six months, spat settling in October are subject to greatest vehicle impact over summer and hence the highest mortality (16.8%), decreasing to a low of 11.8% for spat arriving in April (Figure 22b).

Finally, if toheroa are vulnerable to vehicle impact for nine months, spat arriving on the beach in August are most vulnerable (20.5% added mortality), with least mortality occurring for those arriving in January (17.4%) (Figure 22c).

The overall prediction is for increasingly flatter seasonal patterns and higher overall mortality when we assume the juveniles are vulnerable for 3, 6 and 9 months of the year (Figure 22a-c). If it takes a full year for a newly deposited 3 mm toheroa to grow through to 40 mm (the beginning of the sub-adult stage), there will be no seasonal pattern in vulnerability of juvenile cohorts appearing in different months. In that case the Vehicle Distribution Risk model predicts a flat cumulative mortality of 23% (95% confidence interval: 16 – 32%). If growth rates of juvenile toheroa vary with season, these predicted patterns and overall scale of cumulative mortality may alter. The model demonstrates a need to better understand seasonal patterns of recruitment to the beach and subsequent growth rates of small toheroa before we can more accurately quantify vehicle impacts and identify the times of the year that are most affected, or conversely, which cohorts contribute most to the next generation of breeding toheroa.

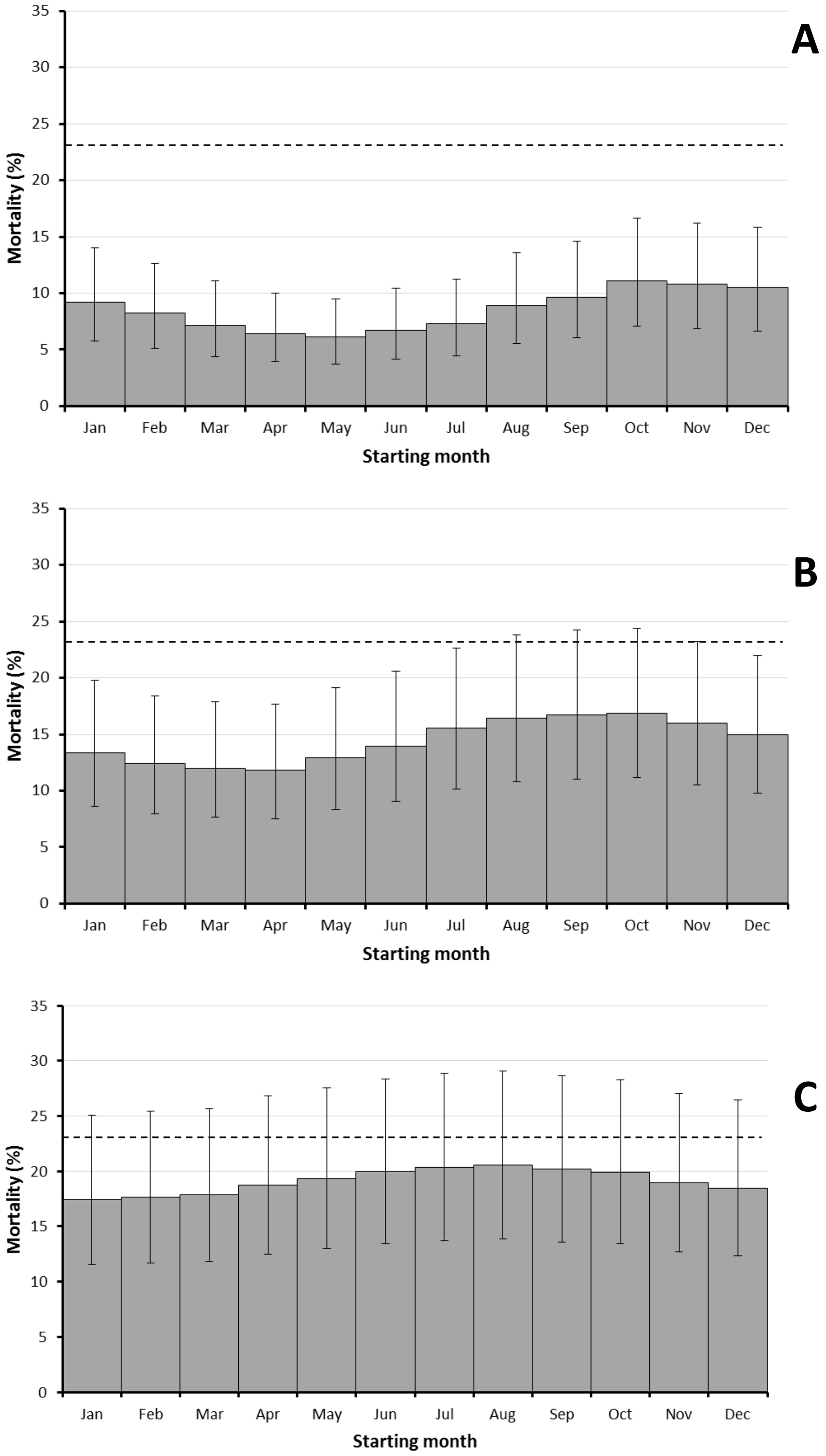

*Figure 22: Average cumulative vehicle-added mortality for cohorts of juvenile toheroa settlind at the start of each month on Oreti Beach using the Vehicle Distribution Risk model. The graphs predict the vehicle impact assuming that toheroa can grow through the juvenile stage (3-40 mm) in a) three months, b) six months, and c) nine months. The dashed line shows predicted mortality if the juveniles take 12 months to reach sub-adult size (40 mm) when they are considered to be no longer susceptable to vehicle damage.*

## 4.6 Association of mortality predictions with toheroa abundance

Our model has made many assumptions and simplified reality to make general predictions. Therefore we now test impacts on toheroa by checking whether variation in toheroa abundance observed in the NIWA surveys correlates with the model's predictions of where vehicle impose most mortality. Our test cross references density estimates of adults along the beach (Figure 23) with the models' predictions (Figure 24).

First we used the model to predict cumulative annual mortality of juveniles for the exact locale of every transect surveyed along Oreti Beach in 2002, 2005 and 2009. We then constructed separate statistical models for predicting the abundance of (a) adults, (b) sub-adults and (c) juveniles at each transect from (i) year, (ii) predicted mortality, and (iii) interactions between them (Table 11). We also included the abundance of both sub-adults and juveniles as potential explanatory variables when predicting adult abundance; and the abundance of juveniles as a potential explanatory variable when predicting sub-adult abundance. Model construction had to trade-off severe loss of sample size whenever juvenile abundance was proposed as an explanatory variable[62] against loss of power when juvenile density was not added as a predictor. In all cases a square root transformation provided best fits of residuals to predicted abundance[63]. Strong associations in the expected directions were found between predicted mortality from vehicles and abundance of all three age classes. However the strength of the associations varied between the 2002, 2005 and 2009 surveys.

Adult abundance declined sharply in transects where we predicted vehicles to have imposed higher juvenile mortality, though this effect was less in 2002 than the other two surveys. There are no data to confirm the virtual absence of adults once mortality exceeds 60%, but this is the obvious expected common sense outcome (Figure 24)[64]. More adults are found in transects where active recruitment is indicated by higher abundance of sub-adults (Table 11).

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[62] Juvenile abundance is only reliably measured in sieved transects and these were a minority in the surveys.

[63] Linear, $\text{Log}_e$ and Log10 transformations were all tested, and where they fitted as well as square root transformations we chose the model with the maximum proportion of the variance explained. Marginal increase in the proportion of variance explained could be obtained by adding interactions between subadult density, juvenile density and year, but these models were rejected to keep models as simple as practicable.

[64] Extrapolation of the GLM for higher mortalities predicts renewed increase in adult abundance at higher mortalities because of the square root transformation underlying the model. This is a statistical artefact based on the lack of transect data at high mortality, so we assume density remains at zero from the point where the GLM intercepts the x axis in Figure 24.

