

## Are Tornado Vortex Generators fit for purpose?

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1           **Are Tornado Vortex Generators fit for purpose?**

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5

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  
28 moment and are in need of significant modification if they are to be used to give  
29 reliable loading data. Alternatively it may be that the wind engineering  
30 community should consider different types of simulation to obtain the required  
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  
41 guide vanes used to introduce the appropriate degree of circulation. The vast  
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  
46 multiple fans) sits above a convection chamber, which in turn is located  
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  
57 assess whether they are representative of real tornadoes, and if so, at what  
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.  
63 The analysis will be seen to suggest that even the largest of existing TVGs are  
64 only able to reproduce geometrically scaled flows (rather than kinematically or  
65 dynamically scaled) at scales and Reynolds numbers that are at best only  
66 marginally acceptable for wind loading studies, particularly on low rise  
67 buildings.

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

## 73 2. Dimensional analysis

74 The pressure load on a low rise building in a tornado can be given by the  
75 following functional expression

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

77 where the symbols are defined as follows.

- 78 •  $\Delta p$  is the pressure on the surface of the building relative to a reference  
79 pressure outside the tornado;
- 80 •  $N$  is the number of cells in the tornado, that characterizes its overall form  
81 – a one cell tornado will be a simple inflow and updraft, whilst a two cell  
82 tornado will have a (usually weak) outflow and downdraft near the  
83 vortex centre, and an inflow and updraft away from the centre.
- 84 •  $V_m$  is the maximum circumferential velocity;
- 85 •  $U_m$  is the maximum radial velocity;
- 86 •  $Q_t$  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;
- 91 •  $r_{Um}$  is the radial distance from the vortex centre at which the radial  
92 velocity is a maximum;
- 93 •  $z_{Um}$  is the vertical distance above the ground at which the radial velocity  
94 is a maximum;
- 95 •  $H$  is the length scale (often the height) of the structure under  
96 consideration;

- 97 •  $R$  is the radial distance of the structure from the centre of the tornado;
- 98 •  $k_s$  is the surface roughness.
- 99 •  $\rho$  is the density of air;
- 100 •  $\mu$  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  
112 will determine the thickness of the boundary layer, so  $z_{vm}$  and  $k_s$  are not wholly  
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  
115 require that simplifications be made in what follows.

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  
 122 velocities, and the translational velocity. Models of tornado vortices, such as  
 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  
 126 the vertical velocity) and pressure fields within the vortex. This is a major  
 127 assumption, albeit one that is made implicitly in much work within the field of  
 128 wind engineering studies of tornado loading.

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

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

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

136 Here the 14 dimensional parameters have resulted in 11 dimensionless groups  
 137 in accordance with the Buckingham Pi theorem (number of parameters minus  
 138 number of dimensions, with the latter being three in this case). If a properly  
 139 scaled experiment is to be carried out to measure the pressure loads on a  
 140 structure in a tornado, then all the parameters in the functional expression in the  
 141 above equation should have the same values at model scale as at full scale. The  
 142 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.
- 147 •  $N$ , as before, specifies the overall form of the tornado, and is thus an
- 148 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  
167 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  
168 correctly reproduced. To achieve kinematic similarity in addition  $\frac{V_m}{U_m}$  and  $\frac{Q_t}{V_m}$  need  
169 to be correctly reproduced, and to achieve dynamic similarity  $\frac{\rho V_m r_{Vm}}{\mu}$  must also  
170 be reproduced. The latter is impossible of course, and at best any physical model  
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  
173 achieved.  $\frac{H}{z_{Vm}}$  and  $\frac{H}{R}$  are effectively operator controlled modeling choices as to  
174 what scale and position of the building relative to the centre of the tornado is  
175 used. The last dimensionless group in the list (the surface roughness / boundary  
176 layer thickness ratio) is, in principle also a geometric scaling parameter, and, as  
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  
183 to surface roughness in both full scale and TVG measurements.

