Leeds CITY COUNCIL

# Draft Wind & Micro-climate Toolkit for Leeds

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Prepared by RWDI exclusively for Leeds City Council

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# WIND MICROCLIMATE TOOLKIT

## 1. INTRODUCTION

1.1. This document provides general guidelines for wind microclimate studies required as part of the planning applications of new development proposals within the Development Plan bounds of Leeds City Council (LCC).

1.2. Good wind microclimate conditions are necessary for creating outstanding public spaces. Adverse wind effects can reduce the quality and usability of outdoor areas, and lead to safety concerns in extreme cases.

1.3. These guidelines focus on the primary factors that affect the quality and consistency of wind microclimate studies. The guidelines cannot cover every eventuality that may arise in such studies. Therefore, expert judgement from an experienced wind engineer will always be required in wind microclimate studies, particularly for issues that are not explicitly covered by these guidelines.

1.4. Developers are encouraged to address wind microclimate matters at an early stage before their designs are finalized. Using these guidelines, appointing experienced consultants, having dialogue with officers of LCC and commissioning early-stage studies to quantify the wind microclimate conditions will help ensure good pedestrian comfort conditions around proposed development sites.

1.5. It is noted that these guidelines are provided for information only. Developers and design teams should use their experience, know-how and judgement in the most appropriate use of these guidelines for their schemes.

1.6. These guidelines may be updated from time to time, so readers should check the LCC web site (https://www.leeds.gov.uk/) to ensure that the latest version of the guidelines are used.

## 2. RECOMMENDED APPROACH FOR WIND MICROCLIMATE STUDIES

2.1. The table below outlines the general expectations for the types of wind microclimate studies required for various building heights.

2.2. The table does not apply to all developments. For example, developments that feature highly sensitive pedestrian activities (e.g. transport hubs, hospitals, etc.) or those that are located near known windy or exposed areas (e.g. edge of River Aire, or edge of a large park) may require more detailed checks. The wind consultant should use his/her judgement to determine whether the project they are working on has features that require extra care and attention.

2.3. Leeds has clusters of medium-rise and high-rise buildings spread around the city at various locations. The Leeds Tall Building Design Guide provides more information about these and potential future tall building cluster areas. In general, the taller blocks are (or will be) surrounded by 4-5 storey (12-20m high) buildings, apart from edge-of-city zones where the surrounding building stock can be 2-3 storeys (6-12m).

| **Building Height** | **Recommended Approach to Wind Microclimate Studies** |
|---|---|
| Up to 15m in Leeds | Wind studies are not required, unless sensitive pedestrian activities are intended (e.g. around hospitals, transport hubs, etc.) or the project is located on an exposed location (edge of a large park) or near another tall building |
| 15m to 30m in Leeds | Computational (CFD) Simulations **OR** Wind Tunnel Testing |
| 30m to 60m for Leeds | Computational (CFD) Simulations **AND** Wind Tunnel Testing |
| Above 100m | **Early Stage Massing Optimization**: Wind Tunnel Testing **AND** Computational (CFD) Simulations<br><br>**Detailed Design**: Wind Tunnel Testing **AND** Computational (CFD) Simulations to demonstrate the performance of the final building design |

# 3. GENERAL TECHNICAL REQUIREMENTS

3.1. The wind study should include the evaluation of pedestrian-level wind conditions for following scenarios;

- Existing site,
- Proposed scheme with existing surroundings,
- Proposed scheme with planning consented schemes,
- Existing site with planning consented schemes, should the wind conditions for the previous case (3.1.3) exceed the required Lawson comfort categories (see section 7.1 of this document for more information regarding the Lawson Criteria),
- (If mitigation measures are deemed to be required by the wind consultant), The cases above (3.1.2 and 3.1.3) with wind mitigation or improvement features,
- (If applicable or requested by LCC) Proposed scheme with a likely future scenario, including buildings that may not be consented but are being designed at the time of planning submission. Discussion with planning officers can help identifying such future buildings.
- (If applicable or requested by LCC) The construction scenario with a demolished (vacant) site, especially if the existing building is taller than 30m in height.

3.2. When choosing which schemes to include in the wind studies, the planning consultants should liaise with LCC officers, and use the following guidelines;

- Consented/future buildings that are immediately around the proposed development must be included, regardless of their height,
- Consented/future buildings that are taller than the average height of surrounding buildings and are within 300m of the site need to be included.

3.3. Information for consented buildings is publicly available at LCC planning portal. LCC planning officers can provide guidance on future schemes and assist in obtaining information for such schemes (if any).

