Infrastructure NSW

Sydney Football Stadium (SFS) Redevelopment Project

Wind Data Analysis

Wind

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Executive Summary

Further to the provided quantitative Environmental Wind Assessment for the Sydney Football Stadium (SFS) Redevelopment Project, Arup were engaged to undertake an additional assessment to provide further insight into the anticipated wind conditions and practical implications of the outcomes of the quantitative Environmental Wind Assessment by Arup.

The Environmental Wind Assessment (Arup, 2019) concluded that despite not meeting the City of Sydney 2012 DCP wind criteria in all locations, in general, wind comfort conditions were expected to be very similar to that of the former Allianz Stadium. There were no exceedances of the pedestrian safety wind criterion. The overall design of the proposed Stadium was deemed appropriate from a wind comfort and safety perspective.

The assessment conducted in this report has involved re-analysis of the original wind tunnel data against various wind criteria, including the updated criteria in the City of Sydney (2016), Central Sydney Planning Strategy 2016-2036. These proposed criteria are considered more appropriate for pedestrian comfort than in the current City of Sydney (2012) DCP.

Based on the re-analysis of the original wind tunnel data against the City of Sydney 2016 DCP criteria, all locations are predicted to meet the walking criterion, which is considered to be the appropriate comfort criterion category for the tested locations around the Stadium. A large number of locations are classified as suitable for pedestrian standing. All locations are still predicted to meet the safety criterion.

The results indicate that incorporation of trees as a mitigation strategy do improve wind conditions, but not significantly. These comparative results reinforce that if it is considered that the wind conditions need to be improved significantly, a substantial amount of additional mitigation would need to be implemented, such as include numerous trees with a continuous canopy, or vertical screens. As human movement is similar to wind flow in that it takes the simplest route, any wind mitigation would similarly impede pedestrian circulation, and have potential implications for safety and visibility.

Despite all locations meeting the City of Sydney (2016) walking criteria, it is worth reiterating that the precinct is generally only highly occupied on game days where the large numbers of pedestrians offers local wind protection, the penguin-effect, particularly in high-trafficked areas.

In addition, on exceptionally strong forecast wind days, the game or event may be cancelled for weather reasons. No unsafe conditions were measured, and therefore pedestrian safety is not a concern for the development.

One of the windiest areas around the Stadium is predicted to be around the south-west corner. Location 30, in particular, is predicted to experience windy conditions at times. When assessed against the City of Sydney 2016 criterion, this location would be classified as pedestrian walking. This location would meet the

wind speed associated with the pedestrian sitting and standing criteria for about 70% and 90% of the time respectively. The standing criterion would be appropriate for people exercising, or families with children who are enjoying the precinct for outdoor activities. These percentages of time would be considered appropriate for the intended use of the precinct. Considering a location slightly more remote from the Stadium with more open space, for example, Location 4, the wind speeds associated with the City of Sydney (2016) sitting and standing criteria would be met for approximately 91% and 99% of the time respectively.

Proposed informal recreational areas within the precinct have been specifically reviewed in relation to wind comfort and safety. The permanent recreational activity area is located to the north-east of the precinct and this area roughly corresponds to tested Locations 15 (closer to the stadium) and 16 (slightly more remote from the stadium). For such activities the suitable assessment criterion would be considered to be that for pedestrian standing. Location 15 would meet the wind speed associated with the pedestrian standing criteria for about 97% of the time respectively. Location 16 would meet the wind speed associated with the pedestrian standing criteria for about 94% of the time respectively. These percentages of time would be considered acceptable for the intended recreational use of the space. Further to this, the landscape plan indicates a significant number of trees to the north and east of this recreational area. Locations 15 and 16 are most significantly impacted by winds from the east and north quadrants respectively. The trees are not included in the wind tunnel testing as they cannot be relied on for safety, but they offer shielding for comfort conditions, hence the local wind conditions in this area would be expected to better than measured in the wind tunnel.

The outcomes of this additional analysis support the conclusions of the Environmental Wind Assessment (Arup, 2019). The proposed SFS design is deemed to be appropriate from a wind comfort and safety perspective. Additional mitigation measures to significantly improve the wind conditions in the plaza would have an impact of pedestrian traffic flow and visibility in the area and are not necessarily required.

Contents

Appendices

Disclaimer

This assessment of the site environmental wind conditions is presented based on engineering judgement. In addition, experience from more detailed simulations have been used to refine recommendations. No detailed simulation, physical or computational study has been made to develop the recommendations presented in this report.

1 Introduction

Further to the quantitative Environmental Wind Assessment (Arup, 2019) completed in May, 2019 for the Sydney Football Stadium (SFS) Redevelopment Project, Arup have been engaged to undertake an additional assessment and interpretation of the wind tunnel test data against various wind criteria, including those in City of Sydney (2016). This report presents the results of this assessment related to pedestrian wind comfort and safety on the ground level in and surrounding the proposed development.

The objective of this report is to provide further insight into the anticipated wind conditions and provide additional explanation of the practical outcomes of the quantitative Environmental Wind Assessment (Arup, 2019). The report has also been prepared to respond to the Department of Planning, Infrastructure and Environment 'Response to Submissions' comment (DPIE7):

Wind Impact Assessment

- *The submitted "Wind Assessment Report" concludes that wind conditions are expected to be similar to the former SFS conditions with some areas 'becoming windier and others calmer'. The wind tunnel testing report states that the wind conditions in most of the public domain areas around the stadium exceed the walking criterion (except certain locations to the north and south).*
- *The EIS does not include any measures to mitigate the exceedances noted in the Wind Impact Assessment Report.*
- *Please update the submitted schedule of environmental mitigation measures to include appropriate measures that would be implemented on the site to ensure that wind tunnel impacts are reduced in the public domain areas, which are likely to be used on the non-event days as well*

2 Wind Assessment

2.1 Modelling

The assessment is based on the wind tunnel testing conducted on 25/26 March 2019 at the MEL Consultants facility. Further details of this testing can be referred to in Arup (2019). As this test is primarily to assess the space for pedestrian safety, the wind tunnel test models the structural massing and does not include smaller elements that would not necessarily remain during an extreme event, however would offer additional shielding at a day-to-day serviceability comfort level.

Wind tunnel testing was conducted in two configurations: former SFS (Allianz Stadium), and proposed stadium design. Measurements were taken around the exterior of the stadia to measure the wind conditions for pedestrian safety and comfort. Mitigation measures in the form of mature trees were tested at some windy locations, Figure 1, to illustrate their effectiveness in improving the local wind conditions.

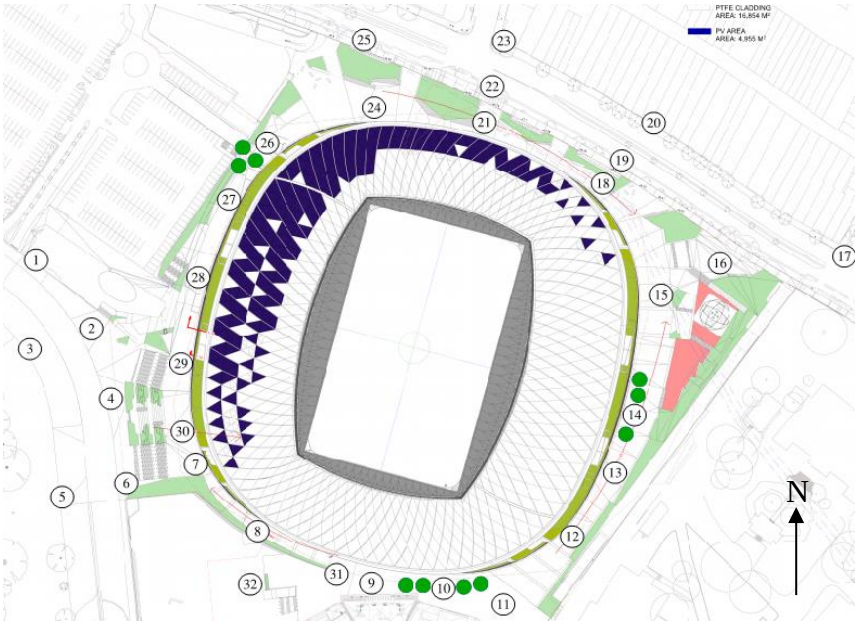

Figure 1: Proposed configuration: test locations mark-up on site plan – green circles indicated of tree locations that were assessed as part of potential mitigation measures.

Arup subsequently re-analysed the wind tunnel testing results for comparison with various comfort criteria. Arup has analysed the results with Sydney Airport climate data (Appendix A1), for years 1995 to 2017 for hours 6 am to 10 pm in line with City of Sydney (2016) criteria (refer to Section 2.2). As the wind speeds during the night are calmer, the results herein are in a relatively windier environment. The results presented in this report are based on Arup's analysis.

2.2 Wind Assessment Criteria

The purpose of this assessment is to re-analyse the original wind tunnel data against various wind criteria, including those in City of Sydney (2016). The Environmental Wind Assessment report was completed using the City of Sydney's DCP 2012 criteria, which are provided in Section 2.2.1 for context. The City of Sydney (2016) criteria were also considered and are summarised in Section 2.2.2.

2.2.1 Currently applicable City of Sydney criteria (2012 DCP)

As outlined in the Environmental Wind Assessment report, the City of Sydney (2012) DCP specifies wind effects are not to exceed 10 m/s for active frontages, and 16 m/s for all other streets, Figure 2. There are few locations in Sydney that would meet the 'active frontage' criterion without significant shielding to improve the wind conditions. With reference to the City of Sydney active frontage map, Figure 2, the SFS is zoned as non-active frontages and therefore, the 16 m/s criterion applies.

Figure 2: Active frontage map from City of Sydney DCP, with the approximate SFS site marked in purple

From personal communications with Council, this reference wind speed is a once per annum gust wind speed as per the wind criteria in the City of Sydney 2004 DCP, but is meant to be interpreted as a comfort level criterion to promote outdoor activities and is not intended to be used as a distress requirement. The once per annum gust wind speed criterion used in the City of Sydney (2012) DCP is based on the work of Melbourne (1978), Table 1, which is for the probability of the 3 second gust occurring in an hour of data for 0.1% of the time for any wind direction, or two peak storm events in a year. The 10 m/s level is classified as generally acceptable for pedestrian sitting, and the 16 m/s for pedestrian walking. The Melbourne criteria give the 'once per annum gust wind speed', and uses this as an estimator of the general wind conditions at a site. A more detailed discussion on wind criteria are presented in Appendix A3. The City of Sydney (2012) DCP criteria are considered more relevant for well-frequented streetscapes rather than open locations where people will frequent when a range of environmental conditions meet their intended needs.

Criteria based on the once per annum gust are dependent on the extreme event in the year, and not necessarily a good descriptor of the serviceability wind climate for pedestrian comfort. Longer probabilities of occurrence being more relevant for serviceability design.

Table 1: Summary of wind effects on pedestrians based on MEL Consultants criteria

'Annual' maximum 3 s gust wind speed	**Result on perceived pedestrian comfort**
> 23 m/s	**Unsafe** (frail pedestrians knocked over)
< 23 m/s	**Unacceptable** for comfort
< 20 m/s	**Waterfront** locations / fast walking
< 16 m/s	Acceptable for **walking** (steady steps for most pedestrians)
< 13 m/s	Acceptable for **standing** (window shopping, vehicle drop-off, queuing)
< 10 m/s	Acceptable for **sitting** (outdoor café, gardens, park benches)

2.2.2 City of Sydney criteria (2016)

The City of Sydney (2016) criteria, on which this assessment is based, are based on the work of Lawson (1990), with the only difference being that the assessment hours are restricted to daylight hours between 6 am and 10 pm Eastern Standard Time (EST). The criteria are presented in Table 2 where the comfort criterion is based on the 5% exceedance level rather than the 0.1% exceedance, which is considered more appropriate for serviceability design.

Table 2: City of Sydney (2016) criteria (measured between 6 am and 10 pm (EST)

'Annual' maximum 0.5 s gust wind speed in one hour	**Result on perceived pedestrian safety**
> 24 m/s	**Unsafe**
Maximum of hourly mean wind speed or gust equivalent mean wind speed (for no more than 5% of hours)	**Result on perceived pedestrian comfort**
< 8 m/s	Acceptable for **walking**
< 6 m/s	Acceptable for **standing**
< 4 m/s	Acceptable for **sitting**

2.3 Results Discussion

The objective of this report is to provide further insight into the anticipated wind conditions and additional interpretation from a practical perspective of the outcomes of the quantitative Environmental Wind Assessment.

The Environmental Wind Assessment (Arup, 2019) concluded that despite not meeting the City of Sydney 2012 DCP 'once per annum' comfort criteria for pedestrian walking at all locations, in general, wind comfort conditions were expected to be similar to that of the former Allianz Stadium. The safety criteria were, however, predicted to be met at all locations. The overall design was deemed to be appropriate from a wind comfort and safety perspective. For reference, results for the proposed and former SFS designs against the 2012 DCP criteria are presented in Figure 4 and Figure 5 respectively. These figures show the test locations and whether the wind conditions would meet the 2012 DCP non-active frontage criterion of 16 m/s for the once per annum gust wind speed.

From re-analysis of the original wind tunnel data against the City of Sydney (2016) criteria, all locations are predicted to meet the walking criterion, which is considered the appropriate comfort criterion category for the tested locations around the Stadium. All locations would still be predicted to meet the safety criterion as well. A summary of the comfort results against the 2016 criteria are presented in Figure 6 and Figure 7.

These results are discussed in detail below and images showing a comparison of the results at each location against various criteria are included in Appendix A2. The results for Location 1, as mapped in Figure 4, are presented in Figure 3, as an example. The chart is a plot of the probability of exceeding a particular wind speed against wind speed. This graph clearly illustrates the expected probability distribution of wind speed at a specific location: for example, the mean wind speed exceeded for 0.1% and 5% amount of time would be 8.6 and 5.6 m/s as illustrated in Figure 3. For the probability of exceedance of 0.1%, the blue line is to the right of the pedestrian walking symbol for the Melbourne criterion and therefore exceeds the walking criterion and would be classified as 'Waterfront' Table 1. The 3 s gust wind speed can be estimated by multiplying this value by 1.85. At the 5% level, the blue line is to the left of the rhombus symbol for the Lawson criteria, and therefore would be classified as suitable for pedestrian standing, Table 2.

On Figure 3, various internationally recognised wind comfort criteria for assessing the wind climate at different probability levels are overlaid by the grey and coloured horizontal lines, with the various symbols indicating the comfort category targets for specific activities. The results for each location are plotted in the solid coloured curves, depending on the applicable results option (existing, proposed or articulated). In the case of SFS, any articulated scheme results are the result of testing trees as mitigation strategies, Figure 1.

The applicable City of Sydney criteria on the chart are as follows:

- The 2012 DCP criteria are based on the work of Melbourne (noted as 'Melbourne GEM (indicative)' in the chart; and
- The 2016 DCP criteria are based on the work of Lawson (1990), but with restricted hours (which these results charts are produced for).

The 2016 DCP criteria take into account the Sydney wind climate removing the assumed extrapolation from the extreme 'once per annum' event to more regular events. This explains the apparent improvement in wind conditions when comparing the results between different criteria.

