Pedestrian Level Wind Study

1376 + 1345 Carling Avenue
Ottawa, Ontario

REPORT: GWE17-038-CFDPLW

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EXECUTIVE SUMMARY

This report describes a computer-based pedestrian level wind study for the proposed multi-phase, mixed-use development located at 1376 and 1345 Carling Avenue in Ottawa, Ontario. The study involves simulation of wind speeds for selected wind directions in a three-dimensional (3D) computer model using the Computational Fluid Dynamics (CFD) technique, combined with meteorological data integration, to assess pedestrian comfort and safety within and surrounding the development site. The results and recommendations derived from these considerations are summarized in the following paragraphs and detailed in the subsequent report.

This study is based on industry standard CFD simulation and data analysis procedures, architectural drawings provided by Geiger Huot Architects in April 2018, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent site imagery.

A complete summary of the predicted wind conditions across the study site is presented in Section 5 of this report. Based on CFD test results, interpretation, and experience with similar developments, the majority of grade level areas within and surrounding the development site will be acceptable for the intended pedestrian uses on a seasonal basis. More specifically, surrounding sidewalks, exterior amenity areas, and most major building access points will experience acceptable wind conditions throughout the year. One area where wind mitigation is recommended is the lobby entrance to Building B. To improve wind comfort at this entrance and ensure proper mechanical function of the doorway during windy periods, it is recommended to either i) recess the doorway within the building façade; ii) incorporate the use of sliding doors as opposed to swing doors; or iii) provide vertical wind barriers on either side of the entrance.

Regarding the podium rooftop terraces, those on Buildings D and E, as well as the southeast rooftop terrace of Building C, will be comfortable for sitting or more sedentary activities throughout the warmer months, without the need for mitigation. For the west portion of the Building C podium rooftop terrace, as well as the terrace on the building rooftop, wind mitigation in the form of vertical wind barriers and canopies are recommended to ensure comfortable and safe conditions during the typical use period.

Of importance, excluding anomalous localized storm events such as tornadoes and downbursts, no area over the study site are considered uncomfortable for walking, or unsafe.

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1. INTRODUCTION

Gradient Wind Engineering Inc. (GWE) was retained by Holloway Lodging Corporation to undertake a computer-based pedestrian level wind (PLW) study for a proposed multi-phase, mixed-use development to be located at 1376 & 1345 Carling Avenue in Ottawa, Ontario. Our mandate within this study, as outlined in GWE proposal #16-159P R2, dated March 8, 2018, is to investigate pedestrian wind comfort within and surrounding the development site, and to identify any areas where wind conditions may interfere with certain pedestrian activities so that mitigation measures may be considered, where necessary.

Our work is based on industry standard CFD simulation and data analysis procedures, architectural drawings provided by Geiger Huot Architects in April 2018, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent site imagery.

2. TERMS OF REFERENCE

The focus of this PLW study is the proposed multi-phase, mixed-use development, comprising buildings A through E, to be located at 1376 & 1345 Carling Avenue in Ottawa, Ontario. The study site is located on a parcel of land bounded by Carling Avenue to the north, Archibald Street to the east, existing residential houses to the south, and Meath Street to the west. In the near-field, the site is surrounded by a suburban mix of low- and medium-rise developments in all directions. The near-field is intersected by the Queensway which runs northeast to southwest, to the north of the site. At greater distances from the study site, a suburban mix of low- and medium-rise developments characterizes the exposures from the south rotating clockwise to the northeast. Further to the northwest is the Ottawa River, approximately 2.5 kilometers from the site. To the northeast rotating clockwise to the south the suburban exposure gives way to the open fields of the Central Experimental Farm.

The development site comprises two phases. Phase 1 contains Building C (20 storeys) and Building E (8 storeys), located north and south on the west side of the site, respectively. Both buildings feature L-shaped podia with the long axes oriented along Carling Avenue (six and three storeys for Building C and E, respectively). Lobby entrances for Buildings C & E are located, respectively, near the centre of the south elevation & center of the north elevation from a shared drop-off area.

Phase 2 comprises Building A (20 stories), Building B (22 stories), and Building D (8 storeys), respectively located clockwise from the west corner of the site. Buildings A and B feature six-storey rectangular podia, and Building D is a mirror image of Building E to the east. A children's play area/park occupies the southwest corner of the site.

Key areas under consideration for pedestrian wind comfort include surrounding sidewalks, building entrances, and various grade-level and rooftop amenity spaces. Figure 1 illustrates the ground floor plan, while Figures 2A and 2B illustrate the computational model used to conduct the study.

3. OBJECTIVES

The principal objectives of this study are to: (i) determine pedestrian level comfort and safety conditions within and surrounding the development site; (ii) identify areas where future wind conditions may interfere with the intended uses of outdoor spaces; and (iii) recommend suitable mitigation measures, where required.

4. METHODOLOGY

The approach followed to quantify pedestrian wind conditions over the site is based on Computational Fluid Dynamics (CFD) simulations of wind speeds across the study site within a virtual environment, meteorological analysis of the Ottawa area wind climate, and synthesis of computational data with industry-accepted guidelines[1]. The following sections describe the analysis procedures, including a discussion of the pedestrian comfort guidelines.

4.1 Computer-Based Context Modelling

A computer-based PLW study is performed to determine the influence of the wind environment on pedestrian comfort over the proposed development site. Pedestrian comfort predictions, based on the mechanical effects of wind, are determined by combining measured wind speed data from CFD simulations with statistical weather data obtained from Ottawa's Macdonald-Cartier International Airport.

The general concept and approach to CFD modelling is to represent building and topographic details in the immediate vicinity of the study site on the surrounding model, and to create suitable atmospheric

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[1] City of Ottawa Terms of References: Wind Analysis

wind profiles at the model boundary. The wind profiles are designed to have similar mean and turbulent wind properties consistent with actual site exposures.

An industry standard practice is to omit trees, vegetation, and other existing and planned landscape elements from the wind tunnel model due to the difficulty of providing accurate seasonal representation of vegetation. The omission of trees and other landscaping elements produces slightly more conservative wind speed values.

4.2 Wind Speed Measurements

The PLW analysis was performed by simulating wind flows and gathering velocity data over a CFD model of the site for 12 wind directions. The CFD simulation model was centered on the study buildings, complete with surrounding massing within a diameter of approximately 822 metres.

Mean and peak wind speed data obtained over the study site for each wind direction were interpolated to 36 wind directions at 10° intervals, representing the full compass azimuth. Measured wind speeds approximately 1.5 metres above local grade were referenced to the wind speed at gradient height to generate mean and peak velocity ratios, which were used to calculate full-scale values. The gradient height represents the theoretical depth of the boundary layer of the Earth’s atmosphere, above which the mean wind speed remains constant. Appendices A and B provide greater detail of the theory behind wind speed measurements.

