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Are Tornado Vortex Generators fit for purpose?

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1 Are Tornado Vortex Generators fit for purpose?

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6 Abstract

7 In recent years a number of Tornado Vortex Generators (TVGs) have been 8 constructed and tested, with a view to providing facilities that can be used to 9 determine wind loads on a variety of structures in tornado conditions. The 10 scaling of TVGs has however proved to be contentious and different authors have 11 taken different approaches. In this paper we address this issue and firstly 12 present a formal dimensional analysis of the flow within full scale tornadoes and 13 TGVs, which identifies a number of important dimensionless groups. We then 14 consider a range of full-scale tornado data and, as far as possible, derive values of 15 these dimensionless groups for each tornado. This analysis is then used to define 16 the ranges of the dimensionless parameter for three tornado types (all of the two 17 cell form) that can be used as simulation targets, rather unimaginatively naming 18 them small, medium and large tornadoes. We then consider the performance of 19 four medium to large TVGs in achieving these simulations. The analysis shows 20 that the larger TVGs can achieve a range of geometrical similarities for the small 21 and medium simulation targets, but none are able to achieve kinematic 22 similarity, in that the ratio of circumferential to radial velocities are significantly 23 lower than at full scale. Dynamic similarity (based on the Reynolds number) is of 24 course not possible for physical models, but the analysis shows that in almost all 25 cases the Reynolds number and model scales fall well below what would be 26 considered acceptable in atmospheric boundary layer wind tunnels. We thus 27 regretfully conclude that current TVGs are not wholly fit for purpose at the moment and are in need of significant modification if they are to be used to give 28 reliable loading data. Alternatively it may be that the wind engineering 29 community should consider different types of simulation to obtain the required 30 31 information.

32 1. Background

33 Tornado wind damage to building structures is of concern in many countries 34 around the world, particularly for low rise domestic structures. There has been 35 much recent research activity both to measure tornado characteristics at full 36 scale and also attempts to simulate these flows at model scale using what have 37 become known as Tornado Vortex Generators (TVGs), in order that the wind 38 loading can be measured on suitably scaled models. These TVGs have taken a 39 number of forms but tend to all have similar features, albeit with different 40 configurations, i.e., a fan or series of fans is used to generate an updraft with guide vanes used to introduce the appropriate degree of circulation. The vast 41 42 majority of the simulators used to date follow the principles of Ward (Ward, 43 1972), where guide vanes are placed around a convergence chamber akin to the 44 atmospheric sub-cloud inflow layer in a real tornado (although in Ward's 45 original design, a rotating mesh was used instead of guide vanes). A fan (or multiple fans) sits above a convection chamber, which in turn is located 46 47 immediately above the convergence chamber. The generated updraft and the 48 convection chamber are assumed to be representative of the convective process 49 in a cumulus cloud. Typically, a flow rectifier of some type is also located close to 50 the fans to act as a vorticity sink. The other type of TVG worth noting are those 51 based on the Iowa State University design (Haan et al., 2008). Unlike traditional 52 ward-type simulators, the guide vanes are located near to the return flow of the 53 updraft enabling a rotating flow to be introduced at the inlet. In principle all 54 types of generator can be moved to model tornado translation, although this 55 becomes progressively more difficult as the size of the facility increases.

56 In this note we consider the nature of the flows produced within such TVGs and assess whether they are representative of real tornadoes, and if so, at what 57 58 physical scale. We firstly set out a formal dimensional analysis of the issue, and 59 then present a collation of full-scale data in the form suggested by the 60 dimensional analysis. On the basis of this, we define a small number of 61 "standard" tornadoes that can act as simulation targets, and assess whether or 62 not a range of current TVGs are capable of achieving these simulation targets. The analysis will be seen to suggest that even the largest of existing TVGs are 63 64 only able to reproduce geometrically scaled flows (rather than kinematically or dynamically scaled) at scales and Reynolds numbers that are at best only 65 66 marginally acceptable for wind loading studies, particularly on low rise 67 buildings.

The conclusions arrived at in this paper will inevitably be regarded by some as controversial. However, the authors hope that this work will stimulate discussion within the wind engineering community on the appropriate use of TVGs and the proper scaling of flows within them, and will also act as a spur for the acquisition of more much-needed full-scale data.

