Auckland Harbour Bridge (AHB)

Desktop Risk Assessment of Wind Related Vehicle Incidents on the AHB

Waka Kotahi

Reference: P522623

Revision: 1.0

2023-03-20

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Report title	Desktop Risk Assessment of Wind Related Vehicle Incidents on the AHB					
Document code	522623/1		**Project number**	P522623		
Client	Waka Kotahi					
Client contact	Tony Fisher		**Client reference**			
Rev	**Date**	**Revision details/status**	**Author**	**Reviewer**	**Verifier** (if required)	**Approver**
0	2022-12-13	Draft for review	s 9(2)(a) [redacted]	[redacted]	[redacted]	[redacted]
0.1	2022-12-16	Final Draft	[redacted]	[redacted]	N/A	[redacted]
0.2	2023-03-01	Revised Final Draft	[redacted]	[redacted]	N/A	[redacted]
1.0	2023-03-20	First Publication	[redacted]	[redacted]	[redacted]	[redacted]
Current revision	**1.0**					

Approval			
Author signature	s 9(2)(a) [redacted]	Approver signature	s 9(2)(a) [redacted]
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1 Executive Summary

Waka Kotahi would like to understand the high-level risk of a wind related vehicle incident occurring on the Auckland Harbour Bridge (AHB). Aurecon have been commissioned to provide a high-level risk assessment to clarify the likelihood of such events. This Desktop Risk Assessment has been based on different scenarios and hypothetical assumptions developed around the AHB High Winds Operating Manual. These scenarios are:

A. No restrictions to traffic during wind events,

B. Restrictions as outlined in the AHB High Winds Operations Manual,

C. Restrictions as outlined in the AHB High Winds Operations Manual + Enforced speed limits,

D. Restrictions as outlined in the AHB High Winds Operations Manual + Enforced speed limits + Enforced detours for high-sided vehicles.

For a wind related accident to occur, there needs to be a wind gust of sufficient speed (referred to as the *critical wind speed*) to cause a particular vehicle to crash, in either an overturning, side slip and/or yaw steer failure mode. This critical wind speed needs to be exceeded at the same time that a particular vehicle is travelling over the AHB, under certain additional conditions. These conditions include short duration wind gust speeds and directions, vehicle speeds, vehicle weights and centre of gravity, vehicle cross-sectional areas, driver reaction time, pavement surface, wind shielding from structures and/or other vehicles, etc. Given all the dynamic variables, it is very difficult to accurately predict the probability of a wind related vehicle incident occurring in real life scenarios.

To assess critical wind speeds, a literature review was undertaken that found several studies assessing critical wind speeds against vehicle speeds for certain vehicle types (Baker & Soper, 2018) (Hemingway & Robbins, 2019) (Cheung & Chan, 2010) (Kim, Yoo, & Kim, 2016) (BAKER & REYNOLDS, 1992). These studies found critical wind speeds varied with the angle of the wind relative to the direction of vehicle travel. The studies also explained that the critical wind speed increased as vehicle speeds decreased. Unladen high sided heavy goods vehicles (HGVs) and empty double decker buses were found to be the most vulnerable vehicle types.

For this desktop assessment the likelihood of a potential wind related vehicle incident occurring has been based around the formula below:

Likelihood of a potential wind related vehicle incident	=	Critical wind speed of vulnerable vehicle types travelling at a certain speed (across certain wind angles relative to direction of vehicle travel)[1]	×	Likelihood of a wind gust exceeding the critical wind speed across certain wind angles on the AHB[2]	×	Number of vulnerable vehicles on AHB at any given time when a critical wind gust occurs[3]

[1] Assessed from literature review findings
[2] Assessed using historical data from MetService on the maximum gust wind speeds and associated directions at the AHB
[3] Taking Waka Kotahi's Traffic Monitoring system (TMS) records to assess the average number of vulnerable high-sided vehicles on the AHB at any given time

Table 1 summarises the approximate return periods of a potential wind related vehicle incident occurring within each of the hypothetical scenarios, along with the associated high-level consequences. These return periods provide a relative comparison of the risk of a vehicle incident. These four scenarios range from no restrictions through to varying levels of restrictions and associated assumed traffic / driver behaviour.

Table 1 - High-level risk profile of wind related vehicle incidents on AHB under the four hypothetical scenarios

	Scenario A (ii) **No restrictions to traffic during wind events**	**Scenario B (iii)** **Restrictions as outlined in the AHB High Winds Operations Manual**	**Scenario C (iv)** **Restrictions as outlined in the AHB High Winds Operations Manual + Enforced speed limits**	**Scenario D (v)** **Restrictions as outlined in the AHB High Winds Operations Manual + Enforced speed limits + Enforced detours for high-sided vehicles**
Potential wind related vehicle incident return period for each hypothetical scenario(i)	Approximately 20 times in 1 year	Approximately 1 in 1 year	Approximately 1 in 10 years	Approximately 1 in 50 years
Consequence of an incident	- Medium to long duration high congestion and travel time costs - Potential bridge damage (vi) - Potential deaths and/or serious injuries	- Medium to long duration high congestion and travel time costs - Potential bridge damage (vi) - Potential deaths and/or serious injuries	- Medium to long duration high congestion and travel time costs - Potential bridge damage (vi) - Potential deaths and/or serious injuries	- Medium to long duration high congestion and travel time costs - Potential bridge damage (vi) - Potential deaths and/or serious injuries
Consequence of bridge closures	NA	- Short duration high congestion and travel time costs - Avoided trips.	- Short duration high congestion and travel time costs - Avoided trips.	- Short duration high congestion and travel time costs - Avoided trips.
Consequence of reduced speeds	NA	NA	- Short duration minor travel time costs	- Short duration minor travel time costs
Consequence of high-sided vehicle detours	NA	NA	NA	- Short duration medium travel time costs for commercial vehicles and buses.

i. These return periods are based on several hypothetical assumptions, which may not reflect actual conditions nor driver behaviour during high wind events. For example, when a high-speed wind gust blows across the AHB deck, a vulnerable high-sided vehicle may be partially or fully sheltered from this wind by part of the bridge structure or another vehicle. Furthermore, there is a good likelihood that at least several vehicles travelling in each direction over the AHB will reduce their vehicle speed during high-winds and the forced lane merging, which could result in a speed reduction of all vehicles. These factors would significantly reduce the potential likelihood of a wind related vehicle incident.

ii. Assumes there is never a meaningful reduction in vehicle speeds over the AHB during high-wind events, which is unlikely.

iii. Assumes there is never a meaningful reduction in vehicle speeds over the AHB during high-wind events and lane closures, which is unlikely.

iv. Assumes there is no meaningful reduction in vehicle speeds for 10% of vehicles travelling over the AHB during high-wind events and lane closures.

v. Assumes 20% of high-sided vehicles do not detour and no meaningful reduction in vehicle speeds for 10% of vehicles travelling over the AHB during high-wind events and lane closures.

vi. If an incident did occur, the accident must occur when the vehicle is in certain locations on the AHB for it to result in significant damage to the bridge structure, which would increase the return period of an incident resulting in potential bridge damage.

The results obtained during the creation of this desktop risk assessment have been reviewed using a sensitivity analysis tool. The outcome of the sensitivity analysis was that a change in the assumed critical wind speed, would have a large effect on the stability of high sided vehicles, when they are traveling at or above 80km/h. A change in the number of critical high sided vehicles in the fleet has a less dramatic effect on the risk profile.

As part of this review, the wind speed at which the Auckland Harbour Bridge is closed was also reviewed. The desk top analysis revealed that increasing the AHB closure wind gust speed from 90km/h to 95km/h, would erode the safety margin for vehicles traveling at the legal speed limit and therefore is not recommended.

Waka Kotahi also has an opportunity to improve safety during wind events on the AHB. There is anecdotal evidence that the advisory speed limits are not always adhered to by vulnerable high sided vehicles. By making the variable speed limits legal and enforceable, a buffer zone would be created, enhancing the separation of vehicle traveling speed from the critical speed. New changeable speed limit signage would be required to achieve this safety improvement.

Should Waka Kotahi wish to build on the work performed in this desk-top risk assessment, and further refine the wind related vehicle incident return periods for the AHB, the following tasks are recommended:

- A detailed analysis of vehicle speeds, during different wind conditions and bridge restrictions, at different times of the day.
- A detailed analysis of vehicle types and weights, and associated volumes travelling over the AHB.
- A detailed analysis to assess site specific wind conditions that could cause an incident on the AHB accounting for the varying conditions analysed in the above two tasks. This could be through computer simulations and/or wind tunnel testing that can also account for shielding effects and wind eddies.

2 Introduction

Waka Kotahi would like to understand the high-level risk of a wind related vehicle incident occurring on the Auckland Harbour Bridge (AHB). This is to be based on Waka Kotahi's AHB High Winds Operations Manual relative to doing nothing.

High winds can cause a vehicle accident under three failure modes (Cheung & Chan, 2010):

1. **Overturning:** the vehicle flips over and may hit another vehicle or the bridge structure.
2. **Side slip:** the vehicle is blown a significant distance sideways and crashes into the bridge structure or another vehicle in the adjoining lane.
3. **Yaw steer / vehicle rotation:** the vehicle rotates through a significant angle and crashes into the bridge structure or another vehicle in the adjoining lane.

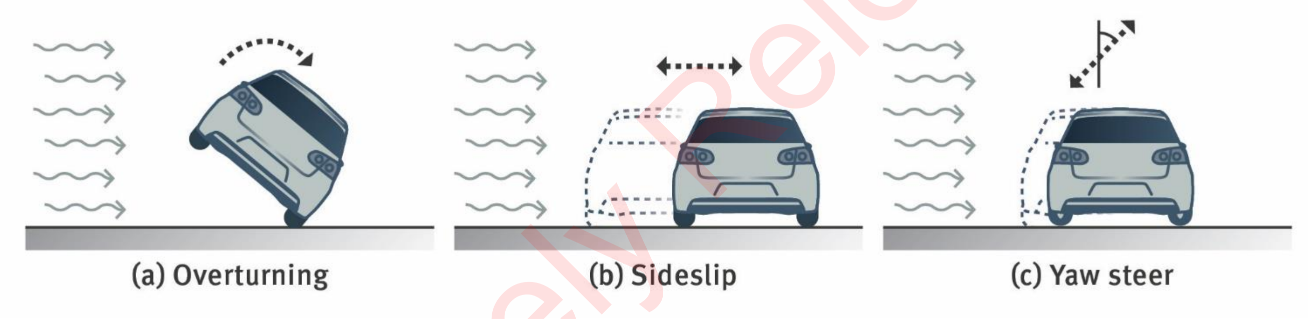

Figure 1 - Wind induced vehicle accidents caused by overturning, sideslip, and yaw steer failure modes

Baker C. (1987) suggests that an accident from one of the above three failure modes would occur within 0.5s of a vehicle entering a cross-wind gust if, one of the tyre reactions fell to zero (overturning failure), lateral displacement exceeded 0.5m (side slip failure), or the lateral displacement angle exceeded 11° (yaw steer failure) (Baker C. , 1987).

However, these assumptions assume that the driver would not react and correct any lateral or rotational movement within 0.5s and are therefore conservative (Guo & Xu, 2006). Furthermore, the accident probability depends on a number of factors including vehicle speed, vehicle weight and centre of gravity, vehicle cross-sectional area, driver reaction time, pavement surface, wind direction, wind shielding from structures and/or other vehicles, etc. (Sun, Wang, Shen, & Chen, 2021) (Guo & Xu, 2006) (William, Oraby, & Metwally, 2014).

There are several studies that have assessed the critical wind speed, that would result in a wind-induced vehicle accident, based on certain vehicle parameters. These assessments have been conducted through wind tunnel testing, computer simulations and static calculations. The assessments were then reviewed against multiple accidents that occurred during a storm event in England on 25 January 1990 (BAKER & REYNOLDS, 1992).

Of the three failure modes, these studies found high-sided vehicles, especially when unladen, are particularly vulnerable to overturning in high winds and are generally the critical case to consider when assessing risk (Baker & Soper, 2018). A side slip type incident will likely be the more dominant failure mode for cars[4], but are generally less likely than a high-sided vehicle overturning (Guo & Xu, 2006) (Cheung & Chan, 2010) (Yang, et al., 2019). This is highlighted in the accident examples outlined below.

- On the AHB on 11th June 2014, a wind gust of 126km/hr caused a truck to overturn on the southbound clip on. At the time of the incident, a 30km/hr speed restriction was in place and every second lane was closed.
- On the Manukau Harbour Crossing on 3rd August 2021, a crosswind of 95km/hr caused the trailer of an empty truck and trailer curtain sider to overturn.
- On the AHB on 18th September 2020, a wind gust of 128km/hr caused two trucks to overturn. One truck was a light curtain sider travelling north, the other was an empty container truck travelling south.
- On the Humber Bridge in England, a wind gust of approximately 80km/hr caused a truck to overturn in 2015 (BBC, 2015).
- On the Forth Road Bridge in Scotland, wind gusts up to 123km/hr caused a truck to overturn in 2017 (Express, 2017).
- During a storm in England on 25 January 1990, there were approximately 400 wind-induced accidents recorded. These accidents were generally caused by wind speeds greater than 72km/hr with gusts between 115km/hr to 144km/hr, and up to 169km/hr. Of these accidents, 47% were from overturning and 19% from course deviation. The remaining accidents were from trees falling over or other miscellaneous reasons. While 66% of the accidents involved high-sided trucks or vans, and 27% involved cars. (BAKER & REYNOLDS, 1992).

[4] Note: Yang, et al. (2019) found a side slip car incident could occur in wet conditions at wind speeds up to 10% lower than critical wind speeds in dry conditions.

3 Overview of AHB High Winds Operations Manual

The AHB High Winds Operations Manual (referred to as the "Operations Manual") was developed to deliver safety of users and to reduce the opportunity for structural impact damage from high wind related incidents.

To achieve this level of safety for users, the Operations Manual defines wind restriction thresholds (refer to Table 2), the roles, responsibilities, readiness, response, recovery, and review to implement these thresholds.