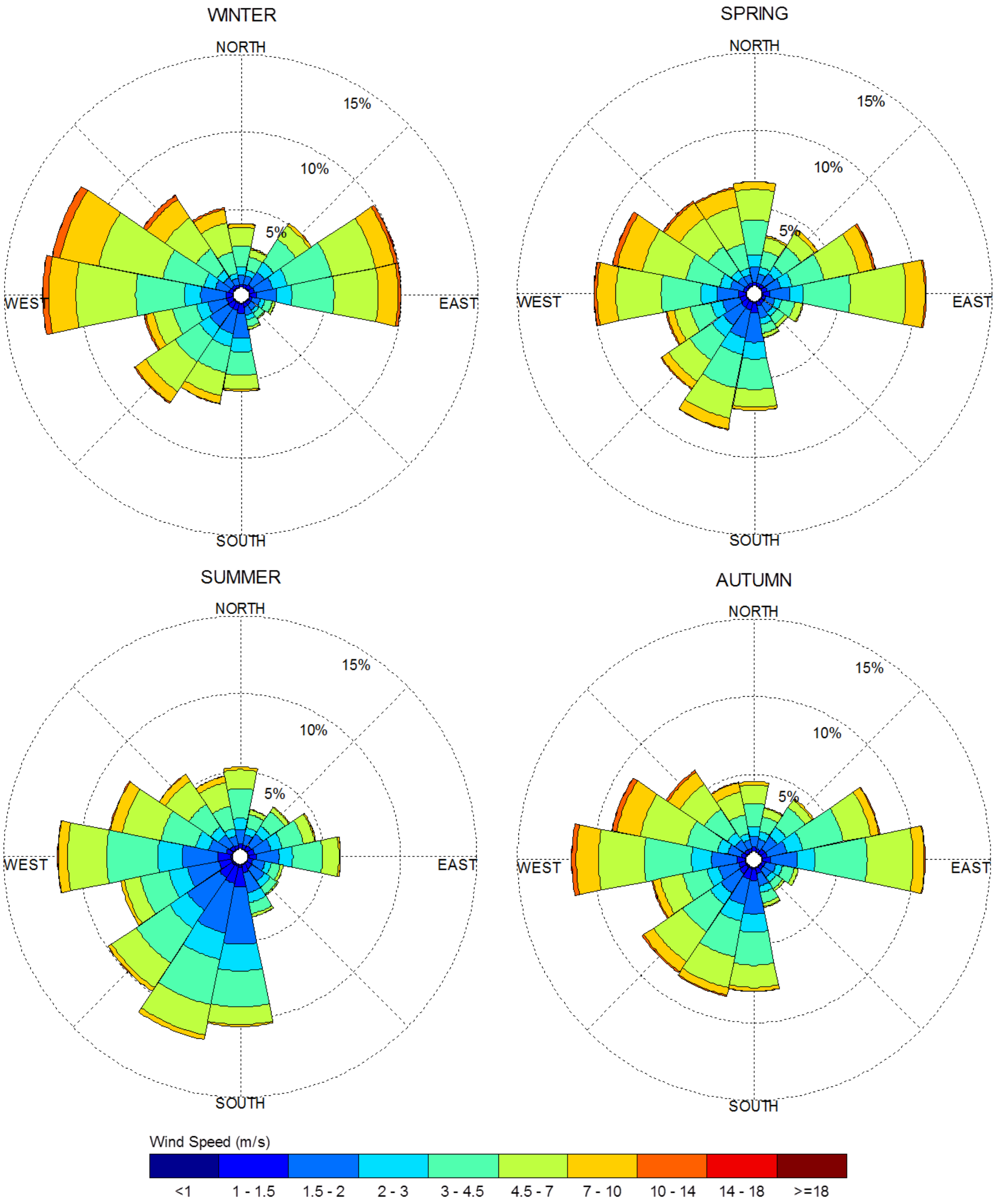
4.3 Meteorological Data Analysis

A statistical model for winds in Ottawa was developed from approximately 40-years of hourly meteorological wind data recorded at Macdonald-Cartier International Airport, and obtained from the local branch of Atmospheric Environment Services of Environment Canada. Wind speed and direction data were analyzed for each month of the year in order to determine the statistically prominent wind directions and corresponding speeds, and to characterize similarities between monthly weather patterns. Based on this portion of the analysis, the four seasons are represented by grouping data from consecutive months based on similarity of weather patterns, and not according to the traditional calendar method.

The statistical model of the Ottawa area wind climate, which indicates the directional character of local winds on a seasonal basis, is illustrated on the following page. The plots illustrate seasonal distribution of measured wind speeds and directions in km/h. Probabilities of occurrence of different wind speeds are represented as stacked polar bars in sixteen azimuth divisions. The radial direction represents the percentage of time for various wind speed ranges per wind direction during the measurement period. The preferred wind speeds and directions can be identified by the longer length of the bars. For Ottawa, the most common winds occur for westerly wind directions, followed by those from the east, while the most common wind speeds are below 10 metres per second (m/s). The directional preference and relative magnitude of wind speed changes somewhat from season to season. By convention in microclimate studies, wind direction refers to the wind origin (e.g., a north wind blows from north to south).

SEASONAL DISTRIBUTION OF WINDS FOR VARIOUS PROBABILITIES

MACDONALD-CARTIER INTERNATIONAL AIRPORT, OTTAWA, ONTARIO



Notes:

1. Radial distances indicate percentage of time of wind events.
2. Wind speeds represent mean hourly wind speeds measured at 10 m above the ground.

4.4 Pedestrian Comfort Guidelines

Pedestrian comfort guidelines are based on mechanical wind effects without consideration of other meteorological conditions (i.e. temperature, relative humidity). The guidelines provide an assessment of comfort, assuming that pedestrians are appropriately dressed for a specified outdoor activity during any given season. Five pedestrian comfort classes and corresponding gust wind speed ranges are used to assess pedestrian comfort, which include: (i) Sitting; (ii) Standing; (iii) Walking; (iv) Uncomfortable; and (v) Dangerous. More specifically, the comfort classes, associated wind speed ranges, and limiting criteria are summarized as follows:

(i) **Sitting:** Mean wind speeds less than or equal to 10 kilometers per hour (km/h), occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 14 km/h.

(ii) **Standing:** Mean wind speeds less than or equal to 14 km/h, occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 20 km/h.

(iii) **Strolling:** Mean wind speeds less than or equal to 17 km/h, occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 25 km/h.

(iv) **Walking:** Mean wind speeds less than or equal to 20 km/h, occurring at least 80% of the time. The gust equivalent mean wind speed is approximately 30 km/h.

(v) **Uncomfortable:** Uncomfortable conditions are characterized by predicted values that fall below the 80% target for walking. Brisk walking and exercise, such as jogging, would be acceptable for moderate excesses of this guideline.

(vi) **Dangerous:** Gust equivalent mean wind speeds greater than or equal to 90 km/h, occurring more often than 0.1% of the time, are classified as dangerous. From calculations of stability, it can be shown that gust wind speeds of 90 km/h would be the approximate threshold wind speed that would cause an average elderly person in good health to fall.

Gust speeds are used in the criteria because people tend to be more sensitive to wind gusts than to steady winds for lower wind speed ranges. For strong winds approaching dangerous levels, this effect is less important because the mean wind can also cause problems for pedestrians. The mean gust speed ranges are selected based on ‘The Beaufort Scale’, which describes the effect of forces produced by varying wind speeds on levels on objects.

THE BEAUFORT SCALE

Number	Description	Wind Speed (km/h)	Description
2	Light Breeze	4-8	Wind felt on faces.
3	Gentle Breeze	8-15	Leaves and small twigs in constant motion; Wind extends light flags.
4	Moderate Breeze	15-22	Wind raises dust and loose paper; Small branches are moved.
5	Fresh Breeze	22-30	Small trees in leaf begin to sway.
6	Strong Breeze	30-40	Large branches in motion; Whistling heard in electrical wires; Umbrellas used with difficulty.
7	Moderate Gale	40-50	Whole trees in motion; Inconvenient walking against wind.
8	Gale	50-60	Breaks twigs off trees; Generally impedes progress.