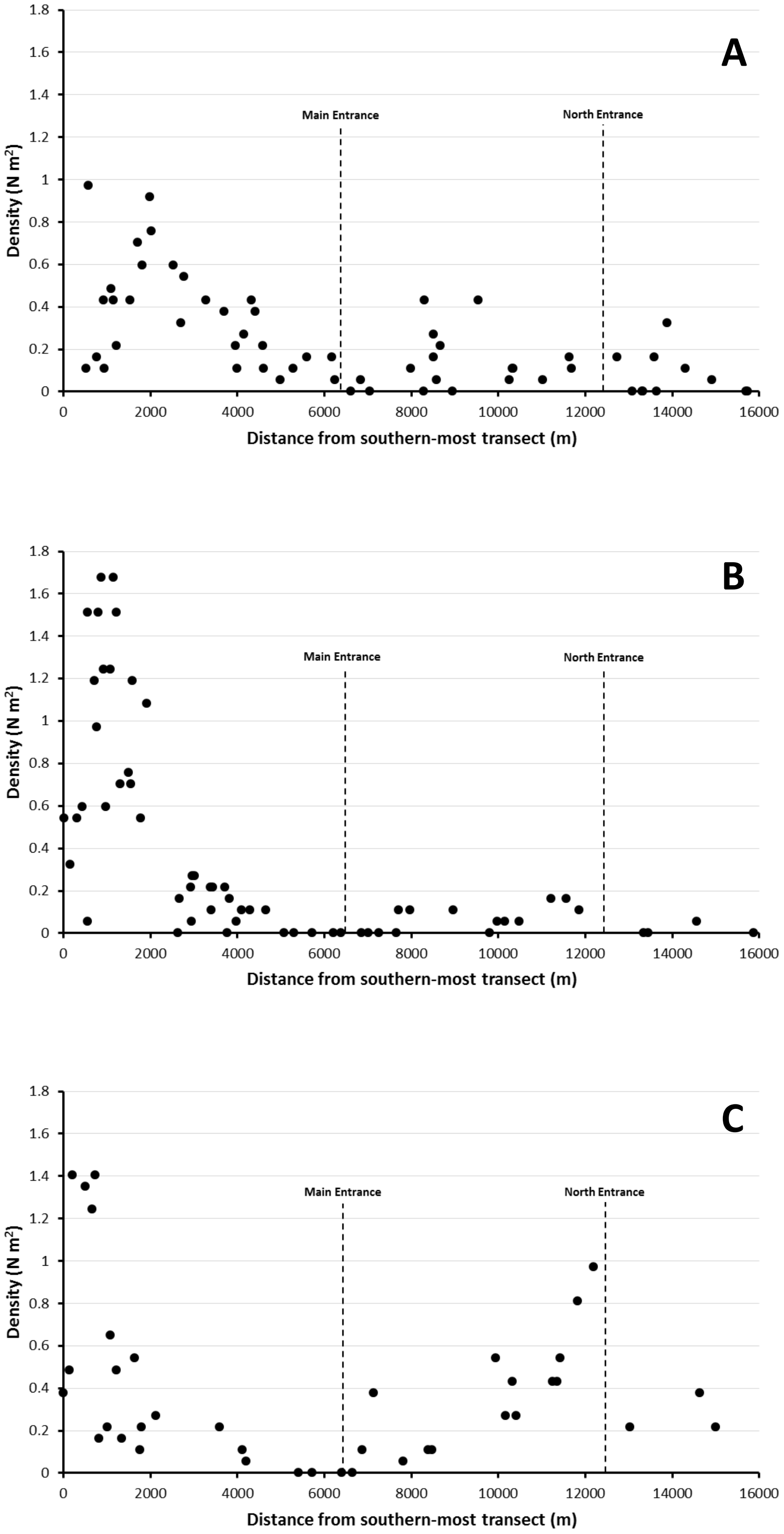

*Figure 23: Adult toheroa density in each NIWA transect along Oreti Beach in a) 2002, b) 2005 and c) 2009.*

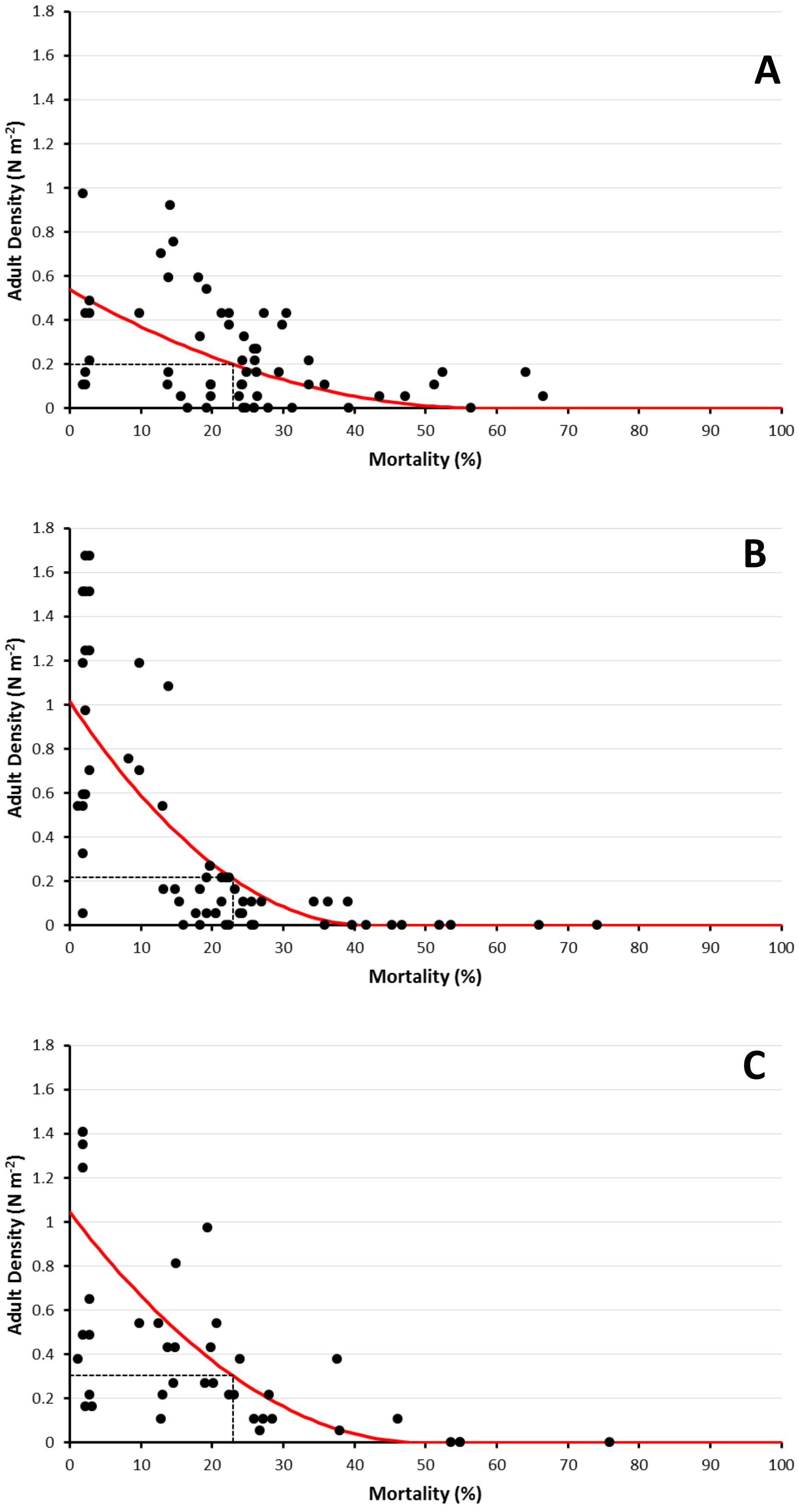

*Figure 24: Adult density vs. predicted annual vehicle-added juvenile mortality for NIWA transects from a) 2002, b) 2005, and c) 2009. The dashed lines indicate the predicted adult density given the annual predicted juvenile mortality of 23%.*