3.4. There are four key steps to a successful wind microclimate study;

- Selecting appropriate wind statistics for the site (see Annex A),
- Determining the impact of the proposed development, through computational fluid dynamics (CFD) tools or wind tunnel testing, to obtain a set of ‘speed-up’ ratios in a

wide area around the site, including the highways and public walkways around the site,

- Combination of speed-up ratios with wind statistics, to obtain comfort ratings,
- Comparison of comfort ratings with intended pedestrian activities using appropriate criteria (see section 7.1 of this document for more information on the Lawson criteria), interpretation and presentation of results, which is covered separately in Chapter 7 of this document.

3.5. **WIND CHARACTERISTICS**: Statistical properties of wind climate are typically characterized by a Weibull probability density function. Annex A provides seasonal Weibull coefficients that can be used for projects in Leeds City Centre (i.e. terrain corrected for Leeds). For projects on more exposed parts of Leeds – e.g. next to large open spaces – an adjustment to these coefficients is required to take account of the site exposure, as described in Annex A. These climate properties have been calibrated for Leeds.

3.5.1. **NUMBER OF WIND DIRECTIONS**: All wind studies should be carried out for a minimum of 18 equally spaced wind directions. Consultants may wish to consider more wind directions if in their expert opinion there could be particular wind directions that could give rise to adverse wind effects.

3.5.2. **WIND PROFILE:** The variation of mean and gust wind speed with height should be modelled based on the wind profiles given in Annex A. Plots of simulated (wind tunnel or CFD) and targeted profile (Annex A) should be provided as part of the planning application.

3.6. **DETERMINATION OF SPEED-UPS:** Computational fluid dynamics (CFD) tools or wind tunnel tests should be used to determine speed-up ratios for each individual wind direction. Speed-ups are defined as the ratio of local wind speed at pedestrian-level locations to the undisturbed reference wind speed. The pedestrian-level wind speeds should be measured at a height of 1.5m above the local ground level (or terrace/balcony level), and the reference wind speed should be determined at a height and location where the building models do not affect the reference speed measurement.

3.7. **MEASUREMENT LOCATIONS:** Critical pedestrian-level locations include building entrances, walkways, sitting areas, drop-off locations, bus stops, disabled parking bays, queuing areas, upper-level terraces, balconies, and other frequently used locations. The consultant should use expert judgement to ascertain the extent of the area to instrument and report.

3.8. **COMBINATION OF SPEED-UPS WITH WIND STATISTICS:** Using CFD or wind tunnel testing, a set of speed-ups will be determined for each wind direction simulated. These need to be combined with the Weibull probability distribution of the wind climate given in Annex A, to calculate the probability of exceedance of a given wind speed for each wind direction. Adding the probability of exceedance for all directions gives the total probability of exceedance of a given wind speed.

3.9. The estimation of comfort or safety speed usually requires a goal-seek calculation, where a certain wind speed is selected, the total probability of exceedance is calculated, and the wind speed is continually altered until the probability of exceedance reaches the desired exceedance value. Note that the Lawson criteria – described in section 7.1 of this document - uses 5% exceedance for comfort and 0.022% exceedance for safety limits, as described subsequently.

# 4. WIND TUNNEL TEST REQUIREMENTS

4.1. Wind tunnel testing has been used to assess pedestrian microclimate conditions for the past several decades. However, significant variability in methodology can exist between different test facilities, and care should be taken to ensure the quality and consistency of wind tunnel tests.

4.2. Wind tunnel models should accurately represent the three-dimensional geometry of the proposed development. It is noted that building features that project more than 0.5m near pedestrian areas can affect the localized wind conditions, and must therefore be modelled for the proposed building and existing buildings immediately around the site. Also, building geometry near entrances and key pedestrian areas could affect the results and must be included in the models.

4.3. It is prudent to ignore landscape features in the baseline wind studies, especially when the landscape elements are smaller than 8m in height. Larger mature trees can be included, but limited published guidance exists for modelling such landscape features, so care should be taken to provide appropriately conservative interpretation of their impacts.

4.4. The wind tunnel models should represent all surrounding buildings that are within 300m from the centre of the site. Other taller buildings outside of this zone that could have an influence on wind conditions within the project site – based on the expert opinion of the wind consultant – should be included for wind directions where they are upwind of the project site.

4.5. The overall blockage in the wind tunnel (percent of tunnel area occupied by models) should be kept below 5% for closed-circuit wind tunnels and 8% for open-jet or blockage tolerant wind tunnels (in accordance of published wind tunnel testing guidelines such as ASCE SEI and AWES QAM).