Experience and research on people’s perception of mechanical wind effects has shown that if the wind speed levels are exceeded for more than 20% of the time, the activity level would be judged to be uncomfortable by most people. For instance, if wind speeds of 14 km/h were exceeded for more than 20% of the time, most pedestrians would judge that location to be too windy for sitting or more sedentary activities. Similarly, if 30 km/h at a location were exceeded for more than 20% of the time, walking or less vigorous activities would be considered uncomfortable. As most of these criteria are based on subjective reactions of a population to wind forces, their application is partly based on experience and judgment.

Once the pedestrian wind speed predictions have been established across the study site, the assessment of pedestrian comfort involves determining the suitability of the predicted wind conditions for their associated spaces. This step involves comparing the predicted comfort class to the desired comfort class, which is dictated by the location type. An overview of common pedestrian location types and their desired comfort classes are summarized on the following page.

DESIRED PEDESTRIAN COMFORT CLASSES FOR VARIOUS LOCATION TYPES

Location Types	Desired Comfort Classes
Major Building Entrances	Standing
Secondary Building Access Points	Walking
Primary Public Sidewalks	Strolling
Secondary Public Sidewalks / Bicycle Paths	Walking
Outdoor Amenity Spaces	Sitting
Cafés / Patios / Benches / Gardens	Sitting
Transit Shelters	Standing
Public Parks / Plazas	Strolling
Garage / Service Entrances	Walking
Parking Lots	Walking
Vehicular Drop-Off Zones	Walking

5. RESULTS AND DISCUSSION

The foregoing discussion of predicted pedestrian wind conditions for the study site is accompanied by Figures 3A through 6B (following the main text) illustrating the seasonal wind conditions at grade level and on the rooftop exterior amenity spaces. The colour contours indicate predicted regions of the various comfort classes. Wind conditions comfortable for sitting or more sedentary activities are represented by the colour green, standing are represented by yellow, strolling by salmon, and conditions suitable for walking are represented by blue.

Carling Avenue Sidewalk (Tag A): The sidewalk along the north side of the site will be comfortable for standing during or better during the summer, becoming comfortable for strolling or better during the three colder seasons. The noted conditions are considered acceptable for a public sidewalk.

Archibald Street Sidewalk (Tag B): The sidewalk area along the east side of the site will be comfortable for strolling, or better, throughout the year, which is acceptable.

Meath Street Sidewalk (Tag C): The sidewalk area along the west side of the site will be comfortable for standing during the summer, becoming comfortable for strolling, or better, during the three colder seasons. Towards the northwest corner of Building A, a portion of the sidewalk experiences walking conditions during the winter months. The noted conditions are considered acceptable for a secondary sidewalk.

Residential Entrance (Tags D - H): The lobby entrances for the majority of the buildings (Tags D – G) will be comfortable for standing, or better, throughout the year, which is appropriate. For the lobby entrance to Building B (Tag H), conditions do not achieve the standing criterion during the winter months owing to winds channelling between Buildings A and B. To improve wind comfort at this entrance and ensure proper mechanical function of the doorway during windy periods, it is recommended to either i) recess the doorway within the building façade; ii) incorporate the use of sliding doors as opposed to swing doors; or iii) provide vertical wind barriers on either side of the entrance.

Internal Laneway & Grade Level Parking (Tag I): The east-west laneway through the centre of the site, including the grade-level parking area, will be comfortable for strolling, or better, throughout the year, which is acceptable.

Park Area (Tag J): The future park space at the southwest corner of the site will be comfortable for sitting or more sedentary activities during all seasonal periods, which is appropriate.

Grade-level Exterior Amenity Spaces (Tag K): The exterior amenity spaces to the south of Buildings E, C, & D will be comfortable for sitting during the typical use period, defined as the late spring through the early autumn, without the need for mitigation. The noted conditions are acceptable for an outdoor amenity space.

Podium Roof Terraces – Building C, D, & E (Tags L - O): Conditions for the rooftop terrace areas on Buildings D and E (Tags L and M, respectively) will be comfortable for sitting or more sedentary activities throughout the warmer months, without the need for mitigation. Conditions for the southeast rooftop terrace of Building C (Tag N) will similarly be comfortable for sitting or more sedentary activities throughout the warmer months, without the need for mitigation. For the west portion of the Building C rooftop terrace (Tag O), conditions are measured to be comfortable for standing or better, during the same period. To provide sitting conditions on the roof space, a perimeter wind barrier measuring 1.8 metres above the walking surface is recommended. However, if only portions of the rooftop spaces will be designated for seating areas, then the wind screen configuration can be modified to suit the terrace plan. Additionally, it is recommended that a canopy be installed on the alongside the west façade. The canopy should project at least two metres over the terrace to effectively deflect downwash winds from Building C. The rooftop mitigation recommendations can be refined as the terrace designs progress.

Building Roof Terrace – Building C (Tag P): On west side of the Building C roof, wind conditions were found to be suitable for standing or strolling during the summer season. Furthermore, wind speeds near the building edge on the west side of the roof could become unsafe. Although the terrace in the test configuration did not contain a perimeter guard, an amenity space in this area would likely not achieve the sitting criterion without supplemental mitigation. As such, it is recommended to provide a 2.4-metre-tall wind screen around the terrace perimeter. However, if only portions of the terrace will be designated for seating areas, then the wind screen configuration can be modified to suit the terrace plan. As such, the rooftop mitigation recommendation can be refined as the terrace designs progress.

Influence of the Proposed Development on Existing Wind Conditions near the Study Site: Wind conditions over surrounding sidewalks and beyond the development site will generally be comfortable for standing, or better, during each seasonal period upon introduction of the proposed development at 1376 and 1345 Carling Avenue.

Wind Safety: Within the context of typical weather patterns, which exclude anomalous localized storm events such as tornadoes and downbursts, no grade-level areas over the study site were found to experience wind conditions that are considered uncomfortable for walking, or unsafe.

Influence of Phased Development on Pedestrian Wind Conditions: Development of the entire site will be phased, with Buildings C and E being built first while the existing three-storey hotel located on the western portion of the site will be retained. Wind conditions for the site at grade, and on the podium terrace of Buildings C and E are not expected to be significantly influenced by the phasing of the development. As such, the conditions and mitigation recommendations noted above are anticipated to be valid during the first phase of the development.

6. SUMMARY AND RECOMMENDATIONS

This document summarizes the results of a pedestrian level wind study undertaken to assess wind for the proposed mixed-use development to be located at 1376 & 1345 Carling Avenue, Ottawa, Ontario. This work is based on industry standard CFD simulation and data analysis procedures, architectural drawings provided by Geiger Huot Architects in April 2018, surrounding street layouts and existing and approved future building massing information obtained from the City of Ottawa, as well as recent site imagery.

Based on CFD test results, interpretation, and experience with similar developments, the majority of grade level areas within and surrounding the development site will be acceptable for the intended pedestrian uses on a seasonal basis. More specifically, surrounding sidewalks, exterior amenity areas, and most major building access points will experience acceptable wind conditions throughout the year. One area where wind mitigation is recommended is the lobby entrance to Building B. To improve wind comfort at this entrance and ensure proper mechanical function of the doorway during windy periods, it is recommended to either i) recess the doorway within the building façade; ii) incorporate the use of sliding doors as opposed to swing doors; or iii) provide vertical wind barriers on either side of the entrance.

Regarding the podium rooftop terraces, those on Buildings D and E, as well as the southeast rooftop terrace of Building C, will be comfortable for sitting or more sedentary activities throughout the warmer months, without the need for mitigation. For the west portion of the Building C podium rooftop terrace, as well as the terrace on the building rooftop, wind mitigation in the form of vertical wind barriers and canopies are recommended to ensure comfortable and safe conditions during the typical use period.