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 dimensional parameters  $N, r_{Vm}, z_{Vm}, r_{Um}, z_{Um}, V_m, U_m$  and  $Q_t$ , and the  
204 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  
205 the dimensional analysis of the last section are either functions of a hypothetical  
206 building or of the ground roughness, and not directly relevant to the  
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

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

- 224 • The ratio  $\frac{r_{Vm}}{z_{Vm}}$ , which can be considered the primary geometric ratio, has  
225 values of between 1.9 and 17.5, and generally decreases as tornado size,  
226 given by  $r_{Vm}$ , increases.
- 227 • 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.
- 231 • The values of  $\frac{V_m}{U_m}$  are in the range 4.5 to 12.3, with a generally increasing  
232 value as tornado size increases (with the size specified by the core radius  
233  $r_{Vm}$ ).
- 234 • The values of  $\frac{Q_t}{V_m}$  are in the range 0.1 to 0.25 (with one exception) and  
235 increase somewhat as tornado size increases.

#### 236 4. Definition of “standard” tornadoes

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

- 240 • 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).
- 242 • Medium sized tornadoes, with values of  $r_{vm}$  of the order of 200m, based  
243 on the data collation of Refan et al (2014) (2017), augmented by data  
244 from Kosiba and Wurman (2010).
- 245 • Large tornadoes, with  $r_{vm}$  of the order of 500 to 1000m, based on the  
246 measurements in the Mulhall tornado (Lee and Wurman, 2005).

247 For each tornado type, a plausible range of the different dimensionless  
248 parameters is given based on the data in table 1. We have chosen this  
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  
256 argument in this paper. Note in particular that as the ranges for  $\frac{r_{Um}}{r_{vm}}$  and  $\frac{z_{Um}}{z_{vm}}$  are  
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 ( $G_1$ )  
260 requires that the tornado be of the two cell or touchdown type and that values of  
261  $\frac{rV_m}{zV_m}$  fall within the required ranges, and secondary and tertiary geometric  
262 similarity ( $G_2$  and  $G_3$ ) requires that  $\frac{rU_m}{rV_m}$  and  $\frac{zU_m}{zV_m}$  also fall within the (less well  
263 defined) ranges; primary kinematic similarity requires that the parameter  $\frac{V_m}{U_m}$   
264 falls within the required range ( $K_1$ ) and secondary kinematic similarity requires  
265 that the translational parameter  $\frac{Q_t}{V_m}$  is within the required range ( $K_2$ ). As full  
266 dynamic similarity ( $D$ ) is impossible, we specify that the Reynolds number based  
267 on maximum tornado velocity and a building length scale of 10m must exceed 5  
268  $\times 10^4$ , in order that the flow patterns around the building are correctly  
269 reproduced. ASCE (2012) suggest a lower value of  $1.1 \times 10^4$  for this parameter,  
270 although with a somewhat vaguely defined length scale, and AWES (2016) give a  
271 value of  $5 \times 10^4$  based on building width. CEN (2016), for tests on trains in low  
272 turbulence conditions, gives a much higher value of  $2 \times 10^5$ . 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  $5 \times 10^4$  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,  
278 particularly of fluctuating quantities, quite unreliable (Lim et al, 2007).

## 279 **5. Assessment of TVGs**

280 Gilleimer et al (2017) classifies TVGs into three types – small (S) (diameter <  
281 1m), medium (M) (diameter between 2m and 5m) and large (L) (diameter  
282 greater than 5m). For reasons that will become apparent we will not consider  
283 here any of the small generators that have been used in the past (Mishra et al  
284 (2008) or the small rig used by Gilleimer et al). The performance of the following  
285 four TVGs was assessed.