4.6. The instrumentation used in the wind tunnel should be capable of capturing both the mean (typically 10-15 minute averaged) and gust speeds, with gust values divided by 1.85 to make them comparable to mean values (also referred to as Gust Equivalent Mean value). Instrumentation should not be blocked or impeded by the models.

4.7. Care should be taken to ensure that in areas with significant localized variation of wind speed (e.g. near corners) that there are sufficient number of probes to be able to capture the windiest conditions. This typically requires 3 probes at each corner of the proposed development, in areas of increased windiness, and increased probe densities in passageways, between closely spaced buildings, and near key pedestrian areas. Furthermore, probes should be placed on the roadways surrounding the site, to capture possible impacts on cyclists and pedestrians at road crossings.

4.8. Probes should also be placed in areas away from the site where cumulative effects of a cluster of tall buildings could lead to adverse wind conditions. The wind consultant should be aware of the wind conditions expected around other cumulative or existing high-rise buildings, by reviewing the publicly available planning applications for major projects near the site, available on the LCC planning portal.

# 5. CFD REQUIREMENTS

5.1. Computational fluid dynamics (CFD) tools can create high quality output that provide a good understanding of fundamental flow features. However, significant variability in methodology can exist between different CFD methods and care should be taken to ensure that appropriate modelling approaches are used.

5.2. The CFD models must include a detailed three-dimensional representation of the proposed development. It is noted that building features that project more than 0.5m near pedestrian areas can affect the localized wind conditions, and must therefore be modelled for the proposed building and existing buildings immediately around the site. Also, building geometry near entrances and key pedestrian areas could affect the results and must be included in the models.

5.3. It is prudent to ignore landscape features in the baseline wind studies, especially when the landscape elements are smaller than 8m in height. Large mature trees can be included, but limited published guidance exists for modelling such landscape features, so care should be taken to provide appropriately conservative interpretation of their impacts.

5.4. Maximum cell sizes near critical locations (e.g. entrances, corners, etc.) must be 0.3m or smaller. It is also expected that sufficient cells are used between buildings with a minimum of 10 across a street canyon. However, the cell size of buildings away from the target can be larger to allow for modelling efficiency.

5.5. The CFD models should represent all surrounding buildings that are within 300m from the centre of the site. Other taller buildings outside of this zone that could have an influence on wind conditions within the project site – based on the expert opinion of the wind consultant - should be included for wind directions where they are upwind of the project site.

5.6. The models must contain at least 3 prism layers below 1.5m height, to capture near-ground effects.

5.7. The standard k-epsilon model, or 0 or 1 equation models, should be avoided. The realisable k-epsilon model is currently a robust industry standard, and other turbulence models - such as k-omega SST - can be used if the user can demonstrate that the mesh is suitable for that model.

5.8. CFD analysis should report conditions in areas away from the site where cumulative effects of a cluster of tall buildings could lead to adverse wind conditions. The wind consultant should be aware of the wind conditions expected around other cumulative or existing high-rise buildings, by reviewing the publicly available planning applications on the LCC planning portal.

## 6. USING WIND TUNNEL and CFD IN COMBINATION

6.1. On some projects (as set out in the table in section 2.4 of this document) wind tunnel testing and CFD are both required for a more comprehensive evaluation. In these situations, two aspects need to be considered;

- It is possible to use the two tools to get a more comprehensive understanding of wind effects around a site. For example, CFD results can guide the placement of wind tunnel probes, or highlight the mechanisms of the fundamental wind patterns which can then be further studied in the wind tunnel. Similarly, the transient data collection provided by the wind tunnel tests may identify areas of high turbulence (gusts) which could inform the type of detail of CFD modelling.
- Where there are differences between wind tunnel and CFD results, an experienced wind engineer should carry out sensitivity checks (e.g. grid sensitivity, surround extend sensitivity, turbulence generation in the wind tunnel, etc.) to better understand the likely reasons for the differences and summarize the most representative set of wind conditions around the proposed scheme.