In classifying the restriction thresholds, wind directions have been categorised into AHB Wind Zones, being Perpendicular or Oblique to the direction of traffic (illustrated in the figure 2 to the right).

The AHB operational wind procedures were reviewed against international best practice by Resolve Group in their report, *"Auckland Harbour Bridge – Review of Wind Operating Procedures against International Practice (April 2021)"*.

That report outlined high-wind operating restrictions for several international bridges. These restrictions have been summarised for bridges in the UK and Australia in Figure 3, Figure 4 and Figure 5.

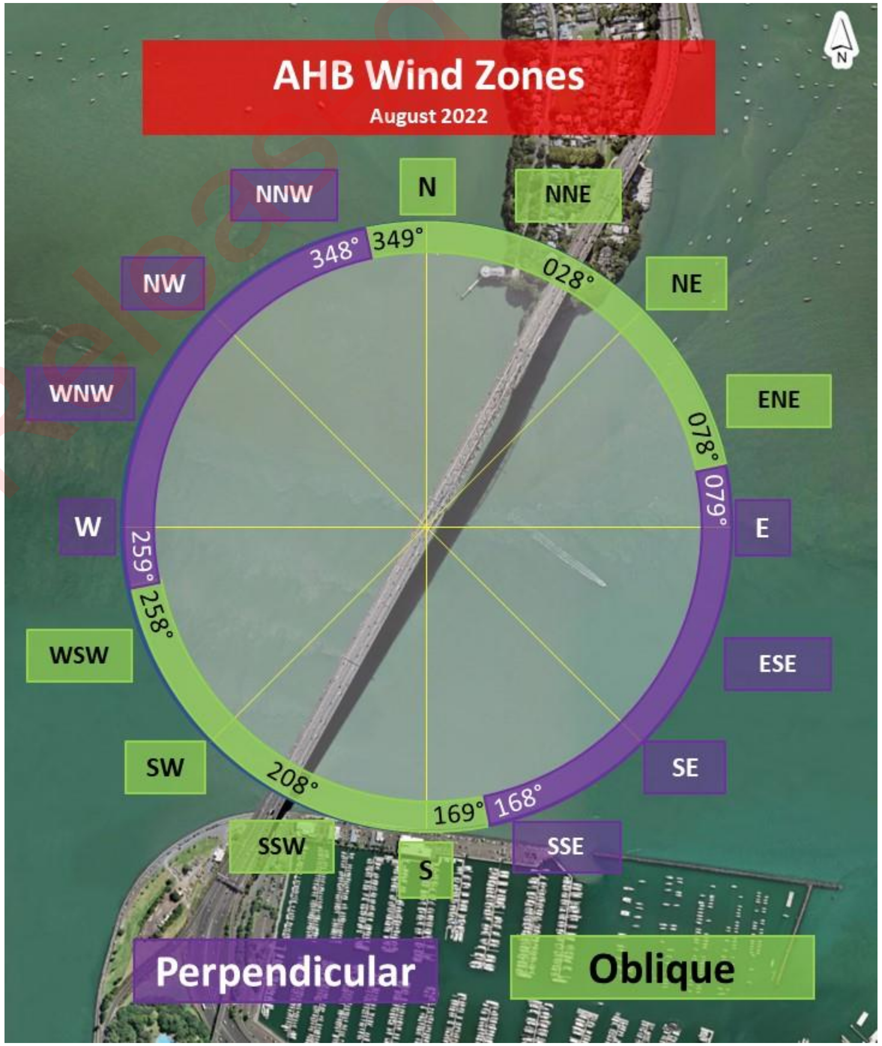

Figure 2 - Auckland Harbour Bridge Perpendicular and Oblique Wind Zones

Table 2 - AHB High Winds Operations Manual – Copy of Restrictions Summary

Restriction Stage	MetService Alert	Wind Gust (perpendicular)	Wind Gust (oblique)	Action (on forecast)	Action (on observation)
1 **Reduce Speed**	No Specific Alert Required	55+ km/h	70+ km/h	▪ Swap to storm flags (regardless of direction)	▪ 70 km/h advisory speed ▪ Messaging: – Wind Gusts – High Sided Vehicles | Motorcyclists Take Extra Care
2 **Detour Vulnerable**	No Specific Alert Required	65+ km/h	80+ km/h	▪ Remove all flags (regardless of direction)	▪ 50 km/h advisory speed ▪ Messaging: – Strong Wind Gusts – High Sided Vehicles | Motorcycles Detour via SH16/18
3 **Close Lanes**	AMBER	75+ km/h	90+ km/h	▪ DE assess intel and circulate op briefing ▪ Lane closure resources standby ▪ Shift MLB into 4/4 ▪ Media release if high confidence of network impact ▪ Remove all personnel from structure	▪ 30 km/h advisory speed ▪ Alternating leeward lanes closed ▪ Messaging: – Severe Wind Gusts – Obey Speed Signs – High Sided Vehicles | Motorcyclists Detour via SH16/18
4 **Full Closure**	RED	90+ km/h	105+ km/h	▪ MetService Briefing ▪ DE assess intel and circulate op briefing ▪ Full resources standby if long duration expected ▪ Media release & customer preconditioning	▪ AHB Fully Closed (either at inner or outer cordons based on event type & MetService advice - at discretion of DE) ▪ Messaging: – Harbour Bridge Closed – Remain In Vehicle OR Detour via SH16/18 (depending on closure type)

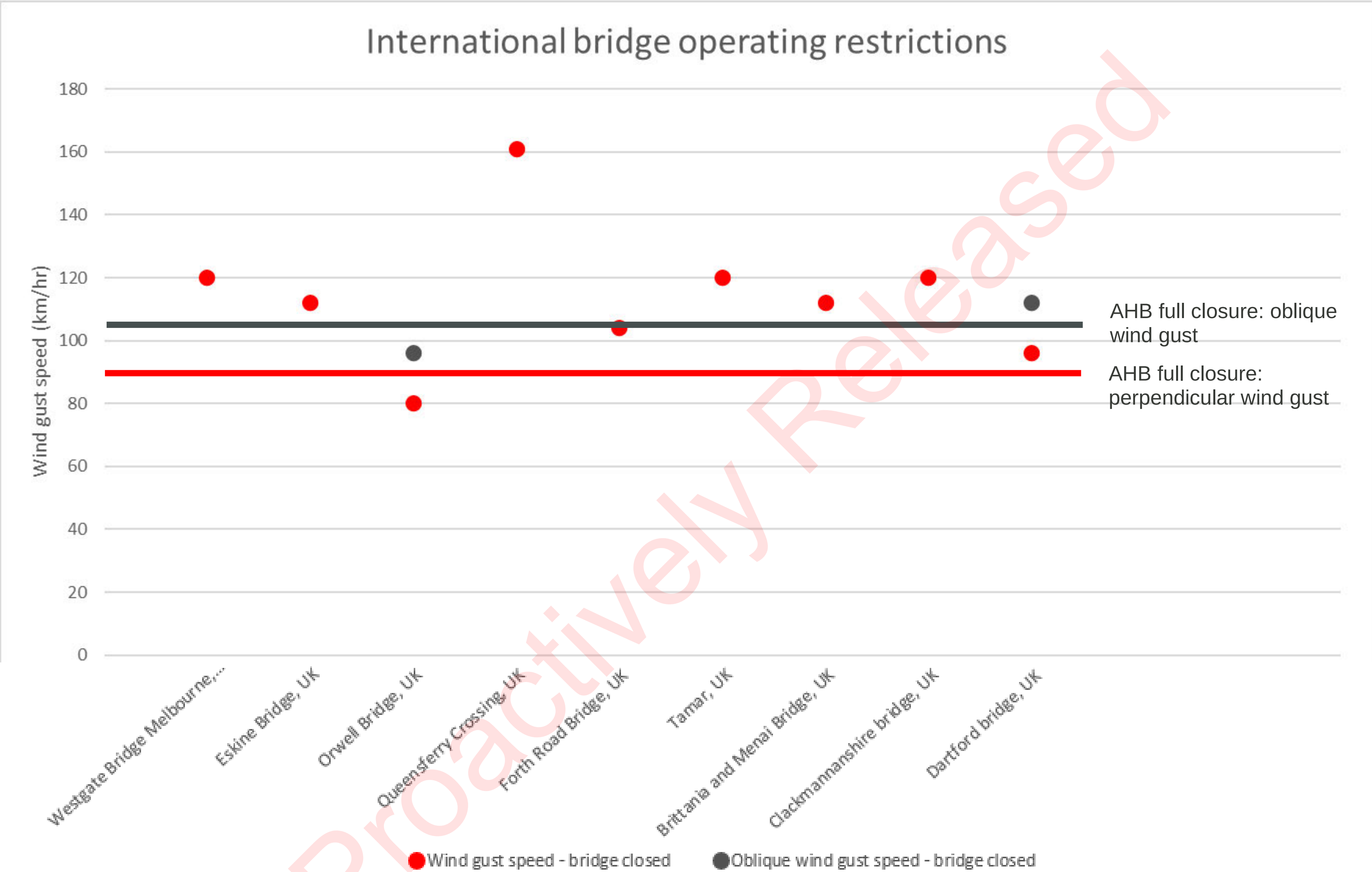

Figure 3 - International bridge high wind operating restrictions – bridge closures

As can be observed in Figure 3, the AHB wind gust limits for full bridge closure are generally slightly lower than these international bridge restrictions.

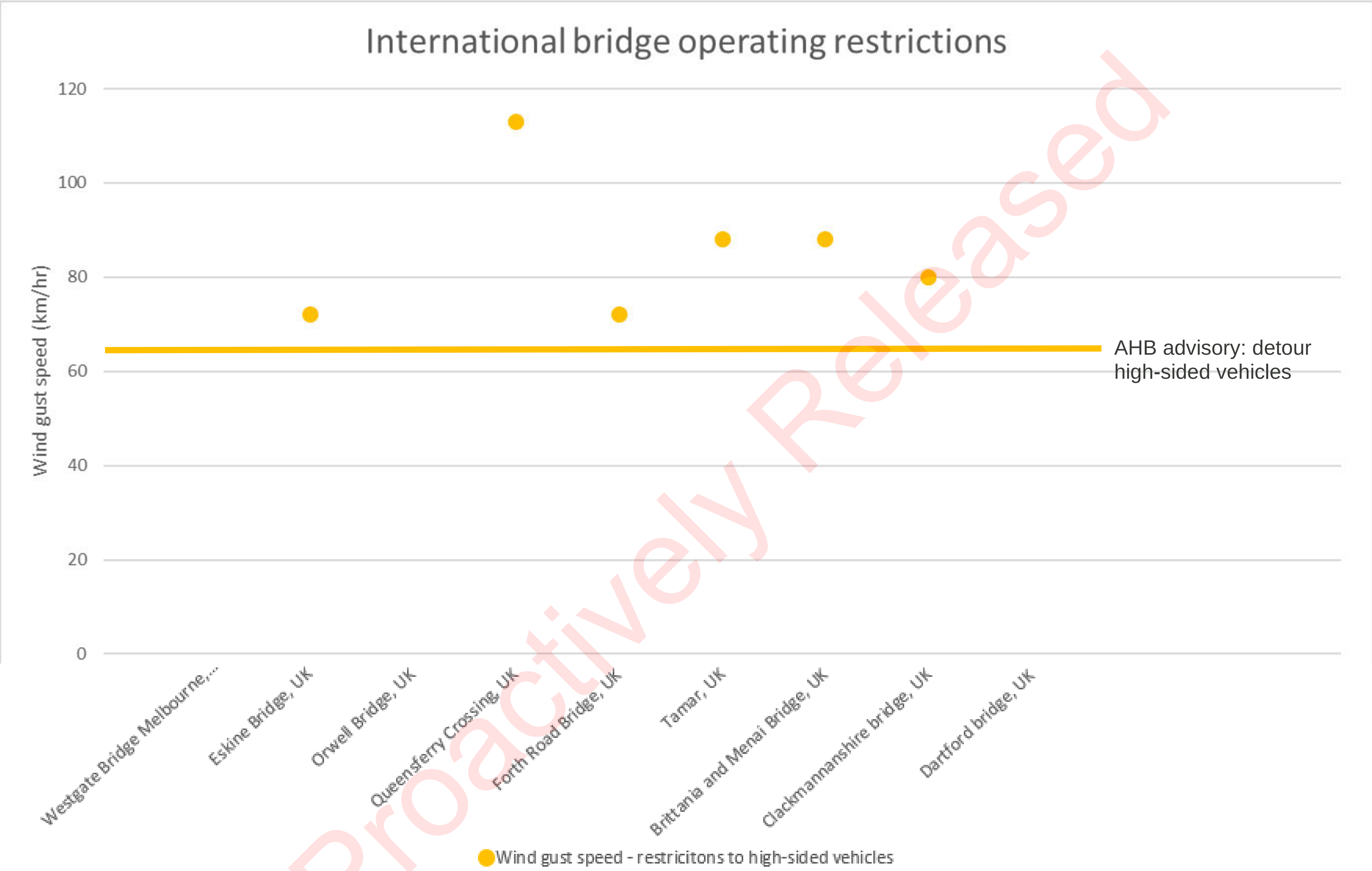

Figure 4 - International bridge high wind operating restrictions – high-sided vehicles

Figure 4 shows the AHB wind gust speed when high-sided vehicles are advised to detour. Note: AHB has a lower wind gust speed detour advisory than the restricted detours of the rest of the international bridges reviewed.

Figure 5 - International bridge high wind operating restrictions – vehicle speeds

Figure 5 illustrates vehicle speed restrictions on international bridges relative to the three AHB advisory vehicle speeds.

4 Methodology used for this Risk Assessment

This desk-top risk assessment, of a wind related vehicle incident occurring on the AHB, has generally followed the below approach:

1. Outline scenarios and conditions to assess the probability of a wind related vehicle incident occurring.
2. Define the potential consequences associated with the different scenarios.
3. Undertake a literature review to assess critical wind speeds that could result in an incident for high-sided vehicles and cars.
4. Assess the historical data of wind gusts on AHB exceeding the critical wind speeds within each of the scenarios.
5. Assess the historical data of high-sided vehicles travelling over the AHB at any given time during the day.
6. Outline the sequence of events and assumptions leading to a wind related vehicle incident on the AHB for each of the scenarios.
7. Summarise and compare the risk profile between the scenarios.
8. Recommend next steps to refine this assessment.