Of importance, excluding anomalous localized storm events such as tornadoes and downbursts, no area over the study site are considered uncomfortable for walking, or unsafe.

Finally, the phased development of the site, with Buildings C and E built first, while the existing three-story hotel will remain on the western portion of the site, is not expected to significantly influence the pedestrian level wind conditions and mitigation recommendations summarized above.

This concludes our pedestrian level wind report. Please advise the undersigned of any questions or comments.

Sincerely,

Gradient Wind Engineering Inc.

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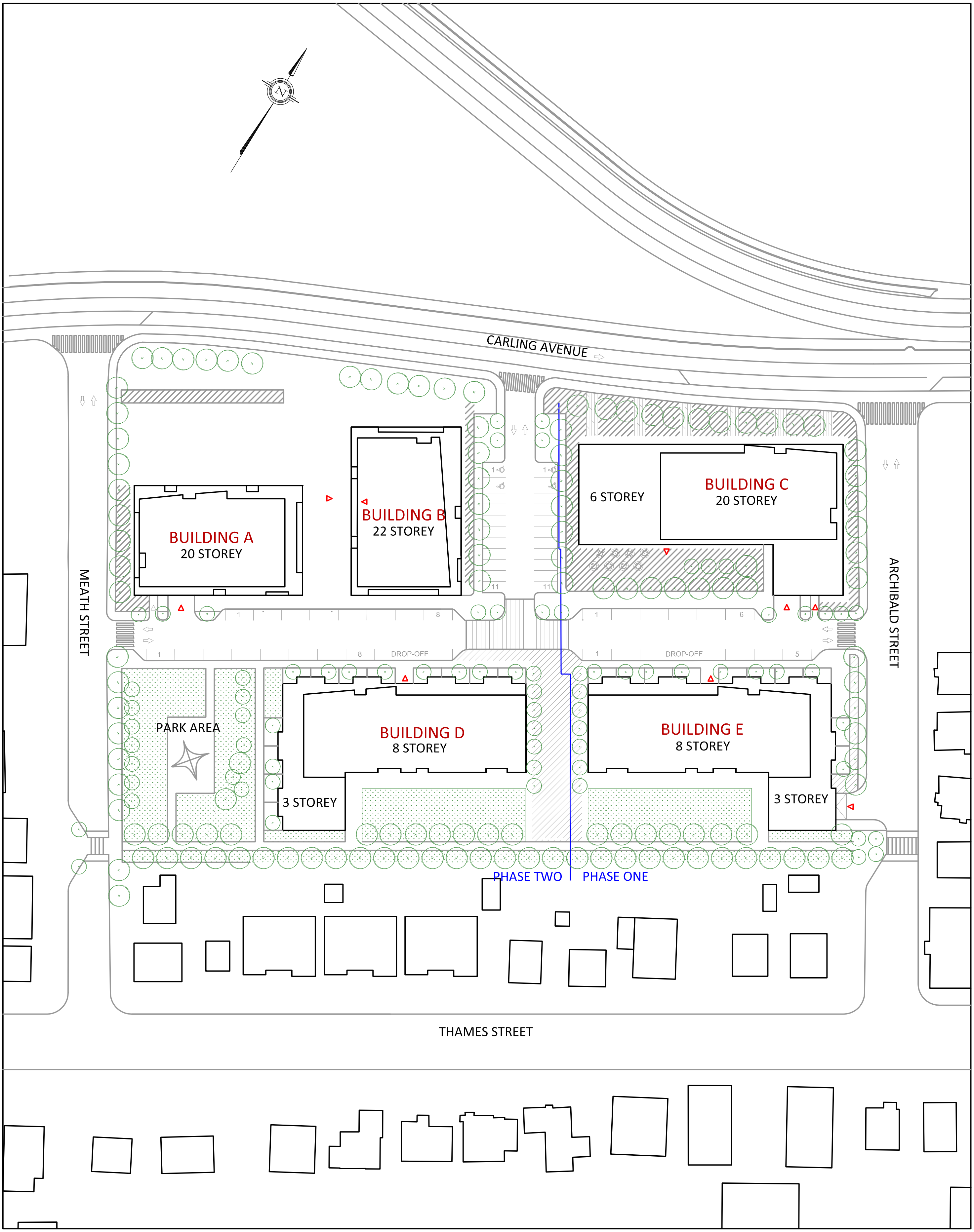

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PROJECT
1376 AND 1345 CARLING AVENUE, OTTAWA
PEDESTRIAN LEVEL WIND STUDY

SCALE
1:1200 (APPROX.)

DRAWING NO.
GWE17-038-CFDPLW-2018-1

DATE
APRIL 23, 2018

DRAWN BY
K.A.