## 7. PRESENTATION OF RESULTS AND REPORTING

7.1. **WIND COMFORT CRITERIA**: A modified version of the Lawson LDDC criteria is to be used for all wind studies as summarized table below;

| **Category** | **Mean and GEM wind speed** (5% exceedance) | **Description** |
|---|---|---|
| Frequent Sitting | 2.5m/s | Acceptable for frequent outdoor sitting use, e.g. restaurant, café. |
| Occasional Sitting | 4m/s | Acceptable for occasional outdoor seating, e.g. general public outdoor spaces, balconies/terraces intended for occasional use, etc. |
| Standing | 6m/s | Acceptable for entrances, bus stops, covered walkways or passageways beneath buildings. |
| Walking | 8m/s | Acceptable for external pavements, walkways. |
| Uncomfortable | >8m/s | Not comfortable for regular pedestrian access. |

7.2. The table above deviates from the original Lawson criteria in a couple of areas,

- The 'Frequent Sitting' category is based on review of other sitting-type criteria in literature, and a desire to create much more 'active' public spaces with more cafes/restaurants in the future.
- The 'Uncomfortable' category is based on experience that Lawson Business Walking conditions often lead to complaints. Therefore, this category is now re-named as 'uncomfortable'. This category is only suitable for areas that are not expected to receive regular public footfall, like service areas, back-of-house areas, etc.
- Discussions with LCC planning officers about the categorisation of sensitive areas would be highly recommended.

7.3. **WIND SAFETY CRITERIA**: A separate safety criteria is to be applied to ascertain the safety risks to pedestrians and cyclists as follows;

| **Category** | **Mean and GEM wind speed (0.022% exceedance)** | **Description** |
|---|---|---|
| Unsafe | 15m/s | Presents a safety risk, especially to more vulnerable members of the public and cyclists. |

7.4. The criteria do not cover wind effects on other activities such as recreation (e.g. concerts, sports, water sports, etc.) or impact on vehicles.

7.5. SEASONAL RESULTS: A 'worst season' scenario should be presented, where the worst comfort conditions at each location are provided regardless of the season. Separately a summer season (June-July-August) results should be presented, for areas that are to be used mainly in warmer months of the year. Other seasonal results can be provided at the discretion of the wind consultant.

7.6. Safety conditions should be reported using annual wind statistics.

7.7. PRESENTATION OF RESULTS: The comfort conditions should be presented using a colour-coded diagram using the colour coding below. A separate plot showing the safety conditions must be provided, in addition to the comfort plot.

| Comfort Category | Colour |
|---|---|
| Frequent Sitting | Grey |
| Occasional Sitting | Blue |
| Standing | Green |
| Walking | Yellow |
| Uncomfortable and/or Unsafe | Red |

7.8. **Acceptability of Wind Conditions**: A detailed review of the intended pedestrian activities around the site should be carried out, and graphically presented and described in the planning submission. This should include the expected pedestrian activities around the proposed development, as well as the pedestrian activities experienced or proposed around existing buildings in the area. If the conditions at any location exceed the levels required for the intended pedestrian activities - or are unsafe - because of the impact of the proposed development, mitigation measures will be required.

**7.9. Existing Wind Problems:** If the existing site or the consented schemes give rise to exceedances of the comfort or safety criteria for the <u>intended</u> pedestrian uses, this should be clearly demonstrated by testing these configurations (i.e. without proposed scheme). The proposed development should not increase the comfort or safety conditions beyond the levels observed for these scenarios. Also new pedestrian uses should not be put in existing locations which exceed the comfort criteria for that new pedestrian use.

7.10. **Presentation of the Test Configurations:** The report should contain detailed photographs or images of the 3D CFD or wind tunnel used in the analysis. This is expected to include;

7.10.1. Far-field views of the entire model from north, south, east and west as a minimum,

7.10.2. Plan view of the entire model,

7.10.3. Close-up images of the proposed scheme and surrounding buildings within 50m from the site,

7.10.4. Close-up views of key pedestrian areas, such as entrances, key pedestrian walkways, outdoor seating areas, etc.,

7.10.5. Other building details or appendages that are relevant for wind conditions.

7.11. **Presentation of Mitigation Measures**: The following details of each mitigation measure or improvement feature should be provided;

7.11.1. Plan showing the location of each mitigation measure, with each measure given an identifier number,

7.11.2. Images of each mitigation measure as tested in the wind tunnel or CFD model (preferably accompanied by an architectural diagram/interpretation),

7.11.3. Table containing the size (height, width, depth), porosity and other relevant aerodynamic parameters.

7.11.4. These requirements apply even if the design feature is not materially categorized as a mitigation measure, but helps improve the wind conditions. It is intended that all features that improve the wind conditions become an intrinsic part of the building design and are fully implemented on-site and cannot be removed without consideration of the wind issues.

# 8. Annex A : Wind Climate Properties

## Introduction

The parameters in the tables below should be used to generate a statistical model of the wind frequency (by speed and direction) for Leeds. Please note that these parameters have been scaled specifically to account for the terrain in Leeds City Centre, and are not valid for use in edge-of-town areas or sites near large open areas (edge of park, edge of River Aire, etc.).