5 Scenarios

This desk-top risk assessment involves assessing the likelihood of a potential wind related vehicle incident / accident occurring based on a sequence of events. For an accident to occur, there needs to be a wind gust of sufficient speed to cause a particular vehicle to crash (overturn, side slip or yaw steer). The incidents that this risk assessment covers only relate to high sided unloaded vehicles that are travelling over the AHB under certain conditions. To evaluate this risk, the following scenarios and hypothetical assumptions have been established in Table 3.

Table 3 - Overview of scenarios for assessing the risk of a wind related vehicle incident occurring on the AHB

A. No restrictions (do nothing) *	B. Restrictions in AHB High Winds Operations Manual * **	C. Restrictions in AHB High Winds Operations Manual + Enforced speed limits ** ***	D. Restrictions in AHB High Winds Operations Manual + Enforced speed limits + Enforced detours ****
▪ Bridge remains open at all wind speeds ▪ Vehicles travel at the historical average speed for this scenario ▪ Minimal vehicles detour or change trip	▪ Bridge closes above 90km/hr (perpendicular) and 105km/hr (oblique) wind gusts. ▪ Alternating lanes close above 75km/hr (perpendicular) and 90km/hr (oblique) wind gusts. ▪ Reduced vehicle speeds are advised within different wind gust thresholds. ▪ High-sided vehicles are advised to detour above a wind gust threshold.	▪ Bridge closes above 90km/hr (perpendicular) and 105km/hr (oblique) wind gusts. ▪ Alternating lanes close above 75km/hr (perpendicular) and 90km/hr (oblique) wind gusts. ▪ The reduced vehicle speeds within the Operations Manual are enforced. ▪ High-sided vehicles are advised to detour above a wind gust threshold.	▪ Bridge closes above 90km/hr (perpendicular) and 105km/hr (oblique) wind gusts. ▪ Alternating lanes close above 75km/hr (perpendicular) and 90km/hr (oblique) wind gusts. ▪ The reduced vehicle speeds within the Operations Manual are enforced. ▪ The detours of high-sided vehicles within the Operations Manual are enforced.

* Assumes the drivers of high sided vehicles do not adjust their speed or driving style.

** Assumes there are no vehicles on the AHB when gusts exceed the closure threshold, however there is still risk of an incident at lower wind speeds.

*** Assumes there is a 90% compliance with the speed restriction.

**** Assumes there is a 90% compliance with the speed restriction and an 80% compliance with the detour restriction.

6 Consequence Analysis

Using the scenarios outlined in Table 3, this desk-top risk assessment sets out to understand the risk of a wind related vehicle incident occurring on the AHB in different wind conditions. These scenarios and wind conditions are based around the AHB High Winds Operating Manual.

If a vehicle incident were to occur, there could be very high consequences and associated economic costs. The purpose of the AHB Operating Manual is to reduce this risk. However, there are economic costs associated with implementing the restrictions outlined in the Operating Manual and Table 3.

Table 4 summarises the four main consequences to be referenced in this assessment. These consequences, which each have an economic cost, will be assessed against the risk factors identified for the different scenarios. This is to provide a relative risk profile for wind related vehicle incidents, with and without restrictions.

Table 4 - Potential Consequences

Incident / Accident	Bridge closed	Mandatory reduced speeds	Detours
▪ Potential deaths and/or serious injuries. ▪ Congestion and travel time costs on vehicles within the Auckland SH1 network, which could propagate out into the wider Auckland transport network until the incident is cleared. ▪ Potential damage to the bridge resulting in ongoing closures (direct travel time costs and wider economic impacts) and repair costs.	▪ Ongoing costs associated with mobilising a team to close the bridge. ▪ Travel time costs on vehicles wanting to travel over AHB (i.e. vehicles are either stuck on motorway approaches when bridge is closed, choose to not detour and remain on motorway until bridge reopens, or detour via SH16/18). ▪ Travel time and reliability costs from congestion on the wider transport network caused by closure. ▪ Wider economic impacts from people choosing to forego trip.	▪ Upfront costs to redesignate the AHB to a variable speed zone and install speed enforcement cameras and any additional variable messaging signs required. ▪ Ongoing costs to administer and police speed limits. ▪ Travel time costs from reduced speed limits.	▪ Upfront costs to install detour enforcement cameras and any additional variable messaging signs required. ▪ Ongoing costs to administer and police detours of high-sided vehicles. ▪ Ongoing costs associated with mobilising a team to enforce high-sided vehicles to detour. ▪ Travel time costs of vehicles detouring via SH16/18.

7 Literature Review of Critical Wind Speeds

The critical wind speed refers to the wind speed that can cause a vehicle incident / accident (overturning, side slip or yaw steer) under certain conditions. These conditions include a wide range of factors including vehicle speed, vehicle weight versus centre of gravity, vehicle cross-sectional area, driver reaction time, pavement surface, wind direction, wind shielding from structures and/or other vehicles, etc. Given all the variable conditions, it is very difficult to accurately predict what the critical wind speed is in any given situation. Critical wind speed curves could theoretically be modelled for multiple situations; however, this would make any operational procedures very complex and impractical to implement.

There have been several studies that have assessed critical wind speeds against vehicle speeds for certain vehicle types (Baker & Soper, 2018) (Hemingway & Robbins, 2019) (Cheung & Chan, 2010) (Kim, Yoo, & Kim, 2016) (BAKER & REYNOLDS, 1992). These studies have primarily focussed on critical wind speeds for high-sided vehicles and considered overturning and/or side slip as the two potential failure modes. Overturning of high-sided vehicles is generally the critical case.

Baker & Soper (2018) recognised the complexity of applying the research from previous studies (including the older papers listed above) into real life scenarios. Therefore, Baker & Soper (2018) developed a simple but rigorous methodology for assessing critical wind speeds that can be used by bridge operators to assess operational restrictions to protect the most vulnerable vehicles. Using this methodology, Baker & Soper (2018) calculated critical wind speeds against varying vehicle speeds for different high-sided vehicle characteristics (unladen and laden), which included: a small box lorry, a large box lorry, an articulated lorry, and a double decker bus.

After the Baker & Soper (2018) study, Hemingway & Robbins (2019) described a prototype Vehicle Overturning (VOT) model developed by the Met Office in the UK[5] that aimed to assess the potential risk to road users during high-wind events. Using the Vehicle Overturning model, Hemingway & Robbins (2019) also calculated critical wind speeds against varying vehicle speeds for an unladen heavy goods vehicle (HGV), a loaded heavy goods vehicle, an unloaded light goods vehicle and a car / small van. These model calculations were performed at different wind angles to illustrate the effect wind angle has on critical wind speeds. The model calculations have been used to generate the data plotted in Figure 6 through to Figure 9 for an unladen HGV. Note: wind angles have been adjusted to make them relative to AHB perpendicular and oblique wind zones shown earlier in Figure 2.

[5] The Met Office is the national meteorological service for the UK.

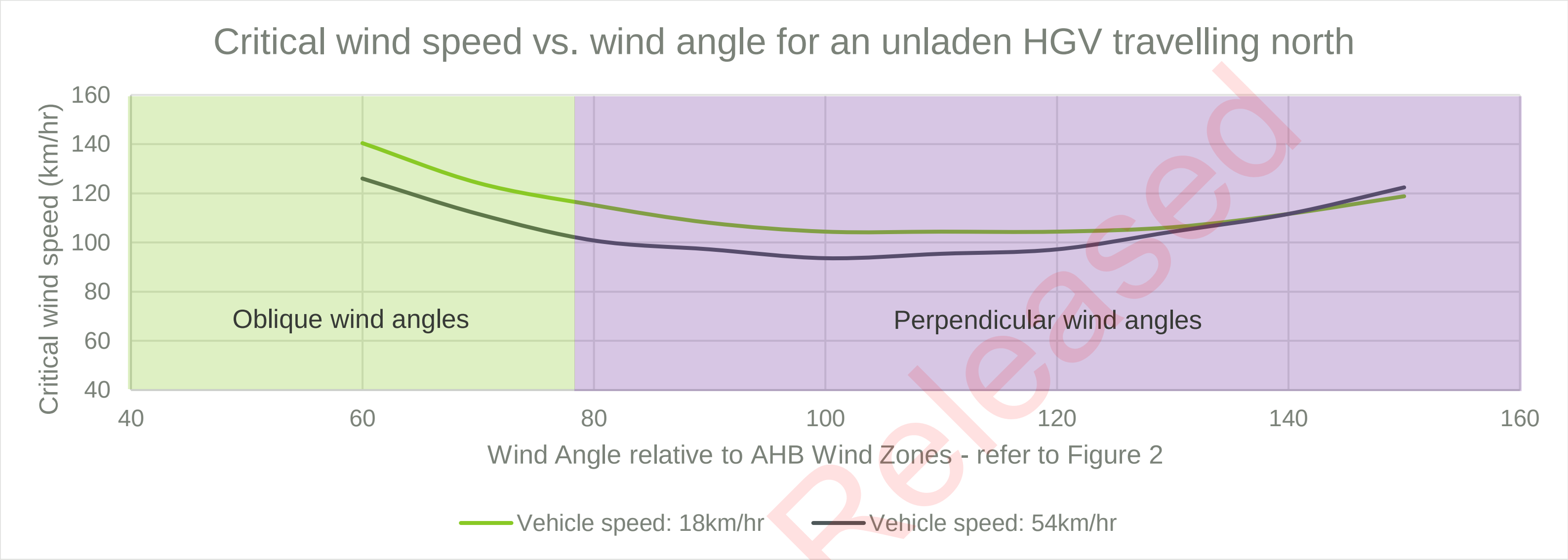

Figure 6 - Theoretical effect of wind angles on critical wind speeds for an unladen heavy goods vehicle (Hemingway & Robbins, 2019)

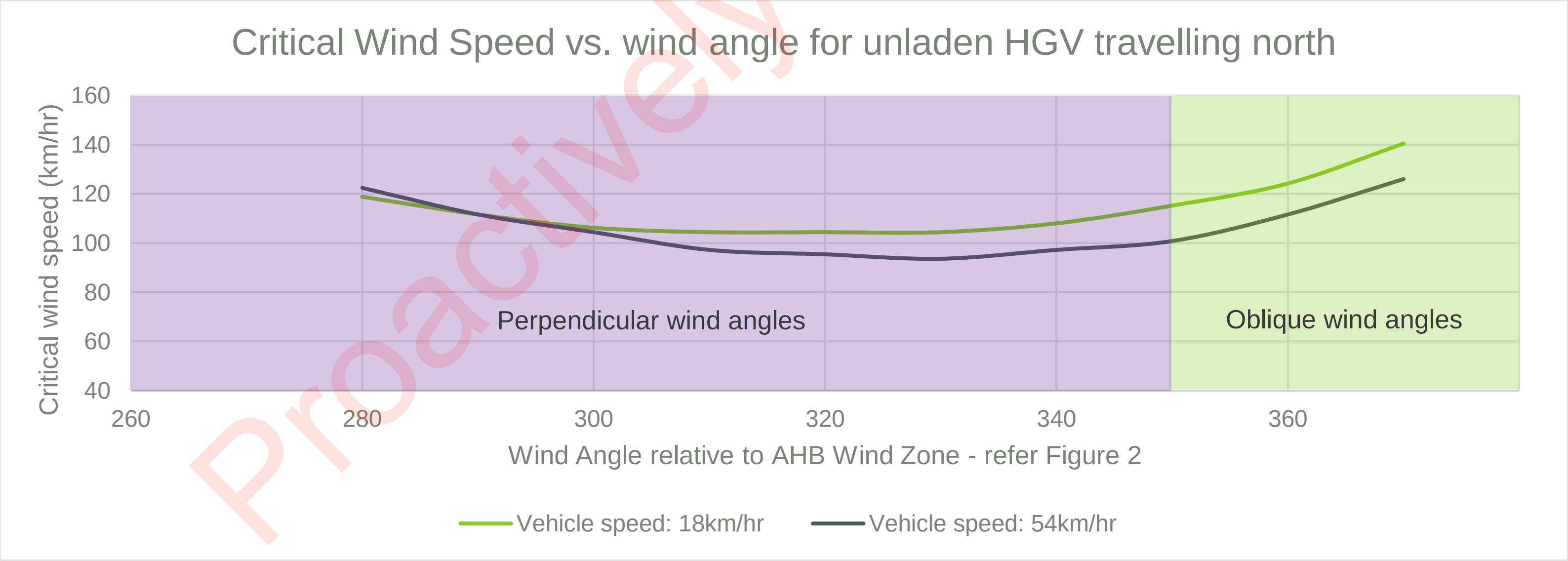

Figure 7 - Theoretical effect of wind angles on critical wind speeds for an unladen heavy goods vehicle (Hemingway & Robbins, 2019)