- 286 • The medium sized University of Birmingham (UOB) facility, which is a  
287 typical Ward type configuration, with an updraft 1m in diameter and a  
288 testing chamber 3.6m in diameter, with 30 turning vanes.
- 289 • The large sized Iowa State University (ISU) facility, which uses the  
290 rotating forced downdraft technique, and has an updraft diameter of  
291 1.83m and an overall vortex diameter of 5.5m. This facility is able to move  
292 above a ground plane (Haan et al, 2008; Case et al, 2014).
- 293 • The large sized Texas Tech University (TTU) VorTECH facility, which is of  
294 a typical Ward type configuration, has an updraft 4m in diameter and a  
295 testing chamber 10.2m in diameter, with 64 turning vanes (Eguchi et al,  
296 2018, Tang et al, 2018).
- 297 • The large sized University of Western Ontario (UWO) WindEEE facility,  
298 which is of the vane type with the flow provided by fans at both the inlets  
299 and the outlets. It has an updraft 4.5m in diameter and an octagonal  
300 testing chamber 25m in diameter (Refan and Hangen, 2018). The fans  
301 primarily responsible for the updraft can also be translated over a  
302 distance of 5m with a translation speed of up to 2m/s.

303 For each of the above, the range of the various dimensionless parameters has  
304 been calculated as far as possible (Table 3). Again this required that in some  
305 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 following  
307 information.

- 308 • The swirl ratio for the TVG. As the definitions of swirl ratio used for each  
309 TVG can vary, this parameter can be a function of the nature of the TVG  
310 itself and as such these values should not be compared between TVGs, but  
311 rather taken as an indication of the operating point of the facility.
- 312 • The length and velocity scales, based on the values measured in the TVGs  
313 and the target values.
- 314 • The Reynolds number based on maximum vortex velocity in the TVG and  
315 a full-scale length scale of 10m.
- 316 • The nature of similarity that is achieved, where the dimensionless  
317 parameters for the simulator coincide with one or more of the parameter  
318 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  $0.5 \times 10^5$  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  $1.53 \times 10^5$ , whilst the  
323 medium sized TVG has values of 0.12 to  $0.33 \times 10^5$ . For the medium tornado the  
324 values are between 0.08 to  $0.38 \times 10^5$  for the large TVGs, whilst the medium TVG  
325 has values between 0.03 and  $0.08 \times 10^5$ . For the large tornado case the values of  
326 Reynolds number do not exceed  $0.15 \times 10^5$  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.  
332 The general conclusion however is that, even the large TVGs have Reynolds  
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  
338 achieve primary geometric similarity based on the position of the maximum  
339 tangential velocity ( $G_1$ ) for certain conditions and, rather sporadically, secondary  
340 and tertiary geometric similarity based on the position of the maximum radial  
341 velocity ( $G_2$  and  $G_3$ ). The UWO facility can also achieve secondary kinematic  
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  
346 the TVGs than the values captured at full-scale.

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

351 with the work of Refan and Hangan (2018), who however only considered  
352 geometric similarity.

353 **6. Discussion**

354 Before considering the adequacy of the TVGs considered, it is worth revisiting  
355 two aspects of the above analysis – the dimensional analysis and the  
356 determination of full-scale parameters. The former is a rigorous analysis, but is  
357 based on an assumed parameter set to describe tornadoes. The essential  
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  
363 parameter ranges, it has to be acknowledged that there is much subjectivity in  
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.  
372 This is significant, as the ratio  $\frac{V_m}{U_m}$  determines the curvature of the flow, which  
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  
375 significantly limit the usefulness of TVGs. However even if geometric and  
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  
382 paper. However, small and medium sized facilities are very useful in developing  
383 a general understanding of the physics of tornado-like flows. Even in the largest  
384 facilities the Reynolds numbers are smaller than would be desired, and the  
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,  
392 by attempting to decrease model scale values of  $\frac{rV_m}{z_{Vm}}$ , perhaps through the use of  
393 floor roughness or barriers close to the vanes in simulators of the vane type to  
394 increase  $z_{Vm}$ . To achieve correct kinematic scale ratios, and in particular larger  
395 values of  $\frac{V_m}{U_m}$ , is more difficult and may require some facility redesign. The  
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.

399 A second approach might be to develop new kinds of facility. For example it is  
400 possible 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  
408 method would be that much larger model scales and Reynolds numbers could be  
409 achieved than in the current generation of TVGs.