*Table 11: Results of Generalised Linear Models to predict the density of adults, sub-adults and juveniles in each transect measured on Oreti Beach in 2002, 2005 and 2009. Mortality is predicted annual additional mortality from vehicles at the location of the transect. Reference year for all models is 2002.*

| | **Adults** | | | | **Sub-adults** | | | | **Juveniles** | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Predicted Variable** | Square root Adult Density | | | | Square Root Sub-adult Density | | | | Square Root Juvenile Density | | | |
| **Transects used** | Sieved and unsieved combined | | | | Unsieved transects only | | | | Unsieved transects only | | | |
| **Probability of model** | < 0.001 | | | | 0.005 | | | | 0.002 | | | |
| **Variance explained** | 50% | | | | 29% | | | | 30% | | | |
| **Predictor** | *Estimate* | *t pr.* | *Lower 95% CI* | *Upper 95% CI* | *Estimate* | *t pr.* | *Lower 95% CI* | *Upper 95% CI* | *Estimate* | *t pr.* | *Lower 95% CI* | *Upper 95% CI* |
| **Constant** | 0.6596 | <.001 | 0.5733 | 0.746 | 0.398 | 0.001 | 0.1675 | 0.6295 | 2.193 | <.001 | 1.826 | 2.559 |
| **Mortality** | -1.242 | <.001 | -1.494 | -0.9902 | -0.863 | 0.015 | -1.55 | -0.1769 | -1.372 | 0.022 | -2.532 | -0.2123 |
| **Year 2005** | 0.2704 | <.001 | 0.1152 | 0.4255 | -0.0133 | 0.892 | -0.2114 | 0.1847 | -0.888 | 0.001 | -1.401 | -0.3752 |
| **Year 2009** | 0.2686 | 0.002 | 0.1 | 0.4373 | 0.0294 | 0.733 | -0.1439 | 0.2027 | -0.52 | 0.055 | -1.051 | 0.0116 |
| **Sub-adult Density** | 0.667 | <.001 | 0.3106 | 1.023 | | | | | | | | |
| **Juvenile Density** | | | | | -0.0102 | 0.616 | -0.051 | 0.03064 | | | | |
| **Mortality.Year 2005** | -1.14 | <.001 | -1.708 | -0.5725 | 0.126 | 0.639 | -0.4142 | 0.6663 | 1.57 | 0.054 | -0.0253 | 3.166 |
| **Mortality.Year 2009** | -0.811 | 0.011 | -1.429 | -0.1923 | 0.489 | 0.067 | -0.0368 | 1.015 | 0.156 | 0.846 | -1.449 | 1.760 |
| **Mortality.Juvenile Density** | | | | | 0.249 | 0.005 | 0.08068 | 0.4174 | | | | |

Variation in sub-adult abundance along Oreti Beach was more unpredictable than for adults and juveniles, perhaps in part because their abundance is low and recruitment is a sporadic event[65]. The best statistical models predicting sub-adult abundance from the full data set (sieved and unsieved transects combined) could only ever explain a maximum of 5% of the variance, whereas models incorporating juvenile abundance all had greater explanatory power (>20% variance explained). As expected, more sub-adults are present where more juveniles were also found. The best fit model used year interactions with both juvenile abundance and mortality to achieve 29% variance (Table 11). Increased vehicle mortality was strongly associated with decreased sub-adult abundance in 2005 (Table 11). There may have been a much weaker association between predicted mortality and sub-adult abundance in 2002 and 2009, but the 95% confidence intervals are wide and coefficients are unreliable, so we can neither confirm nor quantify that sub-adult abundance was also depressed where mortality increased in those two years. More data are needed to test putative associations between vehicle traffic and sub-adult abundance and our preliminary conclusion is that such associations are variable between years.

Juvenile abundance declined steadily as predicted mortality from vehicles increased in 2002 and 2009, but there was no sign of such an effect in 2005 (Figure 25)[66]. The lack of association in 2005 may be related to ongoing recruitment of juvenile toheroa on the beach just before and at the very time of the 2005 survey. This can be seen from the size frequency distribution amongst juveniles in the three surveys (Figure 26). A large number and higher proportion of the juveniles were in the very small size classes in February 2005, indicating recent recruitment. If so, there may have been insufficient time for vehicles to greatly alter the distribution of juvenile abundance along the beach in 2005.

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[65] The lower abundance of sub-adults compared to adults undoubtedly reflects the comparatively short time that individual remain as subadults i.e. the adult class is made up of several annual cohorts of well grown toheroa.

[66] The mean parameter estimates even predict a slight increase in juvenile density as mortality increases. However the 95% Confidence intervals on Mortality and the interaction term (2005 year*mortality) are wide, so there is insufficient information to know whether there is a slight increase, steady or decrease in juvenile mortality in association with increasing mortality from vehicles.

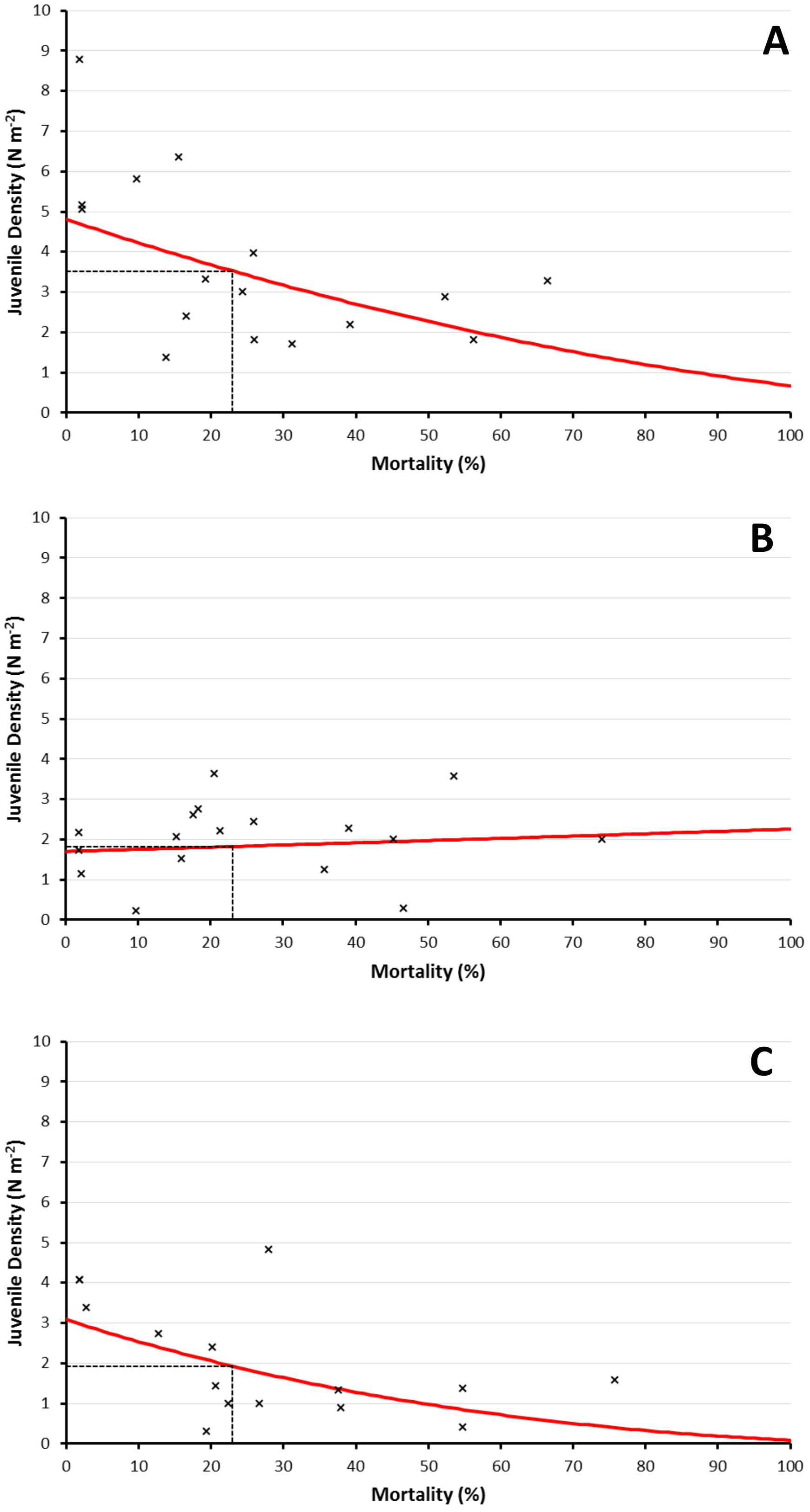

*Figure 25: Juvenile density vs. predicted annual vehicle-added juvenile mortality for NIWA transects from a) 2002, b) 2005, and c) 2009. The dashed lines indicate the predicted juvenile density given the annual predicted juvenile mortality of 23%.*