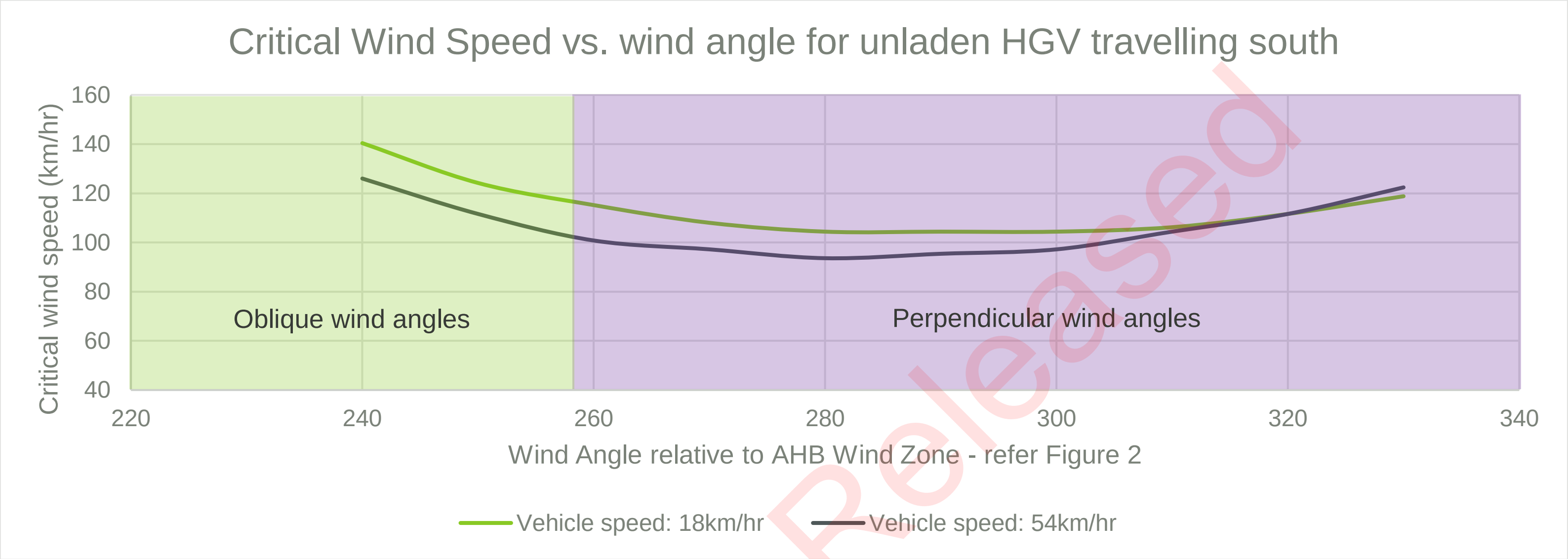

Figure 8 - Theoretical effect of wind angles on critical wind speeds for an unladen heavy goods vehicle (Hemingway & Robbins, 2019)

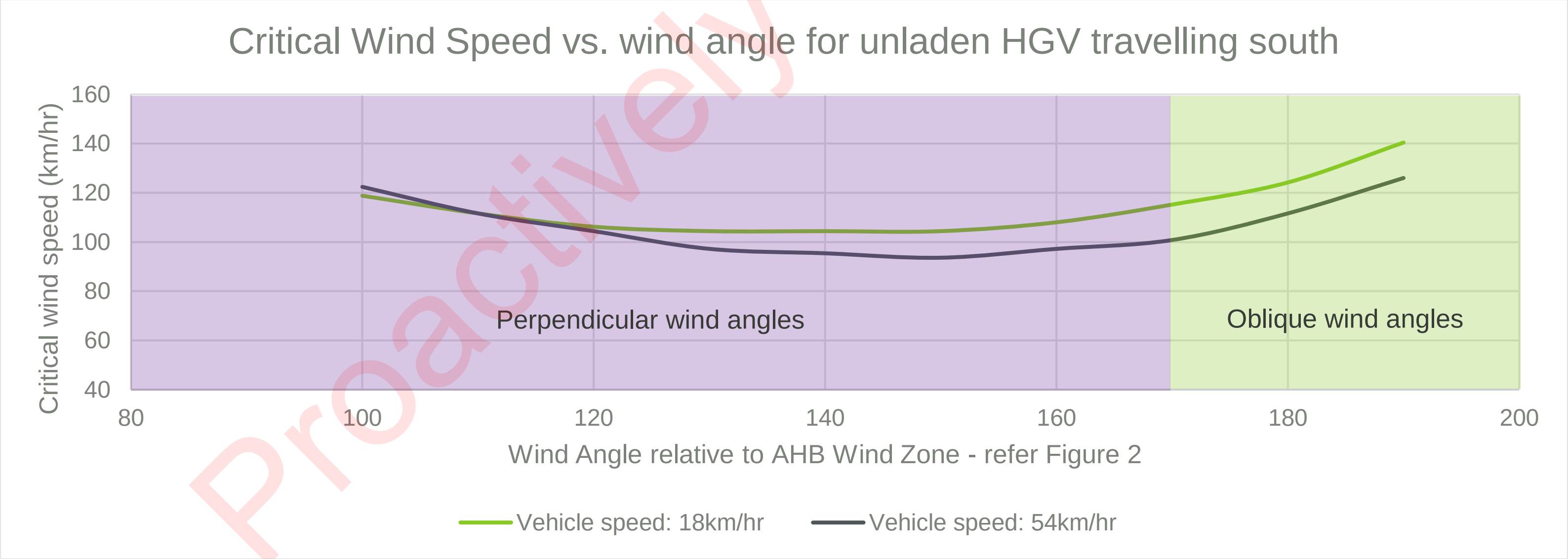

Figure 9 - Theoretical effect of wind angles on critical wind speeds for an unladen heavy goods vehicle (Hemingway & Robbins, 2019)

Using the data shown in Figures 6-9, the critical perpendicular wind angles for the AHB are approximately, 80-130° and 350-300° for vulnerable high-sided vehicles travelling north, and approximately 170-120° and 260-310° for vulnerable high-sided vehicles travelling south. Therefore, all perpendicular wind gusts will be included as part of this assessment.

The results from the case studies in Baker & Soper (2018) and Hemingway & Robbins (2019) have been used to plot perpendicular critical wind speeds versus vehicle speeds for unladen heavy goods vehicles (HGV's) and unladen double decker buses. See Figure 10. Unladen high sided HGVs and empty double decker buses were found to be the most vulnerable in the case studies.

Laden HGVs were assessed as having critical wind speeds approximately 50% higher than these vehicles therefore take no further part in this Risk Assessment. Also plotted in Figure 10, are previous incidents on the AHB and Manukau Harbour Crossing. However, the vehicle speeds for the Auckland incidents have been assumed at this stage. These case studies can be seen to be reasonably calibrated in Figure 10.

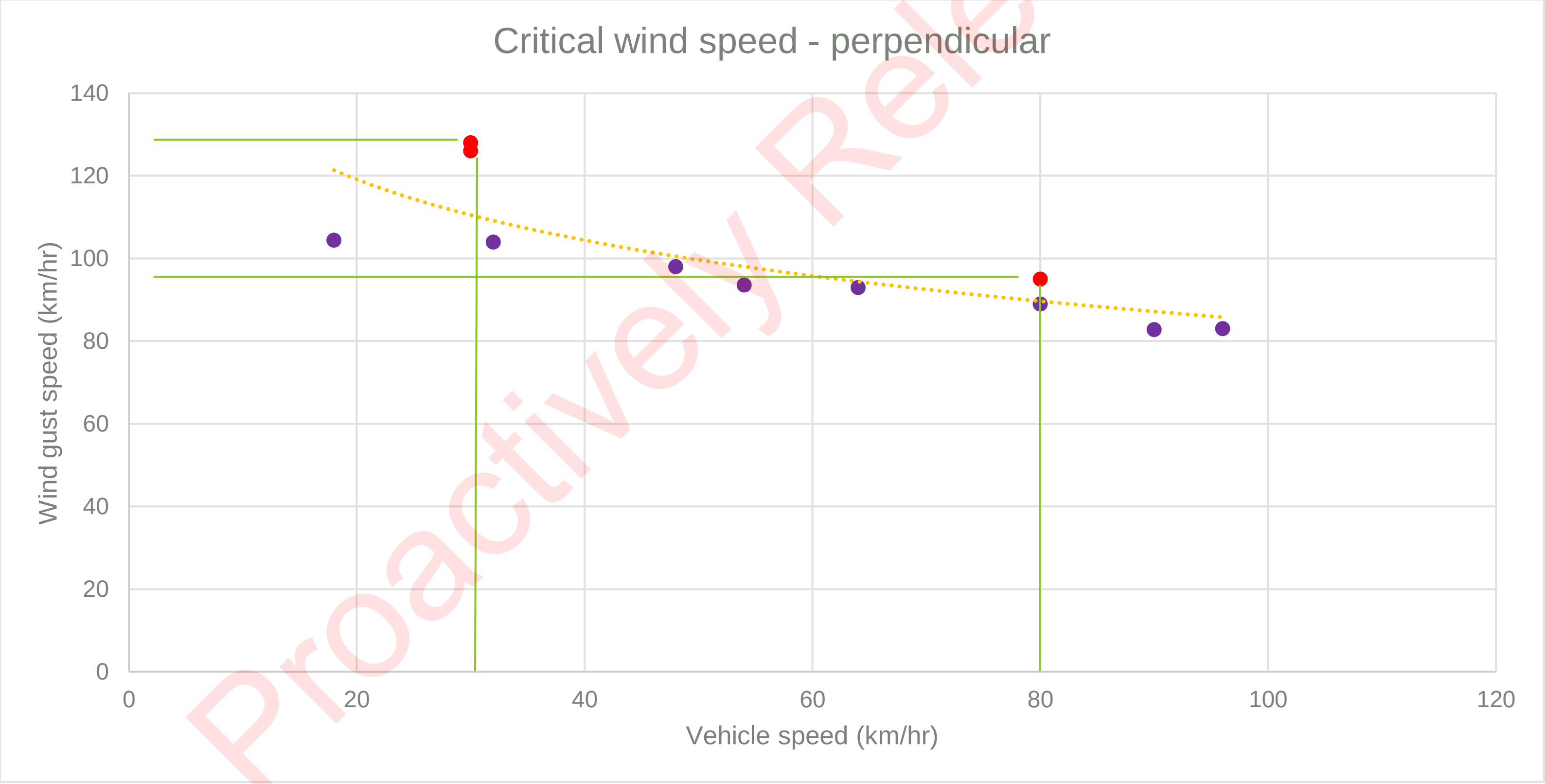

Figure 10 - Critical perpendicular wind speeds of high-sided vehicles from literature (● purple dots) (Baker & Soper, 2018) (Hemingway & Robbins, 2019) and from previous incidents on the AHB and Manukau Harbour Crossing (● red dots). Line of best fit = derived perpendicular critical wind speeds used for this assessment (……. yellow line).

Figure 11 shows the results from the different studies of the oblique critical wind speeds for high-sided unladen heavy goods vehicles from Hemingway & Robbins (2019). However, unlike perpendicular wind angles, the critical oblique wind angles are approximately 70-80° and 350-360° for vulnerable high-sided vehicles travelling north and approximately 170-180° and 260-250° for vulnerable high-sided vehicles travelling south across the AHB. Therefore, only these angles for oblique wind gusts will be assessed as part of this assessment. As the wind angle becomes more parallel with the direction of the vehicle, the critical wind speed is shown in increase and therefore become irrelevant.

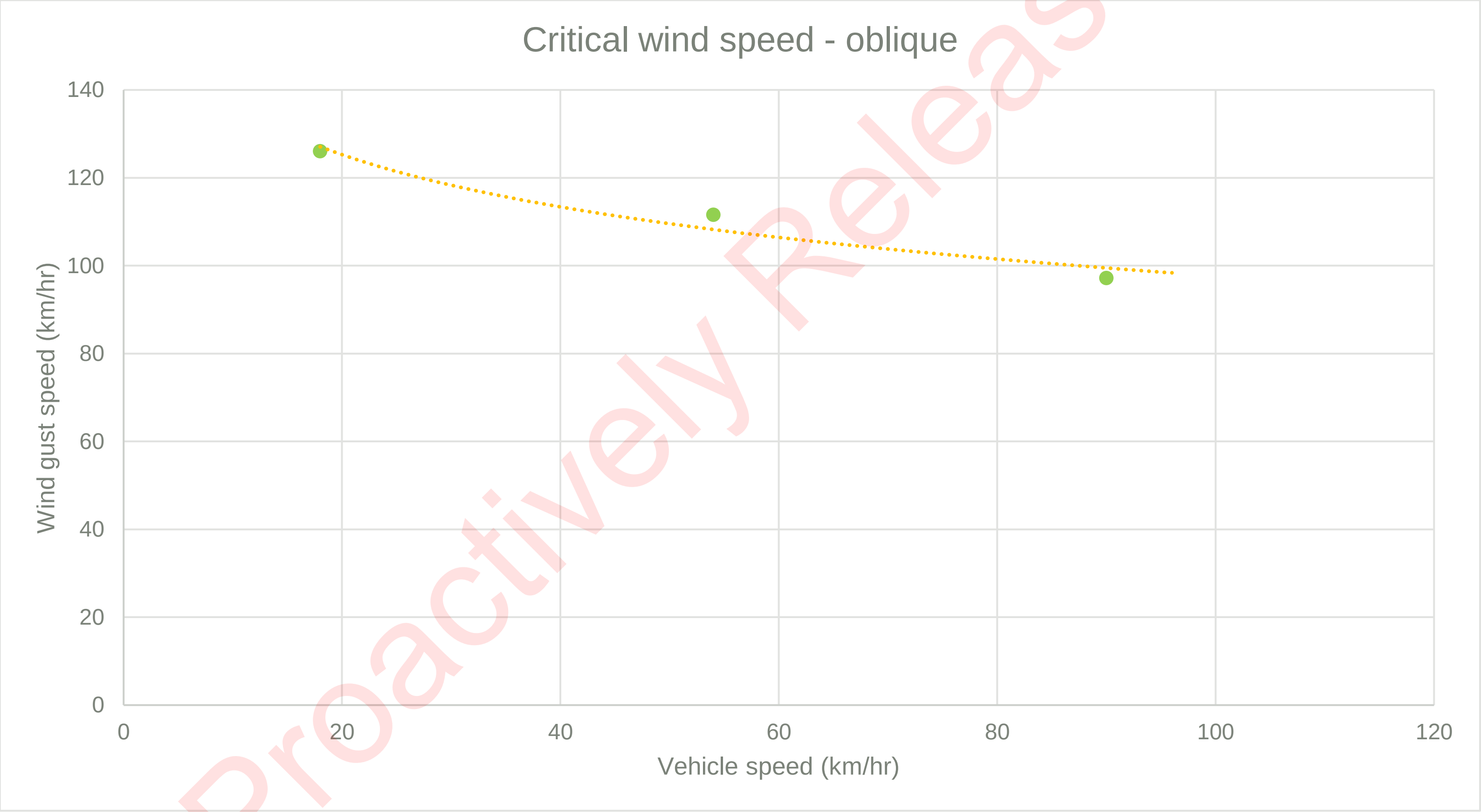

Figure 11 - Critical oblique wind speeds of high-sided vehicles from literature (green dots) (Hemingway & Robbins, 2019).

