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Baker, Christopher; Sterling, Mark

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Are Tornado Vortex Generators fit for purpose?

Chris Baker and Mark Sterling

School of Engineering

University of Birmingham

Abstract

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

1. Background

Tornado wind damage to building structures is of concern in many countries around the world, particularly for low rise domestic structures. There has been much recent research activity both to measure tornado characteristics at full scale and also attempts to simulate these flows at model scale using what have become known as Tornado Vortex Generators (TVGs), in order that the wind loading can be measured on suitably scaled models. These TVGs have taken a number of forms but tend to all have similar features, albeit with different 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 majority of the simulators used to date follow the principles of Ward (Ward, 1972), where guide vanes are placed around a convergence chamber akin to the atmospheric sub-cloud inflow layer in a real tornado (although in Ward's 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 immediately above the convergence chamber. The generated updraft and the convection chamber are assumed to be representative of the convective process in a cumulus cloud. Typically, a flow rectifier of some type is also located close to the fans to act as a vorticity sink. The other type of TVG worth noting are those based on the Iowa State University design (Haan et al., 2008). Unlike traditional ward-type simulators, the guide vanes are located near to the return flow of the updraft enabling a rotating flow to be introduced at the inlet. In principle all types of generator can be moved to model tornado translation, although this becomes progressively more difficult as the size of the facility increases.

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 physical scale. We firstly set out a formal dimensional analysis of the issue, and then present a collation of full-scale data in the form suggested by the dimensional analysis. On the basis of this, we define a small number of "standard" tornadoes that can act as simulation targets, and assess whether or 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 only able to reproduce geometrically scaled flows (rather than kinematically or dynamically scaled) at scales and Reynolds numbers that are at best only marginally acceptable for wind loading studies, particularly on low rise 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.

2. Dimensional analysis

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

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

where the symbols are defined as follows.

- Δp 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;
- U_m is the maximum radial velocity;
- Q_t is the translational velocity;
- r_{Vm} is the radial distance from the vortex centre at which the circumferential velocity is a maximum;
- z_{Vm} is the vertical distance above the ground at which the circumferential velocity is a maximum;
- r_{Um} is the radial distance from the vortex centre at which the radial velocity is a maximum;
- z_{Um} is the vertical distance above the ground at which the radial velocity 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;
- k_s is the surface roughness.
- ρ is the density of air;
- μ is the dynamic viscosity of air.

Note that the parameter list contains observed tornado parameters rather than the underlying meteorological properties that cause tornadoes. This is a deliberate choice that has been made, since this paper addresses engineering rather than meteorological aspects of tornadoes. Similarly we do not consider the geometric parameters of the TVGs, such as aspect ratio, since we are interested in the flow that these geometries produce rather than the geometries themselves. The other point that is worthy of mention at this stage is the nature of the boundary layer near the ground. In principle the flow velocities and turbulence parameters in this region are specified by the thickness of the boundary layer, the nature of the flow field above the boundary layer and the 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 independent of each other. At this stage however, we will keep both parameters in the analysis, although it will be seen below that practical considerations require that simplifications be made in what follows.

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

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

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

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.

- $\frac{\Delta p}{\rho {V_m}^2}$ is a pressure coefficient that will include the effects of both the direct wind loading and of the pressure variation in the tornado. If all the other groups are simulated correctly, then this parameter will also have the 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.
- $\frac{r_{Vm}}{z_{Vm}}$, $\frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ are the geometric scale ratios of the tornado.
- $\frac{V_m}{U_m}$ is the ratio of the circumferential to radial velocities. This is the equivalent of the Swirl ratio used by many physical modellers, although the definition of that parameter can vary somewhat between investigators. The Swirl ratio is a dependent variable, and can be defined from the other variables that are listed here. As normally defined, it is a function of TVG geometry, and cannot be defined for full scale conditions.
- $\frac{Q_t}{V_m}$ is the dimensionless translational velocity of the tornado.
- $\frac{\rho V_m r_{Vm}}{\mu}$ is the Reynolds number based on maximum circumferential velocity and the radius at which it occurs.
- $\frac{H}{z_{Vm}}$ is the model scale factor.
- $\frac{H}{R}$ is the ratio of the height of the structure to the distance from the centre of the tornado.
- $\frac{k_s}{z_{Vm}}$ relates the boundary layer thickness and the surface roughness.

