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Methodology for assessing cycling comfort during a smart city development

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Abstract

Smart city development that encourages more bicycles on the road will pave way for a city with an energy-efficient transport. In this direction, the current work involves developing a cycling comfort matrix based on computational fluid dynamics (CFD). CFD simulations of an urban layout (Niigata city in Japan) under different meteorological conditions (wind directions) enables us to measure cycling comfort through: (a) the Predicted Mean Vote (PMV) a thermal comfort measure and (b) the Turbulence Intensity (TI). Work involves validation of CFD wind prediction with measured experimental data. Results show that during the summer time, the higher wind velocity regions will provide thermal comfort to cyclist (near-zero PMV regions), but such zones also tend to have higher TI (due to high gradients near the buildings at high wind speed) which may be unsafe. This work has the prospect of both aiding in planning of new cycle routes and developing smart urban building layouts.

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Keywords: Cycling; Smart City; Comfort; CFD; Predicted Mean Vote; Turbulence.

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1. Introduction and objective

A smart city development will need to cater for cleaner and energy efficient transit mediums amidst increase in transport demands from ensuing population growth. To meet these challenges, the smart-city planning authorities would like to develop a city in such a way that the growth in road traffic volumes is absorbed by sustainable transport modes with less car usage (i.e. through a combination of cycling, walking and public transports). Bicycling is considered as one of the most energy-efficient machines for transport, but strong wind conditions arising due to building layouts,land-use and terrain features can make this experience uncomfortable. Currently, smart city planners do not have any objective module to connect the land-use categories, existing and planned cycling routes with meteorological factors like wind. There is a scope to make cycling smarter and comfortable by understanding the influence of changing urban microclimate (like wind conditions and meteorological factors) during city development. The current

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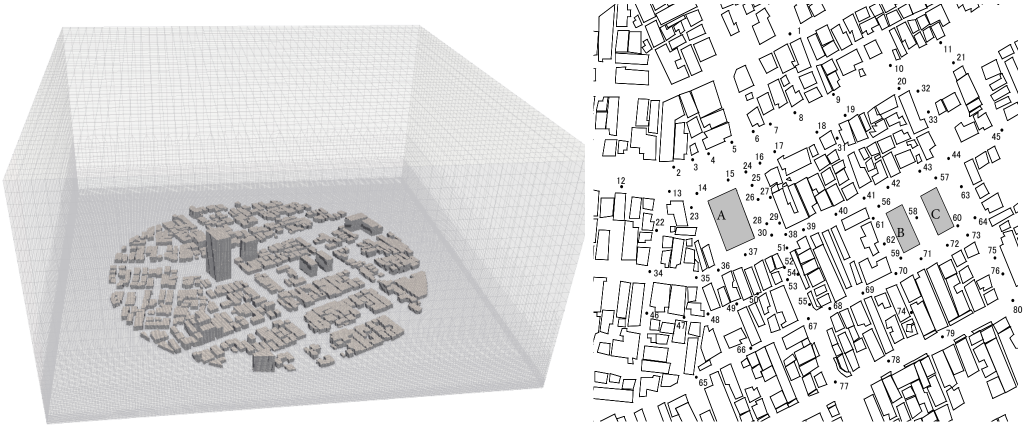
work aims to show case a "cycling comfort matrix" to assess which cycling routes may face difficulties due to (a) changing micro-climate (wind conditions) and (b) urban development. The development of cycling comfort matrix is with the long-term intention to make cycling smarter as cyclists can track comfort associated with cycling routes and make decisions. The work involves conducting micro-scale CFD simulations of a realistic urban area incorporating building layout and nearby terrain features under different meteorological conditions and different urban development scenarios, and analyse the results for developing the cycling comfort matrix. Current literature status shows that a cyclist's perception of dynamic comfort has received scant attention in the scientific community [1]. Ayachi's survey [1] with 244 respondents helped us to understand that a cyclists comfort are guided by certain qualities related to the bicycle components, the road and external conditions (e.g. weather, temperature). To help quantify and measure some of these external conditions, we propose a cycling comfort matrix with two parameters (turbulent intensity and predicted mean vote) which utilizes the wind data computed from hi-fidelity micro-scale simulations involving building. The methods and approach are described below in detail.