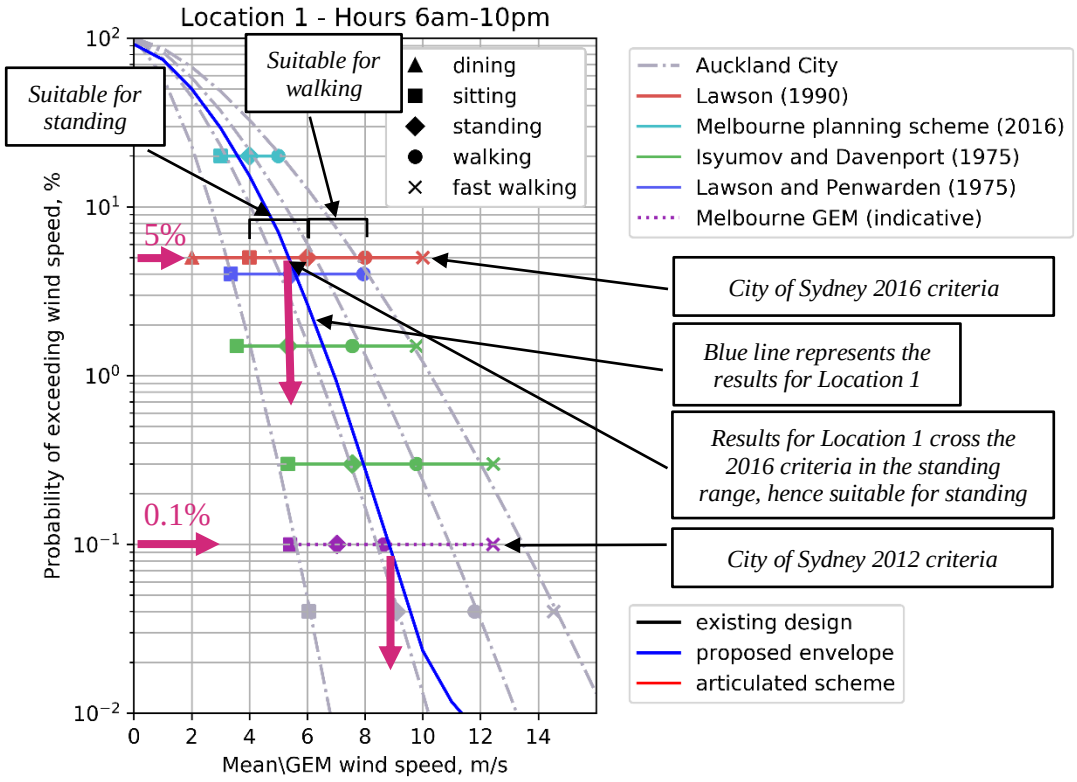

Figure 3: Probabilistic comparison between wind criteria based on mean wind speed (for the hours of 6 am and 10 pm) – Location 1

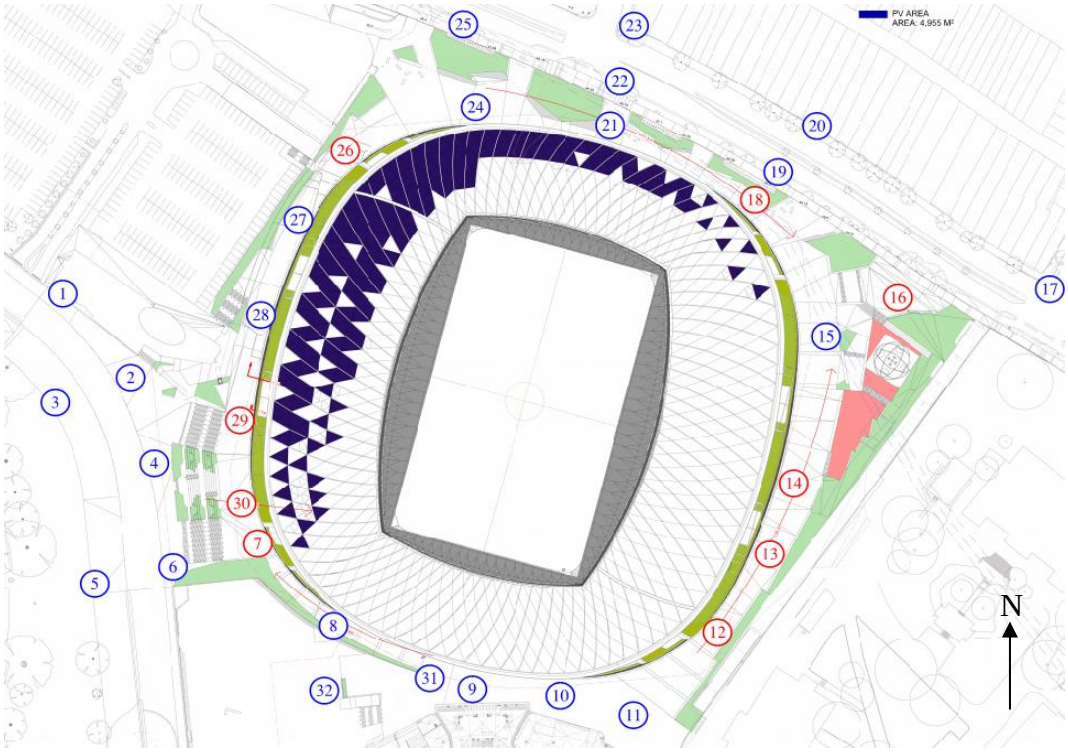

Figure 4: Proposed configuration: test locations mark-up on site plan – red text indicates locations that do not meet the City of Sydney (2012) criterion.

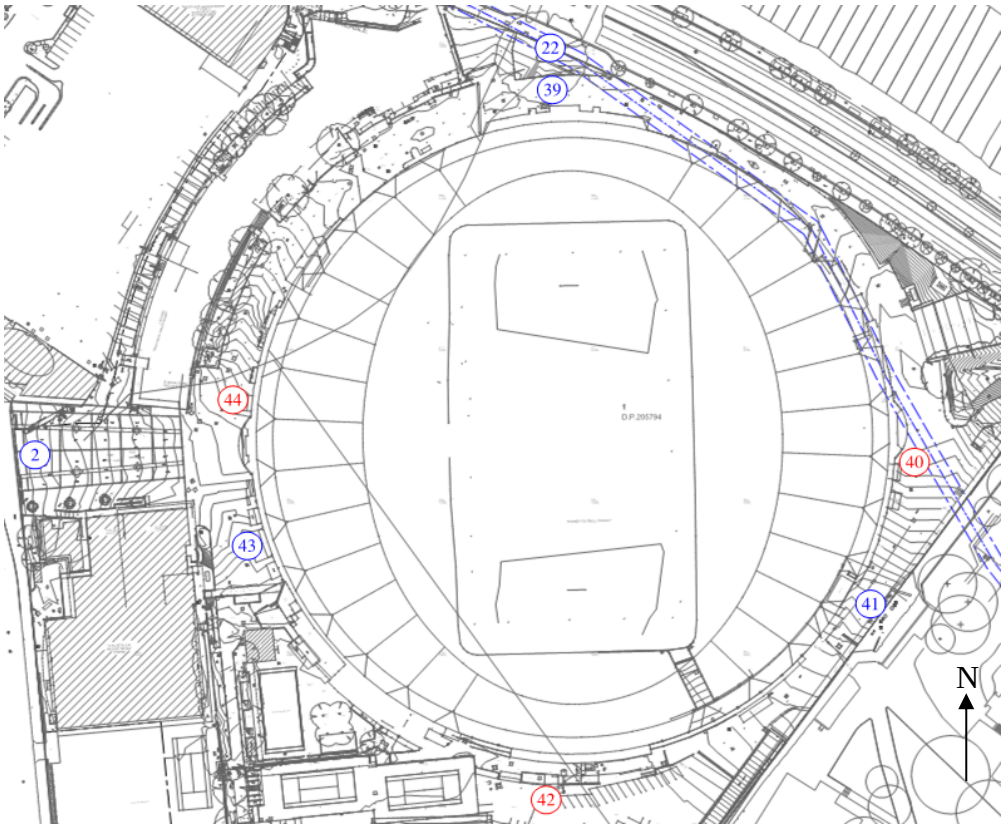

Figure 5: Former SFS configuration (Allianz Stadium): test locations mark-up on site plan – red text indicates locations that do not meet the City of Sydney (2012) criterion.

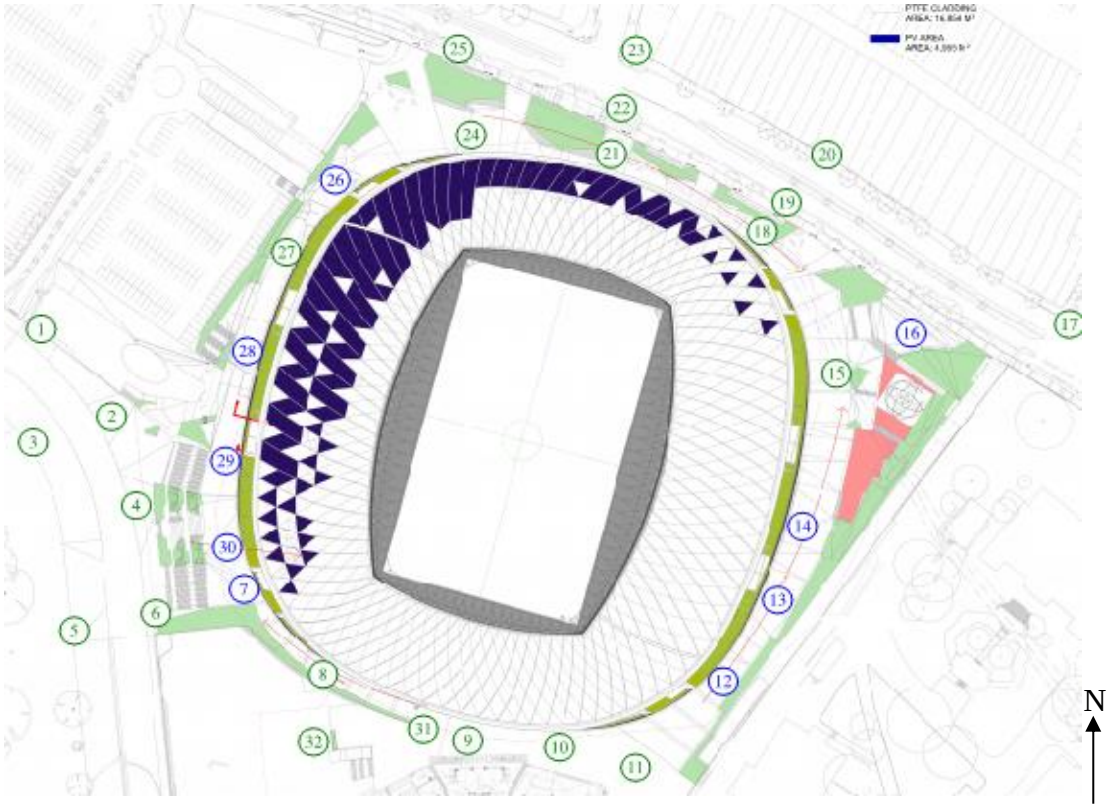

Figure 6: Proposed configuration: test locations mark-up on site plan – green text indicates locations that meet the City of Sydney (2016) standing criterion; blue text indicates meeting the walking criterion.

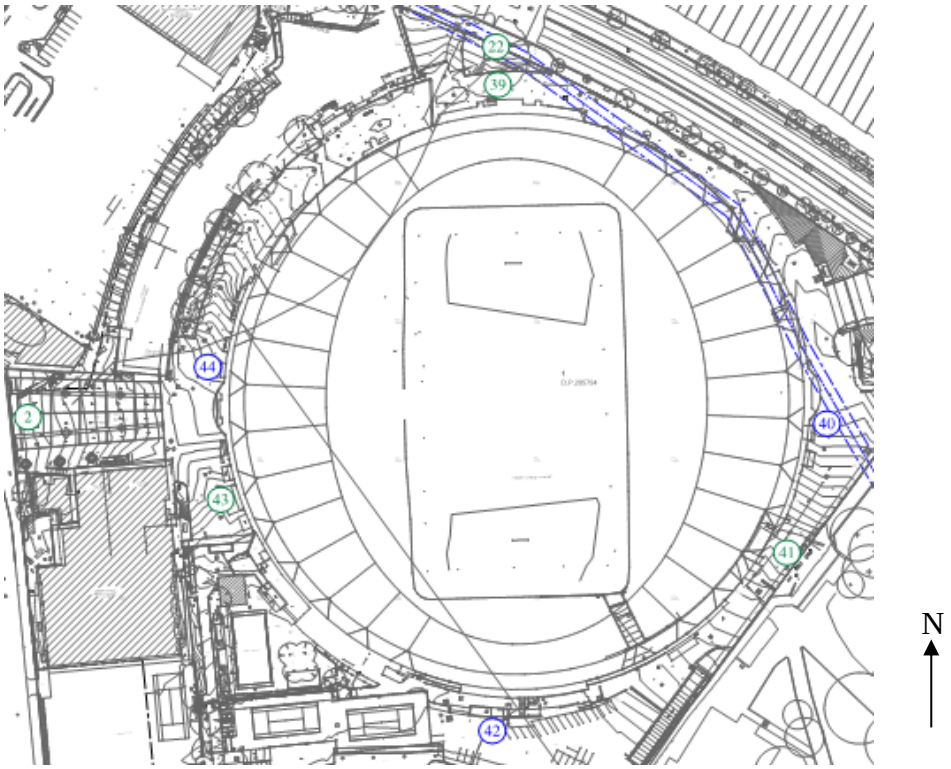

Figure 7: Former SFS configuration (Allianz Stadium): test locations mark-up on site plan – – green text indicates locations that meet the City of Sydney (2016) standing criterion; blue text indicates meeting the walking criterion.

A direct comparison between former SFS and proposed SFS conditions is summarised in Table 3. In general, both configurations meet the 2016 DCP criterion for walking.

Table 3: Comparison of results for the proposed SFS and former SFS against the 2016 criteria

Test Location	Equiv. test location for former SFS	5% exceedance wind speed / comfort category		Meet CoS 2016 DCP walking target?
		Proposed SFS	Former SFS	
2	2	**5.2 m/s, standing**	4.5 m/s, standing	Yes
9	42	5.2 m/s, standing	**6.3 m/s, walking**	Yes
12	41	**6.2 m/s, walking**	4.9 m/s, standing	Yes
14	40	**7.0 m/s, walking**	6.4 m/s, walking	Yes
21	39	**5.2 m/s, standing**	5.1 m/s, standing	Yes
22	22	4.5 m/s, standing	**4.6 m/s, standing**	Yes
28	44	6.2 m/s, walking	**6.6 m/s, walking**	Yes
29	43	**6.4 m/s, walking**	5.1 m/s, standing	Yes
31	42	5.6 m/s, standing	**6.3 m/s, walking**	Yes

The proposed configuration test locations that previously failed the 2012 DCP criteria have been specifically reviewed against the 2016 DCP criterion for walking, Table 4. In general, all locations are predicted to meet the City of Sydney (2016) criterion for walking.

Table 4: Summary of the proposed SFS against the City of Sydney (2016) criteria (for test locations that did not meet the 2012 DCP criteria)

Test Location	5% exceedance wind speed / comfort category	Meet CoS 2016 DCP walking target?
7	6.4 m/s, walking	Yes
13	7.6 m/s, walking	Yes
16	6.1 m/s, walking	Yes
18	5.8 m/s, standing	Yes
26	6.7 m/s, walking	Yes
30	7.2 m/s, walking	Yes

In addition to transient spaces, sitting and informal recreational areas within the precinct have been specifically reviewed in relation to wind comfort and safety. The wind speed associated with the standing criterion (6 m/s) would be considered appropriate for people exercising, or families with children who are enjoying the precinct for outdoor activities. A permanent recreational activity area is located to the north-east of the precinct, Figure 8. This area is between Locations 15 (closer to the stadium) and 16 (slightly more remote from the stadium). Location 15 and 16 would meet the wind speed associated with the pedestrian standing criteria for about 97.5% and 94% of the time respectively. This would be considered acceptable for the intended use of the space. In addition to this, the landscape plan indicates a significant number of trees to the north and also east of this recreational area, Figure 8. From the direction results, Location 15 is most significantly impacted by winds from the east and Location 16, winds from the north. Trees are not included in the wind tunnel testing as they cannot be relied on during extreme events, but would offer shielding for serviceability winds. Hence the local wind conditions would be expected to be better from a comfort perspective than estimated by the wind tunnel results.

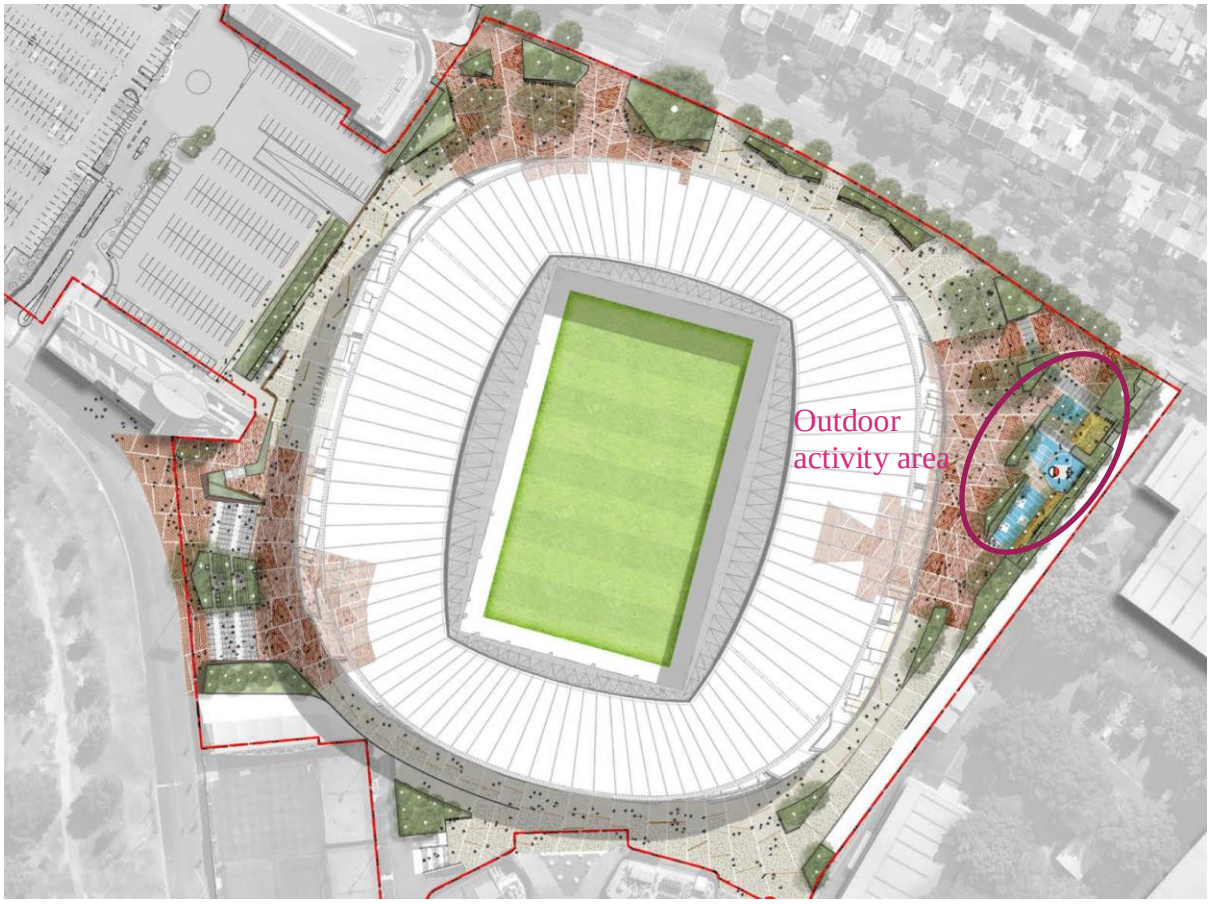

Figure 8: Landscape plan

2.4 Conclusions

In response to the Department of Planning, Infrastructure and Environment comments, the outcomes of this additional analysis support the conclusions of the Environmental Wind Assessment (Arup, 2019). The proposed SFS design is deemed to be appropriate from a wind comfort and safety perspective. Additional mitigation measures to significantly improve the wind conditions in the plaza would have an impact of pedestrian traffic flow and visibility in the area and are not necessarily required.