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

416 Finally, if however future work suggests that even for medium and large  
417 tornadoes, the height above ground at which the maximum velocity occurs is  
418 much lower than currently assumed, as it would seem Kosiba and Wurman  
419 (2013) consider likely, then this definition of “standard” tornado parameters will  
420 need to be revisited.

421 **7. Acknowledgements**

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Tornado name	Data Source	$N$	$r_{Vm}$ (m)	$r_{Um}$ (m)	$z_{Vm}$ (m)	$z_{Um}$ (m)	$V_m$ (m/s)	$U_m$ (m/s)	$Q_t$ (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
Happy 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)

Simulation name	$N$	$\frac{r_{Vm}}{z_{Vm}}$	$\frac{r_{Um}}{r_{Vm}}$	$\frac{z_{Um}}{z_{Vm}}$	$\frac{V_m}{U_m}$	$\frac{Q_t}{V_m}$	$\frac{\rho V_m H}{\mu}$	Full-scale values for determining length and velocity scales	
								$G_1$	$G_2$
Small	2	5 to 20	1 to 4	0.5 to 1.5	4 to 7	0.1 to 0.15	$>5 \times 10^5$	50	40
Medium	2	2 to 6	1 to 4	0.5 to 1.5	4 to 13	0.15 to 0.25	$>5 \times 10^5$	200	50
Large	2	1 to 4	1 to 4	0.5 to 1.5	8 to 16	0.15 to 0.25	$>5 \times 10^5$	500	60

**Table 2 Standard “target” tornadoes**

TVG	S	N	$r_{Vm}$ (m)	$r_{Um}$ (m)	$z_{Vm}$ (m)	$z_{Um}$ (m)	$V_m$ (m/s)	$U_m$ (m/s)	$Q_t$ (m/s)	$\frac{r_{Vm}}{z_{Vm}}$	$\frac{r_{Um}}{r_{Vm}}$	$\frac{z_{Um}}{z_{Vm}}$	$\frac{V_m}{U_m}$	$\frac{Q_t}{V_m}$
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 <sup>s</sup>	0.74	0.20	0.12	12.8	6.24*	2.0 <sup>ss</sup>	2.60	1.43	0.6	2.0	0.16 <sup>ss</sup>
UWO (R18)	1.03	2	0.69	0.69	0.20	0.06	16.2	7.78*	2.0 <sup>ss</sup>	3.45	1.0	0.3	2.08	0.12 <sup>ss</sup>

**Table 3 Characteristics of TVGs**

(\* estimate from graph in paper; <sup>s</sup> corrected from 0.42 in R18; <sup>ss</sup> 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))

	TVG size	S	Length Scale (G)			Velocity Scale (K)			Reynolds number / 10 <sup>5</sup> (D)			Criteria satisfied		
			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)	M	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)	L	1.14	94	377	943	4.1	5.2	6.2	0.70	0.18	0.07	G <sub>1</sub> G <sub>2</sub> G <sub>3</sub>	G <sub>1</sub> G <sub>2</sub> G <sub>3</sub>	
ISU (C18)		2.6	89	357	893	3.4	4.3	5.2	0.89	0.22	0.09	G <sub>1</sub>		
TTU (T18)		0.36	278	1111	2778	3.0	3.7	4.4	0.33	0.08	0.03	G <sub>2</sub>	G <sub>1</sub> G <sub>2</sub>	
TTU (T18)		0.84	96	385	962	3.1	3.9	4.7	0.92	0.23	0.09	G <sub>1</sub> G <sub>2</sub>	G <sub>1</sub> G <sub>2</sub>	
UWO (R18)		0.59	96	385	962	3.1	3.9	4.7	0.91	0.23	0.09	G <sub>2</sub> G <sub>3</sub>	G <sub>1</sub> G <sub>2</sub> G <sub>3</sub> K <sub>2</sub>	
UWO (R18)		1.03	72	290	725	2.5	3.1	3.7	1.53	0.38	0.15	G <sub>2</sub> K <sub>2</sub> , D	G <sub>1</sub> G <sub>2</sub>	

**Table 4 Performance of TVGs against standard target tornadoes**