DESCRIPTION
FIGURE 1:
SITE PLAN AND SURROUNDING CONTEXT

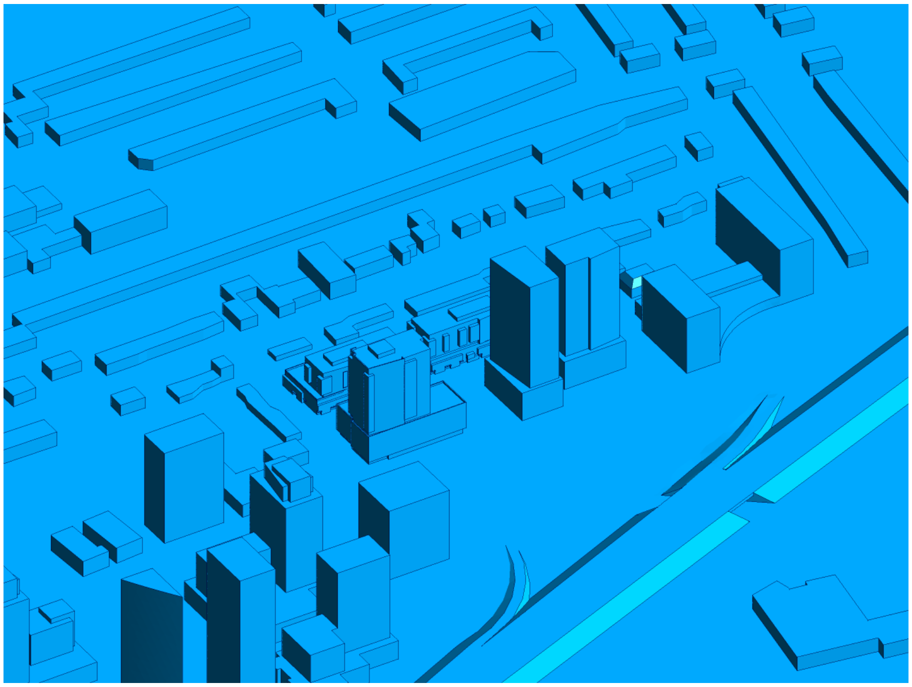

FIGURE 2A: COMPUTATIONAL MODEL, NORTH PERSPECTIVE

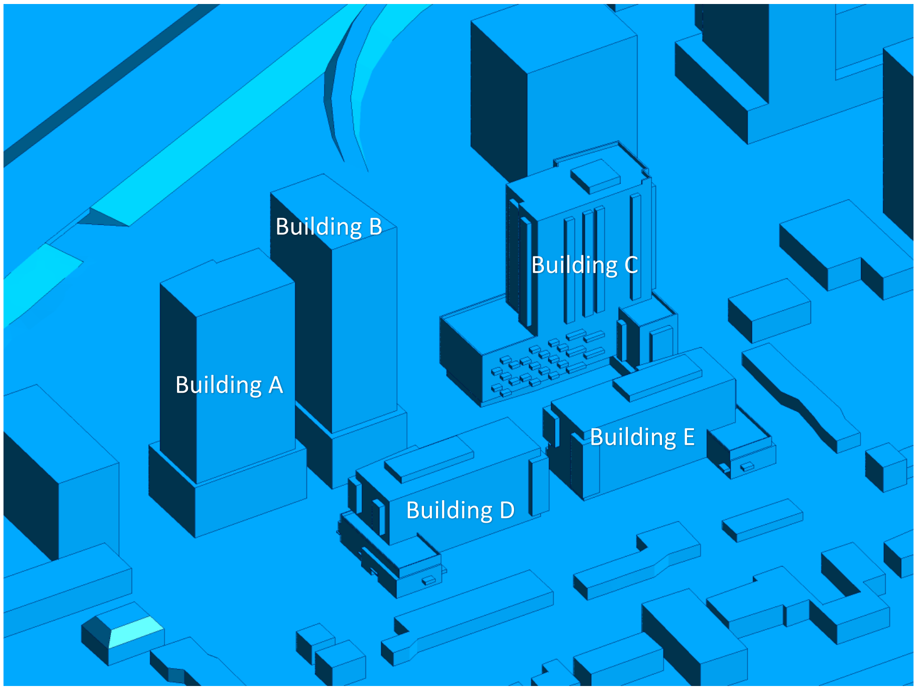

FIGURE 2B: STUDY BUILDINGS, SOUTH PERSPECTIVE

FIGURE 3A: SPRING – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

FIGURE 3B: SPRING – PODIUM ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – ELEVATED TERRACE REFERENCE MARKER LOCATIONS

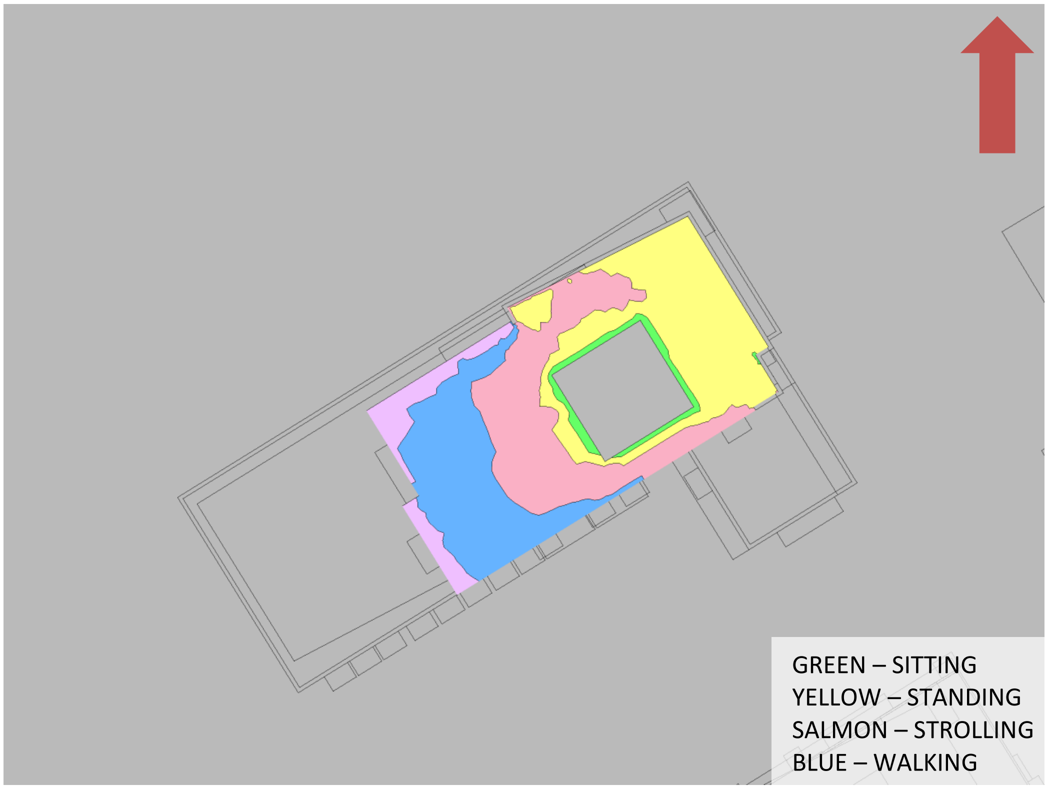

FIGURE 3C: SPRING – BUILDING C ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