Based on the re-analysis of the original wind tunnel data against the City of Sydney (2016) DCP criteria, all locations are predicted to meet the walking criterion, which is considered to be the appropriate comfort criterion category for the tested locations around the Stadium. A large number of locations are classified as suitable for pedestrian standing. All locations are still predicted to meet the safety criterion.

3 References

Arup (2019), Sydney Football Stadium (SFS) Redevelopment Project Environmental Wind Assessment, Issue 04 (May 2019).

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Appendix A

A1 Wind Climate

The wind frequency and direction information measured by the Bureau of Meteorology anemometer at a standard height of 10 m at Sydney Airport from 1995 to 2017 have been used in this analysis, Figure 9. The arms of the wind rose point in the direction from where the wind is coming from. The anemometer is located about 8 km to the south of the site. The directional wind speeds measured here are considered representative of the wind conditions at the site.

It is evident from Figure 9 that strong prevailing winds are organised into three main groups which centre at about the north-east, south, and west quadrants.

Strong summer winds occur mainly from the south and north-east quadrants. Winds from the south are associated with large synoptic frontal systems and generally provide the strongest gusts during summer. Moderate intensity winds from the north-east tend to bring cooling relief on hot summer afternoons typically lasting from noon to dusk. These are small-scales temperature driven effects; the larger the temperature differential between land and sea, the stronger the wind.

Winter and early spring strong winds typically occur from the south-west, and west quadrants. West quadrant winds provide the strongest winds affecting the area throughout the year and tend to be associated with large scale synoptic events that can be hot or cold depending on inland conditions.

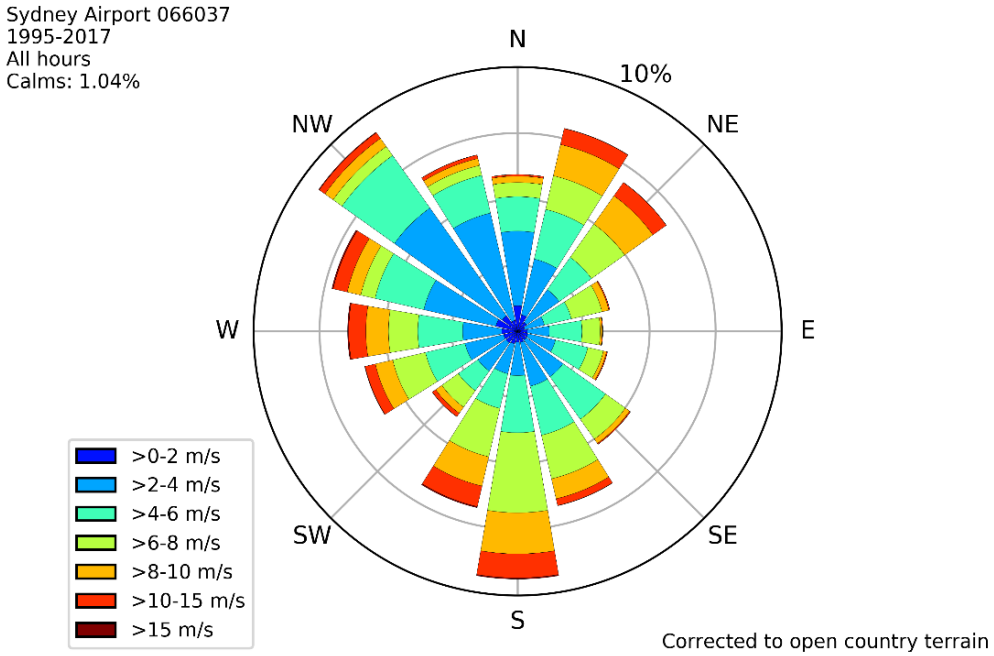


Figure 9: Wind rose showing probability of time of wind direction and speed

City of Sydney (2016) wind criteria restricts hours to between 6 am and 10 pm; a wind rose corresponding to these hours is shown in Figure 10.

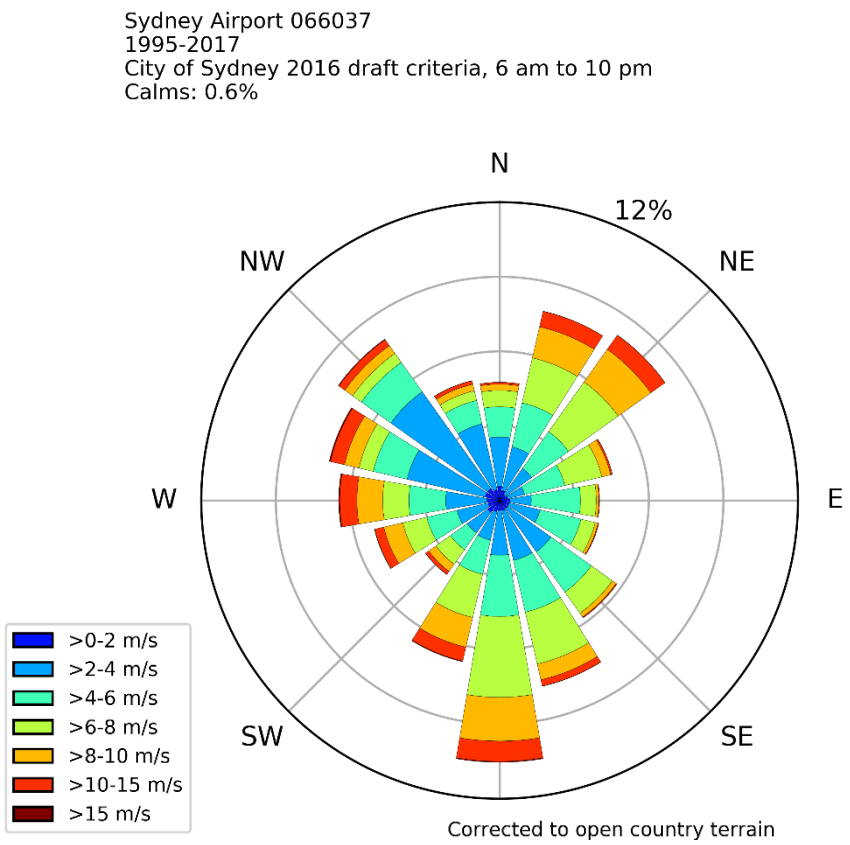
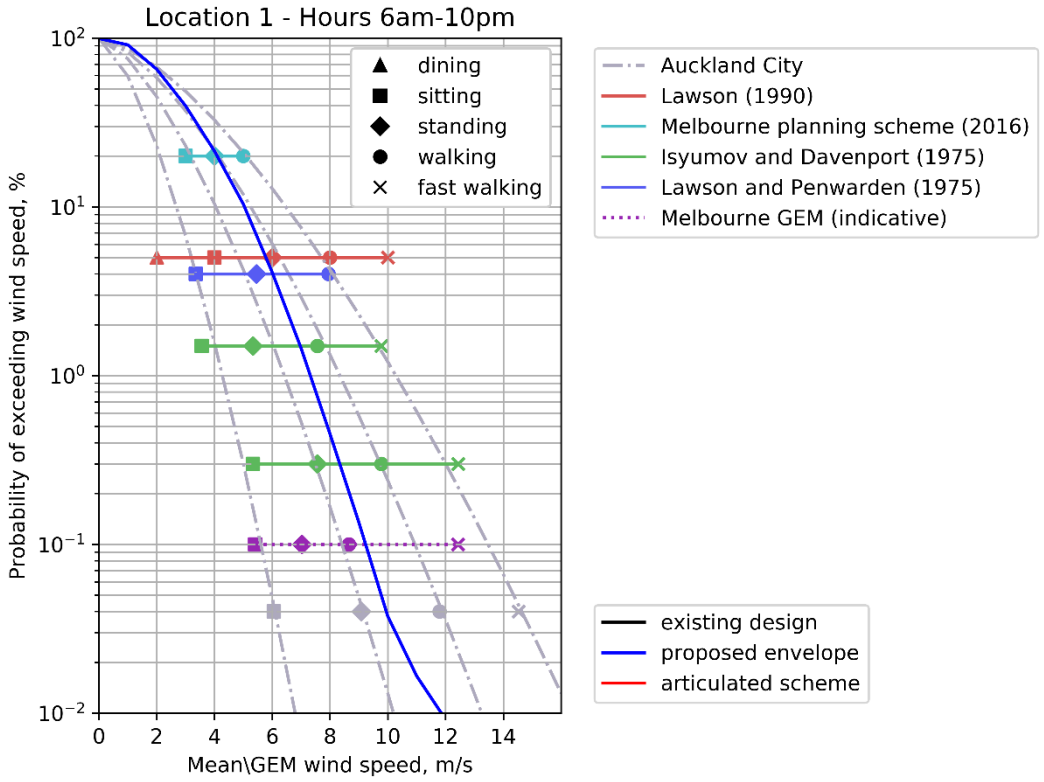
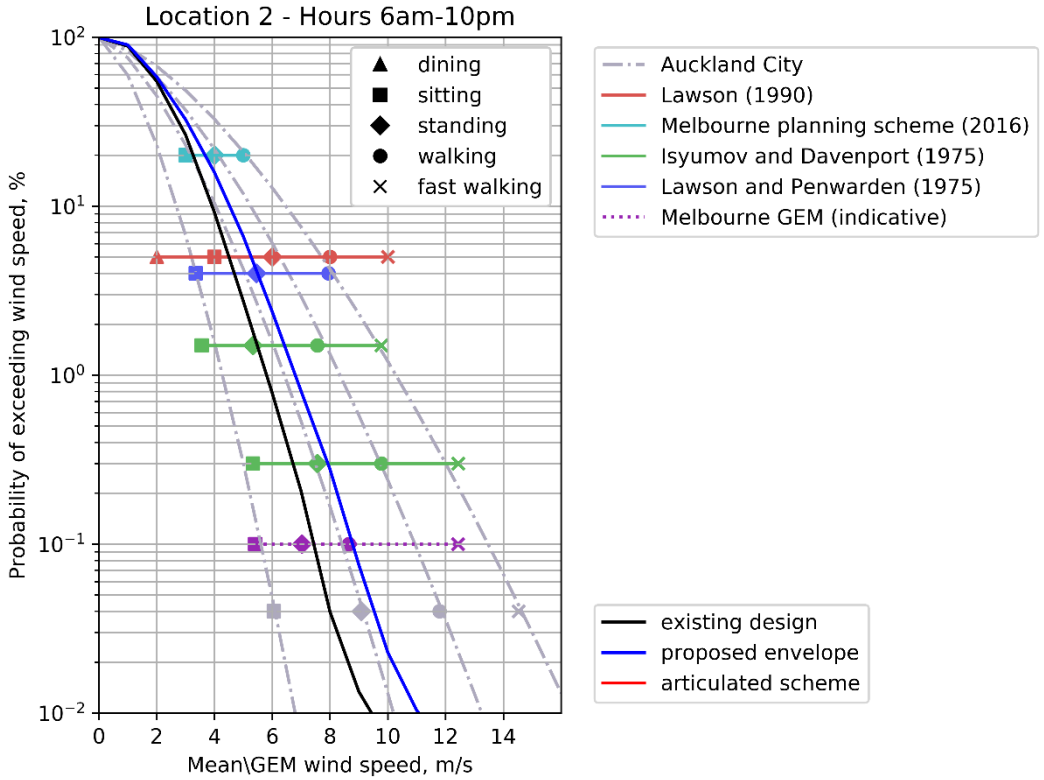
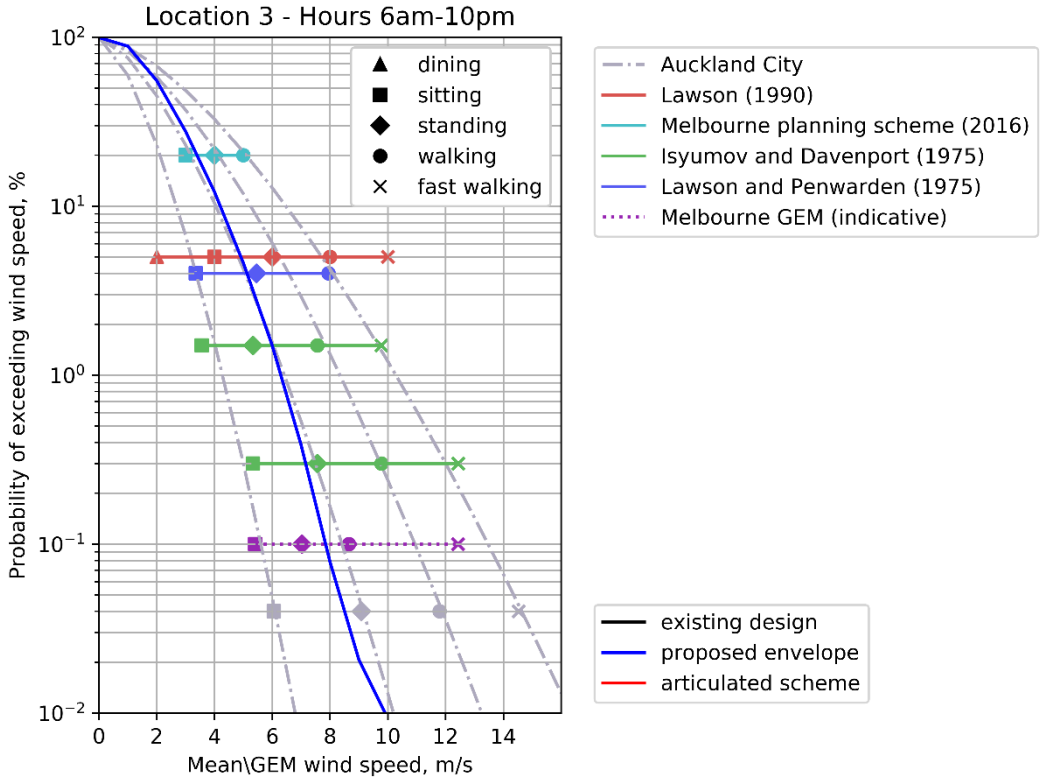


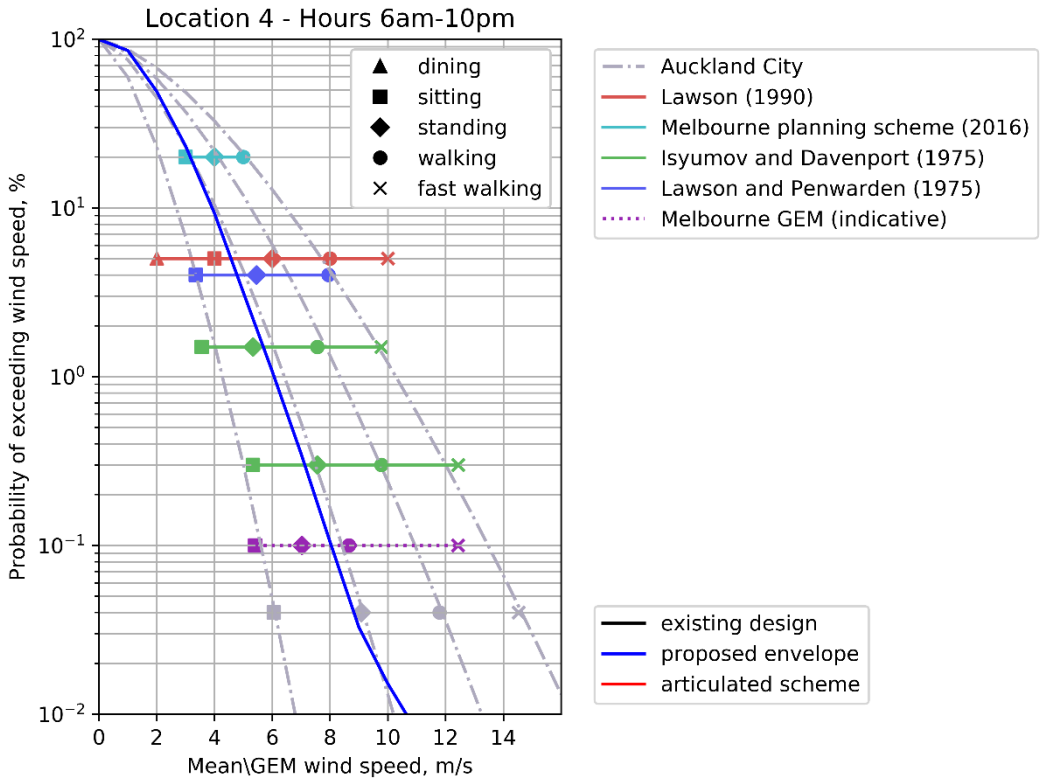
Figure 10: Wind rose showing probability of time of wind direction and speed (2016 DCP criteria, 6 am to 10 pm)