73 **2. Dimensional analysis**

The pressure load on a low rise building in a tornado can be given by thefollowing functional expression

76
$$\Delta p = F(N, V_m, U_m, Q_t, r_{Vm}, z_{Vm}, r_{Um}, z_{Um}, H, R, k_s, \rho, \mu)$$
(1)

- 77 where the symbols are defined as follows.
- Δ*p* is the pressure on the surface of the building relative to a reference
 pressure outside the tornado;
- N is the number of cells in the tornado, that characterizes its overall form

 a one cell tornado will be a simple inflow and updraft, whilst a two cell
 tornado will have a (usually weak) outflow and downdraft near the
 vortex centre, and an inflow and updraft away from the centre.
- V_m is the maximum circumferential velocity;
- 85 U_m is the maximum radial velocity;
- Q_t is the translational velocity;
- 87 r_{Vm} is the radial distance from the vortex centre at which the 88 circumferential velocity is a maximum;
- 89 z_{Vm} is the vertical distance above the ground at which the 90 circumferential velocity is a maximum;
- *r*_{Um} is the radial distance from the vortex centre at which the radial
 velocity is a maximum;
- 93 z_{Um} is the vertical distance above the ground at which the radial velocity 94 is a maximum;
- *H* is the length scale (often the height) of the structure under
 consideration;

- *R* is the radial distance of the structure from the centre of the tornado;
- 98 k_s is the surface roughness.
- 99 ρ is the density of air;
- 100 μ is the dynamic viscosity of air.

101 Note that the parameter list contains observed tornado parameters rather than 102 the underlying meteorological properties that cause tornadoes. This is a 103 deliberate choice that has been made, since this paper addresses engineering 104 rather than meteorological aspects of tornadoes. Similarly we do not consider 105 the geometric parameters of the TVGs, such as aspect ratio, since we are 106 interested in the flow that these geometries produce rather than the geometries 107 themselves. The other point that is worthy of mention at this stage is the nature 108 of the boundary layer near the ground. In principle the flow velocities and 109 turbulence parameters in this region are specified by the thickness of the 110 boundary layer, the nature of the flow field above the boundary layer and the 111 surface roughness. However, to some extent the nature of the surface roughness will determine the thickness of the boundary layer, so z_{Vm} and k_s are not wholly 112 113 independent of each other. At this stage however, we will keep both parameters 114 in the analysis, although it will be seen below that practical considerations require that simplifications be made in what follows. 115

116 It has to be acknowledged that there is always a degree of judgment in writing 117 expressions such as equation (1), which need to contain all the parameters 118 required to characterize the problem under consideration. Here it can be seen 119 that we have taken the tornado is taken to be characterized by a parameter 120 describing the overall form (i.e., N); four lengths, defining the horizontal and 121 vertical scales; and three velocities, defining the circumferential and radial velocities, and the translational velocity. Models of tornado vortices, such as 122 123 those outlined in Baker and Sterling (2017) (2018) suggest that, in principle, the 124 specification of these parameters will also, through the conservation of mass 125 momentum equations, be sufficient to determine the overall velocity (including the vertical velocity) and pressure fields within the vortex. This is a major 126 127 assumption, albeit one that is made implicitly in much work within the field of 128 wind engineering studies of tornado loading.

For the specification of the loads on ground mounted structures the vertical scales are of some importance, as they define the extent of what will be called the boundary layer flow near the ground – the flow region in which at least part of the structure will be situated.

133 Carrying out a formal dimensional analysis, one obtains the following134 expression.

135
$$\frac{\Delta p}{\rho V_m^2} = G\left(N, \frac{r_{Vm}}{z_{Vm}}, \frac{r_{Um}}{r_{Vm}}, \frac{z_{Um}}{z_{Vm}}, \frac{V_m}{U_m}, \frac{Q_t}{V_m}, \frac{\rho V_m r_{Vm}}{\mu}, \frac{H}{z_{Vm}}, \frac{R}{R}, \frac{k_s}{z_{Vm}}\right)$$
(2)

Here the 14 dimensional parameters have resulted in 11 dimensionless groups in accordance with the Buckingham Pi theorem (number of parameters minus number of dimensions, with the latter being three in this case). If a properly scaled experiment is to be carried out to measure the pressure loads on a structure in a tornado, then all the parameters in the functional expression in the above equation should have the same values at model scale as at full scale. The dimensionless parameters in equation (2) have the following significance.