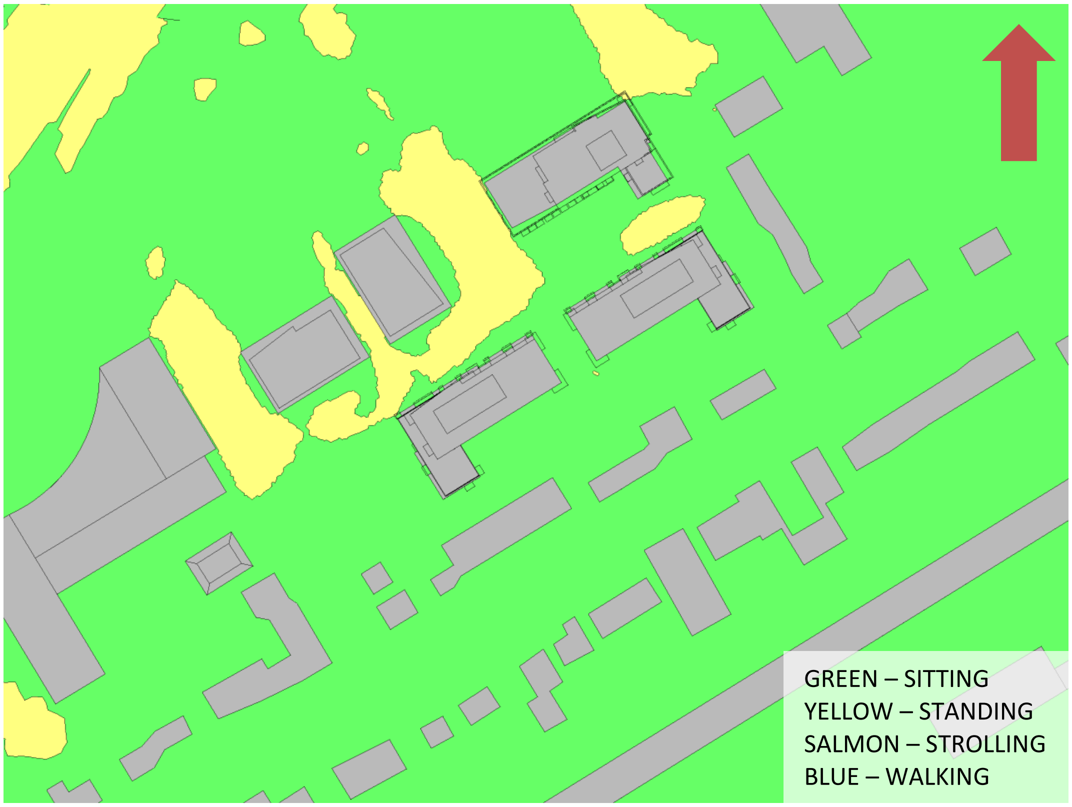

FIGURE 4A: SUMMER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

FIGURE 4B: SUMMER – PODIUM ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

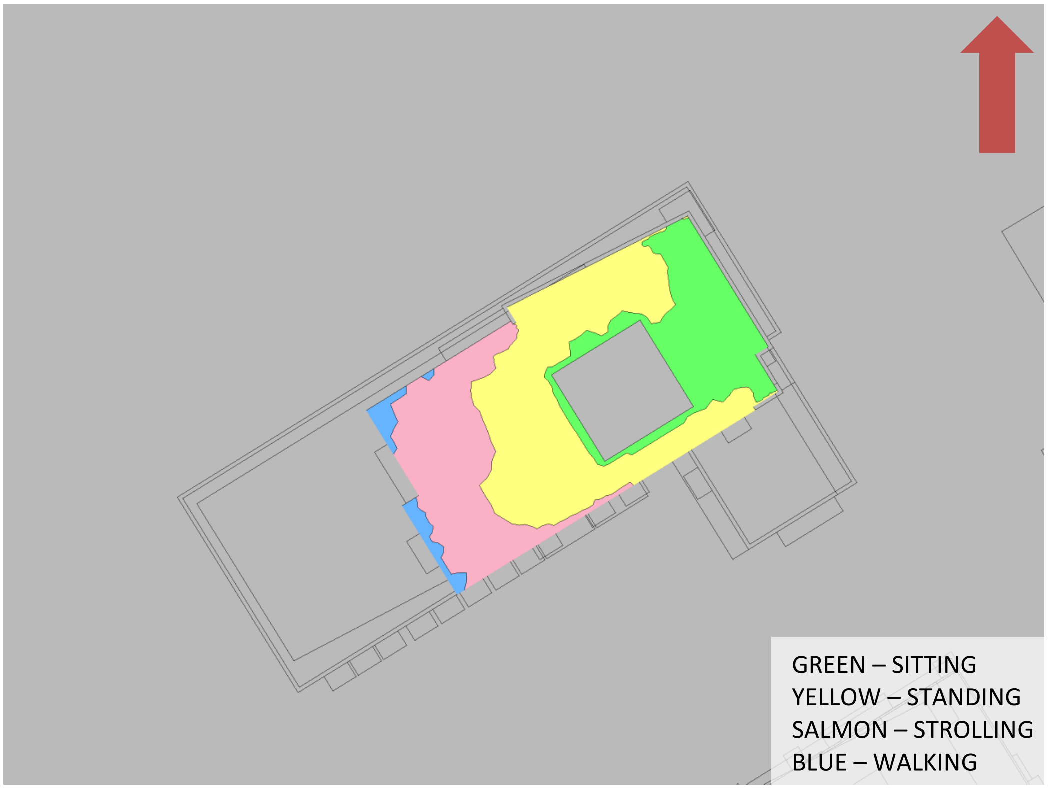

FIGURE 4C: SUMMER – BUILDING C ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

FIGURE 5A: AUTUMN – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

FIGURE 5B: AUTUMN – PODIUM ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

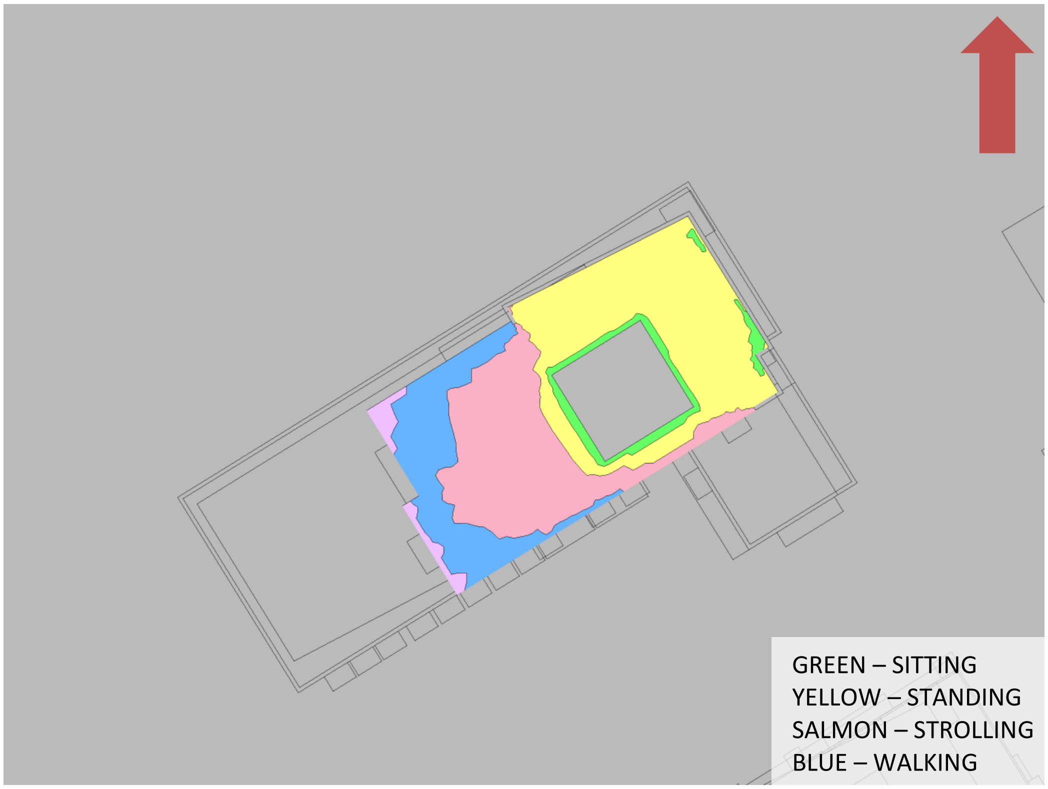

FIGURE 5C: AUTUMN – BUILDING C ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

FIGURE 6A: WINTER – GRADE-LEVEL PEDESTRIAN WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

FIGURE 6B: WINTER – PODIUM ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

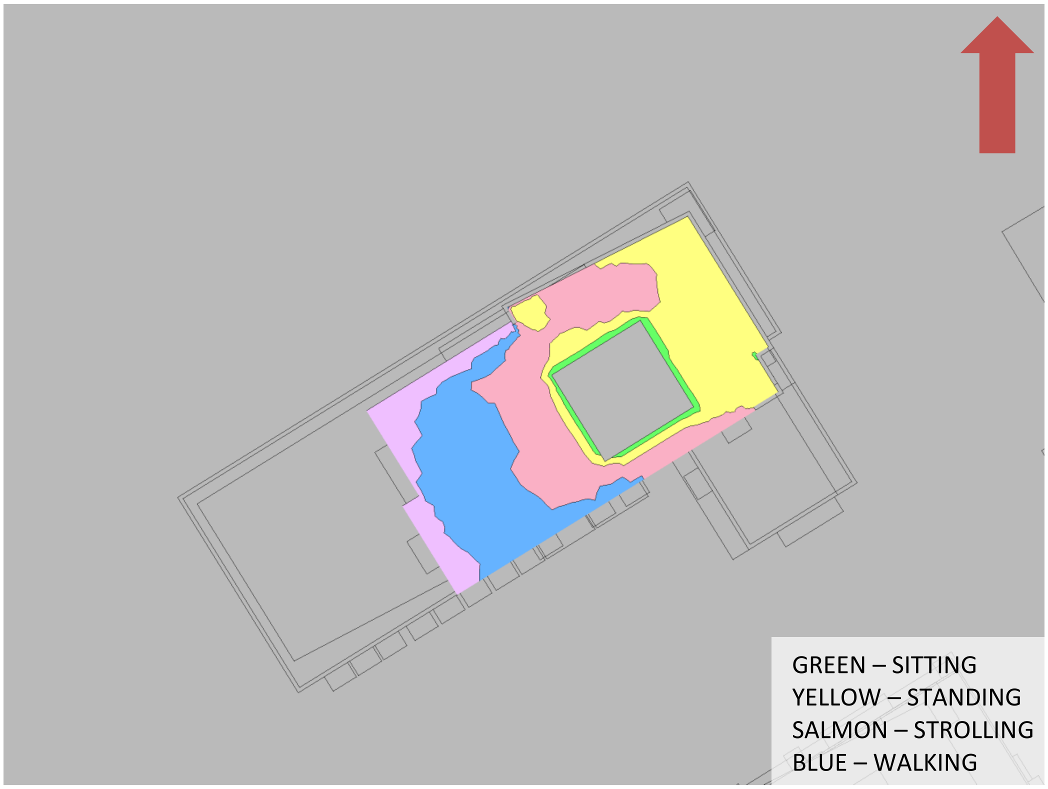

FIGURE 6C: WINTER – BUILDING C ROOFTOP TERRACE WIND CONDITIONS

1376 & 1345 CARLING AVENUE – GRADE LEVEL REFERENCE MARKER LOCATIONS

APPENDIX A

SIMULATION OF THE NATURAL WIND

The information contained within this appendix is offered to provide a greater understanding of the relationship between the physical wind tunnel testing method and virtual computer-based simulations