2. Approach and Methods

Computational fluid dynamics (CFD) simulations provides us with information on wind velocity, pressure, turbulence and temperature in a micro-scale urban surroundings. This information can help us to develop a cycling comfort matrix. The details of numerical techniques and set-up for simulations are given below:



(a) Geometry and Mesh (b) Measurement point locations

Fig. 1. Layout and Computational domain

2.1. Domain of Analysis

CFD simulations have been conducted over a scaled down (1/250th scale of the original) Niigata urban landscape (see figure 1). The urban landscape here is an actual city block in the Niigata city,Japan involving several low-rise houses jammed closely together with some high rise buildings (a 60m high Building A and two 18m high buildings B and C) as seen in figure 1). The cycling paths are along the roads besides the buildings in the city. The wind tunnel experiments are also conducted at 1/250th scale of actual model [2] and the data are available for validation of the CFD (see locations of measurement points in figure 1. This validation and geometry was earlier simulated by using k-ϵ model [2]. In this work, we use a $k-\omega$ SST turbulence model[3] based on Reynolds Averaged Navier-Stokes. For brevity, the equations are not described here. The wind inlet conditions for wind tunnel are represented by a power law exponent of 0.25 and the results are used to validate the CFD measurements. Scalar wind velocities at 8mm above the wind tunnel floor (2m above the ground surface in real scale) were measured by multi-point thermistor anemometers. The building walls are treated as a no-slip boundary and employs a wall function based on Spalding's law [4] that gives a continuous kinematic viscosity profile to the wall over wide range of y^+. This is required because the average

y^+ value near blade wall is 36 while the minimum y^+ value is 0.7 . Simulations are conducted with a profile similar to experimental measurements. The impact of six different wind directions (westerly, easterly,northerly,southerly,North of north easterly,South of south westerly) have been studied in this work and results presented in section below.

3. Result and Discussion results

3.1. Validation study

Figure 2 compares the velocity field predicted by the CFD $k-\omega$ model and the CFD $k-\epsilon$ model to the wind tunnel measurements for the westerly wind direction. Overall, the $k-\omega$ model predictions are better than $k-\epsilon$ as the values of mean least square error (LSE) between predictions and experimental data is lower for $k-\omega$ (LSE=3.2) than for $k-\epsilon$ (LSE=3.5). The measurement locations where both the models predict the highest deviations from experimental wind tunnel measurements are located in the wake region behind the tall buildings (as can be seen from figure 2 and figure 3. This result is along the expected line. After validation for westerly direction, we compute flow for other five wind directions and analyze the results from cycling comfort point of view. The popularly used thermal comfort parameters, the Predicted Mean Vote (PMV) has been computed from the CFD data and results are described below.

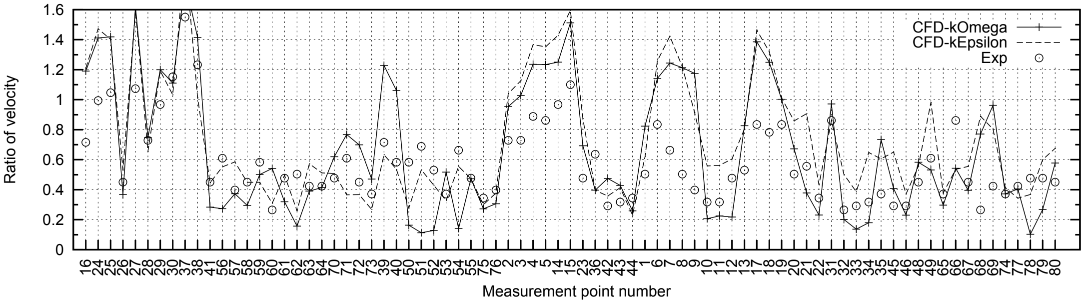
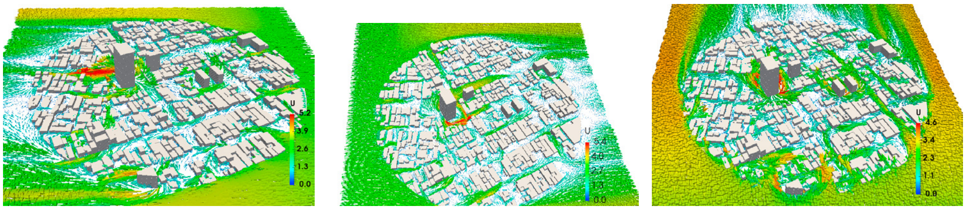
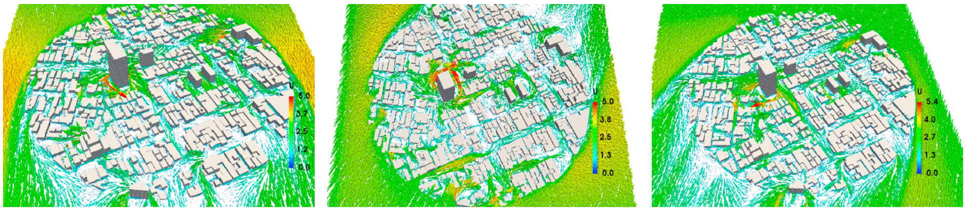