- 143 $\frac{\Delta p}{\rho V_m^2}$ is a pressure coefficient that will include the effects of both the direct 144 wind loading and of the pressure variation in the tornado. If all the other 145 groups are simulated correctly, then this parameter will also have the 146 same values at model scale as at full scale.
- *N*, as before, specifies the overall form of the tornado, and is thus an
 overall similarity parameter.
- 149 $\frac{r_{Vm}}{z_{Vm}}$, $\frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ are the geometric scale ratios of the tornado.
- 150 $\frac{v_m}{u_m}$ is the ratio of the circumferential to radial velocities. This is the 151 equivalent of the Swirl ratio used by many physical modellers, although 152 the definition of that parameter can vary somewhat between 153 investigators. The Swirl ratio is a dependent variable, and can be defined 154 from the other variables that are listed here. As normally defined, it is a 155 function of TVG geometry, and cannot be defined for full scale conditions.

156 •
$$\frac{Q_t}{V_m}$$
 is the dimensionless translational velocity of the tornado.

- 157 $\frac{\rho V_m r_{Vm}}{\mu}$ is the Reynolds number based on maximum circumferential 158 velocity and the radius at which it occurs.
- 159 $\frac{H}{z_{Vm}}$ is the model scale factor.
- 160 $\frac{H}{R}$ is the ratio of the height of the structure to the distance from the centre 161 of the tornado.

162 • $\frac{k_s}{z_{Vm}}$ relates the boundary layer thickness and the surface roughness.

163 Other dimensionless group could also be defined from the above parameter set,164 but these will all be functions of the groups set out above. In particular different

165 Reynolds numbers could be defined, based on different velocities and length 166 scales, but to include them in the above would be to over specify the problem. To achieve geometric similarity in any simulation, $N, \frac{r_{Vm}}{z_{Vm}}, \frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ need to be 167 correctly reproduced. To achieve kinematic similarity in addition $\frac{V_m}{U_m}$ and $\frac{Q_t}{V_m}$ need 168 to be correctly reproduced, and to achieve dynamic similarity $\frac{\rho V_m r_{Vm}}{\mu}$ must also 169 be reproduced. The latter is impossible of course, and at best any physical model 170 171 simulation can only achieve geometric and kinematic similarity. For a simulation 172 to be considered adequate both geometric and kinematic scaling need to be achieved. $\frac{H}{Z_{VM}}$ and $\frac{H}{R}$ are effectively operator controlled modeling choices as to 173 what scale and position of the building relative to the centre of the tornado is 174 used. The last dimensionless group in the list (the surface roughness / boundary 175 layer thickness ratio) is, in principle also a geometric scaling parameter, and, as 176 177 it will to a large extent determine the boundary layer velocity and turbulence 178 intensity profiles, also a kinematic scaling parameter. However this parameter is 179 very hard to specify, since in most full-scale measurements the surface 180 roughness is difficult to determine, and TVGs usually use a smooth floor, rather 181 than simulated roughness. Thus in what follows this parameter will not be 182 considered further – although it is clear that that more attention needs to be paid to surface roughness in both full scale and TVG measurements. 183

184 It would appear from the literature that the only model scale investigations that 185 have recognized the importance of more than one tornado length scale and, 186 effectively, the need to simulate some or all of $\frac{r_{Vm}}{z_{Vm}}$, $\frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ correctly in any 187 model scale simulation, are those of Refan et al (2014) and Refan and Hangan 188 (2018) for the small and large WindEEE simulators. They have developed a 189 method for matching full-scale tornado data for this ratio against their model 190 scale data at one operating condition in their facilities. Other investigators, as far 191 as can be ascertained use just one length scale to specify the tornado geometry – 192 usually r_{Vm} - or base the scale of the simulation on the scale of the structure that 193 is being tested.