Line of best fit = derived oblique critical wind speeds used for this assessment (……. yellow line).

Using Figure 10 and Figure 11, the perpendicular and oblique critical wind speeds for vulnerable high-sided vehicles (unladen heavy goods vehicles and unladen double decker buses) have been assessed for different vehicle speed ranges (refer Table 5).

Hemingway & Robbins (2019) assessed the perpendicular and oblique critical wind speed to be 126 km/hr for cars across different vehicle speeds. As this is greater than the critical wind speeds for vulnerable high-sided vehicles, cars will be excluded in this assessment.

Table 5 - Critical wind speeds for vulnerable high-sided vehicles travelling within different vehicle speed ranges, assumed from Figure 10 and Figure 11

	Vulnerable Vehicle Speed: 20-40 km/hr	Vulnerable Vehicle speed: 40-60 km/hr	Vulnerable Vehicle Speed: 70-90 km/hr
Critical wind speed (perpendicular)	110 km/hr	100 km/hr	90 km/hr
Critical wind speed (oblique)	120 km/hr	110 km/hr	100 km/hr

8 Assessment of Historical Wind Data

MetService have recorded the maximum gust wind speeds and associated directions, that have occurred at the Auckland Harbour Bridge, within each hour from March 2011 to January 2022. Figure 12 shows the likelihood of a wind gust, within the critical wind angles outlined in Section 7, exceeding a given speed within an hour between March 2011 to January 2022 (e.g., During this recorded period, there were 56 events where the maximum hourly perpendicular wind gust exceeded 90 km/hr out of 103,342 hourly events. This equates to a likelihood of exceedance of 0.054% per hour).

Given the critical wind speeds outlined in Table 5 have been exceeded from time to time from 2011 to 2022, it is considered appropriate, for the purposes of this assessment, to assume the historic data has good correlation to the likelihood of critical future wind events. [6]

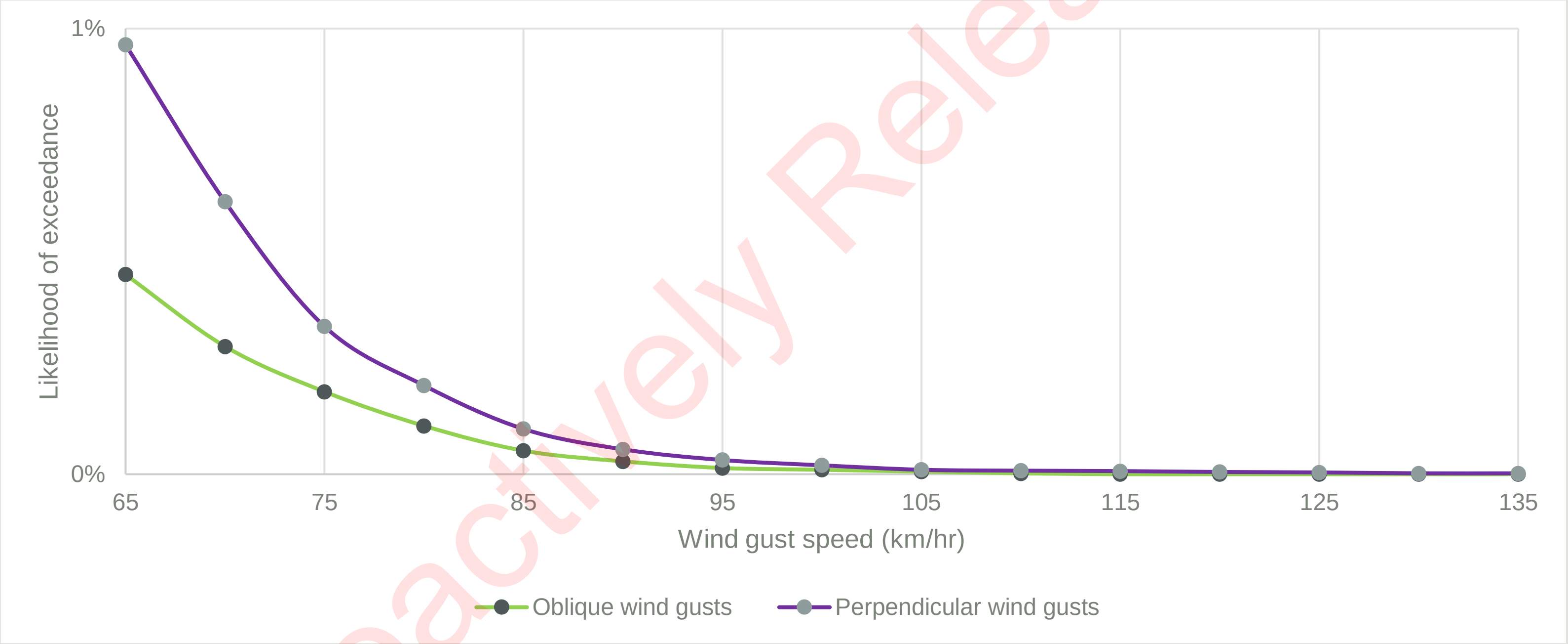

Figure 12 - Likelihood a perpendicular or oblique wind gust (within a critical angle) will exceed a particular speed within any given hour on the AHB

[6] As highlighted in the Resolve Group report, *"Auckland Harbour Bridge – Review of Wind Operating Procedures against International Practice (April 2021)"*, climate change is expected to increase the frequency of severe weather events around the world. However, the NIWA report: *"Auckland Region Climate Change Projections and Impacts (September 2020)"*, predicts the number of windy days and the magnitude of extreme wind events in Auckland to decrease. Under different climate change scenarios this assumption may change.

Figure 13 illustrates the direction of each of these wind gusts recorded from March 2011 to January 2022 with the critical perpendicular and oblique wind angles overlaid (in purple and green respectively). As seen in the figure below, the predominant wind above 90 km/hr is in the oblique wind direction with many of these recorded wind gusts occurring outside of the critical oblique wind angles when considering potential wind related vehicle incidents.

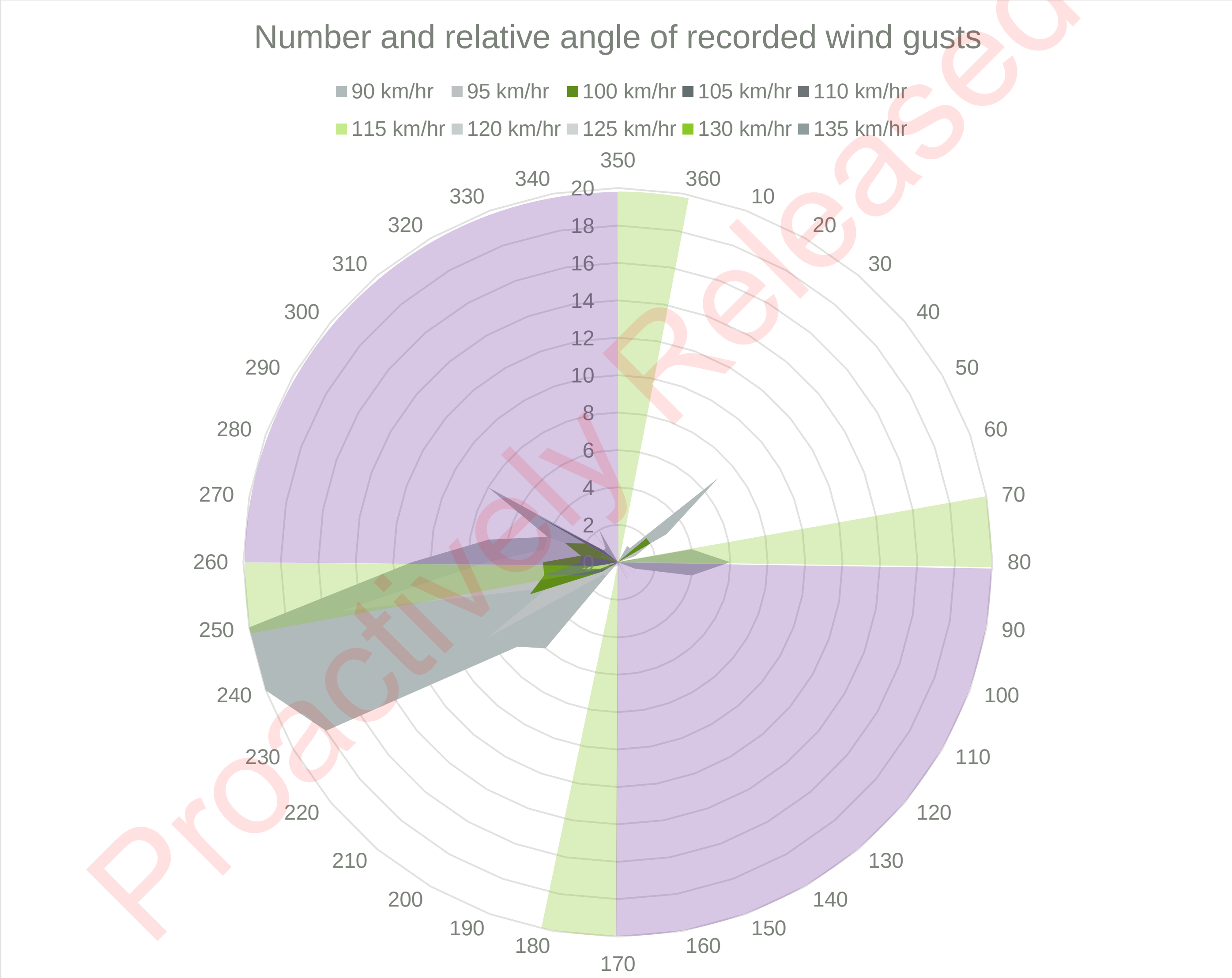

Figure 13 - Wind rose showing the number and relative angle of recorded wind gusts from March 2011 to January 2022

9 Number of Vulnerable High-Sided Vehicles on the AHB

Waka Kotahi's Traffic Monitoring System (TMS) records hourly vehicle counts over the Auckland Harbour Bridge. The TMS identifies either cars, medium commercial vehicles (MCVs) or heavy commercial vehicles (HCVs). For the purposes of this assessment, it is assumed MCVs and HCVs constitute high-sided vehicles. Figure 14 shows the average number of high-sided vehicles in any given minute throughout the day. This has been taken from the hourly vehicle counts from 2016 to 2018 and assumes vehicles are distributed evenly throughout the hour period. When assessing the risk of wind vs vehicle incidents, minute vehicle numbers are considered appropriate, as peak wind gusts are also short in duration.

As illustrated in Figure 14, there is always likely to be at least one high-sided vehicle on the AHB in any given minute. While the average number of high-sided vehicles, on the AHB in any given minute, is 7.5. For the purposes of this assessment, it is assumed 50%[7] of the high-sided vehicles are vulnerable (i.e. have similar characteristics as unladen HGVs and unladen double decker buses). Therefore, it is assumed there are on average 3-4 vulnerable vehicles on the AHB in any given minute.

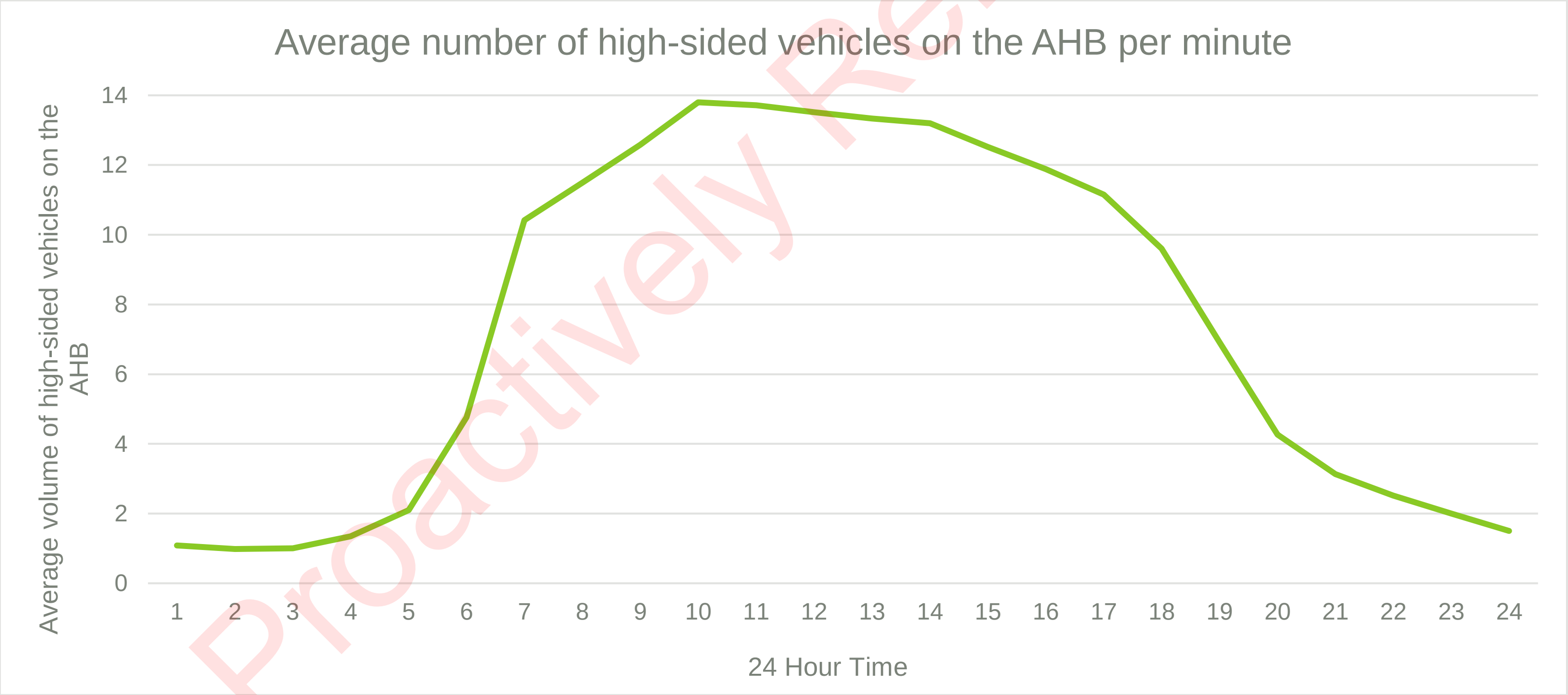

Figure 14 - Average number of high-sided vehicles on the AHB in any given minute across a 24-hour period

[7] Based on conversations with freight forwarders, approximately every second trip across the AHB would be unladen.