Fig. 2. Validation with k-ω SST model and k-ϵ model

3.2. Predicted Mean Vote (PMV) and Wind Velocity



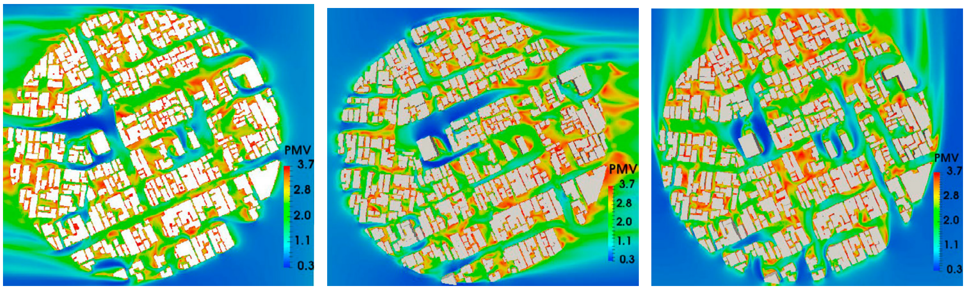
(a) East (b) West (c) South



(d) North (e) SSW (f) NNE

Fig. 3. Wind Velocity Field , U [m/s] for different wind directions.

Wind can perhaps influence a cyclist in different ways, (a) one way is from thermal perspective i.e. the wind convects away the heat being produced by cyclists due to cyclists's high metabolic rate, and (b) second way , that it acts on the cyclist as a force (be it wind shear, turbulence). The thermal comfort levels due to wind is considered by using the Predicted Mean Vote (PMV). The Predicted Mean Vote (PMV) refers to a thermal comfort scale which has been adapted to a cyclist using the Rayman model [5]. It involves heat transfer and energy balance around the human body (cyclist), wherein the difference between the internal heat production and the heat loss to the actual environment helps to determine the thermal comfort levels. The heat transfer through all the three modes (radiation, convection, and conduction) are considered and it is balanced against the cyclist's metabolic rate (which is responsible for the internal heat production). The value of PMV (-3 to 3 scale) suggests how comfortable the cyclist would be feeling: the lower PMV value of -3 indicates that the cyclist will be feeling much colder, and the higher PMV value of +3 indicates that the cyclist will be feeling hotter. The PMV thermal scale was originally developed by P. O. Fanger [6]. Figure 4 plots the contour of PMV at an altitude around the height of the cyclist. The PMV is influenced by the following factors : a. Metabolic rate (the energy generated from the human body); b. Clothing insulation (the amount of thermal insulation the person is wearing); c. Wind temperature (temperature of the air surrounding the cyclist); d. Radiant temperature (the weighted average of all the temperatures from surfaces surrounding an cyclist); e. Wind velocity and d. Relative humidity (which is the percentage of water vapor in the air). Amongst these variables, most are fixed as follows. The conditions at Niigata, Japan is considered for the month of July, when the average wind temperature is around 20^{0}C with a relative humidity of 77% . The metabolic rate is fixed at around 170 W/m^2. The radiant temperature and surface clothing temperature are computed using the Rayman Model [5]. The variation of ambient temperature was not considered in this work and was fixed at 20^{0}C. The wind velocity (as shown in figure 3) was obtained from the CFD simulations. The PMV values are closely related to the wind conditions. PMV contour shows the impact of high humid summer conditions (as no negative PMV values are seen), and the PMV values lies in the range of 0.3 - 3.7 at all wind conditions. From figure 4-3, it can be seen that the PMV values are influenced by the wind velocity, by the wind direction and by the building layout. Depending upon the wind direction, there are changes in the location of low wind speed regions (which are mostly concentrated around the wake regions downstream of the buildings). Similarly, even the regions of high speed winds (existing mostly in regions offering less resistance to flow with some open spaces as seen in vicinity of building A,B and C) changes due to wind directions. The lower PMV