194 **3. Full scale data collation**

195 Table 1 is a collation of full-scale tornado data from a range of sources for two 196 cell tornadoes only. Note that, in line with other authors, we use multiple data 197 sets from the same tornado. There is a danger here that the data will be regarded 198 as non-independent, but as the objective was to define ranges of tornado 199 parameters, it was felt that this was acceptable. Such tornadoes seem to 200 represent the norm, with much less data available for simpler one-cell tornadoes, 201 which seem to have generally lower, less critical wind speeds. The chosen 202 tornadoes are listed by size given by the value of r_{Vm} . Values are given of the 203 parameters $N, r_{Vm}, z_{Vm}, r_{Um}, z_{Um}, V_m, U_m$ and Q_t , and dimensional the dimensionless parameters $\frac{r_{Vm}}{z_{Vm}}$, $\frac{r_{Um}}{r_{Vm}}$, $\frac{z_{Um}}{z_{Vm}}$, $\frac{V_m}{U_m}$ and $\frac{Q_t}{V_m}$. The other parameters in 204 205 the dimensional analysis of the last section are either functions of a hypothetical building or of the ground roughness, and not directly relevant to the 206 207 identification of tornado parameter ranges, although they will be considered 208 below.

209 In most cases the data is incomplete, as some parameter values are not available. 210 As most of the information is taken from radar-based methods, velocities below 211 about 50m above the ground could not be measured and thus the values of the 212 heights at which the maximum velocities occur (z_{Vm} and z_{Um}) may not be truly 213 captured. We have in general taken data from as low a height as possible to use 214 in the analysis. The most recent results by Kosiba and Wurman (2013), which 215 did make measurements at lower heights for the small and relatively low speed 216 Russell tornado, suggest that these heights can be as low as 5m above the ground 217 or below. It should also be noted that full-scale tornado parameters are very

transitory, and can vary very significantly in a small period of time and thus any full-scale dataset in the table is something of a snapshot of a rapidly changing reality. Finally note that some of the data in that table was obtained from reading graphs in published papers and this might lead to inaccuracies. Where this is the case, the table entries are asterisked to indicate this. From this data the following observations can be made.

• The ratio $\frac{r_{Vm}}{z_{Vm}}$, which can be considered the primary geometric ratio, has values of between 1.9 and 17.5, and generally decreases as tornado size, given by r_{Vm} , increases.

• There is significant scatter in the values of the geometric ratios $\frac{r_{Um}}{r_{Vm}}$ and 228 $\frac{z_{Um}}{z_{Vm}}$, with the former being in the range 1.3 to 3.7 and the latter being 229 generally around unity. Thus the maximum value of radial velocity is 230 further from the vortex centre than that for circumferential velocity.

• The values of $\frac{V_m}{U_m}$ are in the range 4.5 to 12.3, with a generally increasing value as tornado size increases (with the size specified by the core radius r_{Vm}).

• The values of $\frac{Q_t}{V_m}$ are in the range 0.1 to 0.25 (with one exception) and increase somewhat as tornado size increases.

236 4. Definition of "standard" tornadoes

From the data in table 1 we can define three "standard" tornadoes that could be used as simulation targets. The characteristics of these are shown in table 2. We define three sorts of tornadoes.

- Small tornadoes, with values of r_{Vm} of the order of 50m, based on the 241 parameters of the Russell tornado (Kosiba and Wurman, 2013).
- Medium sized tornadoes, with values of r_{Vm} of the order of 200m, based on the data collation of Refan et al (2014) (2017), augmented by data from Kosiba and Wurman (2010).
- Large tornadoes, with r_{Vm} of the order of 500 to 1000m, based on the measurements in the Mulhall tornado (Lee and Wurman, 2005).

247 For each tornado type, a plausible range of the different dimensionless parameters is given based on the data in table 1. We have chosen this 248 249 methodology of defining target ranges for standard tornadoes as being of more 250 practical utility than defining individual tornado events as simulation targets, as 251 such events are only individual realisations of a statistical distribution. Note that 252 there is much subjectivity in this approach, and the parameter ranges for the 253 different types of tornado could have been somewhat differently defined. The 254 ranges that have been chosen represent a smooth transition from one tornado 255 type to another. Any slight changes however will not affect the thrust of the argument in this paper. Note in particular that as the ranges for $\frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ are 256 257 not well defined from the full scale data, the same range has been specified for all 258 tornadoes.