WIND TUNNEL SIMULATION OF THE NATURAL WIND

Wind flowing over the surface of the earth develops a boundary layer due to the drag produced by surface features such as vegetation and man-made structures. Within this boundary layer, the mean wind speed varies from zero at the surface to the gradient wind speed at the top of the layer. The height of the top of the boundary layer is referred to as the gradient height, above which the velocity remains more-or-less constant for a given synoptic weather system. The mean wind speed is taken to be the average value over one hour. Superimposed on the mean wind speed are fluctuating (or turbulent) components in the longitudinal (i.e. along wind), vertical and lateral directions. Although turbulence varies according to the roughness of the surface, the turbulence level generally increases from nearly zero (smooth flow) at gradient height to maximum values near the ground. While for a calm ocean the maximum could be 20%, the maximum for a very rough surface such as the center of a city could be 100%, or equal to the local mean wind speed. The height of the boundary layer varies in time and over different terrain roughness within the range of 400 m to 600 m.

Simulating real wind behaviour in a wind tunnel, or by computer models (CFD), requires simulating the variation of mean wind speed with height, simulating the turbulence intensity, and matching the typical length scales of turbulence. It is the ratio between wind tunnel turbulence length scales and turbulence scales in the atmosphere that determines the geometric scales that models can assume in a wind tunnel. Hence, when a 1:200 scale model is quoted, this implies that the turbulence scales in the wind tunnel and the atmosphere have the same ratios. Some flexibility in this requirement has been shown to produce reasonable wind tunnel predictions compared to full scale. In model scale the mean and turbulence characteristics of the wind are obtained with the use of spires at one end of the tunnel and roughness elements along the floor of the tunnel. The fan is located at the model end and wind is pulled over the spires, roughness elements and model. It has been found that, to a good approximation, the mean wind profile can be represented by a power law relation, shown below, giving height above ground versus wind speed.

$$U = U_g \left(\frac{Z}{Z_g} \right)^{\alpha}$$

Where; **U** = mean wind speed, **U_g** = gradient wind speed, **Z** = height above ground, **Z_g** = depth of the boundary layer (gradient height) and α is the power law exponent.

Figure A1 plots three such profiles for the open country, suburban and urban exposures. The exponent α varies according to the type of terrain; α = 0.14, 0.25 and 0.33 for open country, suburban and urban exposures respectively. Figure A2 illustrates the theoretical variation of turbulence in full scale and some wind tunnel measurement for comparison.

The integral length scale of turbulence can be thought of as an average size of gust in the atmosphere. Although it varies with height and ground roughness, it has been found to generally be in the range of 100 m to 200 m in the upper half of the boundary layer. For a 1:300 scale, for example, the model value should be between 1/3 and 2/3 of a metre. Integral length scales are derived from power spectra, which describe the energy content of wind as a function of frequency. There are several ways of determining integral length scales of turbulence. One way is by comparison of a measured power spectrum in model scale to a non-dimensional theoretical spectrum such as the Davenport spectrum of longitudinal turbulence. Using the Davenport spectrum, which agrees well with full-scale spectra, one can estimate the integral scale by plotting the theoretical spectrum with varying L until it matches as closely as possible the measured spectrum:

$$f \times S(f) = \frac{\dfrac{4(Lf)^2}{U_{10}{}^2}}{\left[1 + \dfrac{4(Lf)^2}{U_{10}{}^2}\right]^{\frac{4}{3}}}$$

Where, ***f*** is frequency, ***S(f)*** is the spectrum value at frequency ***f***, $\boldsymbol{U_{10}}$ is the wind speed 10 m above ground level, and ***L*** is the characteristic length of turbulence.

Once the wind simulation is correct, the model, constructed to a suitable scale, is installed at the center of the working section of the wind tunnel. Different wind directions are represented by rotating the model to align with the wind tunnel center-line axis.

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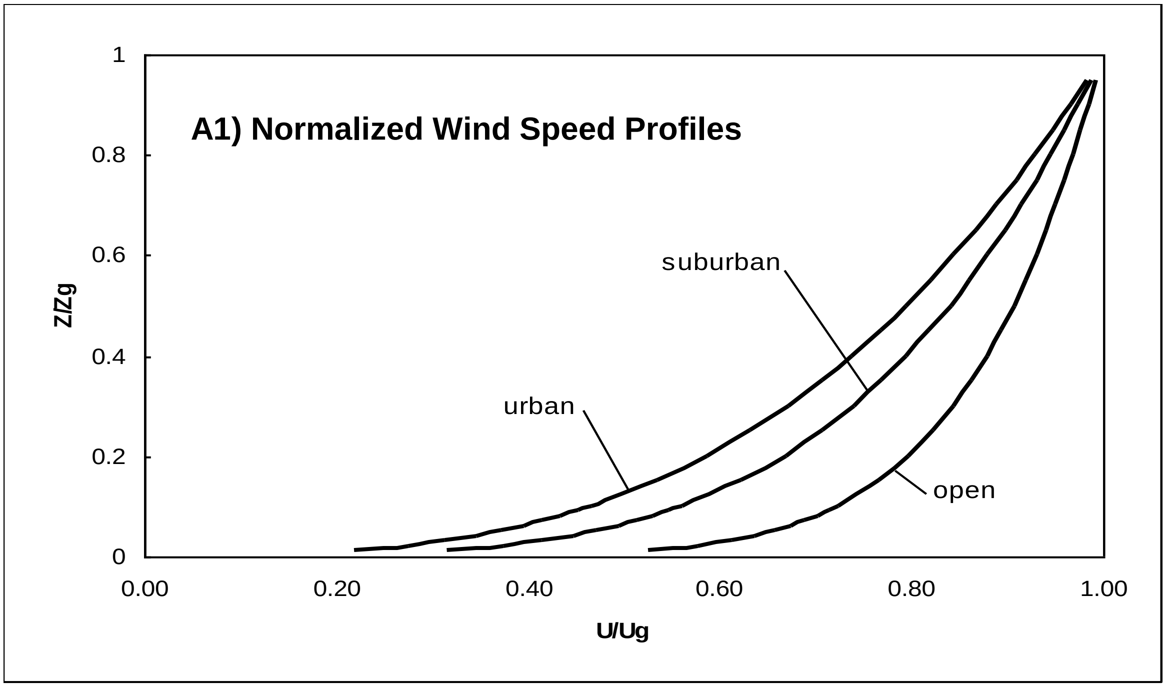