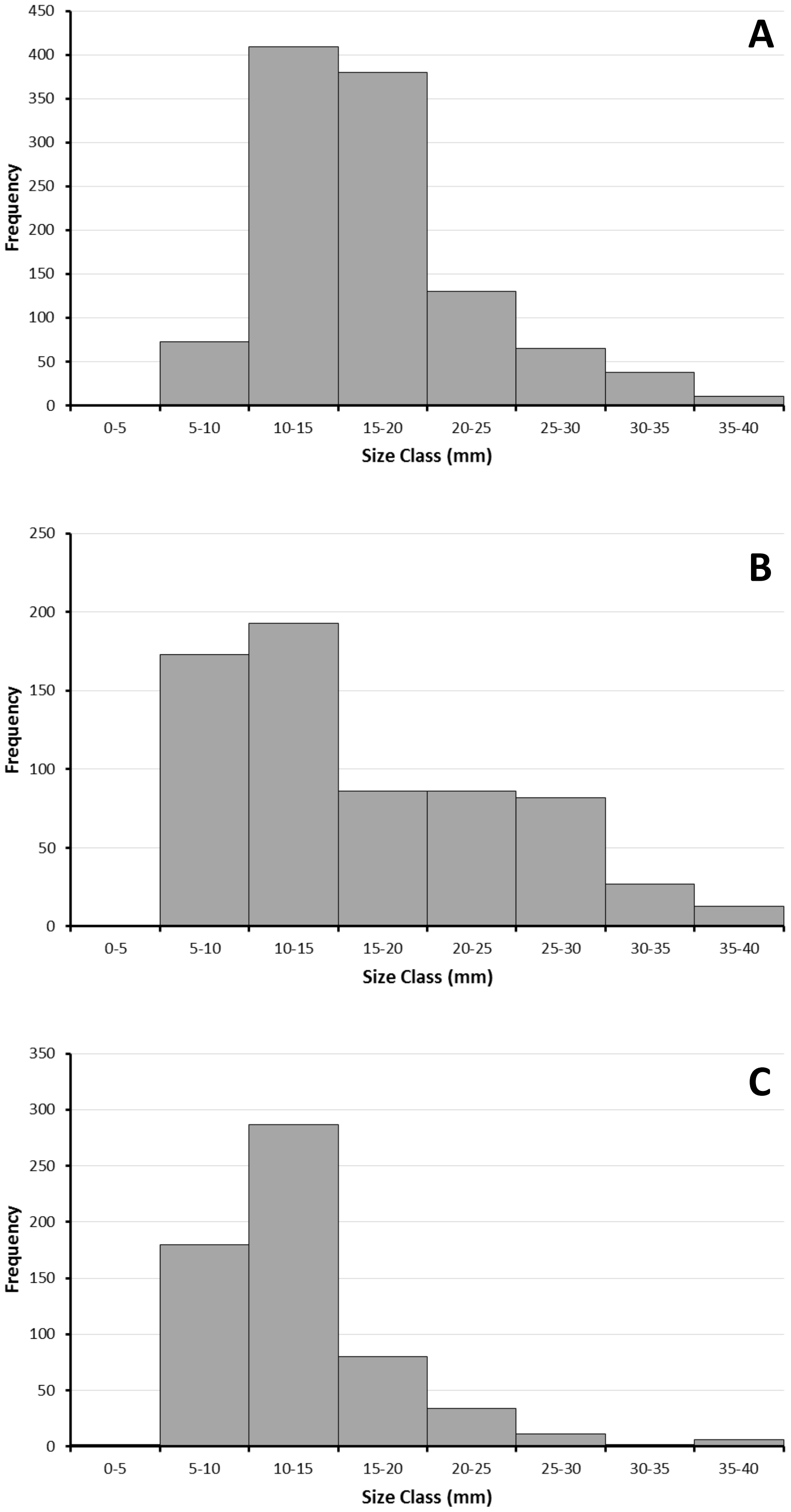

*Figure 26: Size-frequency distribution of juvenile toheroa in 'sieved' transects in a) 2002, b) 2005 and c) 2009.*

## 4.7 Predictions of future toheroa mortality

This study has modelled the current (2010-2012) impact of vehicles on the Oreti Beach toheroa population. Given that the number of vehicle registrations has increased steadily in New Zealand over the past fifty years (Figure 27), it is probable that in the future the number of vehicles using Oreti Beach will also increase, leading to greater vehicle-added mortality. We modelled future changes to vehicle numbers based on a linear function applied to the data in Figure 27. Assuming that the types, distribution and behaviour of vehicles on Oreti Beach remains the same, we predict that annual vehicle-added mortality will increase to 25% in 10 years' time and to 31% in 50 years. National vehicle registrations in the past 10 years appear to be increasingly more rapidly than the linear model fitted to the 50-year data set. If vehicle numbers continue to increase at this rate, vehicle-added mortality will obviously be significantly greater.

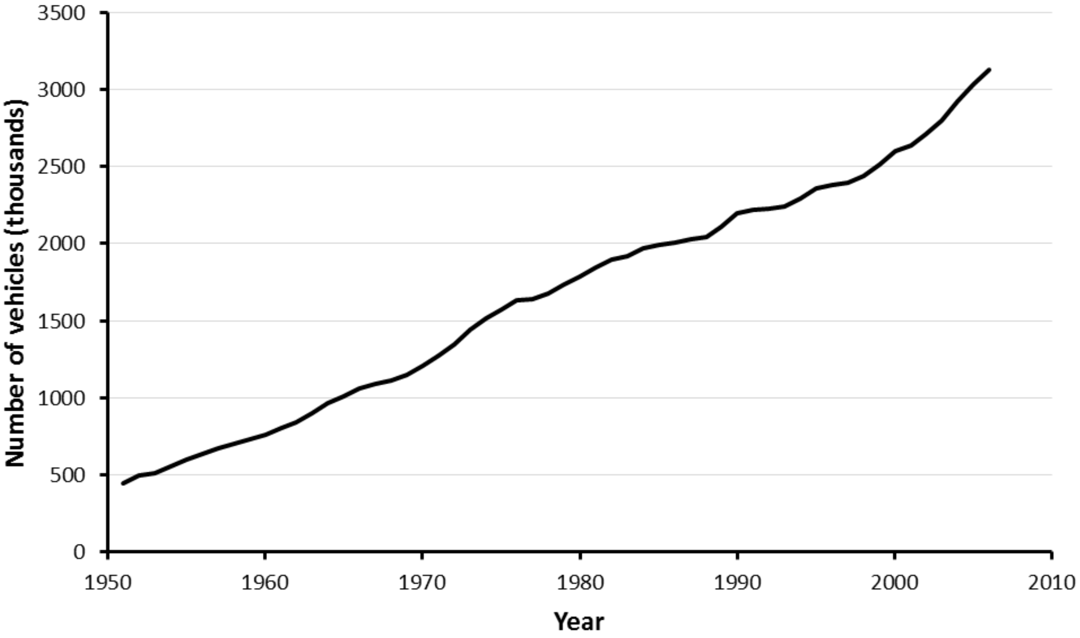

*Figure 27: Number of licensed vehicles in New Zealand per year, 1951-2006. [Source: Graphed from data in Appendix A of Conder (2009)].*

# 5. Discussion

## 5.1 How reliable is the model?

Our spreadsheet model incorporated upper and lower confidence limits on estimates of the proportion of juvenile toheroa that were damaged when run over by test vehicles[67]. However the resulting uncertainty intervals[68] do not account for several other sources of uncertainty, some of which relate to (i) model simplification, some to (ii) parameter estimation (measurement error), and others to (iii) systems uncertainty (issues of ecology).

The model was simplified by:

- Conceptualising the Oreti Beach toheroa colony as a square 18 km x 200 m array of 20 m x 5 m pixels. We simplified the model structure in this way because (a) transect data became sporadic below 200 m, (b) the intertidal zone clearly widens at the extreme south eastern end of the colony, (c) vehicles and juvenile toheroa found lower than 200 m from the dune line make up a small part of the population, and (d) GIS checks demonstrated that errors from curvature of the beach caused relatively small distortions in trip distances simulated for vehicles travelling along the beach at a set distance from the dune lines[69].
- Assuming that cars start a south or northbound trip anywhere on the centre line running to the sea at the middle of the Main Entrance and North Entrance gap in the dunes (in reality cars arch left or right before setting off along the Beach)
- Obtaining sufficient sample sizes by pooling data from the 1 km wide stretches either side of Main Entrance *cf*. beyond when describing distribution of vehicles (Figure 9) and toheroa (Figure 12) down the Beach. This causes the small discontinuities in predicted mortality at the 1 km south and 1 km north boundary (Figures 14 and 15).
- Fitting continuous functions down and along the beach from the fragmentary data available, especially at the extreme distances from the entrances.
- Ignoring a trickle of motorbikes and utilities/4WDs that enter over the Waimatuku Stream and so would not be included in the automatic traffic counter totals and conversion factors that “topped-up” traffic volumes via North Entrance.
- Ignoring vehicles that enter via one entrance and leave by the other (our return trip model for cars and utes/4WDs will slightly exaggerate trip distances for these one way trips).