259 For any particular physical simulation, primary geometric similarity (G_1) requires that the tornado be of the two cell or touchdown type and that values of 260 $\frac{r_{Vm}}{z_{Vm}}$ fall within the required ranges, and secondary and tertiary geometric 261 similarity (G₂ and G₃) requires that $\frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ also fall within the (less well 262 defined) ranges; primary kinematic similarity requires that the parameter $\frac{V_m}{U_m}$ 263 falls within the required range (K_1) and secondary kinematic similarity requires 264 that the translational parameter $\frac{Q_t}{V_m}$ is within the required range (K₂). As full 265 dynamic similarity (D) is impossible, we specify that the Reynolds number based 266 267 on maximum tornado velocity and a building length scale of 10m must exceed 5 $x = 10^4$, in order that the flow patterns around the building are correctly 268 269 reproduced. ASCE (2012) suggest a lower value of 1.1 x 10⁴ for this parameter, 270 although with a somewhat vaguely defined length scale, and AWES (2016) give a 271 value of 5 x 10^4 based on building width. CEN (2016), for tests on trains in low 272 turbulence conditions, gives a much higher value of $2 \ge 10^5$. Bearing in mind the 273 fact that the Reynolds number as defined above will be the maximum in the 274 tornado and can be very much lower away from the region of maximum velocity. 275 a value of 5 x 10^4 seems an appropriate compromise. Lower values of the 276 Reynolds number would particularly affect the dynamics of separated or 277 building-induced vortex flow regions, and render load measurements, particularly of fluctuating quantities, quite unreliable (Lim et al, 2007). 278

279 **5. Assessment of TVGs**

Gilleimer et al (2017) classifies TVGs into three types – small (S) (diameter < 1m), medium (M) (diameter between 2m and 5m) and large (L) (diameter greater than 5m). For reasons that will become apparent we will not consider here any of the small generators that have been used in the past (Mishra et al (2008) or the small rig used by Gilleimer et al). The performance of the following four TVGs was assessed.

- The medium sized University of Birmingham (UOB) facility, which is a
 typical Ward type configuration, with an updraft 1m in diameter and a
 testing chamber 3.6m in diameter, with 30 turning vanes.
- The large sized Iowa State University (ISU) facility, which uses the rotating forced downdraft technique, and has an updraft diameter of 1.83m and an overall vortex diameter of 5.5m. This facility is able to move above a ground plane (Haan et al, 2008; Case et al, 2014).
- The large sized Texas Tech University (TTU) VorTECH facility, which is of
 a typical Ward type configuration, has an updraft 4m in diameter and a
 testing chamber 10.2m in diameter, with 64 turning vanes (Eguchi et al,
 2018, Tang et al, 2018).
- The large sized University of Western Ontario (UWO) WindEEE facility,
 which is of the vane type with the flow provided by fans at both the inlets
 and the outlets. It has an updraft 4.5m in diameter and an octagonal
 testing chamber 25m in diameter (Refan and Hangen, 2018). The fans
 primarily responsible for the updraft can also be translated over a
 distance of 5m with a translation speed of up to 2m/s.

For each of the above, the range of the various dimensionless parameters has
been calculated as far as possible (Table 3). Again this required that in some
instances, various assumptions be made or data read from published figures.

306 Table 4 shows a matrix of tornado type against simulator and gives the following307 information.

- The swirl ratio for the TVG. As the definitions of swirl ratio used for each
 TVG can vary, this parameter can be a function of the nature of the TVG
 itself and as such these values should not be compared between TVGs, but
 rather taken as an indication of the operating point of the facility.
- The length and velocity scales, based on the values measured in the TVGs
 and the target values.
- The Reynolds number based on maximum vortex velocity in the TVG and
 a full-scale length scale of 10m.
- The nature of similarity that is achieved, where the dimensionless
 parameters for the simulator coincide with one or more of the parameter
 ranges of the target tornadoes.

319 Consider first the Reynolds numbers that are based on a model length of 10m. In 320 nearly all cases these are below the value of 0.5×10^5 specified above. The 321 exception is for the small tornado case for the UWO TVG. The three large TVGs 322 have values for the small tornado of between 0.33 and 1.53 x 10^5 , whilst the medium sized TVG has values of 0.12 to 0.33×10^5 . For the medium tornado the 323 324 values are between 0.08 to 0.38×10^5 for the large TVGs, whilst the medium TVG 325 has values between 0.03 and 0.08 x 10^5 . For the large tornado case the values of 326 Reynolds number do not exceed 0.15×10^5 throughout. The length scales follow

327 the same pattern with length scales that would be regarded as reasonable for 328 atmospheric boundary layer testing of low rise buildings of less than (say) 1:200 329 is generally only achieved for the small tornado case in the large generators. If 330 we accept that high rise buildings may be tested at a smaller scale, say 1:400, 331 then the medium tornado case has acceptable length scales in the large TVGs. The general conclusion however is that, even the large TVGs have Reynolds 332 333 numbers that would only be considered marginally acceptable for small and, 334 perhaps, medium tornado simulations.