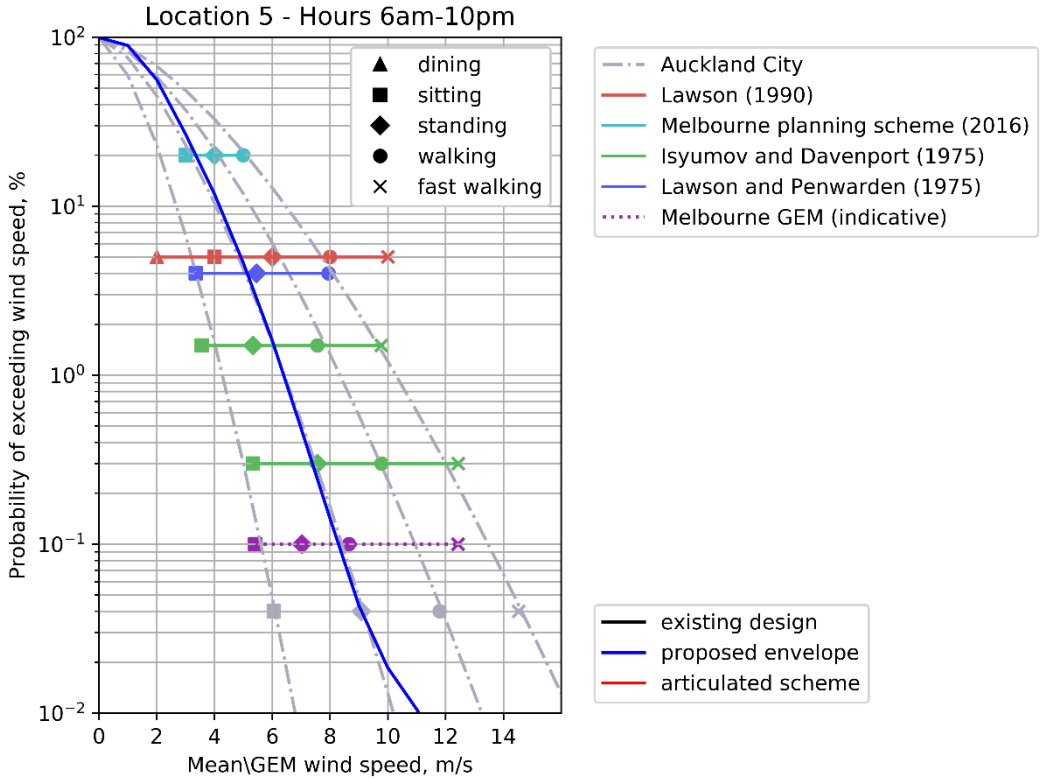
A2 Wind Data – Criteria Comparison






Location 3 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 4 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 5 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
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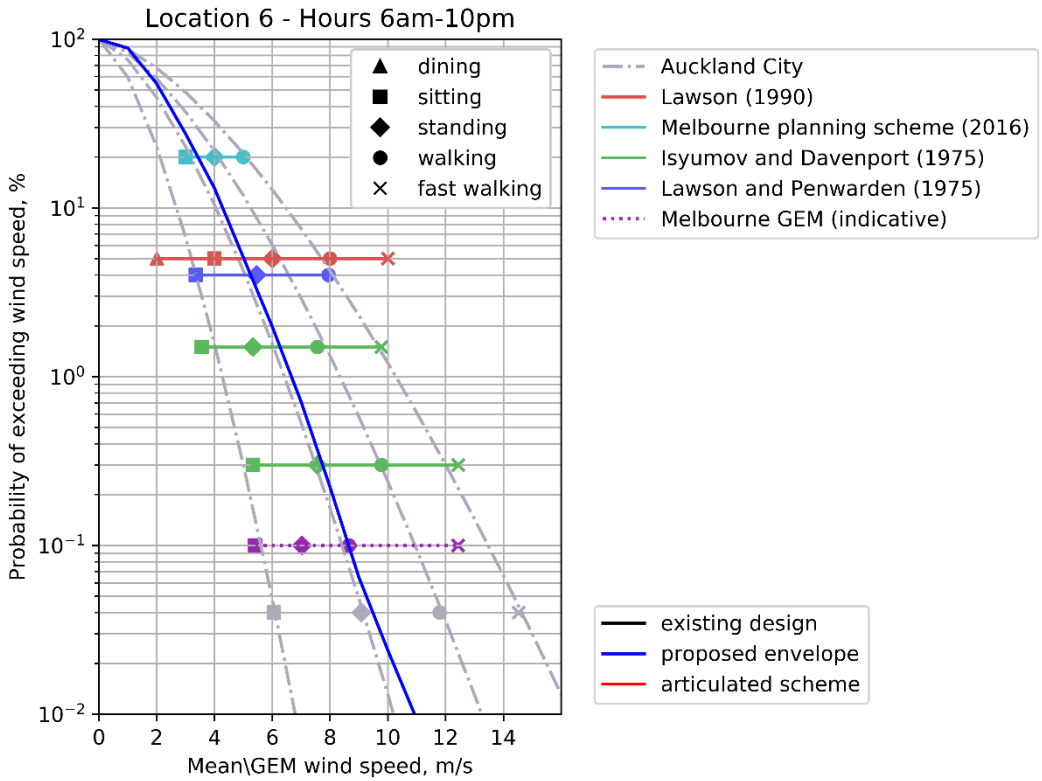
Location 6 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
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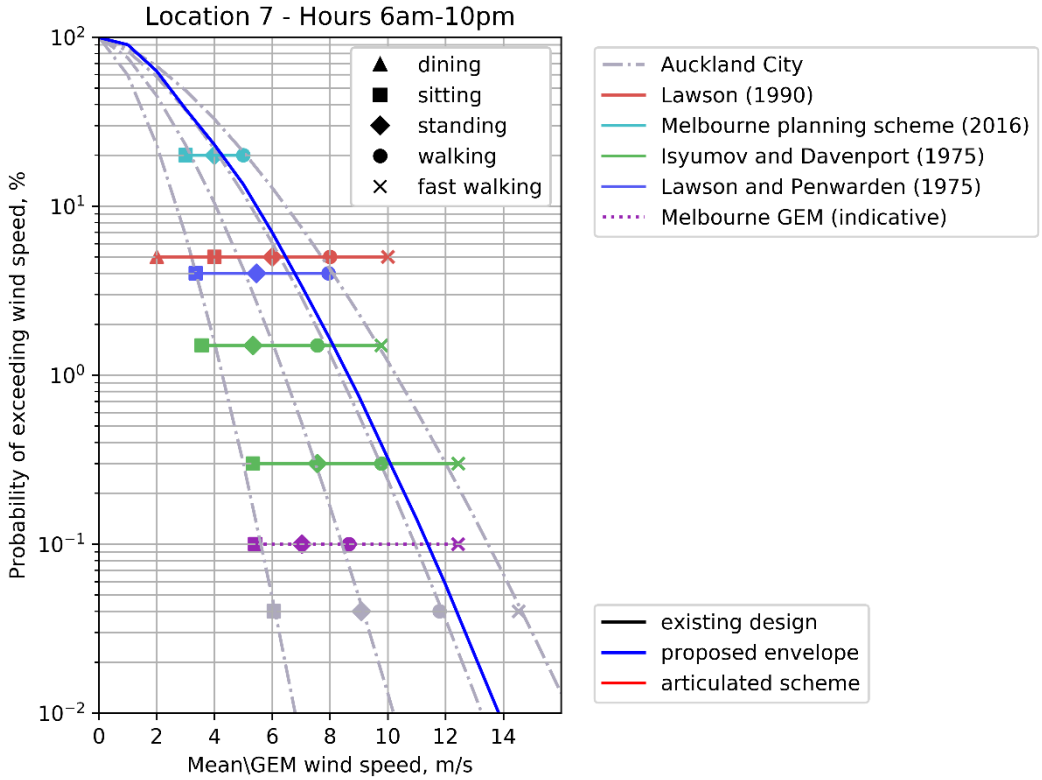
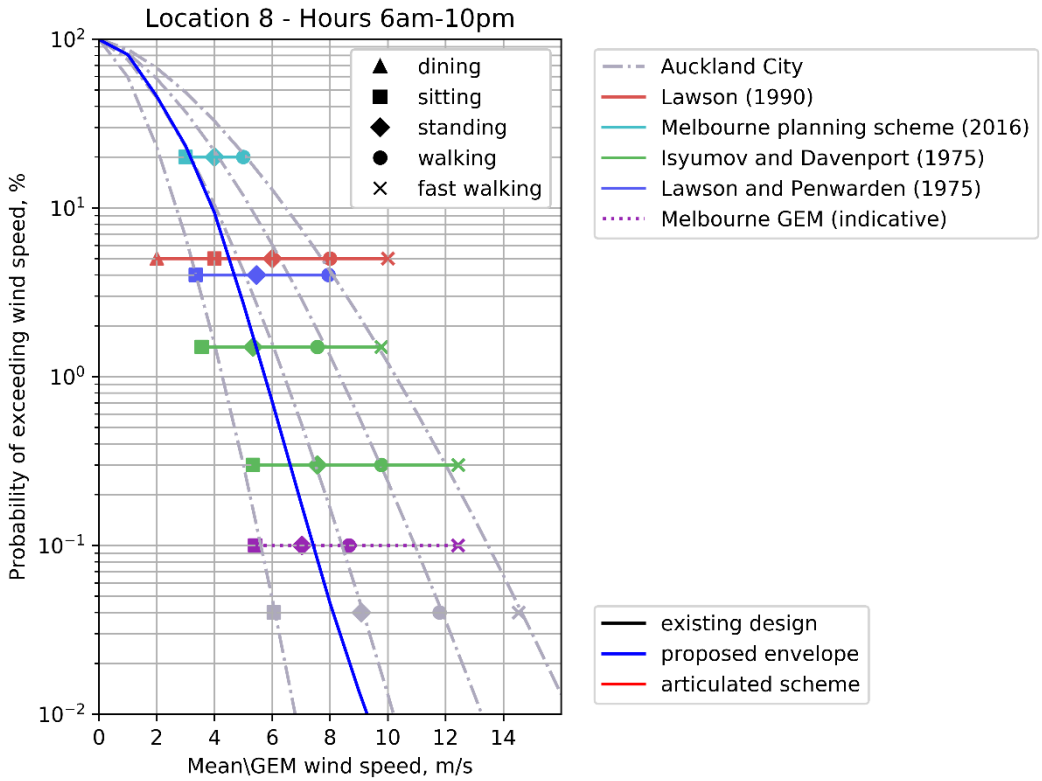
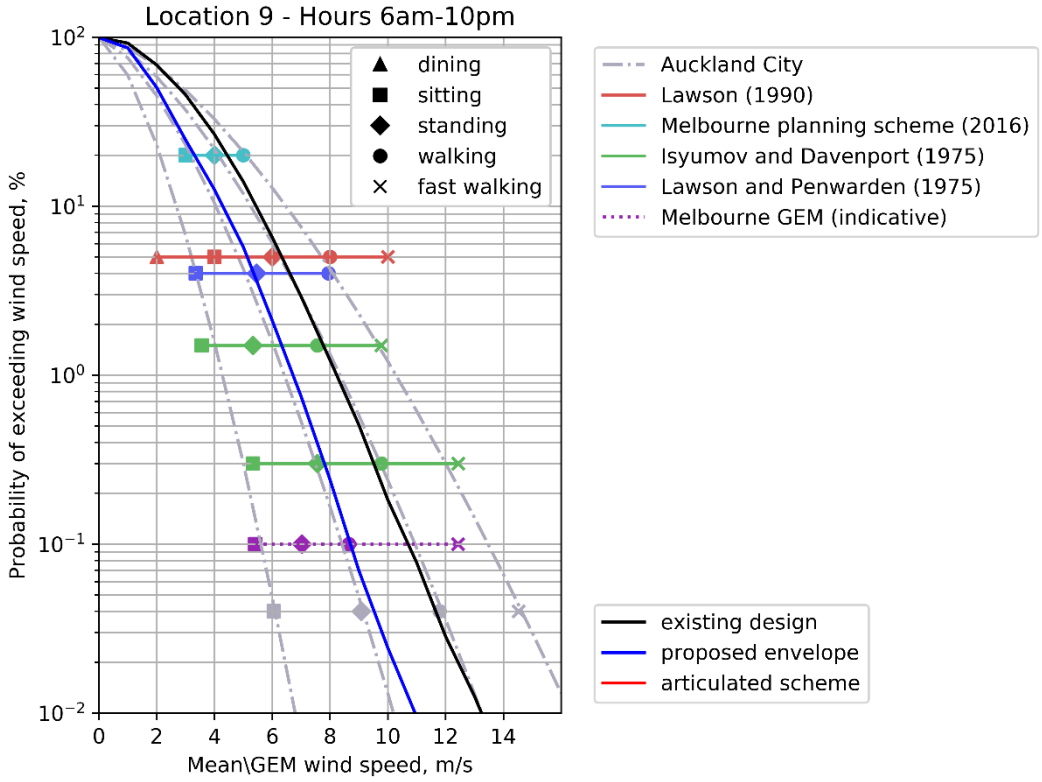
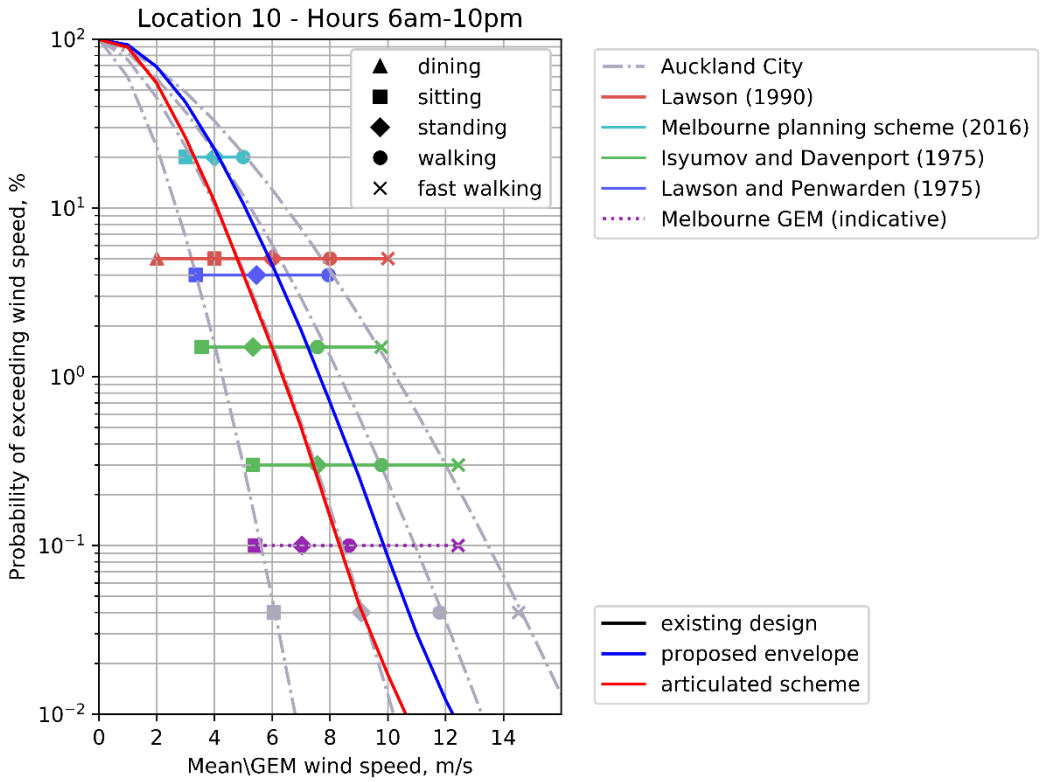
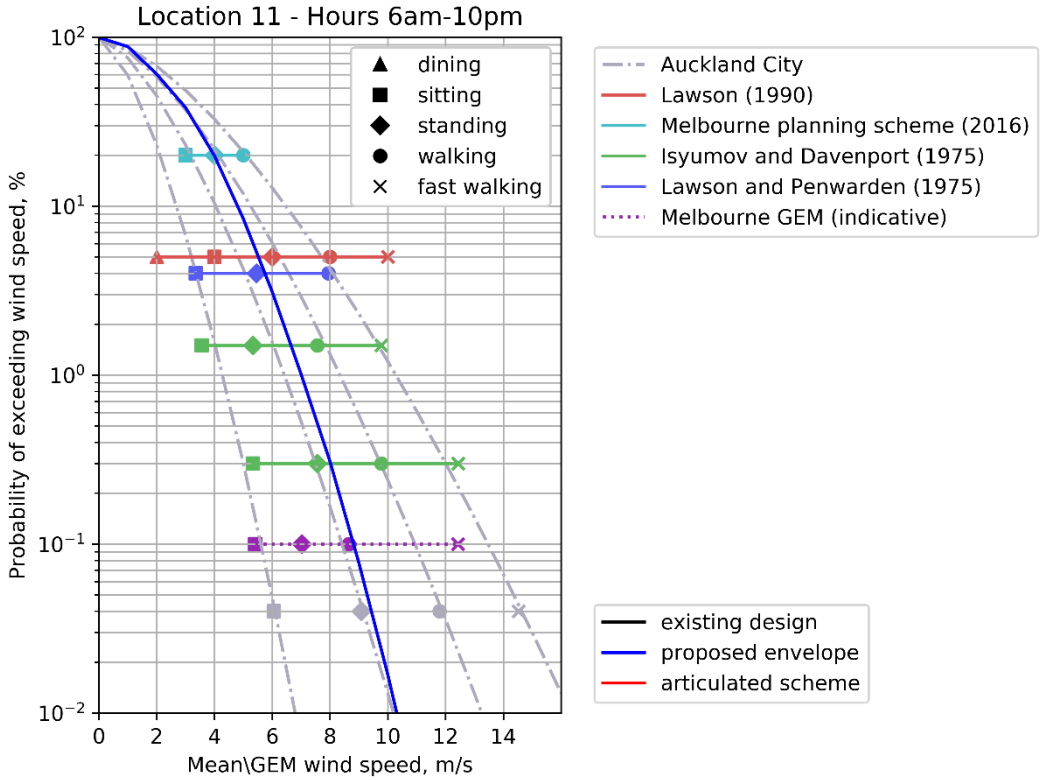
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