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

Reynolds numbers could be defined, based on different velocities and length 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 correctly reproduced. To achieve kinematic similarity in addition $\frac{V_m}{U_m}$ and $\frac{Q_t}{V_m}$ need to be correctly reproduced, and to achieve dynamic similarity $\frac{\rho V_m r_{Vm}}{\mu}$ must also be reproduced. The latter is impossible of course, and at best any physical model simulation can only achieve geometric and kinematic similarity. For a simulation 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 what scale and position of the building relative to the centre of the tornado is used. The last dimensionless group in the list (the surface roughness / boundary layer thickness ratio) is, in principle also a geometric scaling parameter, and, as it will to a large extent determine the boundary layer velocity and turbulence intensity profiles, also a kinematic scaling parameter. However this parameter is very hard to specify, since in most full-scale measurements the surface roughness is difficult to determine, and TVGs usually use a smooth floor, rather than simulated roughness. Thus in what follows this parameter will not be considered further – although it is clear that that more attention needs to be paid to surface roughness in both full scale and TVG measurements.

It would appear from the literature that the only model scale investigations that have recognized the importance of more than one tornado length scale and, 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 model scale simulation, are those of Refan et al (2014) and Refan and Hangan

(2018) for the small and large WindEEE simulators. They have developed a method for matching full-scale tornado data for this ratio against their model scale data at one operating condition in their facilities. Other investigators, as far as can be ascertained use just one length scale to specify the tornado geometry – usually r_{Vm}- or base the scale of the simulation on the scale of the structure that is being tested.

3. Full scale data collation

Table 1 is a collation of full-scale tornado data from a range of sources for two cell tornadoes only. Note that, in line with other authors, we use multiple data sets from the same tornado. There is a danger here that the data will be regarded as non-independent, but as the objective was to define ranges of tornado parameters, it was felt that this was acceptable. Such tornadoes seem to represent the norm, with much less data available for simpler one-cell tornadoes, which seem to have generally lower, less critical wind speeds. The chosen tornadoes are listed by size given by the value of r_{Vm}. Values are given of the dimensional parameters $N, r_{Vm}, z_{Vm}, r_{Um}, z_{Um}, V_m, U_m$ and Q_t , and 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 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 identification of tornado parameter ranges, although they will be considered below.

In most cases the data is incomplete, as some parameter values are not available. As most of the information is taken from radar-based methods, velocities below about 50m above the ground could not be measured and thus the values of the heights at which the maximum velocities occur (z_{Vm} and z_{Um}) may not be truly captured. We have in general taken data from as low a height as possible to use in the analysis. The most recent results by Kosiba and Wurman (2013), which did make measurements at lower heights for the small and relatively low speed Russell tornado, suggest that these heights can be as low as 5m above the ground 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 $\frac{z_{Um}}{z_{Vm}}$, with the former being in the range 1.3 to 3.7 and the latter being generally around unity. Thus the maximum value of radial velocity is 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.

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 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).

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 methodology of defining target ranges for standard tornadoes as being of more practical utility than defining individual tornado events as simulation targets, as such events are only individual realisations of a statistical distribution. Note that there is much subjectivity in this approach, and the parameter ranges for the different types of tornado could have been somewhat differently defined. The ranges that have been chosen represent a smooth transition from one tornado 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 not well defined from the full scale data, the same range has been specified for all tornadoes.