10 Assessment of Scenarios

10.1 Scenario A: No restrictions to vehicles travelling over the AHB during a Wind Event

- There is a high-wind event, with short duration wind gusts exceeding 90km/hr on the AHB.
- Cars, trucks, and buses are able to drive over the AHB during high wind events without any restrictions.
- As vehicles approach the bridge, the drivers' feel the strong winds and make allowances for the yawing moment of their individual vehicles. This could result in vehicle speed reductions. However, in this scenario, there are no meaningful reductions in the speed of vehicles. Cars, trucks, and buses continue to drive over the bridge at approximately 80km/hr.
- At these vehicle and wind gust speeds, unladen heavy goods vehicles (HGVs) and unladen double decker buses are vulnerable to overturning.
- If all vehicles travel at approximately 80km/hr over the AHB at all times of the day and in all weather conditions every day of the year, then there is the potential of a wind related vehicle incident occurring approximately 20 times per year (refer Table 6), resulting in:
  - Congestion and travel time costs on vehicles within the Auckland SH1 network, which could propagate out into the wider Auckland transport network until the incident is cleared.
  - Potential damage to the bridge structure resulting in ongoing closures (direct travel time costs and wider economic impacts) and repair costs. Although, it is noted, if an incident did occur, the accident must occur when the vehicle is in certain locations on the AHB for it to result in significant damage to the bridge structure, which would increase the return period stated above.
  - Potential deaths and/or serious injuries.

As outlined above and in previous sections, this scenario is based on several hypothetical assumptions, which may not reflect actual conditions nor driver behaviour during high wind events. For example, when a high-speed wind gust blows across the AHB deck, a vulnerable high-sided vehicle may be partially or fully sheltered from this wind by part of the bridge structure or another vehicle. Furthermore, there is a good likelihood that several vehicles travelling, in each direction over the AHB, will reduce their vehicle speed when they feel their vehicle yaw steer, which could result in a speed reduction of all vehicles. These factors would significantly reduce the potential likelihood of a wind related vehicle incident.

Table 6 - Scenario A: Hypothetical return period of the potential for a wind related vehicle incident to occur on the AHB

Vehicle speed	Number of vulnerable high-sided vehicles on AHB at any given minute	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (perpendicular)	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (oblique)	Return period of potential wind related vehicle incident
80 km/hr	3.75	90 km/hr (0.055%)	100 km/hr (0.010%)	Approximately 20 times annually *

* 1 ÷ [3.75 × ((0.055% + 0.010%) × 24hrs)] = 1 in 17 days

10.2 Scenario B: Restrictions as per Waka Kotahi AHB High Winds Operations Manual

- There is a high-wind event, with short duration wind gusts exceeding 75 km/hr on the AHB.
- Alternating leeward lanes on the bridge are closed, and a team is ready to fully close the bridge if the forecast is revised with higher perpendicular wind gust speeds exceeding 90 km/hr (or exceeding 105 km/hr if the wind direction is oblique).
- High-sided vehicles are advised to detour via SH16/18. However, in this scenario, the drivers of high-sided vehicles ignore this advisory and continue to drive over the AHB.
- All vehicles are advised to reduce their speed to 30 km/hr and are also forced to merge before they drive onto the bridge due to the lane closures. Lane closures on high volume roads, typically results in congestion and lower speeds. Additionally, the drivers' also feel the strong winds and make allowances for the yawing moment of their individual vehicles, which alone could also result in vehicle speed reductions. However, for the purposes of assessing this scenario, it is assumed there are no meaningful reductions in the speed of vehicles travelling over the AHB. Cars, trucks, and buses continue to drive over the bridge at approximately 80km/hr, which is impractical at most times of the day given the reasons outlined above.
- At these vehicle speeds, unladen heavy goods vehicles (HGVs) and unladen double decker buses are vulnerable to overturning if a perpendicular wind gust exceeds 90 km/hr or an oblique wind gust (within 10° of the perpendicular wind zone) exceeds 100 km/hr.
- Assuming the AHB is closed prior to all wind gust events over 90 km/hr (for perpendicular winds) and 105 km/hr (for oblique winds), then the only time vulnerable HGVs and double decker busses are at risk of overturning is when the oblique wind gusts between 100-105 km/hr are at an angle within 10° of the perpendicular wind zone.
- If all vehicles ignore the advisory speed reductions and continue to travel at approximately 80km/hr over the AHB during lane closure restrictions, at all times of the day, in all weather conditions, every day of the year, then there is the potential of a wind related vehicle incident to occur approximately once in every 1 year on the AHB (refer Table 7), resulting in:
  - Congestion and travel time costs on vehicles within the Auckland SH1 network, which could propagate out into the wider Auckland transport network until the incident is cleared.
  - Potential damage to the bridge structure resulting in ongoing closures (direct travel time costs and wider economic impacts) and repair costs. Although, it is noted, if an incident did occur, the accident must occur when the vehicle is in certain locations on the AHB for it to result in significant damage to the bridge structure, which would increase the damage to bridge return period stated above.
  - Potential deaths and/or serious injuries.

As outlined above and in previous sections, this scenario is based on several hypothetical assumptions, which may not reflect actual conditions nor driver behaviour during high wind events and lane closure restrictions. For example, it is likely that vehicles will be forced to slow down when merging lanes resulting in congestion and reduced speeds when travelling over the AHB. This would significantly reduce the potential of a wind related vehicle incident.

However, there is also a possibility that perpendicular wind gusts above 90 km/hr are not forecasted and therefore the AHB is not closed. These instances may slightly increase the potential of a wind related vehicle incident.

Table 7 - Scenario B: Hypothetical return period of the potential for a wind related vehicle incident to occur on the AHB

Vehicle speed	Number of vulnerable high-sided vehicles on AHB at any given minute	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (perpendicular)	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (oblique)	Return period of potential wind related vehicle incident
80 km/hr	3.75	90 km/hr (0%*)	100 km/hr (0.003%**)	Approximately 1 in 1 year

* The AHB is closed when perpendicular wind gusts are forecasted to exceed 90 km/hr, therefore assumed no vehicles will be on the bridge during these wind gust events.

** This is the likelihood of an oblique wind gust (within 10° of the perpendicular wind zone) being between 100 km/hr and 105 km/hr. NB: Bridge is open under AHB High Winds Operational Manual.

10.3 Scenario C: Restrictions in AHB High Winds Operations Manual + Enforced speed limits

- There is a high-wind event, with short duration wind gusts exceeding 75 km/hr on the AHB.
- Alternating leeward lanes on the bridge are closed, and a team is ready to fully close the bridge if the forecast is revised with higher perpendicular wind gust speeds exceeding 90 km/hr (or exceeding 105 km/hr if the wind direction is oblique).
- High-sided vehicles are advised to detour via SH16/18. However, in this scenario, the drivers of high-sided vehicles ignore this advisory and continue to drive over the AHB.
- As vehicles approach the bridge, drivers are notified of a 30 km/hr speed limit enforcement and are also forced to merge before they drive onto the bride due to the lane closures, which results in drivers' reducing their speed. Cars, trucks and buses generally drive over the bridge at approximately 30km/hr in this scenario.
- At the vehicle of 30km/h, unladen heavy goods vehicles (HGVs) and unladen double decker buses are vulnerable to overturning if a perpendicular wind gust exceeds 110 km/hr or an oblique wind gust (within 10° of the perpendicular wind zone) exceeds 120 km/hr.
- Assuming the AHB is closed prior to all wind gust events over 90 km/hr (for perpendicular winds) and 105 km/hr (for oblique winds), unladen heavy goods vehicles (HGVs) and unladen double decker buses are typically not vulnerable to a potential overturning accident.
- However, if 10% of vehicles ignore the 30 km/hr speed limit and travel at 80 km/hr over the AHB during lane closure restrictions, at all times of the day, in all weather conditions, every day of the year, then there is the potential of a wind related vehicle incident occurring approximately once in every 10 years. (refer Table 8), resulting in:
  - Congestion and travel time costs on vehicles within the Auckland SH1 network, which could propagate out into the wider Auckland transport network until the incident is cleared.
  - Potential damage to the bridge structure resulting in ongoing closures (direct travel time costs and wider economic impacts) and repair costs. Although, it is noted, if an incident did occur, the accident must occur when the vehicle is in certain locations on the AHB for it to result in significant damage to the bridge structure, which would increase the damage to bridge return period stated above.
  - Potential deaths and/or serious injuries.

Although this scenario includes speed limit enforcement, the proportion of vehicles reducing their speed in high-wind events and with lane closure restrictions is likely closer aligned to actual conditions and driver behaviour than the previous two scenarios. Although, actual speed data for vulnerable high-sided vehicles should be collected and analysed. Furthermore, as stated above, a vulnerable high-sided vehicle may be partially or fully sheltered from high wind gusts by part of the bridge structure or another vehicle.

However, there is a possibility that perpendicular wind gusts above 90 km/hr are not forecasted and therefore the AHB is not closed. These instances may slightly increase the potential of a wind related vehicle incident.

Table 8 - Scenario C: Hypothetical return period of the potential for a wind related vehicle incident to occur on the AHB

Vehicle speed	Number of vulnerable high-sided vehicles on AHB at any given minute	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (perpendicular)	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (oblique)	Return period of potential wind related vehicle incident
30 km/hr	3.375 (= 3.75 × 90%)*	110 km/hr (0%**)	120 km/hr (0%**)	-
80 km/hr	0.375 (= 3.75 × 10%)*	90 km/hr (0%**)	100 km/hr (0.003%***)	Approximately 1 in 10 years

* Assumes 90% of vulnerable high-sided vehicles reduce speeds to 30 km/hr and 10% of vehicles do not reduce speed.

** The AHB is closed when perpendicular wind gusts are forecasted to exceed 90 km/hr and oblique wind gusts are forecasted to exceed 105 km/hr, therefore no vehicles will be on the bridge during these wind gust events.

*** This is the likelihood of an oblique wind gust (within 10° of the perpendicular wind zone) being between 100 km/hr and 105 km/hr. NB: Bridge is open under AHB High Winds Operational Manual

10.4 Scenario D: Restrictions in AHB High Winds Operations Manual + Enforced speed limits + Enforced detours

- There is a high-wind event, with short duration wind gusts exceeding 75 km/hr on the AHB.
- Alternating leeward lanes on the bridge are closed, and a team is ready to fully close the bridge if the forecast is revised with higher perpendicular wind gust speeds exceeding 90 km/hr (or exceeding 105 km/hr if the wind direction is oblique).
- Vehicles travelling on SH1 within Auckland are notified of an enforced closure of the AHB for high-sided vehicles and told to detour via SH16/18. Approximately 80% of high-sided vehicles comply with this enforcement. However, as the bridge is still open to cars, approximately 20% of high-sided vehicles, in this scenario ignore this enforcement and continue to drive over the AHB.
- As vehicles that have not detoured approach the bridge, drivers are notified of a 30 km/hr speed limit enforcement and are also forced to merge before they drive onto the bride due to the lane closures. This results in drivers' reducing their speed. Cars, trucks, and buses generally drive over the bridge at approximately 30km/hr in this scenario.
- At these vehicle speeds, unladen heavy goods vehicles (HGVs) and unladen double decker buses are vulnerable to overturning if a perpendicular wind gust exceeds 110 km/hr or an oblique wind gust (within 10° of the perpendicular wind zone) exceeds 120 km/hr.
- Assuming the AHB is closed prior to all wind gust events over 90 km/hr (for perpendicular winds) and 105 km/hr (for oblique winds), unladen heavy goods vehicles (HGVs) and unladen double decker buses are typically not vulnerable to a potential overturning accident.
- However, if 10% of vehicles that have not detoured ignore the 30 km/hr speed limit and travel at 80 km/hr over the AHB during lane closure restrictions, at all times of the day, in all weather conditions, every day of the year, then there is a risk of a wind related vehicle incident occurring approximately once in every 50 years (refer Table 9), resulting in:
  - Congestion and travel time costs on vehicles within the Auckland SH1 network, which could propagate out into the wider Auckland transport network until the incident is cleared.
  - Potential damage to the bridge structure resulting in ongoing closures (direct travel time costs and wider economic impacts) and repair costs. Although, it is noted, if an incident did occur, the accident must occur when the vehicle is in certain locations on the AHB for it to result in significant damage to the bridge structure, which would increase the return period stated above.
  - Potential deaths and/or serious injuries.

Table 9 - Scenario D: Hypothetical return period of the potential for a wind related vehicle incident to occur on the AHB

Vehicle speed	Number of vulnerable high-sided vehicles on AHB at any given minute	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (perpendicular)	Critical wind speed and likelihood of a wind gust exceeding this speed with vehicles on AHB in any given hour (oblique)	Return period of potential wind related vehicle incident
30 km/hr	0.675	110 km/hr (0%*)	120 km/hr (0%*)	-
80 km/hr	0.075	90 km/hr (0%*)	100 km/hr (0.003%**)	Approximately 1 in 50 years

* The AHB is closed when perpendicular wind gusts are forecasted to exceed 90 km/hr and oblique wind gusts are forecasted to exceed 105 km/hr, therefore no vehicles will be on the bridge during these wind gust events.