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[67] The Motorbike Flow model also incorporated upper and lower confidence intervals in mean trip distances.

[68] And so the error bars on Figures 13,14,16-18.

[69] A maximum error of 0.43 % and 0.68% north and south of Main Entrance respectively.

- Ignoring possible seasonal changes in the proportion of different vehicle types or their distance travelled per visit.
- Ignoring impacts of horses, unusual vehicles (sulkies, non-motorised bikes, blowcarts) and specialised activities (doughnuts and race practices).

Amongst parameter estimation errors, we emphasise:

- Some motorbikes are transported on to the Beach on trailers, so they would not be individually counted. The traffic counter was calibrated so as not to double count trailers, whereas the trailer tyres will have added risk to juvenile toheroa.
- Disentangling the streams from the North Entrance and Main Entrance was problematical, but in this instance, error from assigning a particular parked vehicle to the wrong traffic stream would at least be partially counteracted by inflating the traffic from the other stream[70].
- Our sample size of observations of motorbikes was extremely limited and the observed pattern showed that we could not use the intended return trip stream model way of estimating impacts. The alternative trip distance model depended on guestimates of the relative speed of a motorbike travel compared to a ute/4WD. Accordingly the motorbike impact estimates are particularly uncertain. Fortunately motorbikes are relatively infrequent users of Oreti Beach compared to cars and utes/4WDs, so this uncertainty does not greatly impair the reliability of our overall interpretations[71].
- The proportion of vehicle types intercepted during our circuits will only accurately measure the proportion of visits by each type if each spends on average about the same time on the beach per visit.
- Dog exercising (driving next to a running dog) was relatively frequent[72] and will be underestimated by our model that was parameterised mainly from the distribution of stationary vehicles i.e. owners only stop briefly to let the dog out at the start of their exercise, and back in again afterwards.
- We found a considerably lower damage rate by the test motorbike and test utility/4WD used in this 2012 study compared to results from another bike and two other utilities used as test vehicles in 2009[73], even after restricting the estimate only to the more reliable *in situ* testing

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[70] Future studies would benefit from a more interviews of people associated with parked vehicles, and for such interviews to be selected by a more formal stratified (in sections along the beach) and random approach than we deployed this time.

[71] If this study was to be repeated and refined, we recommend that motorbike riders are interviewed before and after their excursion and the kilometre run during the trip is measured directly.

[72] See Scott et al. (2014).

[73] Moller et al. (2009).

method. It may be that the individual characteristics of the tyres, the torque of the turning wheel, the weight of the vehicle, the way the vehicles are driven, or conditions of the sand at the test spots have caused this variation. Whatever its source, it indicates a need for more follow-up studies of vehicle damage rates using a much larger number of different test vehicles and drivers and beach locations so that the accuracy of predictions of the model can be improved. Even if mortality rates are considerably lower than used in this study, the impact on the population may still be significant. We tested this by reducing mortality to 1% per pass for each vehicle type. This resulted in 11% vehicle-added mortality across the whole beach and over a twelve month period.

Broader systems uncertainty issues include the following questions:

- Do rapid repeated passes of a vehicle increase or decrease risk? A study of traffic damage to tuatua (*Paphies subtriangulata*) found that repeated passes over the same area of sand in Pegasus Bay led to increased overall mortality[74], Northland studies[75] assert increased risk to toheroa and our small sample size suggested about the same risk per pass.
- Could there be non-lethal effects that add unquantified risk?[76] Some studies have found that motility (especially time to rebury after extraction from sand) is impaired after being run over even if no cracks are visible. Our preliminary study confirmed that juvenile toheroa with even minor cracks died (and some permanently extended their siphons) within three days in captive conditions, whereas apparently undamaged ones survived well (and actively extended and withdrew siphons) over the same period, so we are confident that the damage detected in the vehicle trials is lethal. However we cannot discount the possibility that several other experimentally treated toheroa without visible cracks were not impaired internally.
- How long do toheroa spend in the juvenile stage? Much more detailed information on toheroa growth rates are needed before the absolute proportion killed by cars can be pinpointed. If toheroa grow through the juvenile size classes in 3 months, the overall added mortality of all vehicles on Oreti Beach is predicted to be about half that if it takes them 12 months to outgrow the vulnerable sizes.
- When in the year do most juvenile toheroa first appear on Oreti Beach? This may affect vulnerability to the main seasonal pulse in visitors (a late summer or autumn cohort of

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[74] Marsden and Taylor (2010).

[75] Hooker and Redfearn (1998).

[76] Sub-lethal effects have been detected in other shellfish species (Sheppard et al. 2009).

juveniles may have improved chance of survival and outgrowing the vulnerable sizes before the next summer's pulse of vehicles flood on to the beach).

- Does mortality from vehicles add directly and independently of natural mortality? For example, if density dependence operates (e.g. natural mortality is more intense in crowded parts of the beach), there could be part compensation for the added mortality imposed by vehicles (i.e. natural mortality becomes less intense there because the vehicles have thinned out some of the toheroa).

We expect (i) uncertainty from model simplification to be relatively trivial and (ii) parameter uncertainty to be potentially important, albeit partly self-correcting (inflation of one variable triggers depression of another). Further long-term research would be needed to assess whether (iii) systems uncertainty is large enough to challenge our overall conclusions.

In view of above uncertainty, the exact predictions of our model should be interpreted with extreme care. It would be inappropriate to rely closely on the absolute value of the predicted mortality (or putative impact on toheroa abundance). However, the model's predictions are likely to be reliable when used as a relative index of impact on toheroa in different areas of Oreti Beach, or at different times of the year, or to assess relative risk posed by motorbikes, utes/4WDs compared to cars. Similarly, the model can usefully predict the relative efficacy of various potential traffic management interventions if these are wanted by the regional stakeholders to simultaneously protect toheroa and recreational values on Oreti Beach. Finally the measure of variation in an index of impact of vehicles is extremely useful in testing associations between vehicle distribution and toheroa distribution along and down the beach and thereby evaluating whether a potential threat occurs at all.

## 5.2 Which model provides the most reliable indication of threat to toheroa?

The *Vehicle Distribution Model* and the *Overlapping Distribution Model* predicted very similar threat levels, although the overlapping distribution model impacts were approximately 2-5% higher than those from the vehicle distribution alone for most scenarios (Figures 13 and 16). The similarity in predicted impact of the two models undoubtedly comes in part from redistribution of juveniles along the beach by drift or alongshore-dispersal of spat. This redistribution resets the overlap between vehicles and toheroa at the beginning of each recruitment period (Figure 11). The vehicles themselves will then start to depress the juvenile density in the middle sections of the beach around Main Entrance in particular. We would expect gradually less overlap between vehicles and the remaining (surviving) juvenile toheroa as the cohort of juvenile recruits ages, unless the rate of infilling of the mid-section of the beach by re-suspended and drifting juveniles is sufficient to obliterate sign of the localised vehicle impact.

Depression of juvenile abundance around Main Entrance (Figure 11) is expected to lead to the overlapping distribution model predicting lower overall mortality than the vehicle distribution model. In fact the reverse, a slightly elevated mortality in the overlapping distribution model, was observed. This comes about because vehicles and juvenile toheroa are concentrated in the same high intertidal zone between 30 and around 70 m from the dune line (Figures 9, 12 and 19). This “collision” in same levels down the beach more than compensates for the thinning of toheroa around the middle sections along Oreti Beach, so that overall predicted mortality is relatively similar for each approach (27% from the overlapping distribution model compared to 23% for the vehicle distribution model).

Actual and potential impacts of vehicles on Oreti Beach are best indicated by using both models in conjunction. The overlapping distribution indicates current impacts of vehicles on recruitment, while the vehicle distribution model best indicates the longer term potential risk to the population, for example where the population can rebuild on the beach if traffic management interventions are instigated. A gradual change in the relative distribution of adults, sub-adults and juveniles would be expected from any such spatial restrictions in vehicles rather than a simple even overall increase in density across the entire area. When scaled against the many uncertainties from other sources, the degree of difference between the models observed in February is unimportant.