## Usage

Parameters *c* and *k* are the scale and shape factors respectively for use in calculating a Weibull probability distribution. Parameter *p* is the probability that wind will approach from a given direction. These parameters can be used in combination with the measured local wind speeds from a wind tunnel test or CFD simulation to determine the probability of exceeding a given wind speed at a given measurement location during a given season.

Probability of exceedance at a given location (for comparison against the modified Lawson criteria) is calculated as follows. For each measurement location:

1) Measure the local wind speed for each wind angle using wind tunnel testing or CFD simulation, and express this speed as a ratio over the wind speed at a known reference height upwind of the site;
    a. Note: the reference height should ideally be greater than 100m above the ground, and should be sufficiently far upwind so as not to be directly influenced by the modelled surrounding buildings.
2) Multiply the wind speed ratio by the factor in **Table 1** corresponding to the chosen reference height.
    a. Note: the probability distributions have been scaled to reference height of 120m above ground, hence the factor in **Table 1** for 120m is equal to 1.
    b. Note: for reference heights not specified in **Table 1**, you may interpolate between the specified values.
3) Multiply the factored wind speed ratio for each angle by the corresponding parameter *c* in **Table 2** (or use Table 3 if using more than 18 wind directions). Repeat for each season and annually.
4) For each angle, calculate the probability of exceedance of each threshold in the criteria (using the parameters for each season for comfort, and using the annual parameters for the safety threshold) using the following formula:

$$f_{(x)} = p \cdot e^{-\left(\frac{x}{c}\right)^k}$$

And sum across all angles to arrive at the total probability of exceedance for that season.

   a. Note: alternatively, you may choose to calculate the wind speed *x* exceeded for 5% and 0.022% of the time. In this case please note that the wind speed should be calculated for a total probability across all wind angles, and not for individual angles. This would likely require a “goal seek” or “solver”-type method, depending on how and in what programming language the calculation is implemented.

5) Compare the seasonal results against the comfort criteria to determine the suitability of the location in terms of comfort, and the annual result against the safety criterion to determine whether the location is safe or not.
   a. Note: if both mean and gust-equivalent mean velocities have been measured (as in the methodology for wind tunnel testing, set out in the main document), then this process should be repeated for both sets of velocities. The worse category of the two assessments should be taken to determine comfort and safety.

**Background**

These probability distributions have been developed based on an amalgamation of historical data from Church Fenton and Leeds Bradford Airports. Both data sets have been checked for data quality, with erroneous data points being removed from the set prior to fitting a Weibull distribution curve.

It is important to note that the directionality of the wind speed data from the two airports varies, possibly due to the large-scale effects of the hills and higher ground to the southwest of Leeds.  Discussion with major wind consultants in the UK indicated that majority of consultants use both sets of airport data and choose the worst-case results.  Amalgamation of the two airport data sets will provide a similar approach.

LCC may update the wind statistics in the future if reliable City Centre data can be used to correlate the airport data sets.

Data from each airport has been corrected to “open country” conditions at 10m height, to account for the effects of nearby terrain, using the methodology set out in ESDU 01008. The terrain-corrected data has subsequently been scaled again to represent specific terrain conditions in Leeds City Centre (again using the methodology set out in ESDU 01008).

Table 1: Reference height scale factors

| Reference height [m] | Scale factor |
|---|---|
| **100** | 0.96 |
| **120** | 1.00 |
| **160** | 1.07 |
| **200** | 1.13 |
| **250** | 1.19 |
| **300** | 1.24 |
| **450** | 1.37 |
| **600** | 1.48 |

## Table 2: Weibull Parameters (c scaled to reference height of 120m above ground)

### 18 Wind Directions (20° Increments)

| Season | Annual | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction [°] | 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 |
| p | 0.041 | 0.048 | 0.046 | 0.041 | 0.045 | 0.042 | 0.026 | 0.026 | 0.032 | 0.052 | 0.085 | 0.113 | 0.111 | 0.093 | 0.070 | 0.051 | 0.041 | 0.037 |
| c [ms$^{-1}$] | 4.63 | 5.40 | 5.85 | 6.29 | 6.77 | 6.38 | 5.36 | 5.21 | 5.50 | 5.98 | 6.67 | 6.91 | 7.06 | 6.58 | 5.67 | 5.13 | 4.86 | 4.72 |
| k | 1.70 | 1.87 | 1.99 | 2.08 | 2.09 | 2.20 | 2.11 | 2.03 | 1.83 | 1.81 | 1.92 | 1.99 | 2.01 | 1.78 | 1.58 | 1.63 | 1.73 | 1.65 |