** This is the likelihood of an oblique wind gust (within 10° of the perpendicular wind zone) being between 100 km/hr and 105 km/hr. NB: Bridge is open under AHB High Winds Operational Manual

11 Risk Profile Summary

The risk of a wind related vehicle incident depends on multiple factors including short duration wind gust speeds and directions, vehicle speeds, vehicle weights and centre of gravity, vehicle cross-sectional areas, driver reaction time, pavement surface, wind shielding from structures and/or other vehicles, etc. Given all the dynamic variables, it is very difficult to accurately predict the probability of a wind related vehicle incident occurring in real life scenarios, which Baker & Soper (2018) recognised.

This desk-top risk assessment has attempted to quantify the high-level risk of a potential wind related vehicle incident occurring on the AHB based on different scenarios developed around the AHB High Winds Operating Manual.

To understand the relative risk between the scenarios, several hypothetical assumptions were made (i.e., driver and transport network behaviours, wind shielding effects, accurate forecasting of wind gust speeds and in-time implementation of associated restrictions, etc.), which could significantly change the likelihood of a wind related vehicle incident. Table 10 summarises the approximate return periods of a potential wind related vehicle incident occurring within each of the hypothetical scenarios, along with the associated high-level consequences.

Table 10 - High-level risk profile of wind related vehicle incidents on AHB under the four hypothetical scenarios

	Scenario A	Scenario B	Scenario C	Scenario D
Potential wind related vehicle incident return period	Approximately 20 times in 1 year	Approximately 1 in 1 year	Approximately 1 in 10 years	Approximately 1 in 50 years
Consequence of an incident	- Medium to long duration high congestion and travel time costs. - Potential bridge damage. - Potential deaths and/or serious injuries.	- Medium to long duration high congestion and travel time costs. - Potential bridge damage. - Potential deaths and/or serious injuries.	- Medium to long duration high congestion and travel time costs. - Potential bridge damage. - Potential deaths and/or serious injuries.	- Medium to long duration high congestion and travel time costs. - Potential bridge damage. - Potential deaths and/or serious injuries.
Consequence of bridge closures	NA	- Short duration high congestion and travel time costs - Avoided trips.	- Short duration high congestion and travel time costs - Avoided trips.	- Short duration high congestion and travel time costs - Avoided trips.
Consequence of reduced speeds	NA	NA	- Short duration minor travel time costs.	- Short duration minor travel time costs.
Consequence of high-sided vehicle detours	NA	NA	NA	- Short duration medium travel time costs for commercial vehicles and buses.

11.1 Sensitivity analysis

Sensitivity analysis is a process that involves identifying how changes in certain parameters can affect the overall results of a risk assessment. In the case of a risk assessment of wind-related vehicle incidents on AHB, the two key parameters that can be varied for sensitivity analysis are the critical wind speeds (Table 5 and fig 9 &10),along with the proportion of vulnerable high-sided vehicles on the bridge (Section 9 and fig 14).

The justification for picking these variables can be based on the relative confidence of the source data.

11.1.1 Sensitivity analysis of critical wind speed (the wind speed that high sided vehicles become vulnerable)

The critical wind speed shown in Table 5 is based on case studies developed by Soper (2018), Hemingway & Robbins (2019) and a model by the UK Met Service. These are very reputable data sources. However, they may not relate directly to:

- the NZ vehicle fleet, e.g., the number of high sided used imports etc
- the NZ weather conditions i.e., the complicated wind concentrating, and wind shadowing created on the unique Auckland Harbour Bridge structure.

With these and other complicating factors being considered, we believe it prudent to show the effect of what a 5% variance in the critical wind speed, would produce. This would equate to the perpendicular critical wind speed moving from 90km/h by a factor of ±5km/h and the oblique wind speed moving form 110km/h by ±5km/h.

11.1.2 Sensitivity analysis of the number of vulnerable high sided vehicles on the AHB at any given time

The number of high sided vehicles on the AHB at any one point in time is known and can be confirmed via CCTV footage. What is not visible to the naked eye is how many are empty and therefore more vulnerable to the effects of wind as they cross the bridge.

The % of the HGV and LGV that are vulnerable to wind when empty is also debatable. The makeup of the NZ fleet is unique. We have a selection of US style HGV's, some lorries developed with European specifications and there are also a number of used imported lite commercial vehicles. How many of each type are on the AHB at any one time is variable.

The assumptions also assume 50% of all double decker buses are empty. This may not be the case as there are often counter peak flow riders on the bus. Whether these riders are sitting on the lower deck, making the bus more stable, or sitting on the upper level adding to the instability, is also a current unknown.

With these complicating factors and unknowns, we believe a sensitivity analysis of +/-30% variance in the vulnerability of high sided vehicles should be considered. We have used the range that 35% to 65% of the high sided vehicle fleet is vulnerable in any given hour.

Table 11 - Sensitivity analysis

	Scenario A	Scenario B	Scenario C	Scenario D
Original values	Approximately 20 times annually (1 in 17 days)	approximately 1 time per annum	Approximately 1 time in 10 years	Approximately 1 time in 50 years
Sensitivity analysis if the critical wind speed (when vehicles tip over etc) is 5% less than expected: 90km/h to 85km/h				
Vary critical wind speeds - 5% **= 90-5=85km/h perpendicular &** **110-5=105km/h oblique**	1 ÷ [3.75 × ((0.100% + 0.014%) × 24hrs)] = 1 in 10 days No restrictions and all vehicles still drive at 80km/h with critical wind speeds of 85km/h perpendicular and 105km/h oblique = 36 times annually	*1 ÷ [3.75 × ((0.100% + 0.014%) × 24hrs)] = 1 in 10 days If all vehicles still drive at 80km/h with critical wind speeds of 85km/h perpendicular and 105km/h oblique = 36 times annually *For scenario B it is still assumed that the AHB is closed at a wind speed of 90km/h. However, if the critical wind speed is less than 90km/h (85km/h) it is assumed that the AHB would still be open.	If 10% of vehicles still drive at 80km/h with critical wind speeds of 85km/h perpendicular and 105km/h oblique = 3.6 times annually	If 20% of the scenario C volume do not detour and of those 10% of vehicles still drive at 80km/h with critical wind speeds of 85km/h perpendicular and 105km/h oblique = 1 time in 1.5 years
Sensitivity analysis if the critical wind speed (when vehicles tip over etc) is 5% higher than expected: 90km/h to 95km/h				
Vary critical wind speeds + 5% **=90+5=95km/h perpendicular &** **110+5=115km/h oblique**	1 ÷ [3.75 × ((0.031% + 0.000%) × 24hrs)] = 1 in 30 days If all vehicles still drive at 80km/h with critical wind speeds of 95km/h perpendicular and 115km/h oblique = 12 times annually	1 ÷ [3.75 × ((0.00% + 0.000%) × 24hrs)] = 1 in N/A If all vehicles still drive at 80km/h with critical wind speeds of 95km/h perpendicular and 115km/h oblique = < 1 in 100 years	If 10% of vehicles still drive at 80km/h with critical wind speeds of 95km/h perpendicular and 115km/h oblique = < 1 in 1000 years	If 20% do not detour and of those 10% of vehicles still drive at 80km/h with critical wind speeds of 95km/h perpendicular and 115km/h oblique = < 1 in 10000 years

	Scenario A	Scenario B	Scenario C	Scenario D
Original values	20 times annually (1 in 17 days)	1 per annum	1 in 10 years	1 in 50 years
Sensitivity analysis, if the number of vulnerable vehicles is decreased by one third to 35% of high-sided vehicles and double decker buses.				
-30% vulnerable high-sided vehicles = 35% of the high sided fleet, on the AHB, are vulnerable.	1 ÷ [4.88 × ((0.055% + 0.010%) × 24hrs)] = 1 in 13 days = 28 times annually	1 ÷ [4.88 × ((0.00% + 0.003%) × 24hrs)] = 1 in 285 days = 1.3 times annually	1/10% x 285 days = 1 in 2850 days = 1 in 7.8 years	1/20% x 2850 days = 14,250 days = 1 in 39 years.
Sensitivity analysis, if the number of vulnerable vehicles is increased by one third to 65% of High sided vehicles and double decker buses.				
+30% vulnerable high-sided vehicles = 65% of the high sided fleet, on the AHB, are vulnerable.	1 ÷ [2.63 × ((0.055% + 0.010%) × 24hrs)] = 1 in 25 days = 14 times annually	1 ÷ [2.63 × ((0.00% + 0.003%) × 24hrs)] = 1 in 528 days = 0.7 times annually	1/10% x 528 = 1 in 5280 days = 1 in 14.5 years	1/20% x 5280 days = 26,400 days = 1 in 72 years.

11.1.3 Conclusion of Sensitivity Analysis

As can been see from Table 11. The analysis is sensitive to the assumed critical wind speed that effects high sided vehicles. A 5 km/h change in critical wind speed result in large swings of scenario results. The original data used, Baker & Soper (2018) and Hemingway & Robbins (2019) is well-regarded when plotted in fig 10 above and is confirmed by real life data obtained during incidents on the AHB and Manukau Harbour Bridge.

The sensitivity to the number of high sided vehicles that are vulnerable is far more consistent. This is because the likelihood of a vulnerable vehicle being on the AHB does not reduce to zero but is a % of the original likelihood. Be it larger or smaller.

As stated above, there are many mechanical, functional, and human factors at play when driving on the AHB in a high sided vehicle in poor weather. Not all of these variables can be accounted for in a high-level desk top analysis.

11.2 Risk of change to closure speed

During the development of this project, the question has been asked:" What if instead of closing the AHB when the wind reaches 90km/h we closed the bridge at the wind speed of 95km/h?".

Currently the legal speed limit is set at 80km/h on the AHB. The variable speed signage is only advisory and therefore not regulatory or enforceable. So, a high sided vehicle could travel at 80km/h on the AHB in any weather, up until the bridge is closed to all traffic.

To illustrate the effect of increasing the closure wind speed we need to refer to fig 10 recreated below:

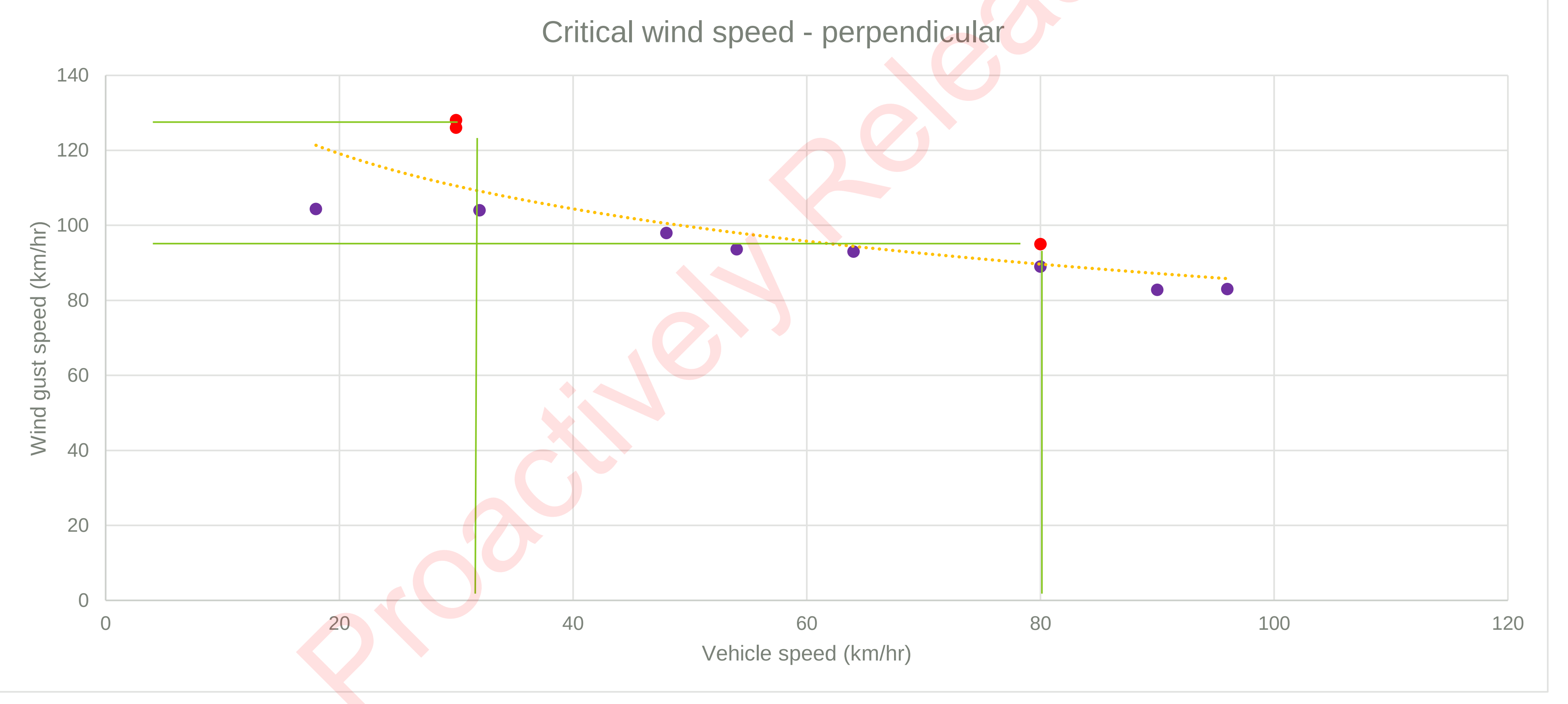

Figure 15 - Copy of Figure 10 – Critical perpendicular wind speeds of high-sided vehicles from literature (● purple dots) (Baker & Soper, 2018) (Hemingway & Robbins, 2019) and from previous incidents on the AHB and Manukau Harbour Crossing (● red dots). Line of best fit = derived perpendicular critical wind speeds used for this assessment (……. yellow line).