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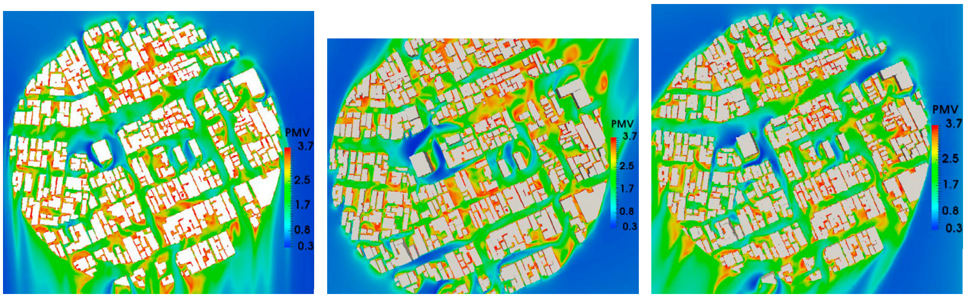


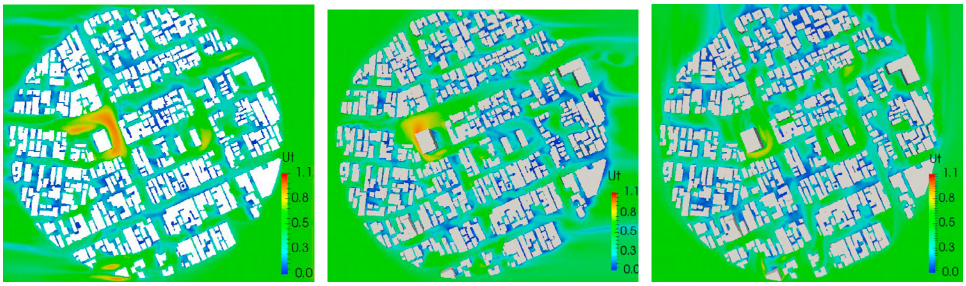
(d) North (e) SSW (f) NNE

Fig. 4. Predicted Mean Vote (PMV) for different wind directions.

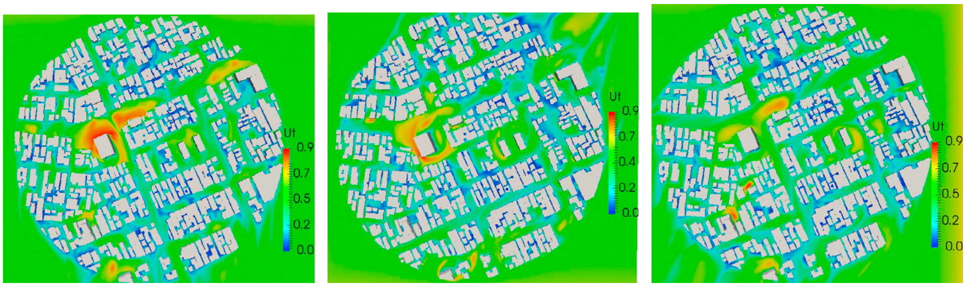
value is obtained in regions of higher wind velocity, while regions with lower wind velocity experiences regions of high PMV value. Hence, with change in wind direction, the PMV contours are also changing. The lower wind speed leads to reduced heat being convected away from the cyclist's body, and as a result high PMV values above 3 are seen. Regions of high PMV (and lower wind speed) suggests that these areas will be very uncomfortable for the cyclists to cycle during the humid summer time. Cyclists would prefer cycling in regions with high wind speed, where the heat from their body will be convected away faster, thus cooling them and leading to the regions with lower PMV values, and this will make them feel comfortable. Generally, regions of lower PMV values are seen in regions vicinity of taller buildings where some open spaces exist for wind to move freely. While, regions of higher PMV (low wind speed) are seen in narrow lanes situated amidst cluster of smaller buildings.