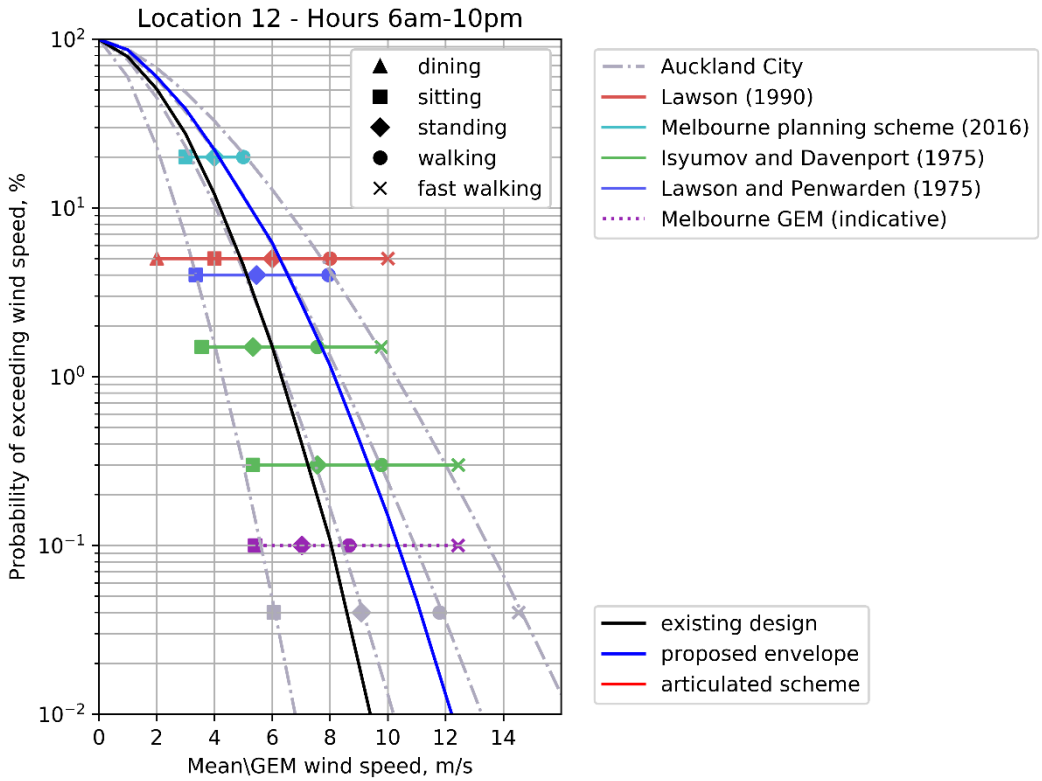

Location 7 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

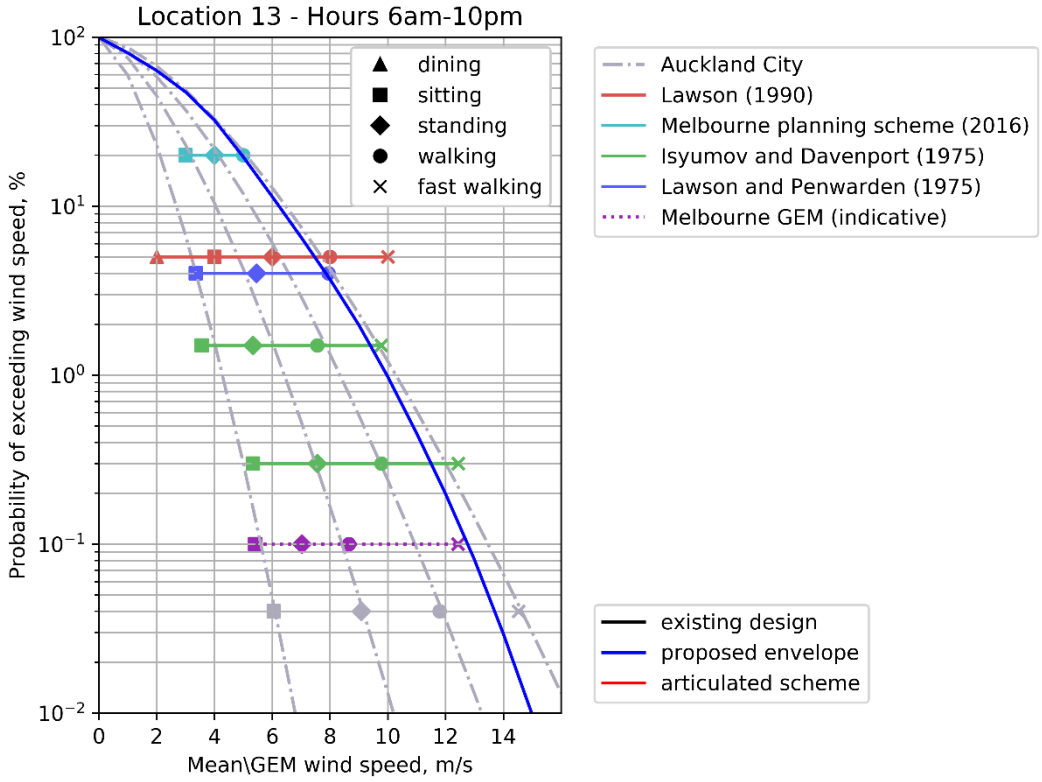

Location 8 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

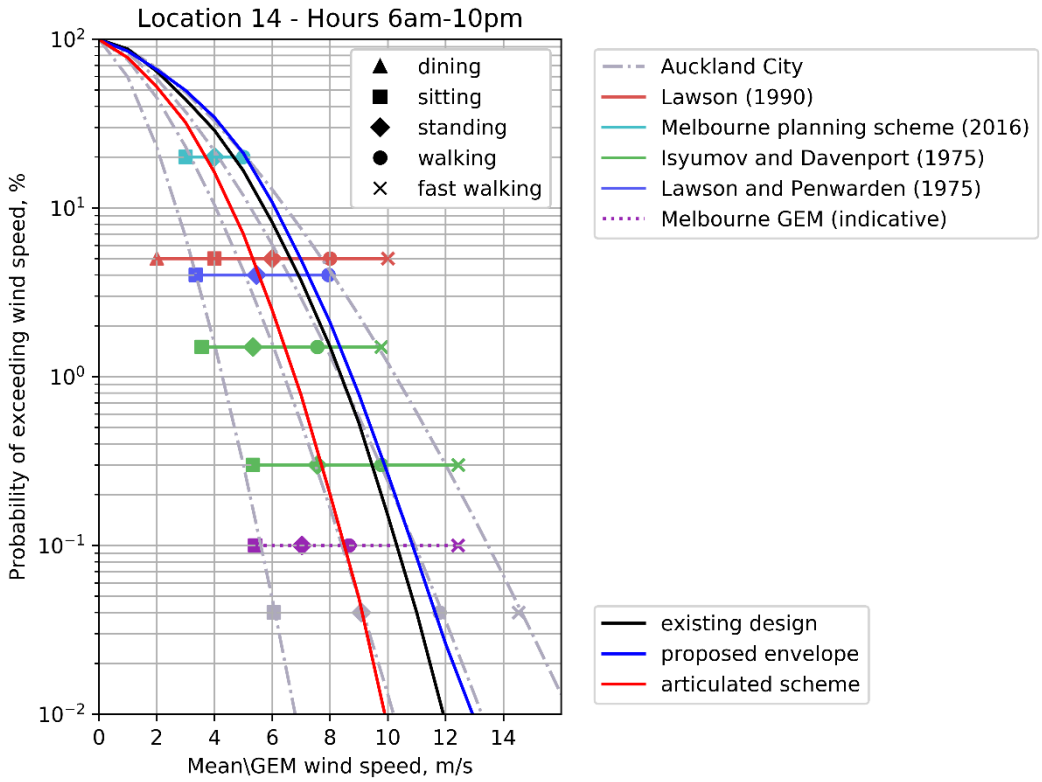

Location 9 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

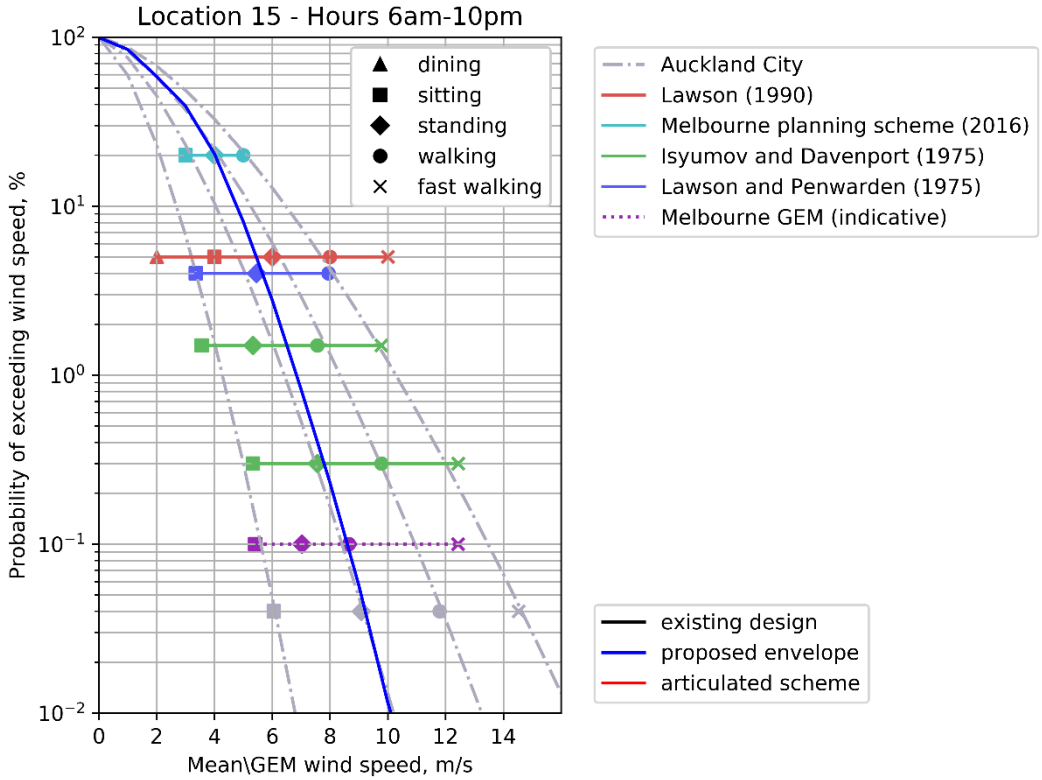

Location 10 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

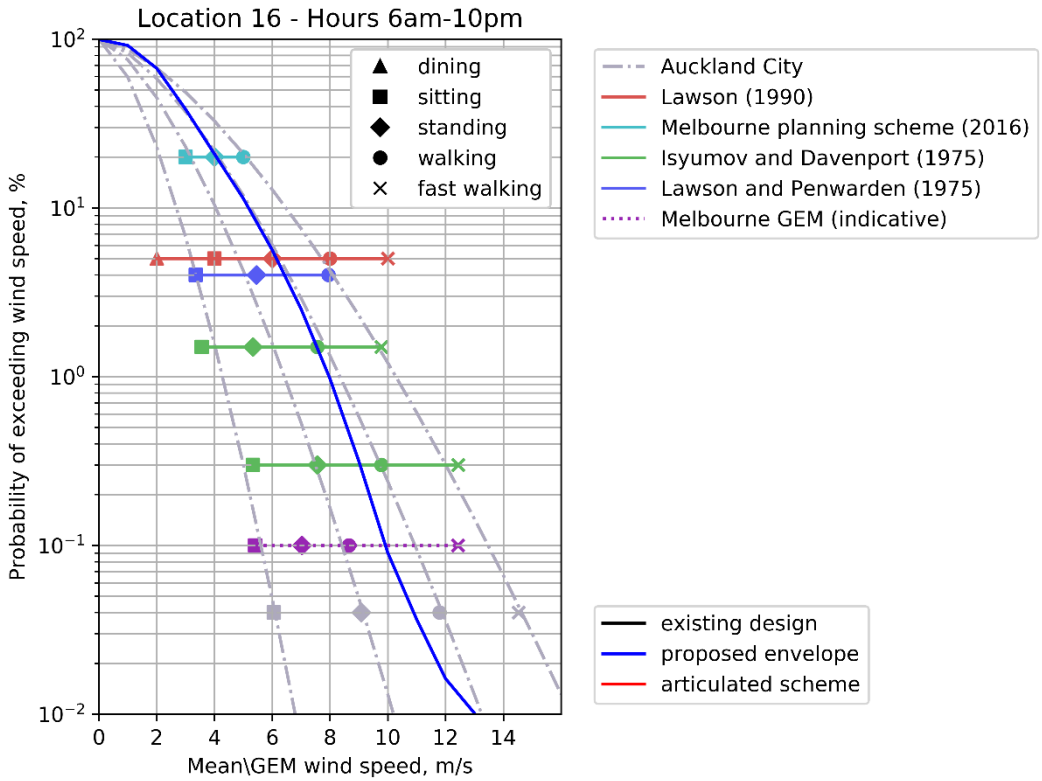

Location 11 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

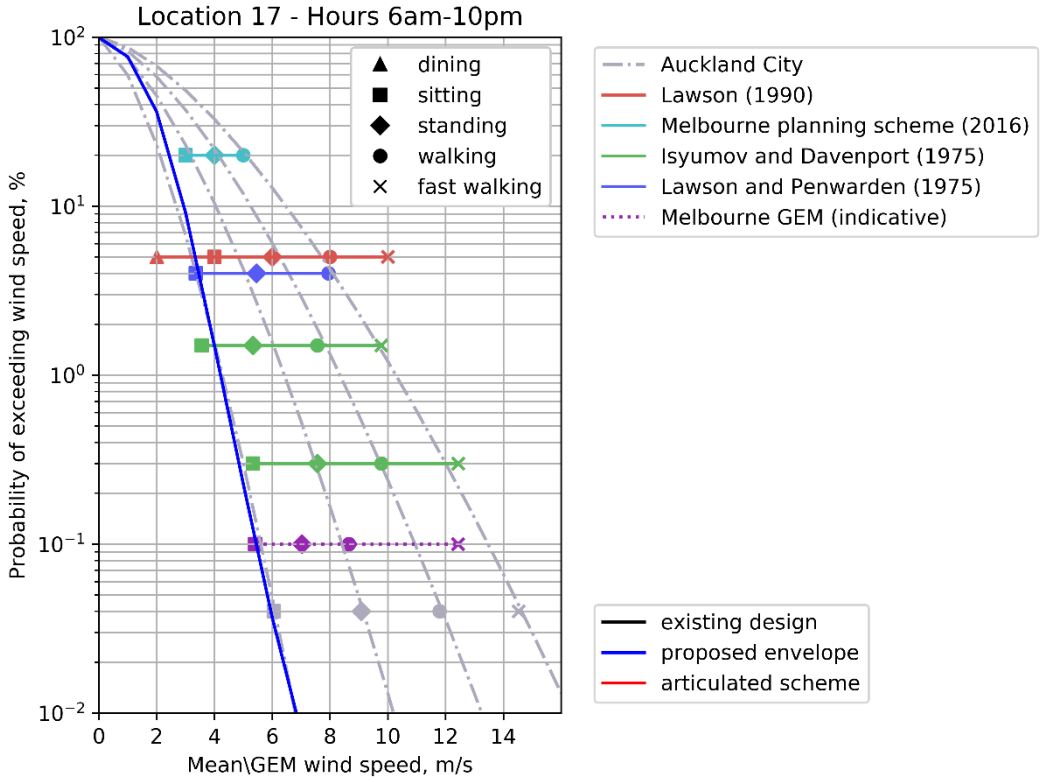

Location 12 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

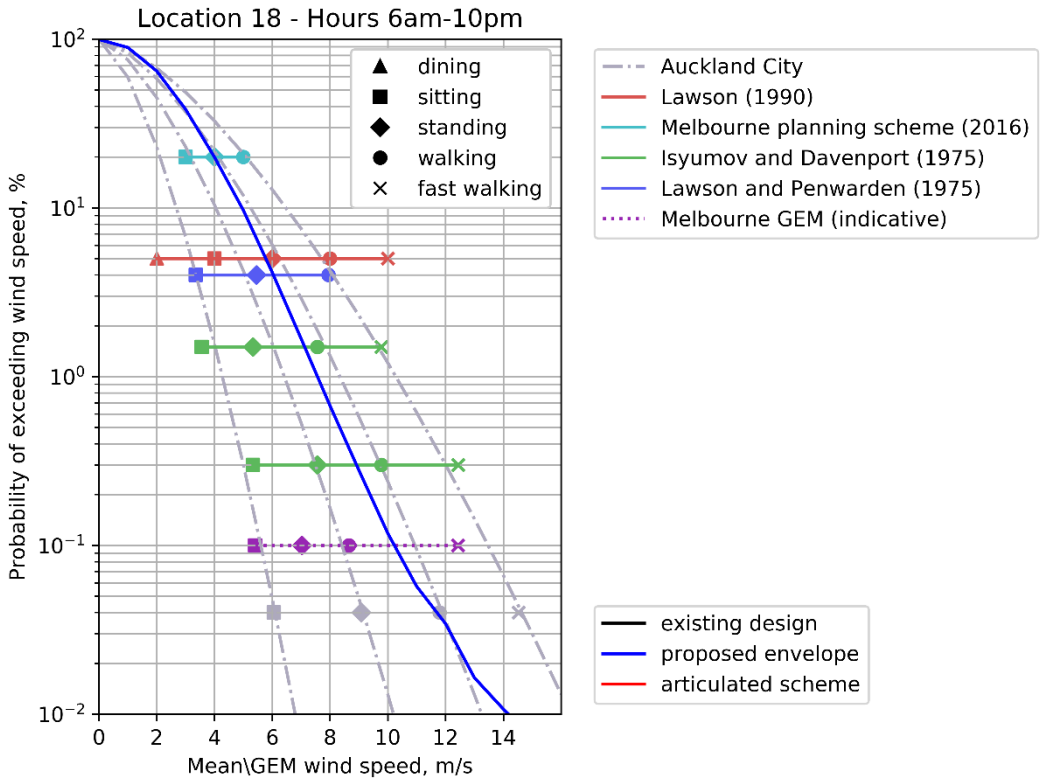

Location 13 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

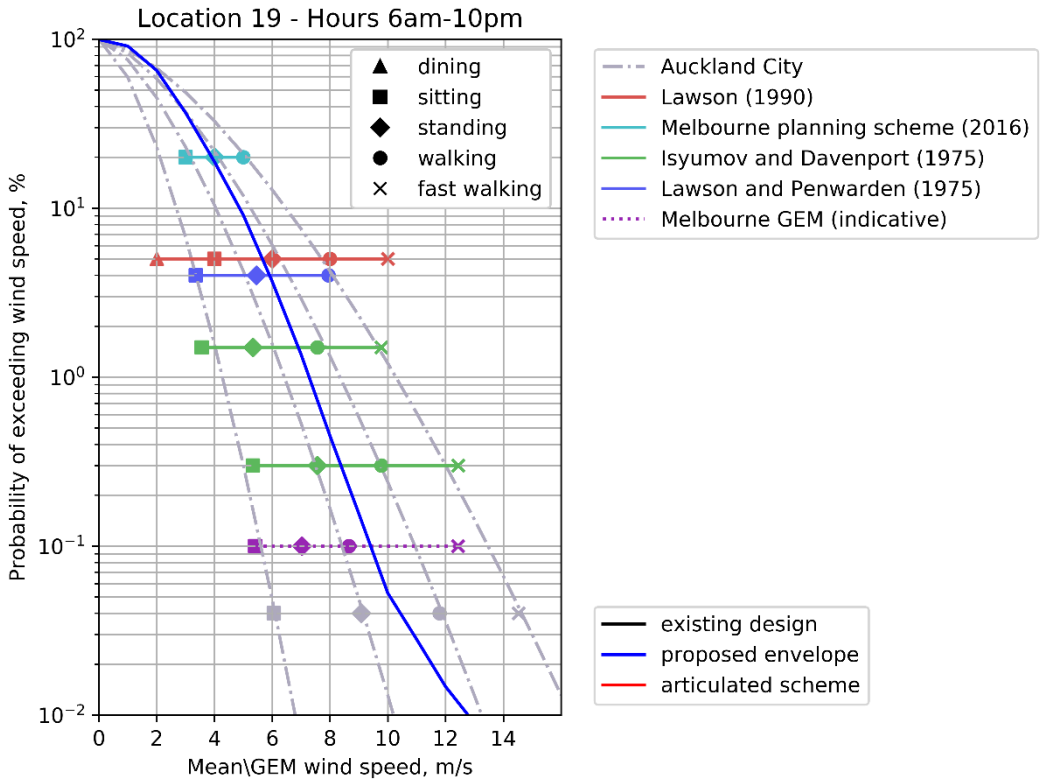

Location 14 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

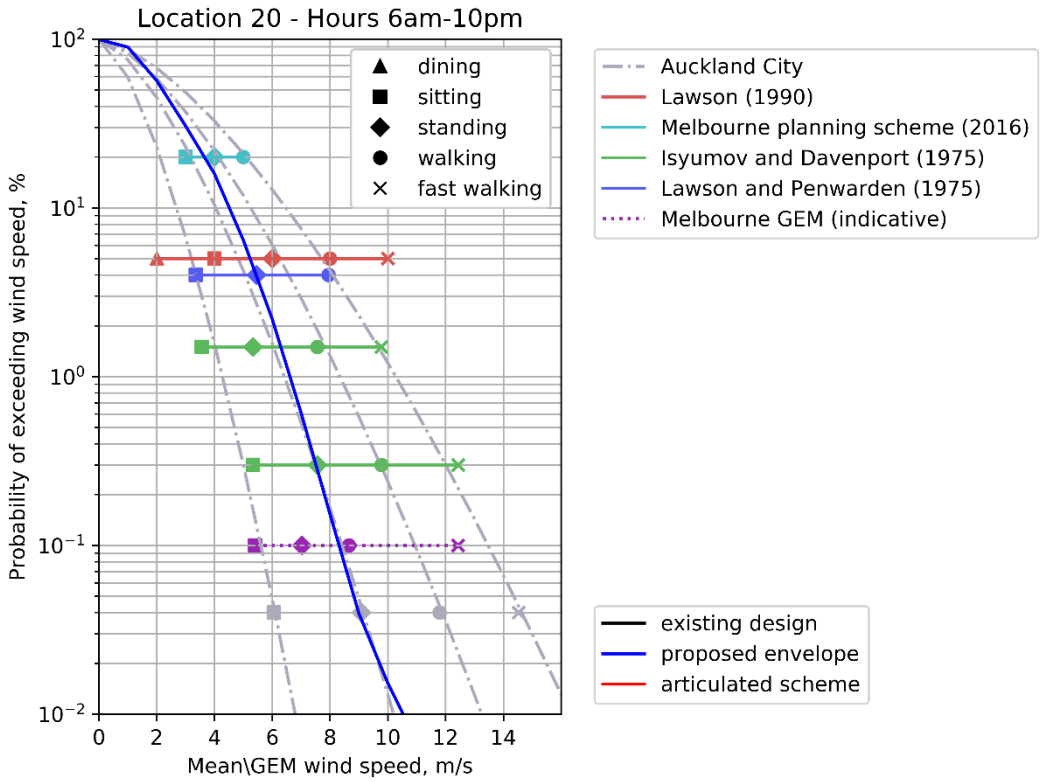

Location 15 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

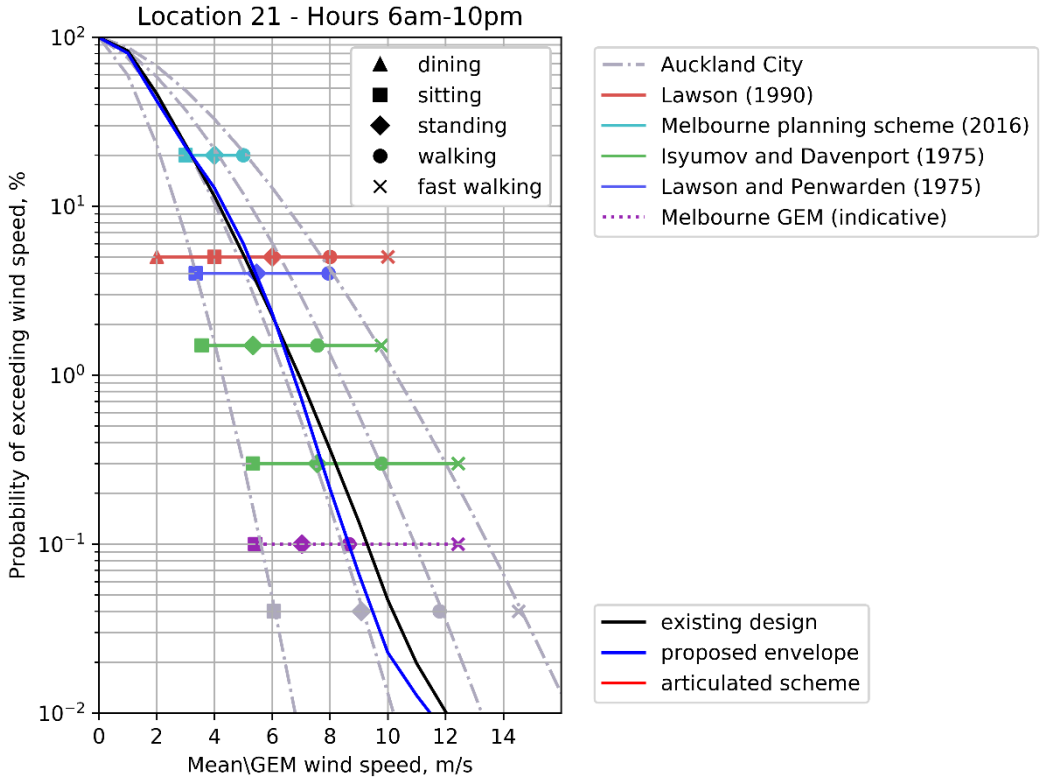

Location 16 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

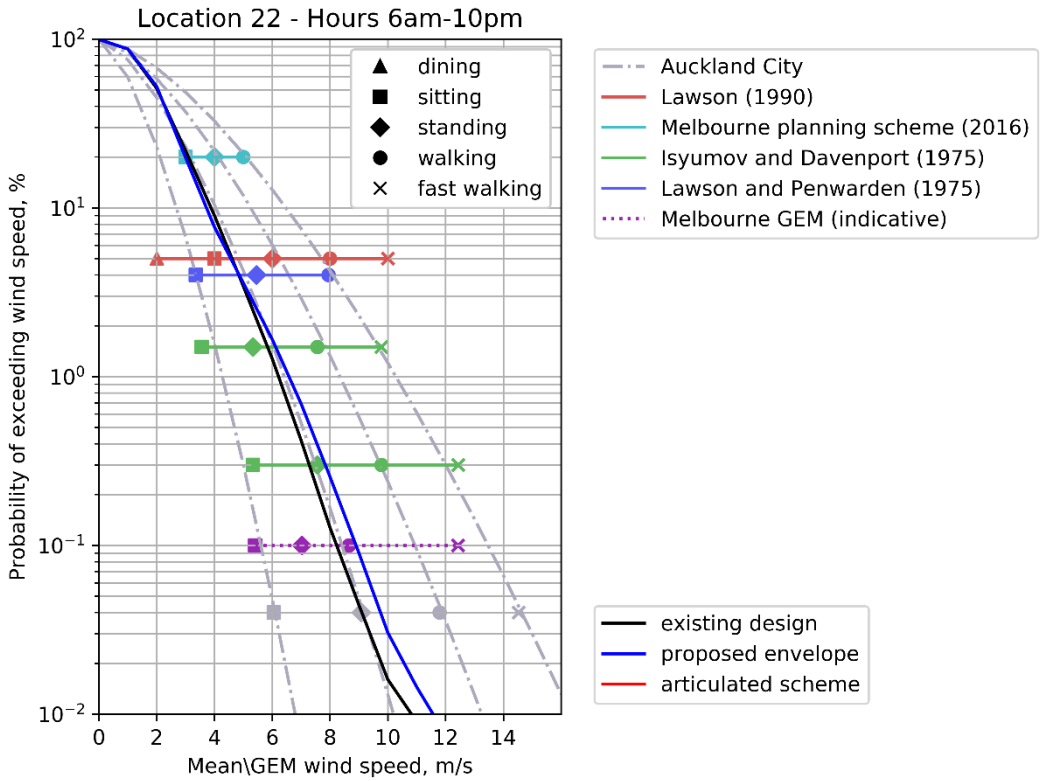

Location 17 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

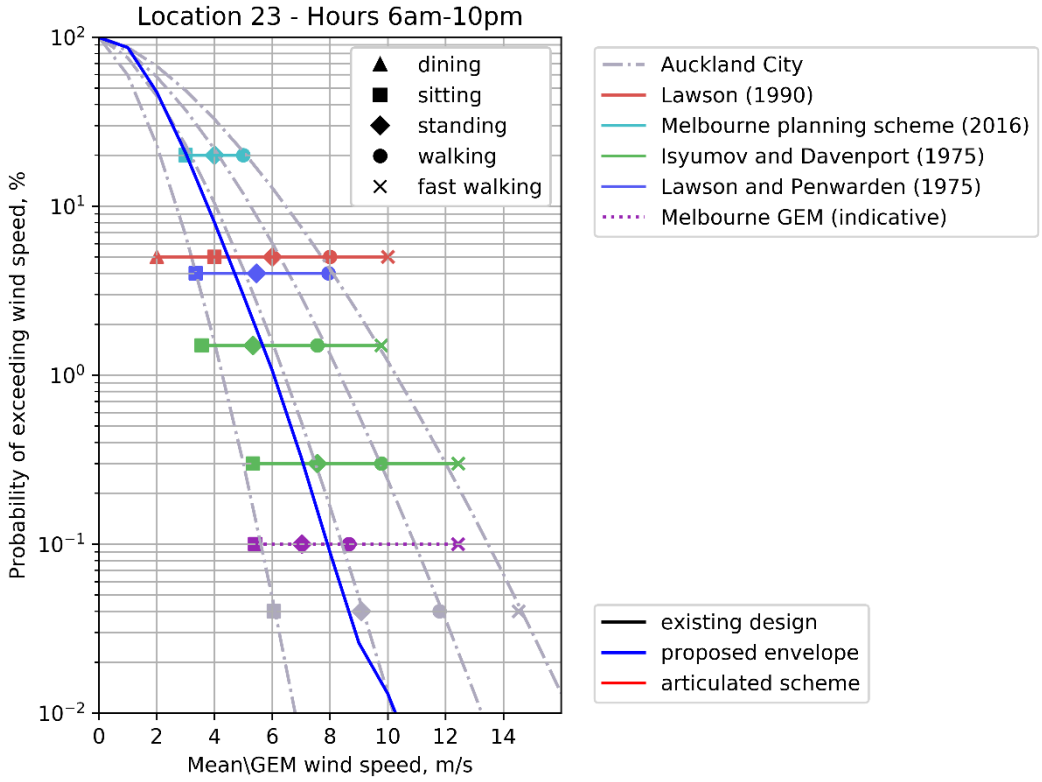

Location 18 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

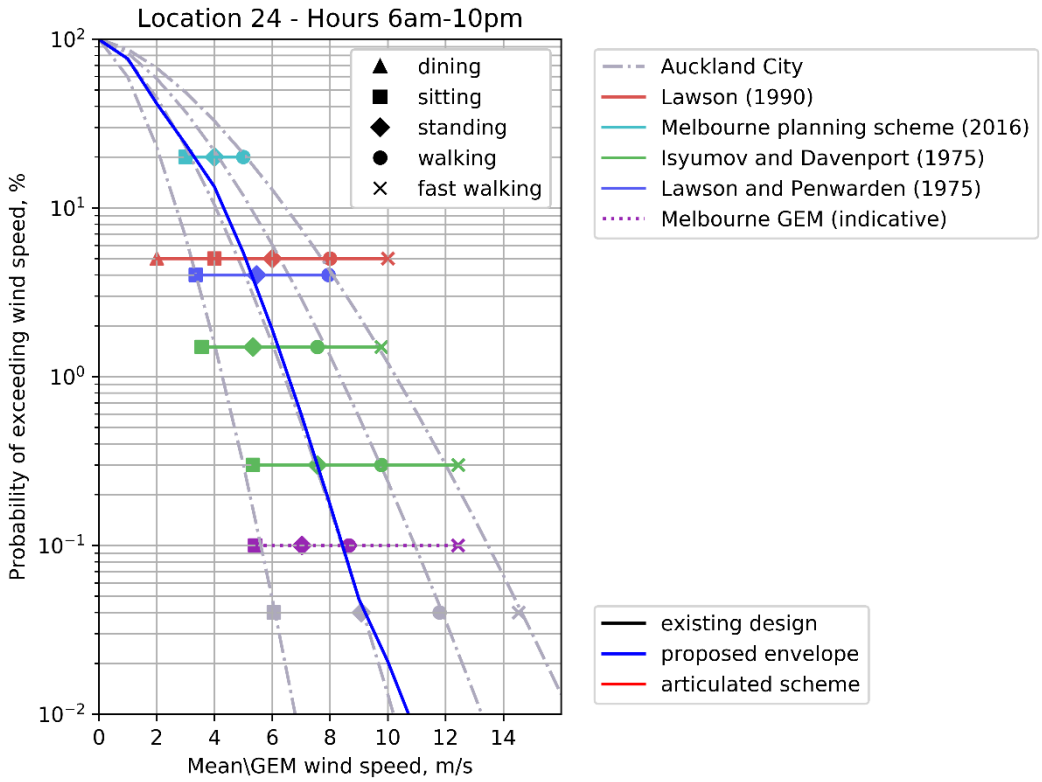

Location 19 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

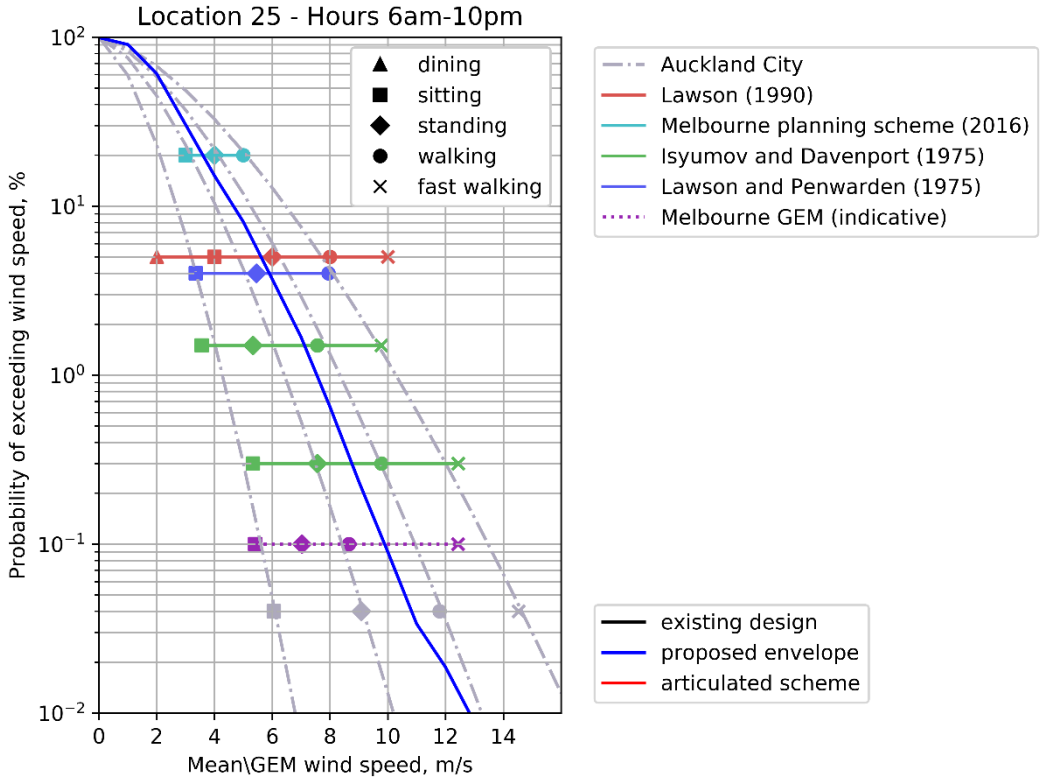

Location 20 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

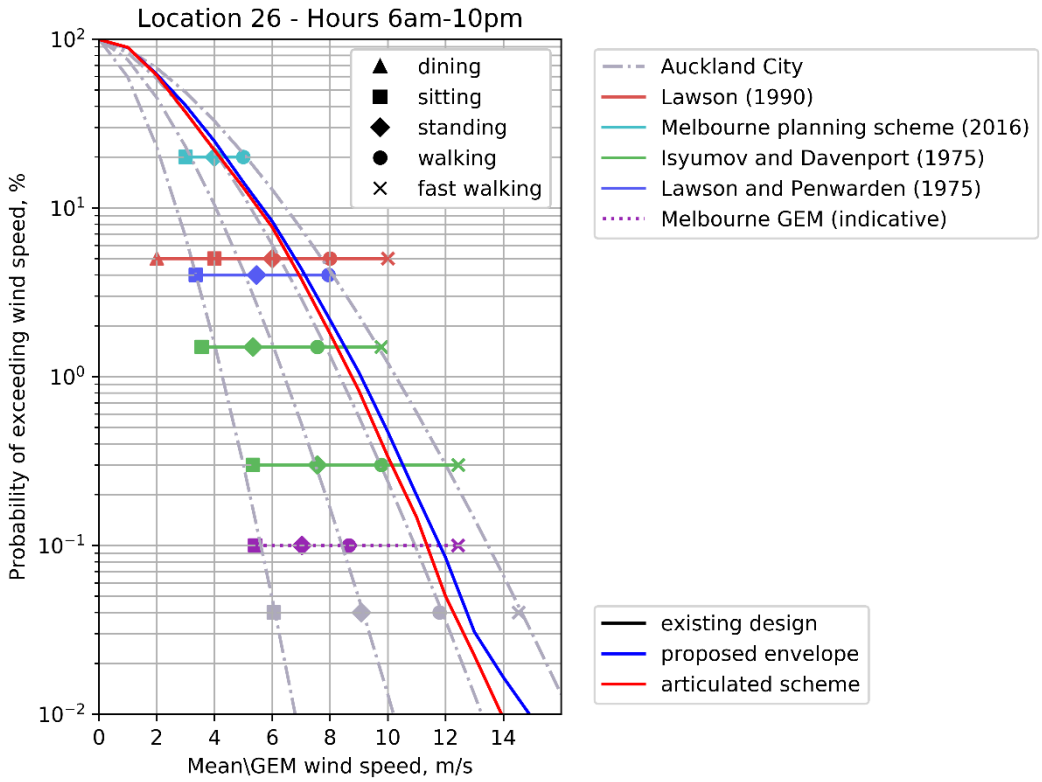

Location 21 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

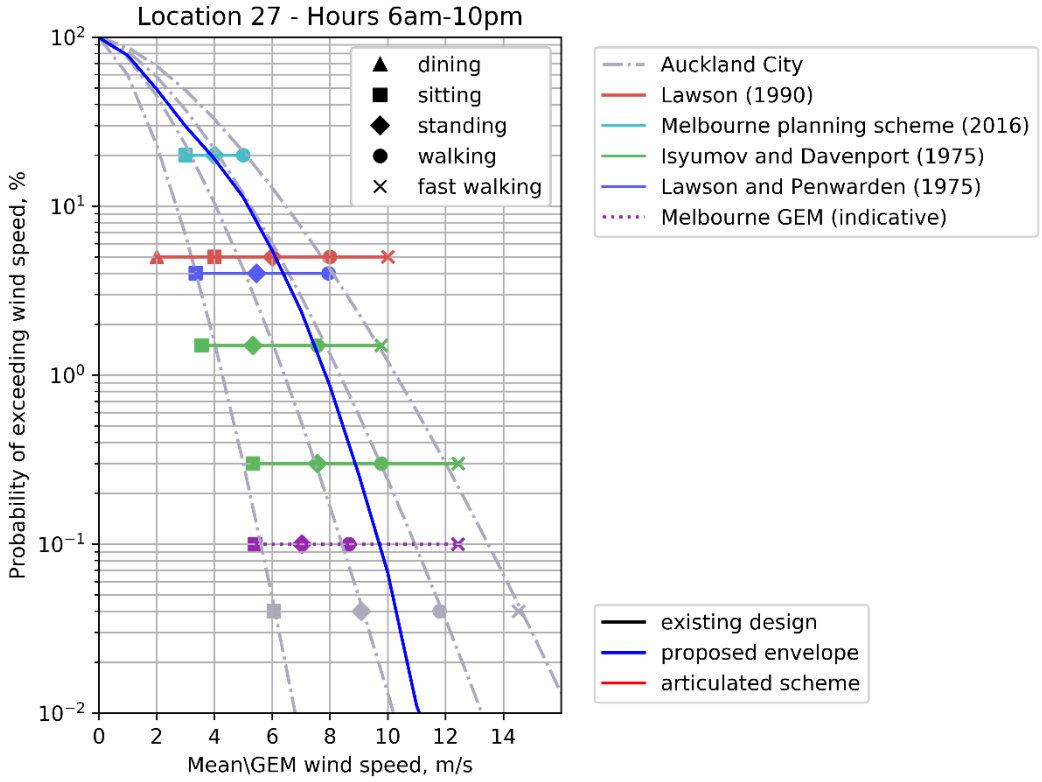

Location 22 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

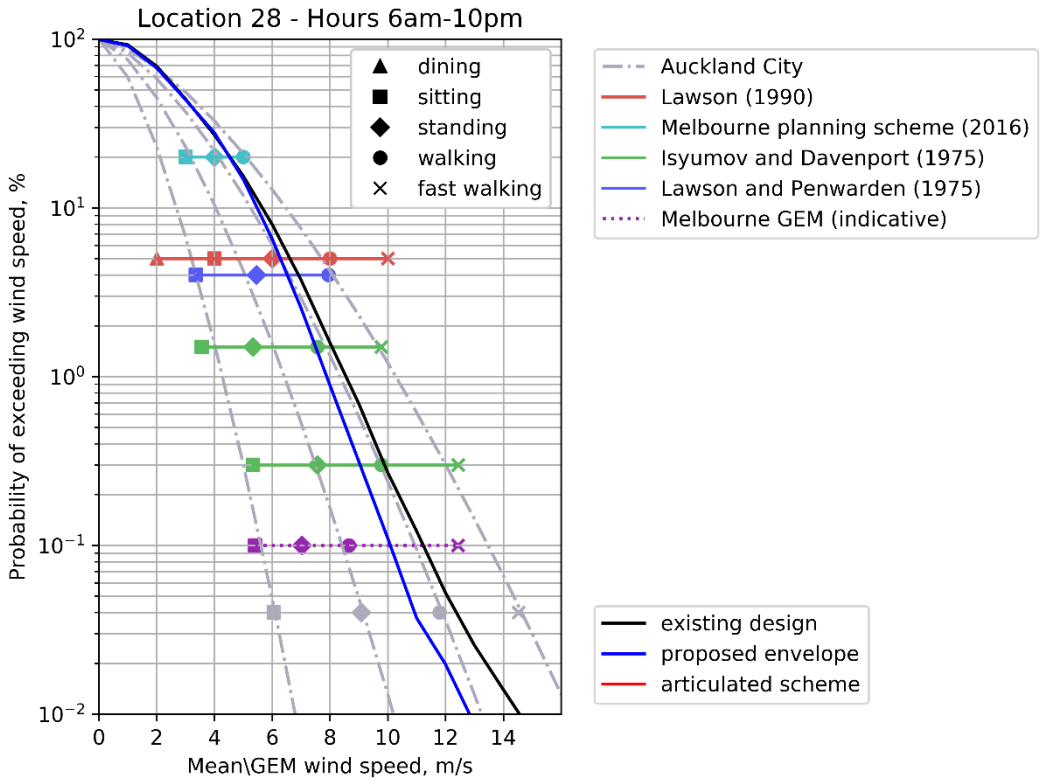

Location 23 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

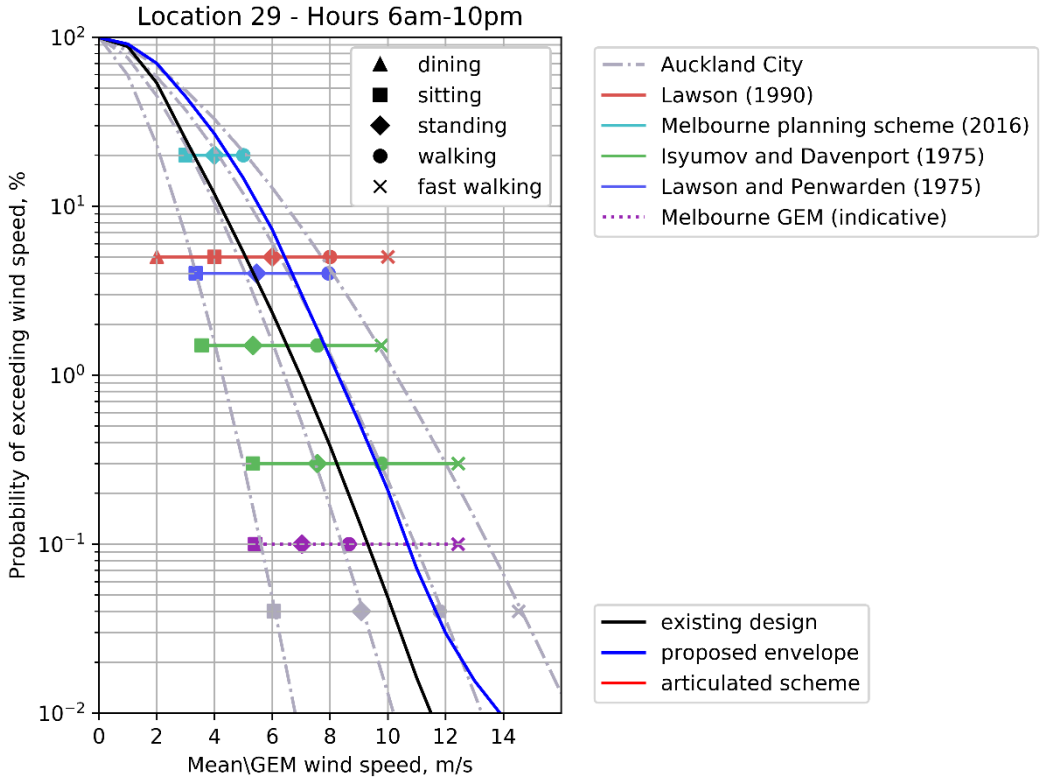

Location 24 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

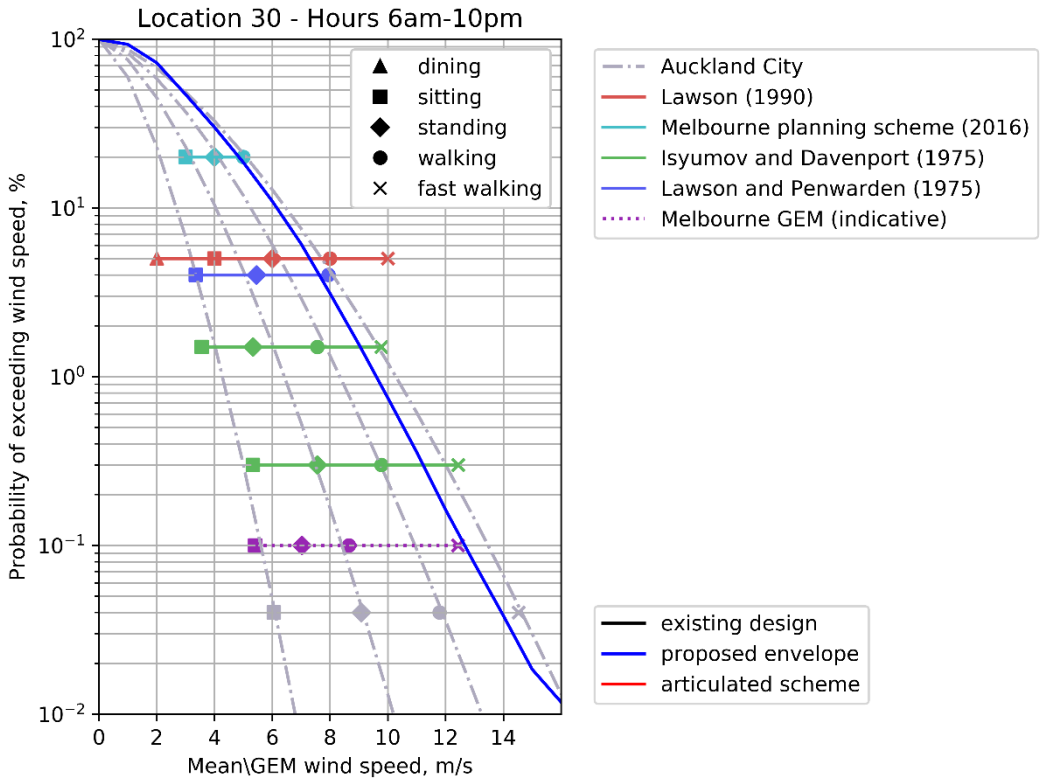

Location 25 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

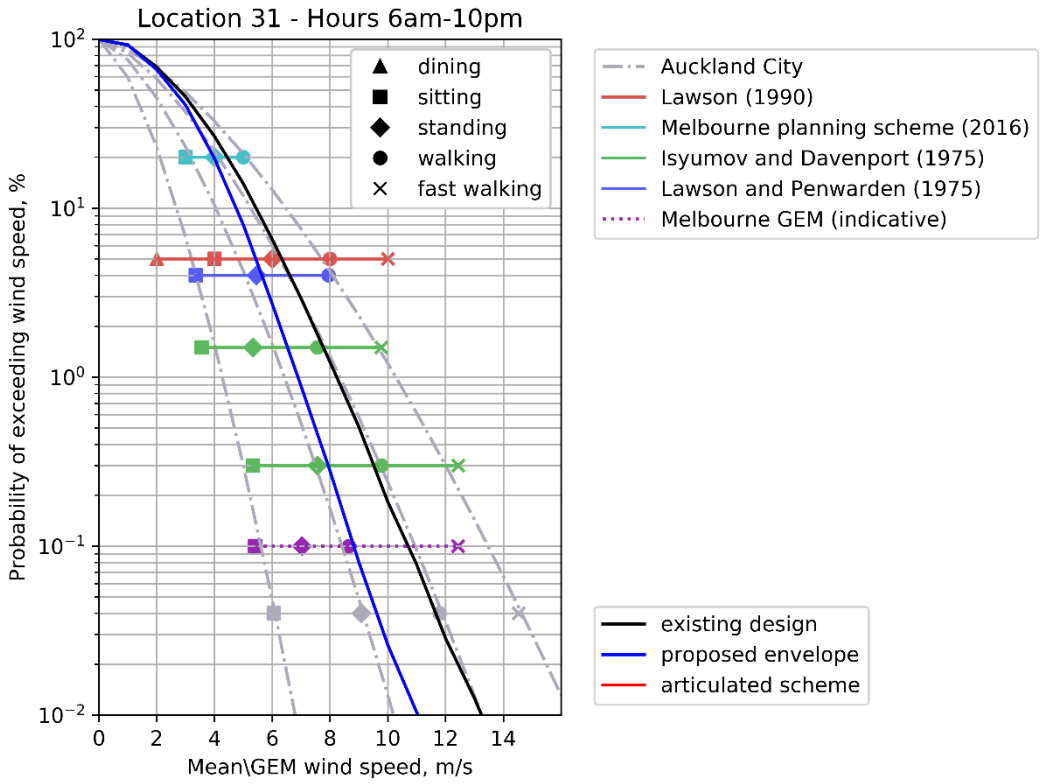

Location 26 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

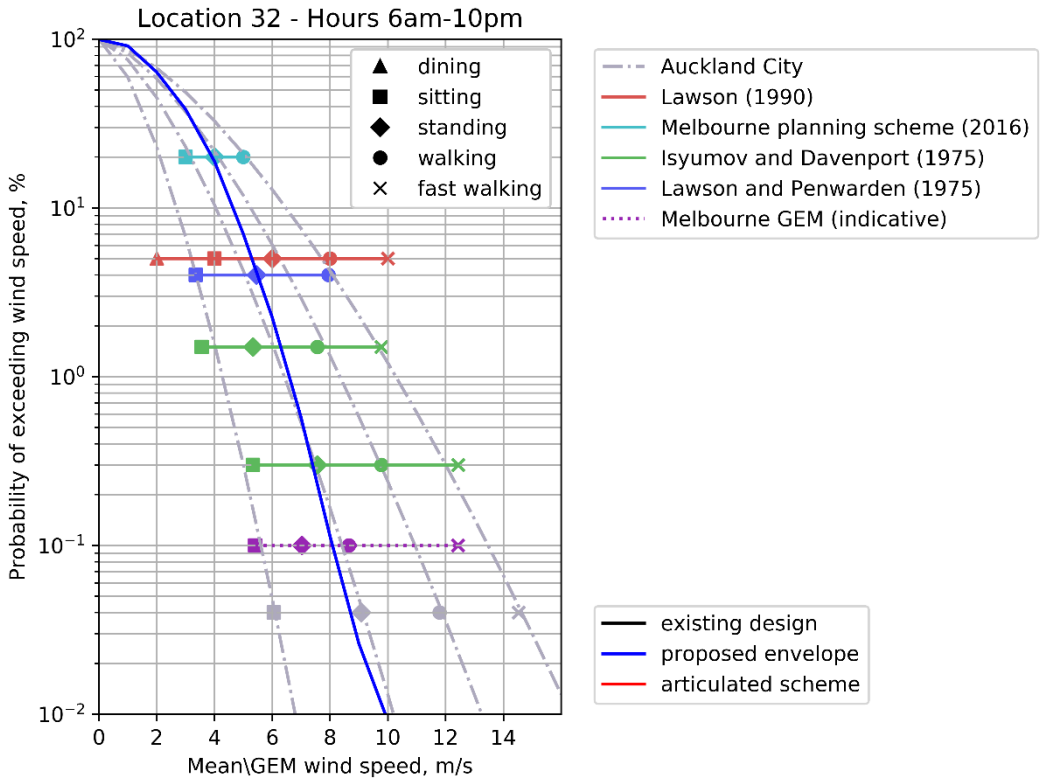