## 5.3 Do vehicles significantly threaten the toheroa population at Oreti Beach?

Our simulations provide strong but indirect indications that vehicles significantly impact on toheroa abundance on Oreti Beach. There were highly significant and consistent spatial associations between predicted added mortality from vehicles and reduced abundance of adults in particular (Table 11, Figure 24). Weaker correlations also occurred between predicted mortality and juvenile abundance, except in the February 2005 survey which took place during and/or just after recruitment by very small/young toheroa. A steeper decline in abundance of adults compared to juveniles is exactly as predicted for (a) a relatively long lived shellfish with overlapping generations of adults, (b) seasonal pulses of recruitment, (c) rapid growth of young and along shore redistribution of juveniles after initial settlement.

One vey approximate way of estimating the impact of vehicles on population size is link Figures 14 and 24. For example, the model predicts that the toheroa adults

- will not occur at all where added mortality from vehicles is above 50%, and this occurs in around 2 km (11%) of the Oreti Beach colony
- will be reduced by *c.* 70-90% where added mortality from vehicles is above 30%, and this occurs in just under a further 2 km stretch (10%) of the Oreti Beach colony

Combining these estimates suggests that breeding and harvestable portion of the Oreti Beach toheroa colony has been eliminated or severely reduced over 21% of its potential range.

Simple substitution of 23% added mortality (our average estimate of vehicle risk over the entire beach) into Figure 24 predicts adult density of 0.20 $m^{-2}$, 0.21 $m^{-2}$ and 0.30 $m^{-2}$ for 2002, 2005 and 2009 respectively. These are equivalent to a 63%, 79% and 71% reduction in adult population compared to that predicted at zero added mortality (the theoretical population if vehicles were completely removed from Oreti Beach).

We caution against using these predicted reductions directly as measures of impact of vehicles on overall population size, but they do indicate that the cumulative effects of successive years of 23% added mortality from vehicles (averaged over the whole 18 km length of the toheroa colony) could reduce the adult population by much more than 23%, and that depletion is severe over 10-20% of the potential breeding area.

An adjunct study of the Burt Munro Challenge motorbike beach race event on 28 November 2008 estimated that around 53,000 juvenile toheroa were killed on the 850 m long race track, but statistical uncertainty means that the number of fatalities could have been as low as 31,000 or as high as 70,000. This indicates a minimum mortality rate of 72% (41 – 90%) amongst the toheroa settled on the race track at that time. Although this impact is severe, it is also localised and juveniles repopulate the race-track area by drifting along the shoreline and resettling in the upper beach zone where the race takes place. The NIWA surveys estimated that there were around 7 and 6 million juveniles living on Oreti Beach in February 2005 and 2009 respectively. If similar densities were present during our studies, the Burt Munro Challenge beach race probably kills less than 1% of all the juveniles in the population, whereas the year-round traffic kills around 23% of the juveniles. Clearly management of risks to toheroa recruitment from every-day traffic is much more important than further reduction of the Burt Munro Challenge impacts which have already been reduced by relocation of the race track and better management of spectator vehicles.

The statistical models and observed variation in toheroa abundance along Oreti Beach (Table 11, Figures 11 & 23) are entirely consistent with vehicles having greatly reduced toheroa abundance. However, some degree of autocorrelation between the model's predictions and observed abundance could confound this interpretation. Interviews with kaitiaki (Māori environmental guardians)[77] and a review of historical surveys[78] both emphasise that the extreme south eastern end of the colony has traditionally always been a stronghold of toheroa abundance and condition. This pattern was in place long before vehicle traffic became intense. Commentators have postulated that the high abundance and good condition of the toheroa at the southern end may result from increased food abundance associated with outflow of the Oreti River. We hypothesise that the wider span of the intertidal zone in the south eastern reach of the beach could also promote abundance there, or that spatfall and recruitment of young could be increased because currents and bathymetry drive a south eastern concentration of the metapopulation. Whatever the reason for the natural concentration of toheroa in the southeast, the fixed and point location of entry of most vehicles some 5-8 km further northwest could drive an apparent rather than real correlation between vehicle-induced mortality and observed decline in toheroa abundance.

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[77] Futter & Moller (2009).

[78] Beentjes (2010).

Although such an autocorrelation with natural variation in abundance could be operating to some degree, several clues suggest that it could not by itself be a sufficient explanation for our observed pattern:

1. Adult abundance rises to intermediate levels further northwest than the main vehicle entrance, exactly as predicted by the vehicle distributions (Figure 23).
2. Adult abundance declines again even further northwest than North Entrance, as predicted from the entry of the North Entrance stream of utes/4WDs in particular. There may, however, be autocorrelation in this area if the population naturally tapers off towards the northern limit of the toheroa zone.
3. Localisation of the reduced abundance of juvenile toheroa in the upper 30-70 m of the beach in the area around Main Entrance (Figure 19) is precisely as predicted by the vehicle impact model. We think that some alongshore natural variation in the metapopulation might exacerbate the apparent correlation, but cannot think of why such an effect would operate in a particular height of the beach in the predicted high vehicle impact zone.
4. The spatial association between the model's predictions and observed toheroa abundance (Figures 24 & 25) is remarkably strong considering that toheroa distribution is extremely patchy down and along the beach over scales of 100 m or less. This patchiness explains a large amount of the scatter from individual transects depicted in Figures 23 to 25.
5. The spatial association remains strong in many years even though some movement of toheroa along the beach could partly obliterate sign of the pattern. Considerable movement of well-grown toheroa along and down the beach has been observed. Flounder fishers occasional recover an adult toheroa as they gather in their nets[79]. Also, there has been repeated speculation that sub-tidal populations of toheroa adults occur, but this has never been proven. Any migration from sub-tidal or alongshore sources could blur spatial correlations, but clearly has not removed them altogether.
6. Finally, for all its uncertainty, the vehicle impact model itself is straightforward in structure, the mechanism of the putative impact is logical and key components of the putative effect are demonstrated, and the size of the injury is predicted to be considerable.

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[79] Kendall Gadomski, pers. comm.

## 5.4 Population knock-downs and resurgence

Even though vehicles are likely to be significantly depressing toheroa abundance at Oreti Beach, other threats to the population are clearly also operating. Die-back events (i.e. mass mortalities) have been noted occasionally on Oreti and Bluecliffs Beaches over the past decades[80]. These events kill a large number of adults, some of which might otherwise live and breed for 20 years[81]. They can therefore be classed as "ecological catastrophes" (rare, high impact events)[82] that are particularly important threats to small or fragmented populations like toheroa. A scientifically robust sampling procedure has been worked out in advance so that when a die-back occurs a team can immediately count, measure and collect specimens in a way that allows the risk to toheroa populations to be quantified and potential causes identified[83]. The effects of a mass die-back may well be evident for decades afterwards. For example, a large dieback event occurred in 1993 from about 2 km south of Main Entrance to almost South Entrance[84]. It is estimated that 20,000 toheroa may have died in this event. This may have contributed to a relatively even distribution of toheroa along the beach between at least 1988 and 1998[85], but clearly something had eliminated the high density at the south eastern end of the beach even before the 1993 event. Pollution of the Oreti River destroyed the health of bull kelp at Omaui around that time[86]. Rapid decline in tītī populations began in 1987 which are correlated in some way with ENSO events and maybe broader oceanic fluctuations[87].

The most useful conceptual model for toheroa population dynamics is one of periodic knockdown by climate, food or pollution events, followed by gradual rebuilding of the population by sporadic recruitment. Sporadic recruitment is a feature of all New Zealand's surf clams and has been noted as a particular issue for toheroa population resilience[88]. The resilience of the population depends on managing potential threats like vehicle-imposed mortality and harvest limits. The long term sustainability of the toheroa population at Oreti Beach depends on the population regaining the same or higher density on average before the next knock-down occurs. If population knock downs become more severe or frequent in coming years, harvest and vehicle pressures may need to be all the more reduced if a viable population is to be retained at Oreti Beach. A preliminary estimate of

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[80] See Eggleston & Hickman (1972), Beentjes et al. (2006b), Futter & Moller (2009) and Moller & Futter (2009) for written reports. Recent sporadic dieback events have also been noted by Dallas Bradley & Lloyd Esler (pers. comm.).
[81] Beentjes & Gilbert (2006b).
[82] Hamilton & Moller (1995).
[83] Moller & Futter (2009).
[84] D. Bradley (in litt.).
[85] Beentjes (2010).
[86] Futter & Moller (2009).
[87] Clucas (2011).
[88] Marsden (1999), (2000), (2002); Williams et al. (2013).

harvest impacts indicated that current off-take is well below maximum sustainable limits[89], whereas our present study indicates that traffic impacts are probably very significant in depressing the population's resurgence in some parts of Oreti Beach. It is noticeable that following evening out of the distribution of adult toheroa between 1988 and 1998, the population has first resurged in at the south eastern end, followed by much more gradual increase in the northern half of the beach (Figure 23). There has been extremely limited resurgence around Main Entrance in the past decade, but recent evidence of it happening south of North Entrance where predicted mortality from vehicles is at its lowest (Figure 14 and 15). Our hypothesized working model for guiding traffic management decisions and interpretation of population monitoring surveys is therefore that sporadic recruitment of toheroa following unexplained population knockdowns is being partially blocked by vehicles in the central and extreme northwest zones of Oreti Beach.