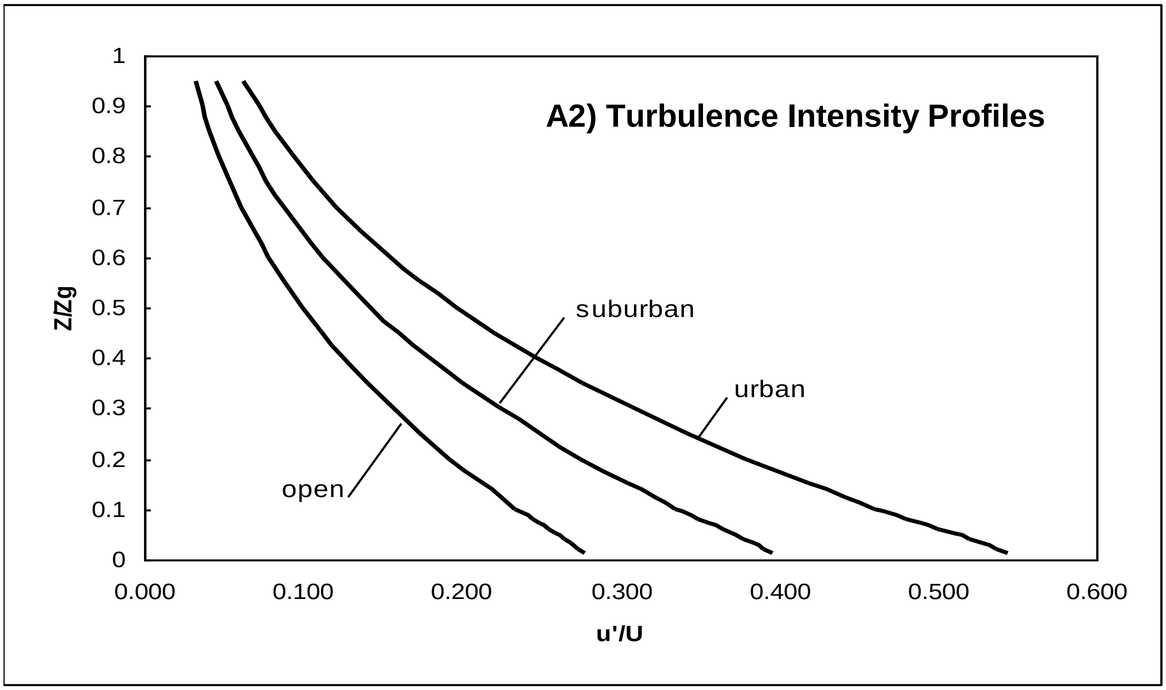


Figure A1 (Top): Mean Wind Speed Profiles

Figure A2 (Bottom): Turbulence Intensity Profiles (u’ = fluctuation of mean velocity)

APPENDIX B

PEDESTRIAN LEVEL WIND MEASUREMENT METHODOLOGY

The information contained within this appendix is offered to provide a greater understanding of the relationship between the physical wind tunnel testing method and virtual computer-based simulations

PEDESTRIAN LEVEL WIND MEASUREMENT METHODOLOGY

Pedestrian level wind studies are performed in a wind tunnel on a physical model of the study buildings at a suitable scale. Instantaneous wind speed measurements are recorded at a model height corresponding to 1.5 m full scale using either a hot wire anemometer or a pressure-based transducer. Measurements are performed at any number of locations on the model and usually for 36 wind directions. For each wind direction, the roughness of the upwind terrain is matched in the wind tunnel to generate the correct mean and turbulent wind profiles approaching the model.

The hot wire anemometer is an instrument consisting of a thin metallic wire conducting an electric current. It is an omni-directional device equally sensitive to wind approaching from any direction in the horizontal plane. By compensating for the cooling effect of wind flowing over the wire, the associated electronics produce an analog voltage signal that can be calibrated against velocity of the air stream. For all measurements, the wire is oriented vertically so as to be sensitive to wind approaching from all directions in a horizontal plane.

The pressure sensor is a small cylindrical device that measures instantaneous pressure differences over a small area. The sensor is connected via tubing to a transducer that translates the pressure to a voltage signal that is recorded by computer. With appropriately designed tubing, the sensor is sensitive to a suitable range of fluctuating velocities.

For a given wind direction and location on the model, a time history of the wind speed is recorded for a period of time equal to one hour in full-scale. The analog signal produced by the hot wire or pressure sensor is digitized at a rate of 400 samples per second. A sample recording for several seconds is illustrated in Figure B. This data is analyzed to extract the mean, root-mean-square (rms) and the peak of the signal. The peak value, or gust wind speed, is formed by averaging a number of peaks obtained from sub-intervals of the sampling period. The mean and gust speeds are then normalized by the wind tunnel gradient wind speed, which is the speed at the top of the model boundary layer, to obtain mean and gust ratios. At each location, the measurements are repeated for 36 wind directions to produce normalized polar plots, which will be provided upon request.

In order to determine the duration of various wind speeds at full scale for a given measurement location the gust ratios are combined with a statistical (mathematical) model of the wind climate for the project site. This mathematical model is based on hourly wind data obtained from one or more meteorological stations (usually airports) close to the project location. The probability model used to represent the data is the Weibull distribution expressed as:

$$P\left(>U_g\right) = A_\theta \bullet \exp\left[\left(-\frac{U_g}{C\theta}\right)^{K\theta}\right]$$

Where,

$P\ (> U_g)$ is the probability, fraction of time, that the gradient wind speed ***U_g*** is exceeded; ***θ*** is the wind direction measured clockwise from true north, ***A***, ***C***, ***K*** are the Weibull coefficients, (Units: A - dimensionless, C - wind speed units [km/h] for instance, K - dimensionless). ***A_θ*** is the fraction of time wind blows from a 10° sector centered on ***θ***.

Analysis of the hourly wind data recorded for a length of time, on the order of 10 to 30 years, yields the ***A_θ, C_θ*** and ***K_θ*** values. The probability of exceeding a chosen wind speed level, say 20 km/h, at sensor *N* is given by the following expression:

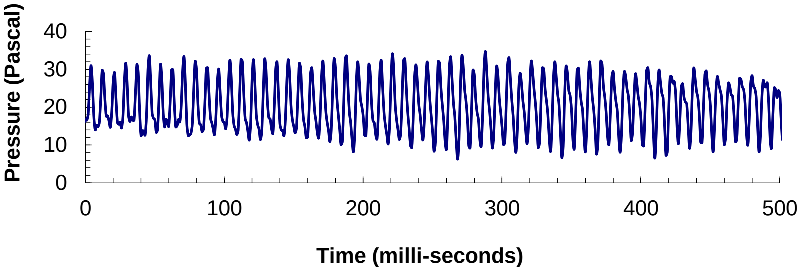
$$P_N(>20) = \Sigma_\theta P\left[\frac{(>20)}{\left(\frac{U_N}{U_g}\right)}\right]$$

$$\boldsymbol{P_N\ (>20) \quad = \quad \Sigma_\theta P\ \{>20/(U_N/Ug)\}}$$

Where, ***U_N/U_g*** is the aforementioned normalized gust velocity ratios where the summation is taken over all 36 wind directions at 10° intervals.

If there are significant seasonal variations in the weather data, as determined by inspection of the ***C_θ*** and ***K_θ*** values, then the analysis is performed separately for two or more times corresponding to the groupings of seasonal wind data. Wind speed levels of interest for predicting pedestrian comfort are based on the comfort guidelines chosen to represent various pedestrian activity levels as discussed in the main text.

FIGURE B: TIME VERSUS VELOCITY TRACE FOR A TYPICAL WIND SENSOR



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