Location 27 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 28 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 29 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 30 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 31 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme


Location 32 - Hours 6am-10pm
Probability of exceeding wind speed, %
Mean\GEM wind speed, m/s
dining
sitting
standing
walking
fast walking
Auckland City
Lawson (1990)
Melbourne planning scheme (2016)
Isyumov and Davenport (1975)
Lawson and Penwarden (1975)
Melbourne GEM (indicative)
existing design
proposed envelope
articulated scheme

A3 Wind Speed Criteria

Primary controls that are used in the assessment of how wind affects pedestrians are the wind speed, and rate of change of wind speed. A description of the effect of a specific wind speed on pedestrians is provided in Table 5. It should be noted that the turbulence, or rate of change of wind speed, will affect human response to wind and the descriptions are more associated with response to mean wind speed.

Table 5 Summary of wind effects on pedestrians

Description	Speed (m/s)	Effects
Calm, light air	0–2	Human perception to wind speed at about 0.2 m/s. Napkins blown away and newspapers flutter at about 1 m/s.
Light breeze	2–3	Wind felt on face. Light clothing disturbed. Cappuccino froth blown off at about 2.5 m/s.
Gentle breeze	3–5	Wind extends light flag. Hair is disturbed. Clothing flaps.
Moderate breeze	5–8	Raises dust, dry soil. Hair disarranged. Sand on beach saltates at about 5 m/s. Full paper coffee cup blown over at about 5.5 m/s.
Fresh breeze	8–11	Force felt on body. Limit of agreeable wind on land. Umbrellas used with difficulty. Wind sock fully extended at about 8 m/s.
Strong breeze	11–14	Hair blown straight. Difficult to walk steadily. Wind noise on ears unpleasant. Windborne snow above head height (blizzard).
Near gale	14–17	Inconvenience felt when walking.
Gale	17–21	Generally impedes progress. Difficulty with balance in gusts.
Strong gale	21–24	People blown over by gusts.