335 Now let us consider the nature of the similarity that the TVGs achieve. In the light 336 of what has been said above, only the three large facilities will be considered for 337 the small and medium tornadoes. It can be seen that all three generators can achieve primary geometric similarity based on the position of the maximum 338 339 tangential velocity (G_1) for certain conditions and, rather sporadically, secondary and tertiary geometric similarity based on the position of the maximum radial 340 velocity (G_2 and G_3). The UWO facility can also achieve secondary kinematic 341 342 similarity for translation speeds (K_2) in specific cases. However none of the 343 facilities show primary kinematic similarity, the ratio of the maximum 344 circumferential velocity to radial velocity (K_1). All facilities show values of this 345 ratio that are too low, i.e. the radial velocity component is relatively stronger in the TVGs than the values captured at full-scale. 346

347 Overall the "best" performing facility for stationary tornadoes, seems to be the 348 UWO WindEEE dome for medium tornadoes, with a range of geometric 349 similarities, reasonable length scales and Reynolds numbers, at least for small 350 tornadoes, that are bordering on the acceptable. This observation is consistent with the work of Refan and Hangan (2018), who however only consideredgeometric similarity.

353 **6. Discussion**

354 Before considering the adequacy of the TVGs considered, it is worth revisiting two aspects of the above analysis - the dimensional analysis and the 355 356 determination of full-scale parameters. The former is a rigorous analysis, but is based on an assumed parameter set to describe tornadoes. The essential 357 358 assumption is that two-cell tornadoes can be specified by four length scales and 359 three velocity scales, and that the velocity and pressure distributions can all be 360 derived from these parameters, at least in principle, through the governing 361 equations of the flow. This assumption of course is implicit in most model scale 362 investigations of tornadoes. With regard to the determination of full-scale parameter ranges, it has to be acknowledged that there is much subjectivity in 363 364 this due to the paucity and variability of the data, but one hopes a sound 365 engineering judgment has been applied to the process of specifying these ranges. 366 In some ways this subjectivity simply reflects the current availability of full scale 367 data and it seems that the enthusiasm to build large scale experimental facilities 368 has run some way ahead of the full scale data needed to verify them.

369 From the above discussion it appears that primary geometric scaling of 370 tornadoes is possible to achieve for a limited range of tornadoes in any one 371 simulator. The simulators however do not achieve primary kinematic scaling. This is significant, as the ratio $\frac{V_m}{U_m}$ determines the curvature of the flow, which 372 373 can be of a similar order to the wake of building model and can thus have a major 374 effect on the flow field around any model and thus on the measured loads. This significantly limit the usefulness of TVGs. However even if geometric and 375 376 kinematic scalings can be achieved, the simulated scales and Reynolds numbers

377 are smaller than generally required and cannot be considered practical for model 378 scale testing, particularly on low rise buildings. The values of these parameters 379 for the medium sized facility that was considered (the authors' own facility at the 380 University of Birmingham) are particularly poor in this regard - indeed it was 381 this poor scaling performance that led to the investigation described in this paper. However, small and medium sized facilities are very useful in developing 382 383 a general understanding of the physics of tornado-like flows. Even in the largest facilities the Reynolds numbers are smaller than would be desired, and the 384 385 similarity of flow around structures at such Reynolds number cannot be 386 guaranteed. Thus it must, regretfully, be concluded that in general TVGs are not 387 fit for purpose and do not provide proper geometric and kinematic scaling of 388 tornadoes at Reynolds numbers high enough to be practical.

389 There are a number of ways to address this situation. Firstly TVGs can be 390 modified to achieve greater levels of similarity. The geometric scale ratios in 391 TVGs might be made more realistic in terms of the target values, in some cases, by attempting to decrease model scale values of $\frac{r_{Vm}}{z_{Vm}}$, perhaps through the use of 392 393 floor roughness or barriers close to the vanes in simulators of the vane type to increase z_{Vm} . To achieve correct kinematic scale ratios, and in particular larger 394 values of $\frac{V_m}{U_m}$, is more difficult and may require some facility redesign. The 395 396 Reynolds number issue can be addressed through the use of larger facilities with 397 greater fan power and higher vortex speeds - although this may not be 398 physically or economically possible.