Using fig 10, when the wind is at 90km/h a vulnerable vehicle traveling at the legal speed of 80km/h is at/or near the critical speed. This wind speed of 90km/h is where the AHB is closed to all traffic. See fig 16 below:

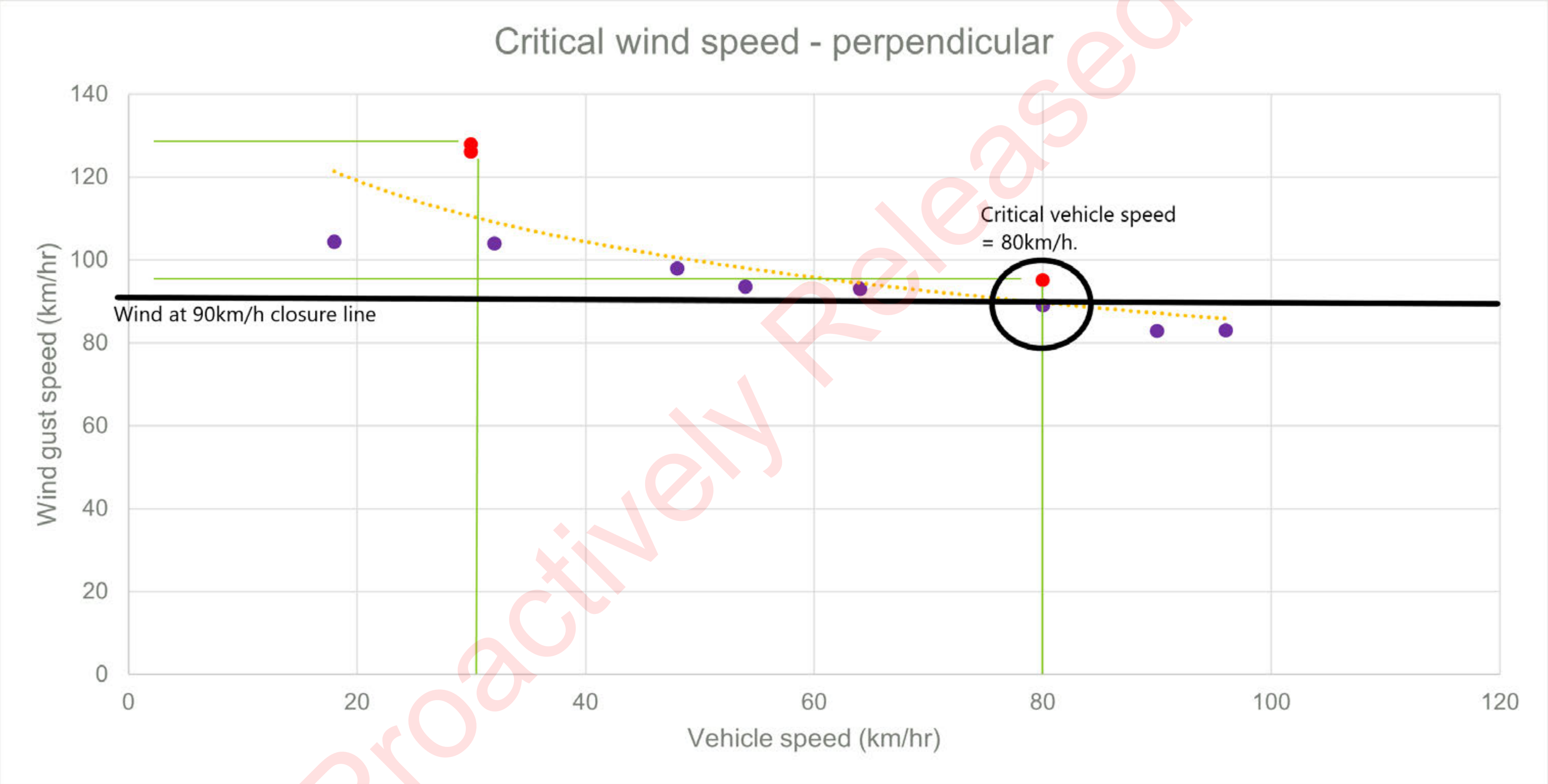

Figure 16 - Current 90km/h wind speed closure limit vs critical wind speed

If the closure speed was raised to 95km/h, then the critical wind speed reduces to around 60km/h. 60km/h is below the legal speed that a driver could travel across the AHB. See fig 17 below:

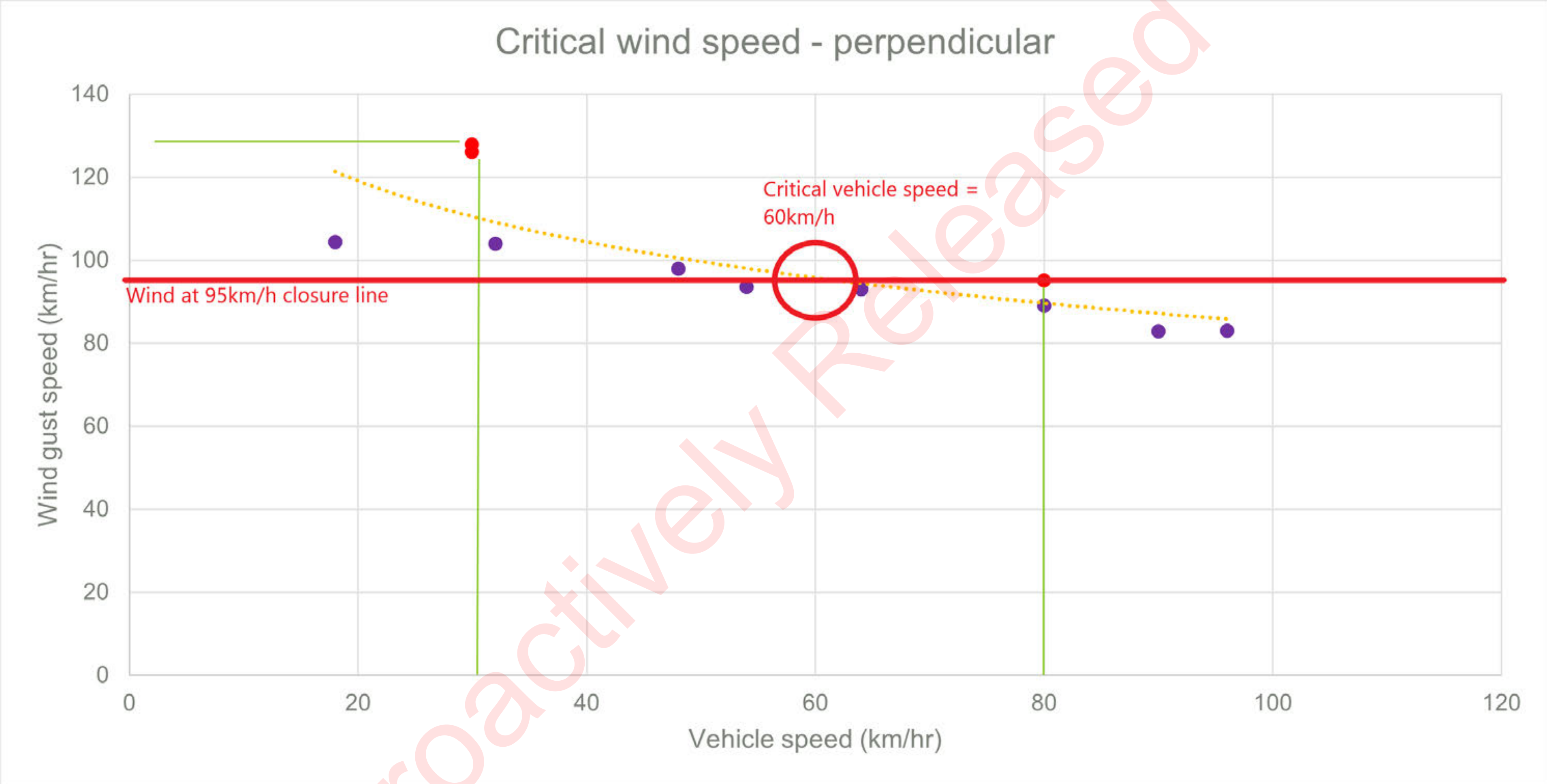

Figure 17 - Alternate 95km/h wind speed closure limit vs critical wind speed

A wind speed of 95km/h has been reported to have caused a crash on the Manukau Harbour Crossing when a vulnerable high sided vehicle was travelling at around 80km/h.

11.2.1 Current Buffer Zones

Currently when the wind gusts on the AHB exceed 65km/h an advisory speed of 50km/h is posted on the changeable message signs. If vehicles abide by this advisory speed, then there is a buffer created between the recorded wind gust speed and the critical wind gust speed. Similarly, when the wind gust speed reaches 75km/h, the advisory vehicle travel speed is reduced to 30km/h. These reductions in advisory vehicle speeds, keep a buffer for freak wind gusts between the expected wind speed and the critical wind speed. These buffers can be seen in Fig 18 below.

It must be noted that these buffers rely on drivers following the advised speed guidance. The legal speed limit is always at 80km/h and in all weather.

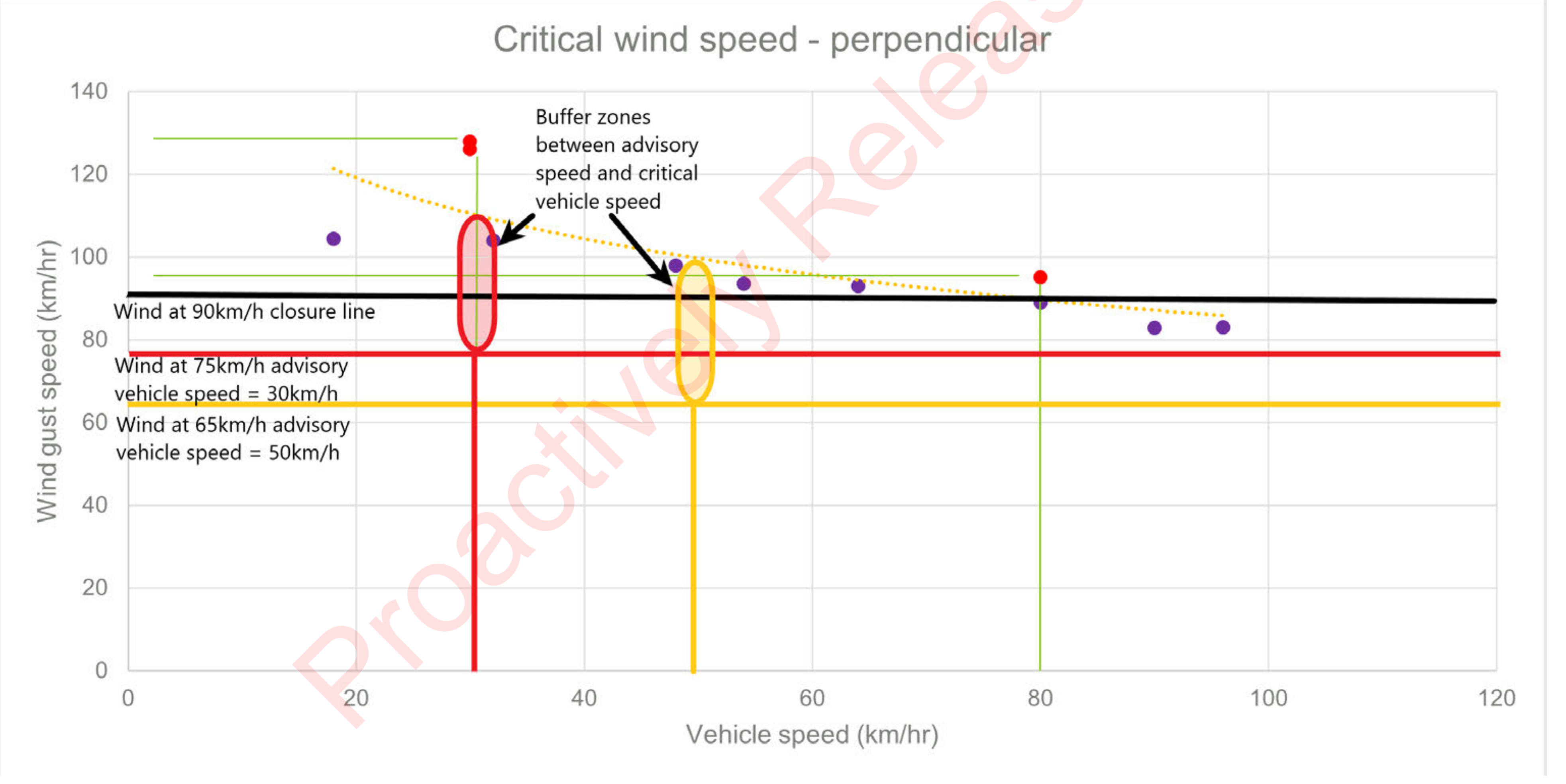

Figure 18 - Current buffer zones between posted advisory speed and critical wind speed

11.2.2 Risk of change in closure speed

Given that the current speed signage on the AHB is only advisory, there is a risk that raising the wind closure speed from 90km/h to 95km/h would increase the risk of a vehicle driving legally, being involved in a wind related incident.

It is therefore not advisable to consider raising the wind closure speed, without having at least enforceable speed limits on the AHB.

12 Recommendations

Waka Kotahi has an opportunity to improve safety during wind events on the AHB. This could be done through making the advisory speeds, legal and enforceable. By doing this the buffer zones shown in fig 18, will enhance the separation of vehicle traveling speed from the critical speed.

Increasing the AHB closure wind gust speed from 90km/h, is not recommended as it would erode the safety margin.

As noted throughout this assessment, there were multiple assumptions made to develop the high-level return periods of potential wind related vehicle incidents occurring on the AHB. The risk profile outlined in Table 10 is based on four hypothetical scenarios and provides a relative comparison of the risk of these vehicle incidents under different restrictions that align to the AHB High Winds Operating Manual.

Should Waka Kotahi want to build on the work performed in this desk-top risk assessment, and refine the wind related vehicle incident return periods for the AHB, the following tasks are recommended:

- A detailed analysis of vehicle speeds during different wind conditions and bridge restrictions at different times of the day.
- A detailed analysis of vehicle types and weights, and associated volumes travelling over the AHB.
- A detailed analysis to assess site specific wind conditions (i.e., site specific critical wind speed graphs) that could cause an incident on the AHB accounting for the varying conditions analysed in the above two tasks. This could be through computer simulations and/or wind tunnel testing to account for shielding effects and wind eddies.

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