Although the abundance of toheroa has been fluctuating, it remains at a sufficient density to allow most harvesters to gather a feed[90]. Currently there is no sign of the need for restricting authorisations, so vehicles pose a longer term threat to the speed and degree of recovery after knock-downs that are beyond the control of the kaitiaki and other environmental managers. Recruitment to rebuild the population after these knock-downs is being partially blocked by vehicles in the central and extreme northwest zones of Oreti Beach in particular, so the resilience of the colony could be future-proofed by restricting vehicle impacts in these areas.

## 5.5 The need for ongoing monitoring

Maintaining the regular 3-4 year surveys of toheroa on Oreti Beach is important. It will cross-check the predictions of our model and if coupled with experimental interventions to manage traffic, such surveys can underpin an "active adaptive management" approach[91] to learning how to best promote the resilience of the toheroa population. Our use of the historical data from the NIWA surveys demonstrates that standardised monitoring and regular long-term databases like these are extremely valuable in ways that might not initially have been expected. Our analysis emphasises that the distribution of toheroa along Oreti Beach changes significantly over a period of decades (Figure 23), so the original stratification imposed on the standardised survey methodology in 1998 should now be reviewed. A more regular distribution of transects along the beach would allow a more systemic understanding of the toheroa metapopulation and in particular why the previously sparsely

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[89] Beentjes et al. (2003).
[90] Scott et al. (2014) surveyed toheroa harvestsers and found them well satisfied with their harvest success.
[91] Walters & Holling (1990).

populated sections of the beach are not resurging. The variation in abundance of sub-adults in the population and putative links to juvenile density and vehicle-imposed mortality are particularly unknown (Table 11). By far the most valuable surveys are those that are sieved, so some consideration should be given to budgeting for more of them in particular. It is very important to standardise the time of year that surveys are taken, and to restrict them to a short period in February as used in the historical NIWA surveys. This allows stronger interpretation of the rolls of juvenile recruitment in population dynamics. More generally, we urge that population recruitment and metapopulation studies are coupled with the regular surveys so that fluctuations in toheroa abundance can be better interpreted.

Standardised monitoring of toheroa is very important and valuable nationally as well as for Southlanders, but the general declines in other toheroa populations suggests that national research emphasis should now shift from primary focus on what is happening to why observed trends are happening. The latter (causes for change and variation in that change between populations) hold the key to designing optimum management interventions to reverse declines. Detailed study of the Oreti Beach population, one of the few remaining abundant populations left in New Zealand, is just as important as studying the depleting populations because it offers a reference comparison against which to measure the urgency and scale of management intervention needed for a national toheroa recovery strategy.

## 5.6 Ways forward: should vehicle traffic be restricted on Oreti Beach, and if so, how?

Oreti Beach harbours one of only two populations of toheroa that are broadly maintaining their abundance[92]. Declines are apparently ongoing in several North Island populations and the previously extensive and abundant population at Bluecliffs in Te Waewae Bay is now virtually extinct[93] because diversion of water from the Waiau River in 1972 triggered erosion of the sand from Bluecliffs Beach[94]. The species is designated as a taonga species in the Ngāi Tahu Settlement Act, and there is no doubt that it is immense cultural importance for all New Zealanders as well as Māori. The species, along with pāua and tītī, featured as a “cultural keystone” species in the testimony of around 100 interviewees of fishers and gatherers from throughout Ngāi Tahu’s rohe[95]. Invercargill

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[92] Williams et al. (2013).

[93] Beentjes et al. (2006), Beentjes (2010).

[94] Futter & Moller (2009).

[95] McCarthy et al. (2013).

citizens can rightfully feel proud to have such an iconic and nationally important species living on their doorstep. The Environmental Precautionary Principle[96] suggests that uncertainties in our model of vehicle impacts should be discounted in favour of minimising ecological and cultural impacts from any decline in toheroa abundance. Our crude forward projection of vehicle numbers suggests that the vehicle impact on toheroa will reach around a third higher (30%) by around 2060 if the traffic threat is not mitigated in some way. The dilemma is that zone or seasonal restrictions to vehicle access will potentially greatly impair enjoyment of Oreti Beach by many Southlanders and tourists[97]. Around 100,000 vehicles drive on to Oreti Beach each year, carrying around a quarter of a million visitors[98].

Vehicle use of Oreti Beach could be restricted in time (time of day, week, season) and/or space (along or down the beach). Preventing access to Oreti Beach at certain times of day would be unlikely to reduce mortality significantly, as beach users would likely adapt their visits so as to increase pressure at previously low-traffic times. As few vehicles visit Oreti Beach during the night and early morning, restricting access at these times would similarly deliver little benefit to toheroa. As motorbikes contribute so little to overall vehicle-added mortality, any restrictions to their use would provide little overall reduction in risk to toheroa.

Seasonal restrictions could be beneficial to the toheroa population. A greater understanding of the seasonality of juvenile recruitment and growth rates is needed before any such options can be optimised in ways that deliver most gain to toheroa population resilience for least impact on recreational use of the beach. If, for example, recruitment occurred throughout summer and autumn, any closure of the beach late in the peak season could allow a higher proportion of juvenile toheroa to survive and grow to an invulnerable size before beach use increased again the following spring and summer.

Spatial restrictions possibly provide more realistic management options. Whereas cars predominantly travel along the beach near to Main Entrance, utes/4WDs and motorbikes travel more widely, spreading impact to most parts of the beach. Restricting traffic to a section of the beach around Main Entrance would be beneficial to the toheroa population further along the rest of the beach. We have shown that vehicles are concentrated at high shore levels along Oreti Beach, a

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[96] Raffensperger & Tickner (1999).

[97] See Taylor et al. (2012) for a discussion of potential vehicle restrictions and both the impact on shellfish populations and recreational use of beaches.

[98] Scott et al. (2014).

zone which corresponds with peak juvenile abundance. This has led to a large reduction in juvenile density in this zone near Main Entrance where vehicle pressure is highest (Figure 19). Restricting vehicles to areas of beach either above or below the natural zone of juvenile abundance could result in significant conservation gains.

A system of palisades running 80-100m down from the dunes on either side of the Main Entrance and North Entrance could be considered. Provided the poles were sufficiently close to prevent a car or ute/4WD from passing through, a palisade would hold the vehicles high on the Beach during the top third of the tide, but also allow access onto the lower part of the beach once the water has receded. This would have the important advantage of keeping traffic off the top margin of the intertidal zone where most of the risk to toheroa occurs[99] while still allowing traffic access along the beach for a large part of the tidal cycle to meet the recreational needs of visitors

Vehicles may well impose significant risk to other toheroa populations, but this is not yet proven. Some national co-ordination of trials of vehicle management options and associated standardisation of methods to monitor their effectiveness would be extremely helpful, minimise costs and maximise rates of learning what to do to support toheroa in general. A mix of locally inspired and motivated research and adaptive management and nationally replicated and co-ordinated interventions is recommended.

Any measures to restrict and reduce the impact of vehicles to the Oreti Beach toheroa population need to be carefully considered in view of the recreational importance of the beach and wide range of community stakeholders that could be affected. Locally determined, consensus decision making is much more likely to create lasting solutions and compliance than top-down regulation. We recommend that a working party of key stakeholders is established to discuss and assess possible solutions. If that working party desires, the preliminary model constructed for this inquiry can be reconfigured to predict the relative efficacy of alternative traffic management solutions so that a cost effective and most beneficial solution is identified to enhance the resilience of the toheroa population with minimal impact on the recreational use of the Oreti Beach.

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[99] Having negotiated their way around the bottom margin of the palisade, drivers are likely to stay on lower sections of the beach where the surface is firmer and smoother.