A second approach might be to develop new kinds of facility. For example it ispossible to conceive of a partial simulation of tornadoes through the simulation

401 of the near ground wind field only by growing thick boundary layers in curved 402 ducts, with the duct curvature being variable and matched to the curvature of the 403 flow in either stationary or moving tornadoes. This curvature can be calculated 404 from models such as that of Baker and Sterling (2018). The boundary layer 405 depth could be equal to z_{Vm} through various combination of inlet screens and 406 floor roughness. As an added complication a vertical flow could be induced 407 through the use of a porous ceiling to such ducts. The advantage of such a method would be that much larger model scales and Reynolds numbers could be 408 409 achieved than in the current generation of TVGs.

It is also clear that more full-scale data is required of tornado wind conditions very close to the ground, in particular to determine the height at which the maximum velocity occurs – effectively the thickness of the tornado boundary layer. Full-scale experiments of this type are difficult and large-scale LES / DES simulations may also be able to give an indication of flow conditions in the near ground region.

Finally, if however future work suggests that even for medium and large tornadoes, the height above ground at which the maximum velocity occurs is much lower than currently assumed, as it would seem Kosiba and Wurman (2013) consider likely, then this definition of "standard" tornado parameters will need to be revisited.

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Tornado name	Data Source	Ν	<i>r_{Vm}</i> (m)	r _{Um} (m)	<i>z_{Vm}</i> (m)	<i>z_{Um}</i> (m)	<i>V_m</i> (m/s)	<i>U_m</i> (m/s)	<i>Q_t</i> (m/s)	$\frac{r_{Vm}}{z_{Vm}}$	$\frac{r_{Um}}{r_{Vm}}$	$\frac{Z_{Um}}{Z_{Vm}}$	$\frac{V_m}{U_m}$	$\frac{Q_t}{V_m}$
Russell 1 02:40:53	K13	2	30*	90*	4*	4*	46.0*	8*	5	7.5	3	1.0	5.8	0.11
Russell 2 02:41:36	K13	2**	70*	90*	4*	4*	36.0*	8*	5	17.5	1.3	1.0	4.5	0.14
Goshen County 3	R14	2	100	-	41	-	42.9	-	9.5	2.43	-	-	-	0.22
Goshen County 1	R14	2	150	-	42	-	41.6	-	9.5	3.57	-	-	-	0.23
Нарру 2	R14	2**	160	-	50	-	37.9	-	19.4	3.2	-	-	-	0.51
Spencer 3 01:34:23	K10	2	190*	700	40*	40*	72.1*	16.2 *	10.6*	4.75	3.7	1.0	4.5	0.15
Spencer 1	R14, R17	2	192	-	40	-	58.2	-	15.0	4.80	-	-	-	0.26
Spencer 2	R14, R17	2	208	-	40	-	62	-	15.0	5.20	-	-	-	0.24
Spencer 4 01:40:02	K10	2	210*	700	40*	160*	71.5*	5.8*	10.6*	5.25	3.3	4.0	12.3	0.15
Mulhall 1 03:16:28	L05	2	590*	1500	150*	150*	76.0*	12*	11.0*	3.93	2.54	1.0	6.3	0.14
Mulhall 2 03:20:24	L05	2	690*	2500	350*	225*	55.0*	12*	11.0*	1.97	2.62	0.64	4.6	0.20

Table 1 Full-scale tornado characteristics

(* estimate from graph in reference; ** for these tornadoes, the downdraft in the centre only just reaches ground level, and are referred to in R14 as "touch down" tornadoes: K10 – Kosiba and Wurman, 2010: K13 – Kosiba and Wurman, 2013; L05 – Lee and Wurman 2005: R14 – Refan et al, 2014; R17 – Refan et al, 2017)