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 $\frac{r_{Vm}}{z_{Vm}}$ fall within the required ranges, and secondary and tertiary geometric similarity (G_2 and G_3) requires that $\frac{r_{Um}}{r_{Vm}}$ and $\frac{z_{Um}}{z_{Vm}}$ also fall within the (less well defined) ranges; primary kinematic similarity requires that the parameter $\frac{V_m}{U_m}$ falls within the required range (K_1) and secondary kinematic similarity requires that the translational parameter $\frac{Q_t}{V_m}$ is within the required range (K_2). As full dynamic similarity (D) is impossible, we specify that the Reynolds number based 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 reproduced. ASCE (2012) suggest a lower value of 1.1 x 10^4 for this parameter, although with a somewhat vaguely defined length scale, and AWES (2016) give a value of 5 x 10^4 based on building width. CEN (2016), for tests on trains in low turbulence conditions, gives a much higher value of 2 x 10^5. Bearing in mind the fact that the Reynolds number as defined above will be the maximum in the tornado and can be very much lower away from the region of maximum velocity, a value of 5 x 10^4 seems an appropriate compromise. Lower values of the Reynolds number would particularly affect the dynamics of separated or building-induced vortex flow regions, and render load measurements, particularly of fluctuating quantities, quite unreliable (Lim et al, 2007).

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.

Table 4 shows a matrix of tornado type against simulator and gives the following 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.

Consider first the Reynolds numbers that are based on a model length of 10m. In nearly all cases these are below the value of 0.5×10^5 specified above. The exception is for the small tornado case for the UWO TVG. The three large TVGs have values for the small tornado of between 0.33 and 1.53×10^5, whilst the medium sized TVG has values of 0.12 to 0.33×10^5. For the medium tornado the values are between 0.08 to 0.38×10^5 for the large TVGs, whilst the medium TVG has values between 0.03 and 0.08×10^5. For the large tornado case the values of Reynolds number do not exceed 0.15×10^5 throughout. The length scales follow the same pattern with length scales that would be regarded as reasonable for atmospheric boundary layer testing of low rise buildings of less than (say) 1:200 is generally only achieved for the small tornado case in the large generators. If we accept that high rise buildings may be tested at a smaller scale, say 1:400, 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 numbers that would only be considered marginally acceptable for small and, perhaps, medium tornado simulations.

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

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

6. Discussion

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

From the above discussion it appears that primary geometric scaling of tornadoes is possible to achieve for a limited range of tornadoes in any one 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 can be of a similar order to the wake of building model and can thus have a major 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 kinematic scalings can be achieved, the simulated scales and Reynolds numbers are smaller than generally required and cannot be considered practical for model scale testing, particularly on low rise buildings. The values of these parameters for the medium sized facility that was considered (the authors' own facility at the University of Birmingham) are particularly poor in this regard – indeed it was this poor scaling performance that led to the investigation described in this paper. However, small and medium sized facilities are very useful in developing 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 similarity of flow around structures at such Reynolds number cannot be guaranteed. Thus it must, regretfully, be concluded that in general TVGs are not fit for purpose and do not provide proper geometric and kinematic scaling of tornadoes at Reynolds numbers high enough to be practical.

There are a number of ways to address this situation. Firstly TVGs can be modified to achieve greater levels of similarity. The geometric scale ratios in 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 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 values of $\frac{V_m}{U_m}$, is more difficult and may require some facility redesign. The Reynolds number issue can be addressed through the use of larger facilities with greater fan power and higher vortex speeds – although this may not be physically or economically possible.

A second approach might be to develop new kinds of facility. For example it is possible to conceive of a partial simulation of tornadoes through the simulation of the near ground wind field only by growing thick boundary layers in curved ducts, with the duct curvature being variable and matched to the curvature of the flow in either stationary or moving tornadoes. This curvature can be calculated from models such as that of Baker and Sterling (2018). The boundary layer depth could be equal to z_{Vm} through various combination of inlet screens and floor roughness. As an added complication a vertical flow could be induced 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 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	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	G_3	K_1	K_2	D	r_{Vm} (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	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	$0.52^{\$}$	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))

	TVG size	S	Length Scale (G)			Velocity Scale (K)			Reynolds number / 10^5 (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_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	G_1		▨
TTU (T18)		0.36	278	1111	2778	3.0	3.7	4.4	0.33	0.08	0.03	G_2	G_1 G_2	▨
TTU (T18)		0.84	96	385	962	3.1	3.9	4.7	0.92	0.23	0.09	G_1 G_2	G_1 G_2	▨
UWO (R18)		0.59	96	385	962	3.1	3.9	4.7	0.91	0.23	0.09	G_2 G_3	G_1 G_2 G_3 K_2	▨
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