| Season | Spring | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction [°] | 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 |
| p | 0.048 | 0.068 | 0.068 | 0.056 | 0.058 | 0.046 | 0.024 | 0.024 | 0.030 | 0.049 | 0.076 | 0.092 | 0.085 | 0.084 | 0.063 | 0.048 | 0.041 | 0.040 |
| c [ms$^{-1}$] | 5.02 | 5.94 | 6.46 | 6.79 | 7.08 | 6.65 | 5.63 | 5.48 | 5.55 | 6.01 | 6.65 | 6.92 | 7.08 | 6.97 | 6.20 | 5.50 | 5.01 | 5.04 |
| k | 1.83 | 2.01 | 2.14 | 2.23 | 2.22 | 2.30 | 2.15 | 2.14 | 1.93 | 1.91 | 2.02 | 2.04 | 2.09 | 1.90 | 1.69 | 1.66 | 1.77 | 1.82 |

| Season | Summer | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction [°] | 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 |
| p | 0.039 | 0.040 | 0.040 | 0.032 | 0.041 | 0.042 | 0.021 | 0.018 | 0.023 | 0.043 | 0.086 | 0.126 | 0.120 | 0.106 | 0.080 | 0.058 | 0.047 | 0.039 |
| c [ms$^{-1}$] | 4.42 | 5.16 | 5.60 | 5.90 | 6.57 | 6.66 | 5.44 | 4.96 | 5.08 | 5.41 | 6.15 | 6.49 | 6.55 | 6.34 | 5.67 | 5.08 | 4.64 | 4.43 |
| k | 1.98 | 2.18 | 2.21 | 2.14 | 2.28 | 2.40 | 2.21 | 2.10 | 2.04 | 2.13 | 2.30 | 2.24 | 2.23 | 2.15 | 2.07 | 1.93 | 1.93 | 1.96 |

| Season | Autumn | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction [°] | 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 |
| p | 0.042 | 0.040 | 0.034 | 0.034 | 0.041 | 0.043 | 0.033 | 0.033 | 0.039 | 0.056 | 0.089 | 0.117 | 0.113 | 0.086 | 0.068 | 0.053 | 0.041 | 0.037 |
| c [ms$^{-1}$] | 4.41 | 4.90 | 4.87 | 5.39 | 6.20 | 5.96 | 5.25 | 5.17 | 5.30 | 5.66 | 6.33 | 6.49 | 6.88 | 6.26 | 5.51 | 4.88 | 4.74 | 4.60 |
| k | 1.67 | 1.74 | 1.86 | 2.02 | 2.08 | 2.14 | 2.02 | 2.10 | 1.89 | 1.86 | 1.91 | 1.99 | 2.03 | 1.79 | 1.66 | 1.67 | 1.70 | 1.63 |

| Season | Winter | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hours | 2166 | | | | | | | | | | | | | | | | | |
| Direction [°] | 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 | 200 | 220 | 240 | 260 | 280 | 300 | 320 | 340 |
| p | 0.035 | 0.042 | 0.043 | 0.040 | 0.039 | 0.037 | 0.026 | 0.029 | 0.035 | 0.058 | 0.090 | 0.119 | 0.126 | 0.097 | 0.071 | 0.047 | 0.035 | 0.031 |
| c [ms$^{-1}$] | 4.49 | 5.07 | 5.82 | 6.60 | 6.89 | 6.20 | 5.06 | 5.11 | 6.01 | 6.60 | 7.32 | 7.52 | 7.77 | 7.21 | 6.29 | 5.53 | 5.08 | 4.79 |
| k | 1.51 | 1.68 | 1.91 | 2.07 | 1.93 | 2.07 | 2.11 | 1.91 | 1.82 | 1.80 | 1.90 | 1.99 | 2.05 | 1.78 | 1.63 | 1.62 | 1.64 | 1.49 |