	N	r_{Vm}	$\frac{r_{Um}}{\pi}$	$\frac{Z_{Um}}{Z}$	V _m	Q_t	$\rho V_m H$	Full-scale values for determining			
Simulation	IN	Z_{Vm}	^r _{Vm}	Z_{Vm}	$\overline{U_m}$	$\overline{V_m}$	μ	length and v	elocity scales		
name											
		<i>G</i> ₁	G2	G3	<i>K</i> ₁	<i>K</i> ₂	D	<i>r_{Vm}</i> (m)	$V_m (m/s)$		
Small	2	5 to 20	1 to 4	0.5 to 1.5	4 to 7	0.1 to 0.15	>5 x 10 ⁵	50	40		
Medium	2	2 to 6	1 to 4	0.5 to 1.5	4 to 13	0.15 to 0.25	>5 x 10 ⁵	200	50		
Large	2	1 to 4	1to 4	0.5 to 1.5	8 to 16	0.15 to 0.25	>5 x 10 ⁵	500	60		

Table 2 Standard "target" tornadoes

TVG	S	Ν	r_{Vm}	r _{Um}	Z_{Vm}	Z _{Um}	V_m	Um	Q_t	r_{Vm}	$\frac{r_{Um}}{r}$	Z _{Um}	$\frac{V_m}{U}$	$\frac{Q_t}{W}$
			(m)	(m)	(m)	(m)	(m/s)	(m/s)	(m/s)	Z_{Vm}	T_{Vm}	Z_{Vm}	U_m	Vm
UOB (G17)	0.30	2	0.09	0.08	0.003	0.003	9.56	2.06	-	15	0.9	0.5	4.64	-
UOB (G17)	0.69	2	0.225	0.21	0.012	0.003	10.70	4.79	-	18.7	0.93	0.25	2.22	-
ISU (H08)	1.14	2	0.53	2.12*	0.106*	0.106*	9.7	4.16*	-	5	4	1	3.21	-
ISU (C14)	2.6	2	0.56	-	0.019	-	11.6	-	0.15	29.5	-	-	-	0.013
TTU (T18)	0.36	2	0.18	0.22*	0.04*	0.01*	13.5	6.9 *	-	4.5	1.22	0.25	1.9	-
TTU (T18)	0.84	2	0.52	0.61*	0.09*	0.01*	12.9	8.1*	-	5.8	1.19	0.11	1.6	-
UWO (R18)	0.59	2	0.52\$	0.74	0.20	0.12	12.8	6.24*	2.0\$\$	2.60	1.43	0.6	2.0	0.16\$\$
UWO (R18)	1.03	2	0.69	0.69	0.20	0.06	16.2	7.78*	2.0\$\$	3.45	1.0	0.3	2.08	0.12\$\$

Table 3 Characteristics of TVGs

(* estimate from graph in paper; \$ corrected from 0.42 in R18; \$\$ maximum values; H08 – Haan et al (2008); C14 – Case et al (2014); T18

- Tang et al (2018); G18 - Gilleimer et al (2017); R18 - Refan and Hangan (2018))

		c	L	ength Scale	9	V	elocity Sca	le	Reynol	ds numb	er / 105	Criteria satisfied			
	še	5		(G)			(K)			(D)					
	TVG siz		Small Tornado	Medium Tornado	Large Tornado	Small Tornado	Medium Tornado	Large Tornado	Small Tornado	Medium Tornado	Large Tornado	Small Tornado	Medium Tornado	Large Tornado	
UOB (G18)	М	0.30	556	2222	5556	4.2	5.2	6.3	0.12	0.03	0.01				
UOB (G18)		0.69	222	889	2222	3.7	4.7	5.6	0.33	0.08	0.03				
ISU (H08)		1.14	94	377	943	4.1	5.2	6.2	0.70	0.18	0.07	$G_1 \ G_2 \ G_3$	$G_1 G_2 G_3$		
ISU (C18)		2.6	89	357	893	3.4	4.3	5.2	0.89	0.22	0.09	G1			
TTU (T18)		0.36	278	1111	2778	3.0	3.7	4.4	0.33	0.08	0.03	G ₂	G_1G_2		
TTU (T18)	L	0.84	96	385	962	3.1	3.9	4.7	0.92	0.23	0.09	G_1G_2	$G_1 G_2$		
UWO (R18)		0.59	96	385	962	3.1	3.9	4.7	0.91	0.23	0.09	G2 G3	G1 G2 G3 K2		
UWO (R18)		1.03	72	290	725	2.5	3.1	3.7	1.53	0.38	0.15	G ₂ K ₂ , D	$G_1 G_2$		

Table 4 Performance of TVGs against standard target tornadoes