Local wind effects can be assessed with respect to a number of environmental wind speed criteria established by various researchers. These have all generally been developed around a 3 s gust, or 1 hour mean wind speed. During strong events, a pedestrian would react to a significantly shorter duration gust than a 3 s, and historic weather data is normally presented as a 10 minute mean.

Despite the apparent differences in numerical values and assumptions made in their development, it has been found that when these are compared on a probabilistic basis, there is some agreement between the various criteria. However, a number of studies have shown that over a wider range of flow conditions, such as smooth flow across water bodies, to turbulent flow in city centres, there is less general agreement among. The downside of these criteria is

that they have seldom been benchmarked, or confirmed through long-term measurements in the field, particularly for comfort conditions. The wind criteria were all developed in temperate climates and are unfortunately not the only environmental factor that affects pedestrian comfort.

For assessing the effects of wind on pedestrians, neither the random peak gust wind speed (3 s or otherwise), nor the mean wind speed in isolation are adequate. The gust wind speed gives a measure of the extreme nature of the wind, but the mean wind speed indicates the longer duration impact on pedestrians. The extreme gust wind speed is considered to be suitable for safety considerations, but not necessarily for serviceability comfort issues such as outdoor dining. This is because the instantaneous gust velocity does not always correlate well with mean wind speed, and is not necessarily representative of the parent distribution. Hence, the perceived 'windiness' of a location can either be dictated by strong steady flows, or gusty turbulent flow with a smaller mean wind speed.

To measure the effect of turbulent wind conditions on pedestrians, a statistical procedure is required to combine the effects of both mean and gust. This has been conducted by various researchers to develop an equivalent mean wind speed to represent the perceived effect of a gust event. This is called the 'gust equivalent mean' or 'effective wind speed' and the relationship between the mean and 3 s gust wind speed is defined within the criteria, but two typical conversions are:

$$U_{GEM} = \frac{(U_{mean} + 3 \cdot \sigma_u)}{1.85} \text{ and } U_{GEM} = \frac{1.3 \cdot (U_{mean} + 2 \cdot \sigma_u)}{1.85}$$

It is evident that a standard description of the relationship between the mean and impact of the gust would vary considerably depending on the approach turbulence, and use of the space.

A comparison between the mean and 3 s gust wind speed criteria from a probabilistic basis are presented in Figure 11 and Figure 13. The grey lines are typical results from modelling and show how the various criteria would classify a single location. City of Auckland has control mechanisms for accessing usability of spaces from a wind perspective as illustrated in Figure 11 with definitions of the intended use of the space categories defined in Figure 12.

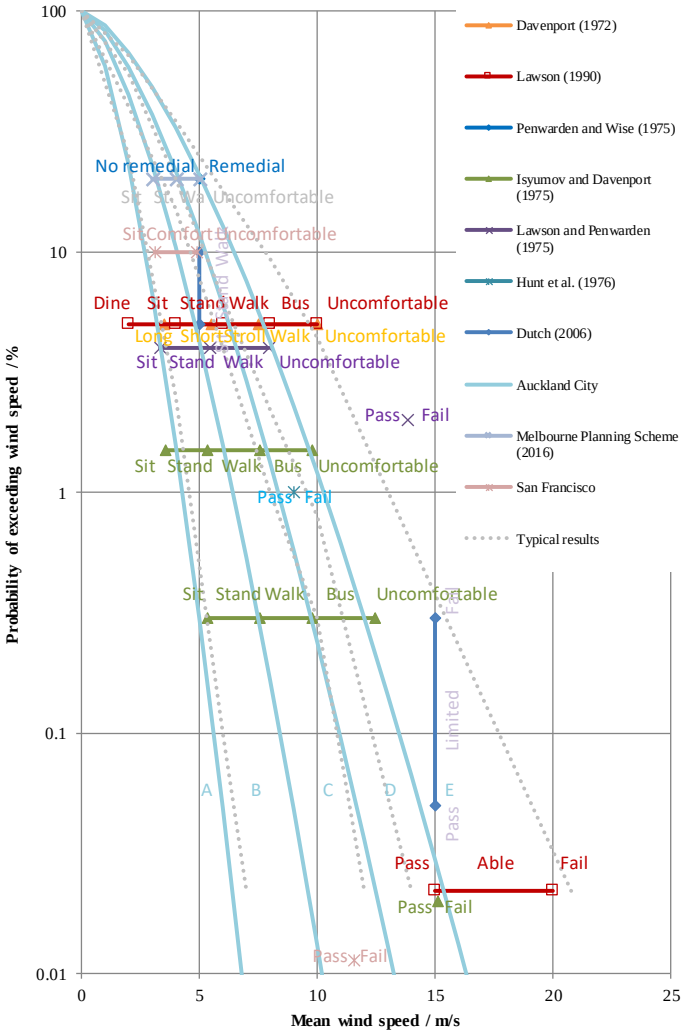


Figure 11: Probabilistic comparison between wind criteria based on mean wind speed

Category A	Areas of pedestrian use or adjacent dwellings containing significant formal elements and features intended to encourage longer term recreational or relaxation use i.e. public open space and adjacent outdoor living space
Category B	Areas of pedestrian use or adjacent dwellings containing minor elements and features intended to encourage short term recreation or relaxation, including adjacent private residential properties
Category C	Areas of formed footpath or open space pedestrian linkages, used primarily for pedestrian transit and devoid of significant or repeated recreational or relaxational features, such as footpaths not covered in categories A or B above
Category D	Areas of road, carriage way, or vehicular routes, used primarily for vehicular transit and open storage, such as roads generally where devoid of any features or form which would include the spaces in categories A - C above.
Category E	Category E represents conditions which are dangerous to the elderly and infants and of considerable cumulative discomfort to others, including residents in adjacent sites. Category E

Figure 12: Auckland Utility Plan (2016) wind categories

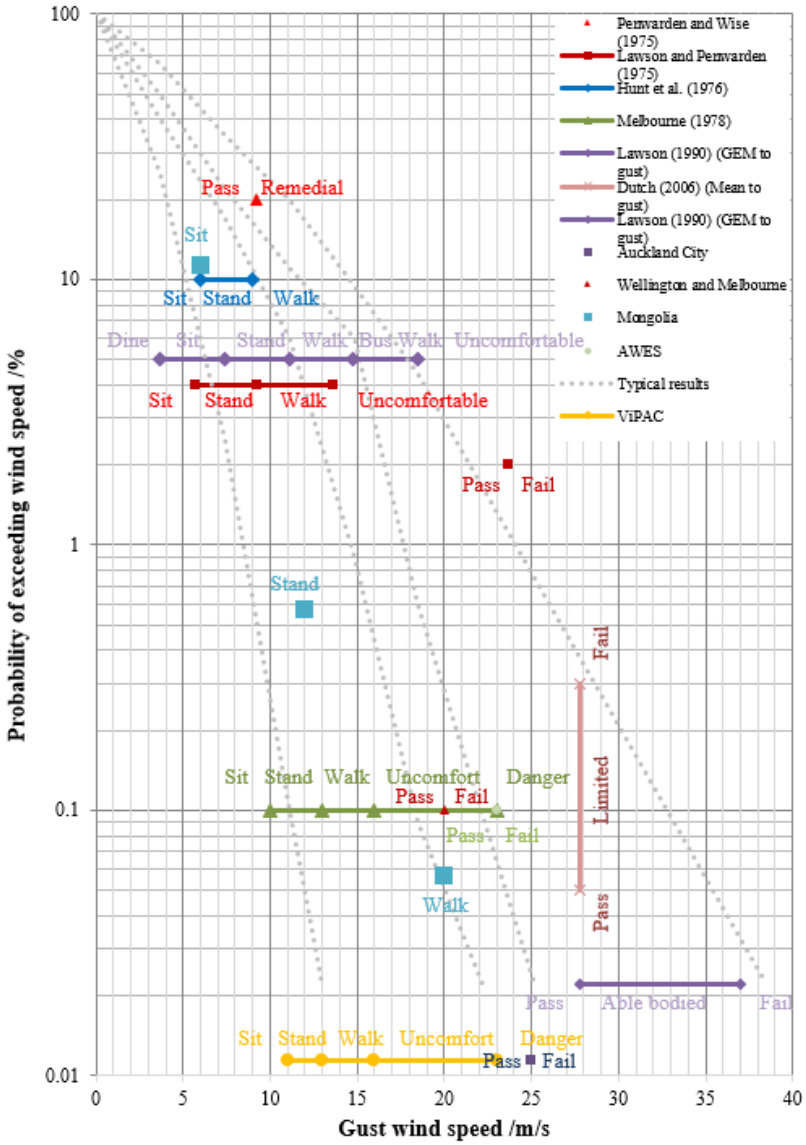


Figure 13: Probabilistic comparison between wind criteria based on 3 s gust wind speed