**Table 3: Weibull Parameters (c scaled to reference height of 120m above ground)**

**36 Wind Directions (10° Increments)**

| Season | Annual | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
| p | 0.021 | 0.020 | 0.024 | 0.026 | 0.023 | 0.021 | 0.020 | 0.020 | 0.021 | 0.028 | 0.021 | 0.015 |
| c [$ms^{-1}$] | 4.63 | 5.06 | 5.40 | 5.65 | 5.85 | 6.07 | 6.29 | 6.45 | 6.77 | 6.66 | 6.38 | 5.71 |
| k | 1.70 | 1.80 | 1.87 | 1.92 | 1.99 | 2.07 | 2.08 | 2.06 | 2.09 | 2.16 | 2.20 | 2.18 |

| 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.013 | 0.013 | 0.013 | 0.014 | 0.015 | 0.020 | 0.025 | 0.033 | 0.041 | 0.056 | 0.057 | 0.053 |
| 5.36 | 5.26 | 5.21 | 5.27 | 5.50 | 5.72 | 5.98 | 6.34 | 6.67 | 6.89 | 6.91 | 7.03 |
| 2.11 | 2.08 | 2.03 | 1.92 | 1.83 | 1.79 | 1.81 | 1.87 | 1.92 | 1.96 | 1.99 | 2.04 |
| 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
| 0.055 | 0.058 | 0.044 | 0.043 | 0.034 | 0.030 | 0.025 | 0.023 | 0.020 | 0.020 | 0.018 | 0.020 |
| 7.06 | 6.90 | 6.58 | 6.02 | 5.67 | 5.37 | 5.13 | 5.02 | 4.86 | 4.79 | 4.72 | 4.64 |
| 2.01 | 1.88 | 1.78 | 1.64 | 1.58 | 1.57 | 1.63 | 1.69 | 1.73 | 1.70 | 1.65 | 1.64 |

| Season | Spring | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
| p | 0.024 | 0.026 | 0.035 | 0.038 | 0.034 | 0.030 | 0.028 | 0.027 | 0.028 | 0.033 | 0.022 | 0.014 |
| c [$ms^{-1}$] | 5.02 | 5.47 | 5.94 | 6.24 | 6.46 | 6.62 | 6.79 | 6.84 | 7.08 | 6.94 | 6.65 | 6.00 |
| k | 1.83 | 1.92 | 2.01 | 2.06 | 2.14 | 2.20 | 2.23 | 2.21 | 2.22 | 2.28 | 2.30 | 2.25 |

| 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.011 | 0.012 | 0.012 | 0.013 | 0.014 | 0.019 | 0.024 | 0.030 | 0.037 | 0.048 | 0.046 | 0.041 |
| 5.63 | 5.53 | 5.48 | 5.44 | 5.55 | 5.80 | 6.01 | 6.28 | 6.65 | 6.92 | 6.92 | 6.98 |
| 2.15 | 2.13 | 2.14 | 2.03 | 1.93 | 1.89 | 1.91 | 1.96 | 2.02 | 2.05 | 2.04 | 2.06 |
| 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
| 0.041 | 0.049 | 0.040 | 0.039 | 0.030 | 0.027 | 0.023 | 0.022 | 0.020 | 0.020 | 0.020 | 0.022 |
| 7.08 | 7.19 | 6.97 | 6.52 | 6.20 | 5.89 | 5.50 | 5.23 | 5.00 | 4.97 | 5.04 | 5.02 |
| 2.09 | 2.04 | 1.90 | 1.78 | 1.69 | 1.64 | 1.66 | 1.71 | 1.77 | 1.78 | 1.82 | 1.82 |

| Season | Summer | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
| p | 0.020 | 0.018 | 0.020 | 0.022 | 0.020 | 0.017 | 0.016 | 0.015 | 0.019 | 0.028 | 0.021 | 0.014 |
| c [$ms^{-1}$] | 4.42 | 4.85 | 5.16 | 5.41 | 5.60 | 5.81 | 5.90 | 6.05 | 6.57 | 6.76 | 6.66 | 5.94 |
| k | 1.98 | 2.08 | 2.18 | 2.21 | 2.21 | 2.19 | 2.14 | 2.17 | 2.28 | 2.38 | 2.40 | 2.34 |

| 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.010 | 0.009 | 0.008 | 0.010 | 0.011 | 0.015 | 0.021 | 0.029 | 0.041 | 0.063 | 0.064 | 0.056 |
| 5.44 | 5.18 | 4.96 | 4.94 | 5.08 | 5.22 | 5.41 | 5.74 | 6.15 | 6.47 | 6.49 | 6.51 |
| 2.21 | 2.10 | 2.10 | 2.06 | 2.04 | 2.05 | 2.13 | 2.24 | 2.30 | 2.26 | 2.24 | 2.25 |
| 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
| 0.059 | 0.064 | 0.050 | 0.050 | 0.039 | 0.033 | 0.029 | 0.025 | 0.023 | 0.022 | 0.019 | 0.019 |
| 6.55 | 6.54 | 6.34 | 6.02 | 5.67 | 5.37 | 5.08 | 4.86 | 4.64 | 4.49 | 4.42 | 4.38 |
| 2.23 | 2.20 | 2.15 | 2.10 | 2.07 | 2.00 | 1.92 | 1.90 | 1.93 | 1.97 | 1.96 | 1.95 |