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# Appendix A: Formulae used to calculate mortality of juvenile toheroa

Section 3.3 provides a general and intuitive description of the way the spreadsheet model was constructed. Here we formalise the description of the way we calculate the proportion of juvenile toheroa killed by vehicles in each pixel of the study area.

## A1.1 Calculating the number of vehicle passes within each 20 m x 5 m pixel

Let subscripts denote different estimates of a variable as follows:

t = a given scenario period (we have modelled 1, 3, 6, 9 and 12 month periods)

v = vehicle type (sometimes further specified as C for cars, U for utes/4WDs and B for Motorbikes)

S = traffic stream (sometimes further specified as M for Main Entrance, N for North Entrance and M for Motorbikes)

a = distance along the beach of each pixel from that vehicle stream's entrance

d = distance down the beach of each pixel

D = Direction turned at each entrance (left = southbound; right = northbound) at each entrance

The main parameters can be denoted and estimated as

$I_t$ = the number of incoming vehicles counted at the automatic traffic counter at Main Entrance in a given time period t (Figure 3)

$R_{Sv}$ = the multipliers used to split the Main Entrance Stream and estimate the size of the unmonitored North Entrance stream for cars and utes/4WDs (from the second to last two columns of Table 6)

$P_{SvD}$ = The proportion that turned in each direction by cars and utes/4WDs for each stream (from 2nd and 6th rows of Table 7)

$F_{SvDt}$ = the total number of vehicles of each type entering the south and northbound flows of each stream during time t

Then

$F_{SvDt} = I_t \,.\, R_{Sv} \,.\, P_{SvD}$

We have denoted $p_{SvD}$ as the probability that each vehicle of a given type travels across each pixel positioned at 'a' along the beach from a given entrance and 'd' down the beach. These probabilities are given by the reverse cumulative frequency distributions depicted in Figures 6 and 7 (for along the beach) multiplied by the proportion of travelling vehicles passing along each 5 m swathe down the beach (depicted Figures 9a and 9b). Note that the latter proportions down the beach were estimated differently in four zones and for cars cf. utes/4WDs.

The traffic (number of vehicles) passing over each pixel from each stream is

$T_{SvDadt} = F_{SvDt} . p_{SvD} . 2$

The total has been doubled because the reverse cumulative frequency distributions measure a return journey (the car or ute/4WD passes back over the pixel as it returns to the entrance it entered by).

If

$N_v$ = total number of passes over each vehicle type over a given pixel

Then,

$N_v = \quad T_{MvDadt} + T_{NvDadt}$

## A1.2 Calculating the proportion killed by each pass of a vehicle

Let

$g_v$ = the proportion of a 5 m wide (5000 mm) swath that is run over by a passing vehicle of a given type v, so that

$(1 - g_v)$ = the proportion of the 5 m swath missed by that passing vehicle;

$h_v$ = number of sets of aligned front and back wheels (2 for cars and utilities/4WDs, 1 for motorbikes),

$w_v$ = average width of tyres (mm) on each vehicle type (Table 9),

$\phi_v$ = the proportion of juvenile toheroa surviving when run over by an aligned front and back tyre of a given vehicle type as measured in our field experiments (estimated from 1 - the *in situ* risk measures in Table 2)

$\delta_v$ = survival of all juveniles present in the 5 m swath for each pass of a given vehicle type.

Then:

$$g_v = h_v . w_v / 5000$$

$\delta_v = g_v \cdot \phi_v + (1 - g_v)$ .... (1)

## A1.3 Modelling the proportion killed by all passes of cars or utes/4WDs

The remaining step is to calculate the proportion of the juvenile toheroa in each pixel that are killed (or survive) the passage of all the vehicles during the time period t.

$\mu_v$ = survival of juvenile toheroa after a given pixel has been run over by all the vehicles of a given type that reach that pixel.

Then

$\mu_v = \delta_v$^$N_v$ ... (2)

The added mortality of all the juveniles in a given pixel from a given vehicle type is $1 - \mu_v$. These estimates are depicted in Figures 14 to 16, and are tabulated in Appendix B.

## A1.4 Calculating the proportion killed by motorbikes

The constant coursing back and forth along the beach by some motorbikes means that the stream model was configured completely differently than as described above for four-wheeled vehicles.

If

$R_B$ = the multiplier used to estimate the proportion of the automatic vehicle count that were motorbikes (from the last column of Table 6)

$K_B$ = average distance travelled per motorbike visit (estimated in m at the last column of Table 8)

$L_{Bt}$ = total number of 20 m wide pixels passed over by all motorbikes visiting in time period t

Then

$L_{Bt} = I_t \cdot R_B \cdot K_B / 20$ ... (3)

These $L_{Bt}$ pixels were then distributed along the beach according to the probabilities shown by the regression lines in Figure 8, and down the beach according to the distribution in Figure 9c to estimate the total number of passes over each pixel in the study area by motorbikes in time t.

The proportion of the swath passes over by a motorbike was then calculated by substituting the tyre width for motorbikes (Table 9) and setting $h_v = 1$ in Equation 1. This was used to estimate $\mu_{B,}$ the proportion of juveniles surviving all the passes of motorbikes in a given pixel from Equation 2.

## A1.5 Calculating the proportion killed by all types of vehicle in each pixel

The above methods have separately estimated the proportion of all the juvenile toheroa in a given pixel that survive cars, utes/4WDs or motorbikes. An estimate of the combined injury from all vehicle types was calculated by multiplying all these separate survival rates for each vehicle type together i.e.

If

$\mu_A$ = survival of all passes of all vehicle types

Then

$$\mu_A = \mu_C \,.\, \mu_U \,.\, \mu_B \qquad \ldots (4)$$

and the overall added mortality from all vehicle types is $(1 - \mu_A)$. These estimates are depicted in Figures 14, and tabulated in Appendix B.

# Appendix B: Estimates of annual mortality added by vehicles

## B1. Vehicle Distribution Risk Model

| ***Whole Beach*** | | | |
|---|---|---|---|
| | *Mean* | *Lower CI* | *Upper CI* |
| Cars | 15.1 | 10.4 | 19.0 |
| Utes/4WDs | 12.0 | 7.2 | 19.2 |
| Motorbikes | 1.1 | 0.8 | 4.5 |
| ALL VEHICLES | 23.0 | 15.8 | 32.1 |
| | | | |
| ***North Half*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| Cars | 14.7 | 9.9 | 18.7 |
| Utes/4WDs | 13.6 | 8.0 | 22.2 |
| Motorbikes | 1.7 | 1.2 | 6.7 |
| ALL VEHICLES | 24.8 | 16.6 | 35.6 |
| | | | |
| ***South Half*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| Cars | 15.7 | 11.0 | 19.4 |
| Utes/4WDs | 10.1 | 6.2 | 15.6 |
| Motorbikes | 0.4 | 0.3 | 1.8 |
| ALL VEHICLES | 20.8 | 14.7 | 27.6 |
| | | | |
| | | | |
| ***Main Stream*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| ALL VEHICLES | 18.8 | 13.0 | 26.4 |
| | | | |
| ***North Stream*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| ALL VEHICLES | 4.9 | 3.0 | 7.7 |

## B.2 Overlapping Distribution Risk Model

| ***Whole Beach*** | | | |
|---|---|---|---|
| | *Mean* | *Lower CI* | *Upper CI* |
| Cars | 17.9 | 12.1 | 22.5 |
| Utes/4WDs | 13.5 | 7.9 | 21.9 |
| Motorbikes | 1.3 | 0.9 | 5.3 |
| ALL VEHICLES | 26.8 | 18.3 | 37.1 |
| | | | |
| | | | |
| ***North Half*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| Cars | 19.5 | 12.9 | 24.8 |
| Utes/4WDs | 16.7 | 9.6 | 27.7 |
| Motorbikes | 2.2 | 1.5 | 8.7 |
| ALL VEHICLES | 32.1 | 22.4 | 46.0 |
| | | | |
| | | | |
| ***South Half*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| Cars | 16.6 | 11.5 | 20.6 |
| Utes/4WDs | 10.9 | 6.6 | 17.1 |
| Motorbikes | 0.6 | 0.4 | 2.4 |
| ALL VEHICLES | 22.5 | 15.7 | 30.2 |
| | | | |
| | | | |
| ***Main Stream*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| ALL VEHICLES | 22.2 | 15.2 | 30.9 |
| | | | |
| | | | |
| ***North Stream*** | | | |
| | *Mean* | *Lower CI* | *Upper CI* |
| ALL VEHICLES | 5.4 | 3.4 | 8.6 |