Thus, this section addresses the thermal comfort due to wind. The next section involves the turbulence generated by building wakes which can cause impediment to cycling.

3.3. Turbulent Intensity



(a) East (b) West (c) South



(d) North (e) SSW (f) NNE

Fig. 5. Turbulent Intensity (Ut $[m/s]$) for different wind directions.

Turbulent intensity (Ut) is used commonly in the aviation field to evaluate flight safety. In aviation, the prevalence of the two conditions, the $F-$factor or wind shear (with $F < -0.1$) and the turbulence (represented by turbulent kinetic energy dissipation rate - $\epsilon^{1/3} > 0.5\,m^{2/3}s^{-1}$) correspond to severe turbulence for commercial aircrafts and represent potential danger. These severe conditions are met when $Ut = \sqrt{K} > 3\,ms^{-1}$. The turbulent wind conditions often form due to regions of high wind shear. A cyclist will find it difficult to commute in high turbulence regions. However, guidelines that classify impact of turbulent intensity on the safety of cyclist do not exist (from light to extreme turbulence). This work aims to generate a database and encourage a discussion towards developing a guideline for cyclist's comfort from turbulence perspective. The results in figure 5 shows regions where the higher values of turbulent intensity lies. The wakes generated by building corners located in high wind speed region are often turbulent in nature. In the neighbourhood of the building, there is velocity gradient owing to no-slip wall boundary condition on building wall and the accelerated flow due to channeling in building vicinity. This velocity gradient results in production of turbulence as seen in figure 5. CFD reveals that in almost all the cases the maximum turbulent intensity values lies between 0.9 - 1.1 m/s range lies in the region of building A near which higher wind speeds exists (which are also regions of near zero PMV). For certain wind directions (NNE, West and South), this region of maximum turbulence is limited to a smaller region, while for other wind directions (Easterly,Northerly,SSW), this region of maximum turbulence is more widespread. The interesting thing to note is that due to existence of many flow passages (channels) that leads the inlet wind towards the tallest building A, it is not easy to predict the location of highest turbulent intensity without the use of CFD. The next step will be to develop a quantitative measure to classify turbulent intensity from a cyclist's safety perspective.

3.4. Cycling Comfort Region

For the summer conditions, a cyclist would like to cycle in a city region with near zero PMV and a safe TI level. For all the 6 wind directions, the regions of high wind speed (pertaining to near-zero low PMV) exist near the taller building A due to more openness and less flow restrictions, but also lies in the same region, the maximum TI zone (due to high wind velocity gradients from high speed). At this stage, we do not know if the maximum TI obtained here can be classified as unsafe for cyclist. It is difficult to find a region with both near-zero PMV and near-zero TI exists as both conditions are difficult to achieve for similar wind conditions. But, there are certain regions in the city where both PMV below 1 and TI between 0.2 - 0.4 exists, perhaps, such regions can be considered safe.

4. Conclusion

The current work suggests a methodology for obtaining a ”cycling comfort matrix” for measuring cycling comfort in an urban layout. The methodology involves conducting micro-scale CFD simulations of an realistic urban area (Niigata from Japan) under different meteorological conditions (wind directions)to obtain these two parameters (the Predicted Mean Vote (PMV) and the Turbulent intensity (TI)). The CFD model is validated with an experimental data, and then the impact of wind and layout on these parameters are analyzed. Results indicate that the wind velocity impacts both the PMV and TI in different ways. During the high humid summer time, the higher wind velocity zones in the urban land-scape will provide thermal comfort to cyclist (as indicated by the low PMV values), while, the same higher wind velocity regions can also lead to establishment of higher gradients near the building vicinity (thus leading to higher TI which will be unsafe for the cyclist). The regions that could be preferable for cycling in humid summer time is a near-zero PMV and a near-zero TI region (or TI values in safer limits). But obtaining conditions of near-zero PMV and near-zero TI both in the same region is difficult as seen in this work. Future work involves developing a guideline for TI based on discussion with cyclist, and using this methodology on urban cycling pathways available through the CYCLE-TO-ZERO (CTZ) and CLIMAMOB projects involving Norwegian municipalities like Oslo, Bergen, Trondheim and Stavanger. This work has the prospect of both aiding in planning of new cycle routes and developing smart urban localities for comfortable cycling.

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