| Season | Autumn | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
| p | 0.021 | 0.020 | 0.020 | 0.020 | 0.017 | 0.016 | 0.017 | 0.018 | 0.019 | 0.027 | 0.021 | 0.017 |
| c [$ms^{-1}$] | 4.42 | 4.79 | 4.90 | 4.86 | 4.87 | 5.07 | 5.39 | 5.76 | 6.20 | 6.18 | 5.96 | 5.43 |
| k | 1.67 | 1.75 | 1.74 | 1.78 | 1.86 | 1.98 | 2.02 | 2.04 | 2.08 | 2.15 | 2.14 | 2.08 |

| 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.016 | 0.017 | 0.016 | 0.018 | 0.019 | 0.023 | 0.028 | 0.035 | 0.043 | 0.058 | 0.059 | 0.055 |
| 5.25 | 5.24 | 5.17 | 5.13 | 5.30 | 5.43 | 5.66 | 6.00 | 6.33 | 6.48 | 6.49 | 6.72 |
| 2.02 | 2.07 | 2.10 | 1.98 | 1.89 | 1.85 | 1.86 | 1.87 | 1.91 | 1.94 | 1.99 | 2.03 |
| 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
| 0.056 | 0.057 | 0.040 | 0.039 | 0.033 | 0.030 | 0.026 | 0.024 | 0.020 | 0.019 | 0.017 | 0.021 |
| 6.88 | 6.75 | 6.26 | 5.82 | 5.51 | 5.16 | 4.87 | 4.76 | 4.74 | 4.73 | 4.60 | 4.46 |
| 2.03 | 1.93 | 1.79 | 1.68 | 1.66 | 1.64 | 1.67 | 1.68 | 1.70 | 1.69 | 1.63 | 1.63 |

| Season | Winter | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Direction | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 | 90 | 100 | 110 |
| p | 0.018 | 0.018 | 0.022 | 0.023 | 0.021 | 0.020 | 0.020 | 0.019 | 0.019 | 0.023 | 0.019 | 0.014 |
| c [$ms^{-1}$] | 4.50 | 4.82 | 5.07 | 5.45 | 5.82 | 6.20 | 6.60 | 6.76 | 6.89 | 6.56 | 6.20 | 5.44 |
| k | 1.51 | 1.62 | 1.68 | 1.77 | 1.91 | 2.04 | 2.07 | 1.98 | 1.93 | 1.97 | 2.07 | 2.15 |

| 120 | 130 | 140 | 150 | 160 | 170 | 180 | 190 | 200 | 210 | 220 | 230 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.013 | 0.014 | 0.014 | 0.015 | 0.017 | 0.023 | 0.028 | 0.037 | 0.044 | 0.057 | 0.060 | 0.059 |
| 5.06 | 5.00 | 5.11 | 5.49 | 6.01 | 6.27 | 6.60 | 7.04 | 7.32 | 7.53 | 7.52 | 7.65 |
| 2.11 | 2.04 | 1.91 | 1.83 | 1.82 | 1.78 | 1.80 | 1.86 | 1.90 | 1.95 | 1.99 | 2.05 |
| 240 | 250 | 260 | 270 | 280 | 290 | 300 | 310 | 320 | 330 | 340 | 350 |
| 0.062 | 0.065 | 0.045 | 0.042 | 0.035 | 0.029 | 0.023 | 0.020 | 0.017 | 0.016 | 0.015 | 0.017 |
| 7.77 | 7.67 | 7.21 | 6.71 | 6.29 | 5.89 | 5.53 | 5.34 | 5.08 | 4.98 | 4.79 | 4.55 |
| 2.05 | 1.93 | 1.78 | 1.67 | 1.63 | 1.61 | 1.62 | 1.65 | 1.64 | 1.58 | 1.49 | 1.44 |

## For more information, please contact:

Policy and Plans Group &
Environment and Design Group
Merrion House
110 Merrion Centre
Leeds LS2 8BB

**Email: ldf@leeds.gov.uk**
**Web: www.leeds.gov.uk/localplan**

Leeds CITY COUNCIL

**Draft Wind & Micro-climate Toolkit for Leeds**

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